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# Biological Effects and Health Implications of Microwave Radiation

## Symposium Proceedings

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Edited by
3a Stephen F. Cleary, ed.
Department of Biophysics
Virginia Commonwealth University

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# EDITORIAL NOTE

The papers included in this printed version of the Proceedings of the Symposium on the Biological Effects and Health Implications of Microwave Radiation were submitted by the authors as written versions of the papers presented at the Symposium. The discussions are verbatim transcriptions of presentations made during the Symposium. Time limitations for publication, unfortunately, did not permit this material to be edited by the speakers. Editorial changes in the transcriptions and in the papers were restricted entirely to minor modifications for consistency of style in an attempt to accurately preserve the sense of the meeting.

## ACKNOWLEDGMENTS

The Department of Biophysics of Virginia Commonwealth University gratefully acknowledges the contributions of the Bureau of Radiological Health of the United States Public Health Service to the inception and conduct of this Symposium.

The members of the Symposium Program Committee: Alvin M. Burner, Allan H. Frey, J. Arthur Lazell, Sol M. Michaelson, Norman C. Telles, and George M. Wilkening must be acknowledged for their contributions in the planning and arranging of the program for the Symposium.

A debt of gratitude is also due to the individuals who served as chairmen for the various sessions of the Symposium, namely: Sol M. Michaelson, Paul O. Vogelhut, Allan H. Frey, George M. Wilkening, and Alvin M. Burner.

# PREFACE

The primary goal of the Symposium on the Biological Effects and Health Implications of Microwave Radiation was to provide an indication of the present "state of the art" in this area. This necessitated the inclusion of much of what has been known for many years, as well as material that is perhaps too new or speculative in nature to be properly evaluated at this time. It is important, however, that these areas of uncertainty and controversy be presented, openly discussed, and that opposed views be contrasted in order to achieve a more realistic picture of the biological effects of microwaves.

Since there is presently a great deal of uncertainty concerning the effects of low-intensity microwave and radio-frequency radiation on the mammalian central nervous system, a concerted effort has been made to include a comprehensive presentation of various aspects of this problem. The majority of the CNS effects on humans have been reported by scientists from the U.S.S.R. and Eastern European nations and it is most unfortunate that, with the exception of Dr. Karel Marha from Praha, Czechoslovakia, these researchers were not present to express their views and discuss their findings at this Symposium. It is most fortunate, however, that reviews of the reported findings of the U.S.S.R. and Eastern Bloc scientists have been included in this Symposium. The difficult and somewhat vexing task of reporting on the results of scientific investigations one is not personally involved in is fully recognized and the contributions in this area are a much appreciated and significant contribution to the Symposium. Hopefully, the questions raised by the dissemination of this information will provide the necessary stimulus for more definitive work in this area in this country.

The rate of progress in the unravelling of the unknown factors in microwave-exposure effects will undoubtedly depend to a significant extent upon the development of new concepts and methods for the quantification of microwave and radio-frequency fields. To this end, an attempt has been made to unveil new measurement parameters as a possible means of reducing the uncertainty presently encountered in this field. The need for improvements in the presently existing measurement techniques is underscored by the complex nature of the electromagnetic fields encountered in the vicinity of nonradiating microwave and radio-frequency devices which increase the difficulty of power-density measurements.

The related problem of measurements standards and standardization of the methods of reporting microwave or r. f. exposure parameters used in biological research is of great concern since, at present, the intercomparison of the data of different investigators studying similar biological effects is in many cases rendered difficult if not impossible. The discussion of the present situation and suggestions for remedies for these difficulties presented in the course of the Symposium will hopefully serve as an impetus for the development of the necessary standards.

Underlying many of the difficulties encountered in the understanding of the biological effects of microwave and radio-frequency radiations is the lack of basic mechanisms of interaction that could, for example, help to explain the reported CNS effects of low-intensity electromagnetic radiation. This difficulty is certainly not unique to the biological effects of this particular type of radiation. It is, in fact, frequently encountered, since our knowledge of the structure and function of biological systems is at present not adequate enough to enable us to fully understand the unperturbed state, much less the effect of stressors on complex biological systems. The theoretical approaches to the understanding of the basic mechanisms of microwave interactions presented in this Symposium will hopefully provide a basis and a direction for a more complete future understanding of such effects.

S.F.C.

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# CONTENTS

# SYMPOSIUM ON THE BIOLOGICAL EFFECTS AND HEALTH IMPLICATIONS OF MICROWAVE RADIATION

## CHAIRMAN'S REMARKS

S. F. CLEARY

*Department of Biophysics, Health Sciences Division,*
*Virginia Commonwealth University, Richmond, Virginia*

The Symposium on the Biological Effects and Health Implications of Microwave Radiation is an outgrowth of an idea presented to the Department of Biophysics of the Virginia Commonwealth University by the Division of Biological Effects, Bureau of Radiological Health, United States Public Health Service. It is not difficult to appreciate the need for a Symposium devoted to this subject since there is a growing need for a better understanding of the biological effects of microwave radiation.

We have attempted, in this cooperative effort with the Division of Biological Effects, to assemble as complete a picture as possible of the various aspects of the subject matter and we feel most fortunate in having elicited the contributions of many of the foremost scientific authorities in this field. It is most likely that controversies will arise during the Symposium as a natural consequence of the incompleteness of our present knowledge concerning the biological effects of microwaves. It is to be hoped that such controversy will provide a stimulus for the attainment of greater insight and further knowledge in this field.

## WELCOME

WILLIAM T. HAM, JR.

*Department of Biophysics, Health Sciences Division,*
*Virginia Commonwealth University*

As many of you probably know, we have within the past year become a part of a new University known as the Virginia Commonwealth University of which the Medical College of Virginia is now the the Health Sciences Division. Our first president, Dr. Warren Brandt, was unable to be here this morning and he has asked me to welcome you in his place. Dr. Brandt will be here for the banquet on Thursday night and he will speak to you and meet with you at that time. Virginia Commonwealth University, and specifically our Department of Biophysics feels very honored to have this distinguished group of scientists at this Symposium. As you all know this Symposium on the Biological Effects and Health Implications of Microwave Radiation is being co-sponsored by the Bureau of Radiological Health, United States Public Health Service, and we are very proud that the Bureau has asked the Department of Biophysics to work with them on this Symposium. I would like to say to begin with that my younger colleague, Dr. Stephen F. Cleary, is entirely responsible for setting up this Symposium in Richmond with the help, of course, of the Public Health Service. I think he deserves a great deal of credit and I certainly have little more to say except that not only are you welcome but we ourselves are proud to have such a distinguished group of people visiting us here in Richmond and I hope this will be a very successful Symposium. I might mention that the Department of Biophysics and for that matter any other department at the Medical College of Virginia is only a short distance from the John Marshall Hotel. If any of you should wish to visit any of these departments you are very welcome to do so. If any of you are interested in visiting the Medical College or seeing any of the activities that are going on there please let me or Dr. Cleary know and we will be very happy to arrange it for you. I hope this will be a successful conference and let me say again that we're very proud to have you.

## INTRODUCTORY COMMENTS

S. F. CLEARY

*Department of Biophysics, Health Sciences Division,*
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I would like to give a few of my own impressions concerning the significance of the Symposium.

I feel there are many questions in the minds of many people regarding the biological effects of microwaves and we hope that some of these will be answered during the course of this Symposium. Certainly we can't expect that all of the questions will be answered but I think that we will do well to put the questions before the group and consider them in the light of the information presented by the Symposium speakers.

One question that I think is quite important is whether or not we fully understand the thermal effects of microwaves. Certainly we know that microwaves can produce thermal damage such as cataracts and there has been a lot of work on thermal effects and I raise the question of the completeness of our knowledge in this area. Do we really know all there is to know about the thermal effects? Another question I think is of great importance is whether or not there are frequency specific effects of microwave radiation either on the cellular level or molecular level. There again seems to be evidence for such effects but how significant these effects are in terms of biological damage is uncertain. Another question that I feel is quite significant is the question of peak power versus average power. There are indications that peak power is a significant parameter in considerations of biological damage yet I don't think we know enough about this yet to evaluate such effects. A very interesting and important consideration is the effect of microwave and high frequency radiation on the human central nervous system. Behavioral effects of microwave radiation, even though they may be of a reversible nature, certainly are of significance in a biological system and such effects should therefore be further investigated.

A consideration that I think will become more important in reference to the future microwave and radio frequency environment is the biological effect of simultaneous exposures to multiple radiation frequencies. Are such effects additive? Are there significant interactions between biological effects and specific combinations of microwave and radio frequency radiations? Another very important consideration is whether or not microwave effects are cumulative. Low level exposure ($<10$ mW/cm$^2$) certainly has not been shown to be very damaging to biological systems in the studies that have been reported in this country. I would like to be able to conclude that this indicates there are no cumulative effects of microwave exposure at low levels, yet I am not so sure that this is a valid statement at this point. Have we really looked for the proper effects?

The significance of the exposure to the alternating magnetic field component of the electromagnetic wave is not completely understood at present. I think we certainly need to look into this further to determine if in fact the magnetic field component of the electromagnetic wave is of significance in the production of the biological effects of microwaves and radio frequencies. It has been generally assumed that the magnetic field is not as significant as the electric field. Have we possibly overlooked magnetic field induced effects? There are no standards for exposure to alternating magnetic fields and this may require additional research before we can definitely assume such standards are unnecessary. Another problem worthy of great consideration is the measurement problem. There are at present no measurement standards set for biological research on microwave or radio frequency effects. Standards are necessary for intercomparisons of the results obtained by researchers in this area. We should come to some agreement as to what field parameters should be measured and reported in the literature.

What are the genetic effects, if any, of microwave or high frequency radiation exposure? Although there are at present no strong indications of genetic effects, can we dismiss such effects from further consideration? In order to answer questions such as this there is, in my opinion, a great necessity to obtain more information on the basic mechanisms of interaction or microwave and high frequency radiation with biological systems on all levels of organization including the molecular, cellular, organ, organ system and organism. We certainly have difficulty interpreting the results of studies in the absence of an understanding of basic mechanisms. For example, the possible effects of microwaves on the central nervous system present a difficult situation since neither basic mechanisms of CNS function or microwave interactions are presently well understood. Basic research on such mechanisms should be of great value in determining whether or not non-thermal microwave effects are in fact of any significance.

These are just a few of the questions that I feel should be considered and I am hopeful that in the ensuing discussions other questions will be brought up so that we will have the problems before us to aid in determining the future research needs in the area of the biological effects of microwaves.

# FEDERAL RESPONSIBILITY IN RADIOLOGICAL HEALTH

JOHN J. HANLON, M.D.

*Assistant Surgeon General*
*Deputy Administrator*
*Consumer Protection and Environmental Health Service*
*Public Health Service*

As one who claims no expertise in the field, it is my understanding that, with respect to knowledge about the effects of microwave radiation, many of those present today have been in the vanguard in this very specialized area of concern. Hopefully, the time spent here will stimulate additional ideas and impetus for venturing further in a region filled with many unknowns which must be carefully evaluated both as to their nature and their implications for man's health.

In reading testimony about microwave radiation during Congressional hearings on the Radiation Control for Health and Safety Act of 1968, I was impressed by the frequent use of such phrases as "no systematic work has been done" . . . "no one knows if" . . . "we do not know if there are other harmful effects" . . . "our present knowledge is limited," and so forth. The testimony pointed up the great need for additional, well-controlled microwave research and the need to develop better standards in order that we might have a sound basis for regulating microwave producing devices.

You, of course, have been familiar for many years with the questions and the problems that are posed by such phrases. In referring to them, I am merely laying the groundwork for making it clear that the Consumer Protection and Environmental Health Service of the Public Health Service anticipates important contributions to result from this Symposium. Therefore, we view this three-day meeting as a potentially very fruitful intellectual exercise on matters affecting a special aspect of consumer interests and the environment. We hope that you will provide important value judgments which will make a positive impact on the activities of the Service's Bureau of Radiological Health in its day-to-day administration of the Radiation Control for Health and Safety Act of 1968—known as Public Law 90-602.

It might be of some value if I briefly reviewed our responsibilities under the Act. The legislation empowered the Secretary of Health, Education, and Welfare to develop and administer a radiation control program for protecting the public from unnecessary exposure to potentially harmful radiation—ionizing, nonionizing, and particulate; and to sonic, ultrasonic or infrasonic waves emitted by electronic products. The delegation of the broad responsibility for administering the Act was made by the Secretary to Mr. Charles C. Johnson, Jr., the Administrator of the Consumer Protection and Environmental Health Service. Thus, while our Environmental Control Administration and its Bureau of Radiological Health are involved with administering the law on the immediate operational level, the Consumer Protection and Environmental Health Service itself is nonetheless vitally involved in meeting the responsibilities of the Act.

We have the responsibility to "assure effective protection for every American against controllable hazards to life in his environment and in the products and services which enter his life." We have a genuine concern for the total well-being of the individual, a person who is not merely a mathematical or statistical integer, or part of an anonymous herd, but a personality, needing protection from potentially harmful situations about which he frequently has little if any knowledge, and against which he more often than not has no means of protecting himself and his family.

What I emphasize is that, in this Symposium as well as in every approach to defining and resolving problems in man's environment, we must come to grips with more than the hypothetical and the scientifically interesting. As the recent maiden issue of Bioengineering News states very pertinently, pure science must now join applied political science in order to have any true relevance for the world of the present and future. We must be prepared to apply our new knowledge promptly to prevent or to overcome specific threats to man's health and well-being.

Viewed from another vantage point, most of us are skillful and professional practitioners in one or another discipline. In areas other than that in which we have our competence, we may be extremely naive and fearful. We need to consider the concerns of people who are not knowledgeable about our disciplines in the same manner we would want them to consider our concerns about the mysteries in which they have special competence.

I do not wish to give even the impression of speaking gratuitously. If my language seems to have acquired a faintly didactic quality, please be tolerant, for my intention is merely to underscore how seriously we in the CPEHS take our responsibilities under Public Law 90-602, the Radiation Control for Health and Safety Act of 1968. The legislation places a much larger responsibility upon us than might superficially appear. It goes well beyond developing and administering a radiation control program per se. The Act requires that we "plan, conduct, coordinate, and support research, development, training, and operational activities to minimize the emissions of and the exposure of people to, unnecessary electronic product radiation." Another part of the Act directs that we shall "collect and make available, through publications and other appropriate means, the results of, and other information concerning, research and studies relating to the nature and extent of the hazards and control of electronic product radiation . . ."

There is a much longer list of responsibilities which have been given to us under the Act, as well as a number of mandated studies which include the evaluation of the effectiveness of current radiological health protection programs, the development of "practicable procedures for the detection and measurement of electronic product radiation," and the determination of "the necessity for the use of non-medical electronic products for commercial and industrial purposes."

These are but examples of the many studies and actions required of us by the Radiation Control for Health and Safety Act. Taken as a whole, the Act is very extensive in its coverage, and was designed to enable the Secretary to meet almost any situation that might arise with respect to developing and administering a program to protect our people from unnecessary exposure to radiation. The point is that, whether or not one agrees with the broad nature of the Act's mandate, it is the responsibility of the Federal agency involved, the Consumer Protection and Environmental Health Service and its Environmental Control Administration, through its Bureau of Radiological Health, to administer the Act and to recommend to the Secretary the establishment of performance standards for radiation emissions whenever it is determined that such standards are needed to protect the public's health.

At this point, I should like to turn your minds calendar back for a few moments. As you probably know, the interest and responsibility of the Federal Government in matters pertaining to radiological health did not begin with passage of the Radiation Control for Health and Safety Act of 1968. It is true that up to that point no Federal agency had true regulatory authority in the field of radiation protection, apart from the authority held by the Atomic Energy Commission, until enactment of the 1968 legislation. But many years ago we saw the beginning within the Public Health Service of concern and action for the protection of the public from unnecessary exposure to radioactivity. The first step in that direction was the establishment of a Radiation Energy Unit within the Public Health Service in 1947. Ten years later, in July 1958, the Surgeon General created the Division of Radiological Health within the Public Health Service. Then, a decade later, in January 1967, the program became the National Center for Radiological Health of the Bureau of Disease Prevention and Environmental Control. Finally, as part of the reorganization of the Department of Health, Education, and Welfare in 1968, the principal agency of the Federal Government for discharging the Government's responsibility for radiological health, except for the specialized role of the Atomic Energy Commission, became the Bureau of Radiological Health of the Environmental Control Administration, within the Consumer Protection and Environmental Health Service. The latter is one of the three components of the Public Health Service, the others being the Health Services and Mental Health Administration and the National Institutes of Health.

It sometimes comes as a surprise to realize that nearly a quarter of a century has elapsed since the Public Health Service's first radiological health unit was formed. In those days, a proper, and sometimes exclusive, concern was with fallout. When a former Surgeon General, Dr. Luther L. Terry, and Dr. Donald R. Chadwick, then Chief of the Division of Radiological Health, coauthored a two-part article on "Current Concepts in Radiation Protection" in the June 23, 1962 issue of the *Journal of the American Medical Association,* they began by saying that "the resumption of atmospheric nuclear tests by the Soviet Union last September (in 1961 that is) and by the United States in April 1962 has renewed official and public concern over radioactive fallout in" the United States. The scope of those two articles on current concepts in radiation protection was reviewed within the context of the fallout problem.

We have passed far beyond that limited approach taken in 1962. But it must be admitted that from the viewpoint of the Federal Government, research into and understanding and control of, problems of radiation protection have not moved ahead as quickly as the technology which has produced the sources and devices which produce the emissions with which the Radiation Control for Health and Safety Act is concerned. It now appears obvious, for example, that our industrial productivity is placing major emphasis on the development of electronic products for the home and industry that will, on the one hand, make life easier and provide more time for leisure, and on the other hand open up new economic vistas and long-range possibilities for industrial development. We have not been nearly as assiduous in assuring that electronic devices that are developed are as safe as possible under any condition of operation. Under such circumstances, it is the necessary role of the Federal Government in radiological health to make certain that the concept of total user safety be incorporated into design specifications. I do not think that a society, a culture such as ours, can accept a philosophy that proposes anything less than that. It would be little less than suicidal for a responsible Federal agency to consider, much less adopt, a point of view that is not geared to protecting the consumer or the user of a device capable of producing unnecessary radiation, or emissions that are not essential to the task for which the device was designed. After all, who can be expected to protect the public as a primary responsibility in radiation matters if not the Federal Government? We would be interested in learning of a really practical alternative.

Let me hasten to add that we do not for one moment minimize the significant role played by radiological health programs at the local and State levels. For many years, those agencies were about the only enforcement arm of the Federal Government's radiological health program. We had no other and we remain indebted to them. Nothing that can be said or may be said about the significance of the Federal responsibility for radiological health can diminish the past contributions or blind us to the importance of the future role of the State and local radiological health agencies in cooperation with the Federal Government, especially under the Radiation Control for Health and Safety Act.

It is obvious, however, that technological and social circumstances have passed the leadership role to the Federal Government in terms of authority to act. There is a rationale for this that is obvious: the problem, standard setting and their enforcement must be dealt with on a nationwide basis, the sources of the problem are interstate in nature as well as international, and the coordination of the bulk of the effort and underwriting of research can probably only be done with Federal funding, plus whatever funds industry may add.

The challenge which confronts the Federal Government in radiological health matters may be gauged in terms of the present size of the electronic products industry, domestic, commercial, and industrial devices; the rate of increase in size of the industry; and the multiplicity of products that can produce unneeded radiation. The nature of the problem may be illustrated, for example, by the case of microwave ovens for home use. The industry is in its infancy. It must direct its appeal to several generations of housewives all of whom were raised to believe in the efficacy and efficiency of the gas range and the electric stove. One cannot easily convert oldtimers to new concepts. But the housewives of tomorrow will have no such psychological restraints. In adulthood they are likely to look upon the microwave oven, for example, as being as essential to their kitchens as were the gas range and electric stove to their mothers. From a most practical viewpoint, it is the women of tomorrow who are of particular interest to the microwave oven industry. They are also of interest to the Federal Government. We want to be certain that electronic products for the home being built upon today's and tomorrow's technology will be as safe as the most carefully developed performance standards can make them. It is the unavoidable responsibility of the Federal Government to make certain that steps to assure such complete safety are taken today.

Naturally, you are concerned with a much broader approach than consumer interests when you consider the question of biological effects and health implications of microwave radiation. This is necessary and understandable. You cannot afford a limited or parochial point of view. For one thing, any potential problems posed by any one microwave consumer device occupies only one small part of the spectrum of possible hazards.

There are, we realize, many applications of microwaves and many areas of their use other than in the home. Among these are in communication and in tracking for aerospace and defense purposes, industrial heating, and perhaps power transmission. Nonetheless, although this Symposium may have taken place without the stimulus of the requirements of the Radiation Control for Health and Safety Act, your deliberations, the record you develop, and the suggestions you make for the future that derive from this Symposium will be viewed in terms of their implications for the health of the individual. We in the Consumer Protection and Environmental Health Service do understand that an effective radiological health program goes far beyond the home and may affect activities that have heretofore been outside civilian-oriented radiological health activities. For that reason, therefore, we are also very much interested in the total contribution which this Symposium will make to our present knowledge and the guidance you will offer us for future efforts in developing required performance standards for devices that emit unneeded microwave radiation.

In closing, let me assure you of my satisfaction in being here and of the fact that our interest extends beyond my words. We will be indebted to you for the results of your deliberations during the next three days.

# PHYSICAL CHARACTERISTICS OF MICROWAVE AND OTHER RADIO FREQUENCY RADIATION

DR. JOSEPH H. VOGELMAN

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## INTRODUCTION

The biological effects and health implications of exposure to microwave and other radio frequency radiation have been under investigation for more than a decade by various investigators in many countries. In order to critically evaluate the reported results, it is essential to understand the physical characteristics of such radiation.

First, it is necessary to understand that the behavior of microwave and other radio frequency radiation is radically different from ionizing radiation (x-rays or nuclear radiations). The photon energy of microwave radiation is so small that there is no ionization when it is absorbed in living organisms. It follows, therefore, that conclusions drawn from ionizing radiation research are not applicable to the microwave case; and when such conclusions are drawn they are almost invariably wrong.

The biological effects of microwave radiation can be divided into two major categories:

a. Thermal effects where the microwave energy is converted into heat in the living organism. These effects can be macroscopic where whole organisms or major portions of organisms are participating in the heat transfer process, or microscopic where a cellular component such as bound water is vaporized by the selective application of the microwave heating.

b. Nonthermal effects are effects which cannot be directly explained by thermal equivalents. Unfortunately, the validity of most of the research reported as demonstrating nonthermal effects is highly suspect, and this author is hard-pressed to accept any of the results to date as being truly nonthermal.

The thermal effects are always a function of the actual average power absorbed by the particular organisms affected and not due to the field density per unit area within which the organism is placed. In the case of pulsed microwave exposures the effect may appear excessive when compared to the average power absorbed, but this is usually found to be the result of the individual pulses being long compared to the biological reaction time. In this latter case, the effect is a function of the peak power.

The so-called nonthermal phenomena include molecular resonance where the molecular bonds are stressed or the cyclic motion of the molecular structure is enhanced or restricted. Even these effects can be considered in thermal terms in the same way as repeated pounding on a metal member at its natural resonant frequency will cause a continually increasing excursion until the member breaks. This type of explanation fits the reported cases of resonance phenomena if the heating is considered in terms of single cycles of microwave energy. It will also fit the nerve excitation experiments if the heating is considered to be in the form of microscopic selective heating such as the vaporization of bound water in the cells. If we accept that the vaporization time of bound water could be as small as one pulse width, the so-called pulse nerve effects can be explained in terms of thermal effects.

All reported cumulative effects from "sub-threshold" doses are questioned by this author because, in every case, the method of establishing the threshold does not withstand critical examination.

The other important area of nonthermal effects includes the whole gamut of Soviet and Soviet-bloc clinical and experimental data concerning effects from field density levels well below the American Safety Standards. This author has been reviewing this literature for the past ten years and has yet to find any report that will withstand critical examination. Either the exposure level and the method of exposure are suspect or the clinical results are hearsay. It must always be kept in mind that no manager of a Soviet Bloc factory or laboratory would jeopardize his position by admitting that he permitted the legal maximum exposure level to be violated. Also, it is important to note that all personnel who work in so-called radiation hazardous areas work fewer hours than other Soviet workers. Furthermore, if you attribute some real or imagined ailment to microwave radiation, you can get the day off with full pay in the Soviet Union. Under these conditions, it proves very difficult to accept the reported results.

## FACTORS AFFECTING BIOLOGICAL RESPONSE TO MICROWAVE RADIATION

The response of a living organism to microwave energy is a function of a wide variety of factors related to the physics of interaction between the recipient body and the source of the radiation. The factors which affect the magnitude and characteristic of the hazard are the following:

a. The frequency of the radiating microwave energy.

b. The power density at the receiving point. This power density is a function of the absolute power of the source of microwave energy, the antenna dimensions and whether or not the measurement is made in the near or far field of the antenna.

c. Reflection characteristics of the surface of the recipient subject and the characteristics of the surrounding environment in so far as such environment contributes to the enhancement of the received signal by virtue of energy arriving from a multiplicity of reflective sources.

d. The ambient temperature in which the subject is maintained.

e. The size of the recipient with respect to the wavelength.

f. The depth of penetration of the incident microwave energy which is a function of the frequency and the dielectric and resistivity properties of the subject.

## SKIN DEPTH EFFECTS

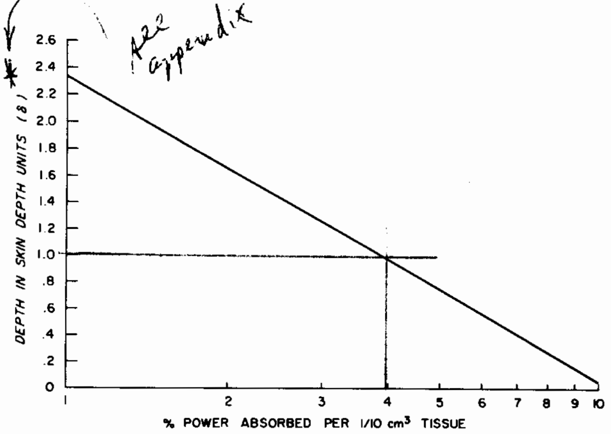

Figure 1. Microwave power absorption as a function of the depth below the surface in a typical living organism.

Figure 1 shows the power absorbed as a function of the depth below the surface in a typical living organism. The units of skin depth for typical living tissue and the percentage of power absorbed is given in intervals of 0.1 $cm^3$ of a volume for a cross section of 1 $cm^2$. It can be seen that for any given incident power density the absorbed power per volume sample would vary from 10% down to well below 1%.

Figure 2 shows the power in the first 0.1 cubic centimeter and in the tenth 0.1 cubic centimeter as a function of the frequency or wavelength and the depth of penetration in centimeters to the point at which 61% of the 10 $mW/cm^2$ power is absorbed. From this curve it can be seen that the power in the tenth volume increment maximizes in the region of 8 GHz and that the total power in each volume unit at this depth would never exceed 0.42 milliwatts. Even in the first 0.1 $cm^3$, the power remains below 2.2 milliwatts at 30 GHz and is less than 1 milliwatt at all frequencies below 3 GHz.

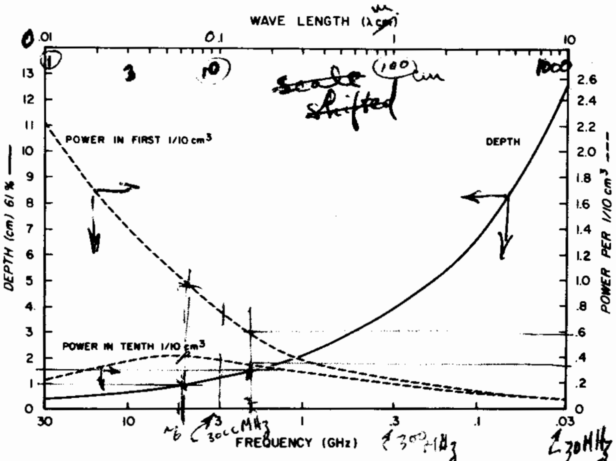

Figure 2. Microwave power in the first 0.1 $cm^3$ and in the tenth 0.1 $cm^3$ as a function of the frequency or wavelength and the depth of penetration to the point at which 61% of the 10 $mW/cm^2$ power is absorbed.

3GHz = 10 cm

10 GHz = 3cm

## REFLECTION EFFECTS

Figure 3 shows the power absorbed as a function of the relative dielectric constant of living tissue. For tissue with high saline content the dielectric constants are well in excess of 20 and the percentage of power available for absorption from the incident field density will not exceed 20%. This implies that in actual radiated cases (not inside cavities or between capacitor plates) the available power to be absorbed for a 10 mW/cm$^2$ field density is less than 2 milliwatts and of that 2 milliwatts the absorbed power in the first 0.1 cm$^3$ volume would be less than 0.2 milliwatts at all frequencies below 5 GHz and not more than 0.5 milliwatts at frequencies as high as 30 GHz.

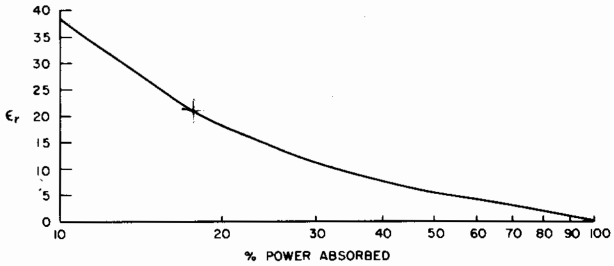

Figure 3. Microwave power absorption as a function of the relative dielectric constant of living tissue.

## ANTENNA EFFECTS

Antenna effects may be divided into two categories; when the recipient subject is in the near field and when the subject is in the far field. The dividing line between near field and far field is a function of the dimensions of the antenna and is equal to twice the diameter divided by the wavelength. In the near field the bigger the antenna the smaller the magnitude of the field density for a constant level of transmitter power. The bigger the antenna, the longer the near field. In the far field, the bigger the antenna, the bigger the field density. The bigger the antenna, the narrower the cross sectional area for which a given field density is present; the field density falling off very rapidly outside the beam created by the antenna aperture.

Figure 4 shows the envelope of near field characteristics of an antenna in terms of the power required to produce 10 mW/cm$^2$ at 40′ as a function of wavelength and the diameter of the antenna required to maintain the near field at that distance.

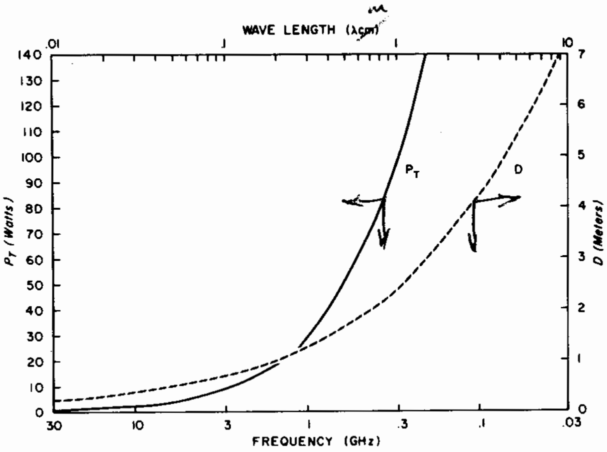

Figure 4. Envelope of the near field characteristics of an antenna in terms of the power required to produce 10 mW/cm$^2$ at 40 ft. as a function of wavelength and antenna diameter.

Figure 5 shows the near field in meters as a function of the antenna diameter and the envelope of power density in mW/cm$^2$ per 100 watts of transmitter input power as a function of antenna diameter in meters. From this data it can be seen that at 100 meters an antenna of 7 meters would have an absolute maximum of field density of 1 mW/cm$^2$ per 100 watts of transmitter input.

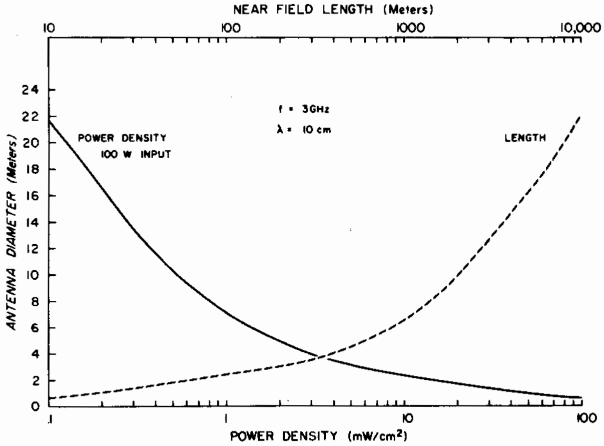

Figure 5. Near field of an antenna as a function of the antenna diameter and the envelope of power density in mW/cm$^2$ per 100 watts of transmitter input power as a function of antenna diameter.

Figure 6 shows the effect of antenna size on the existence of a potential hazard as measured at 100 meters and 14 meters, respectively, from the antenna, per 100 watts of transmitter power. It should be noted that as the antenna diameter in meters increases, a maximum power density is reached after which increasing the antenna diameter results in continually decreasing power density. The beam angle within which a hazard would exist is also shown on the curve as a function of the antenna diameter. This data is furnished for 3 GHz as a typical operating wavelength.

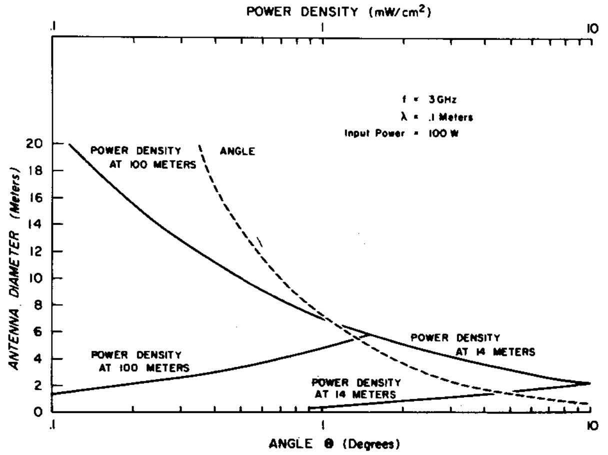

Figure 6. The effect of antenna size on the existence of a potential hazard as measured at 100 meters and 14 meters from the antenna, per 100 watts of transmitter power.

Figure 7 is the envelope within which the power density will oscillate as the subject is moved away from the antenna. This data is plotted for the situation of 3 GHz, a transmitter power of 100 watts, and a diameter square of 40 m². It can be seen that in the near field the envelope stays uniform after which it drops rapidly with distance. The inverse square law is only applicable in the far field.

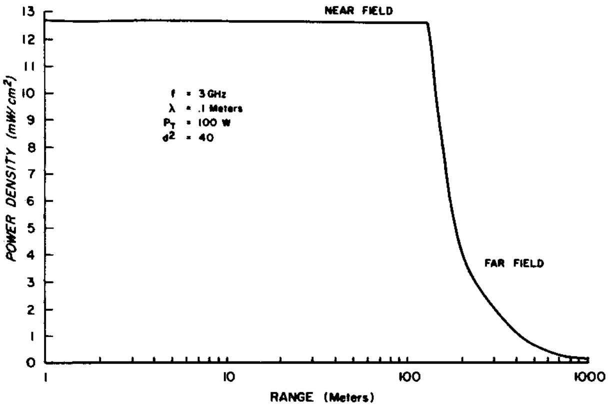

Figure 7. The envelope within which the power density will oscillate as the subject is moved away from an antenna of 40 m²; 100 watts transmitted power at 3 GHz.

## CONCLUSIONS

From the data presented it should be apparent that measurements made in situations other than free fields in the far field radiation pattern of antennas are subject to a great degree of careful evaluation before the numbers produced from the experiments can be translated into real "hazard" situations. Ten milliwatts in a cavity means hundreds of milliwatts of exposure in free space. Too much of the reported research has ignored this very fundamental fact. It must always be kept in mind that the absorbed microwave power in the free field (radiation hazard) is at most a small fraction of the available power density.

## APPENDIX I

for $f = 6\times10^3$ MHz $\cong 60\times10^2$ MHz

Skin depth $\delta$:

$$\delta=\frac{6.61\times10^4}{f^{1/2}}, \cong \frac{6.6\times10^4}{8\times10} \; ? \qquad (1)$$

$= 8\times10^2$

where $f$ is the frequency in megahertz.

Near field:

$$L=\frac{2d^2}{\lambda}, \qquad (2)$$

where the dimensions are in centimeters.

## DISCUSSION

*Dr. Cleary*: I might start the questioning by asking Dr. Vogelman if he would comment on the measurement of lower frequency fields. You primarily restricted your comments to microwaves but since we are also interested in biological effects of high frequency electromagnetic fields I wonder if you would give us some background on measurement problems that are involved in high frequency fields at wavelengths greater than 10 meters.

*Dr. Vogelman*: In general what I said about microwaves applies. The numbers change to the extent that invariably the wavelength is very large compared to the specimen so that you are no longer dealing with fields which are not affected by the character of the specimen. When you are dealing with wavelengths of larger than 10 meters it must be considered that none of the biological specimens are much longer than 2 meters. As a result, the specimen itself changes the field configuration so that if you put a measuring instrument in the field and get a number and then put a specimen in the field you get an entirely different field at the biological specimen. At the present time there is a great deal of controversy as to whether there is a way of making the measurement other than the temperature rise of the biological specimen itself. That might be a good measuring tool.

*Dr. Cleary*: Along these same lines would you suggest that the problem of measurement in biological research with microwaves and high frequency fields could at least partially be solved by calorimetric measurements?

*Dr. Vogelman*: Yes. If you can do this without producing an effect on the field. The typical situation that can arise is that if you put a calorimeter in the biological specimen say at a depth of 10 centimeters to see what the effect is, that device will change the characteristics of the biological specimen.

*Dr. Zaret*: There were two of your graphs I would like to question. The one of wavelength versus penetration and power absorbed. You show smooth functions. I can not believe that this exists biologically.

*Dr. Vogelman*: That is the envelope of the data rather than all of the wiggles.

*Dr. Zaret*: I did not want to leave that point unmentioned. Also you mentioned the penetration of skin in increments of a tenth of a mm. These measurements were not made on live skin, were they?

*Dr. Vogelman*: No.

*Dr. Schwan*: I would like to comment about the depth of penetration. As a matter of fact if you use the knowledge of the electric characteristics which is available and interpret it in terms of absorption coefficient and depths of penetration you will find that at low frequencies the depth of penetration does not increase rapidly as you lower the frequency. At low frequencies the depth of penetration varies approximately as the square root of frequency while at very high frequencies, in excess of 300 megacycles, it varies inversely with the square of the frequency. This means that typically at one megahertz you have a depth of penetration of approximately 4 times larger. But even at the lowest frequencies, for example at 100 kc, the body is by no means transparent, even though the depths of penetration are three times larger than at one megahertz.

*Dr. Vogelman*: What I thought I had pointed out before was that as the wavelength becomes larger with respect to the specimen the depth of penetration rules that are useful at higher frequencies no longer apply and this is what you are confirming. If you deal with human specimens that are under 2 meters, when the wavelength is large compared to two meters your specimen size is small compared to the wavelength and the microwave rules no longer apply. You have absorption as a different kind of phenomena than the skin depth one. I didn't intend to deal with that kind of phenomena at all. I assumed you would.

*Question from the floor*: Several of us who have been involved with microwave ovens were a bit surprised by your graph which describes the variation of hazard as you enter the field. Almost all microwave ovens are most hazardous in the near field in view of the fact that that is where the observer is apt to be. Your statement that this hazard was uniform with distance surprised us. I wondered if you could give us some references or some other work since this is quite at variance with our observation.

*Dr. Vogelman*: This data is based on antennas. When you deal with a microwave oven you no longer deal with an antenna system and you don't have a coherent wave front. For all intents and purposes the microwave oven is a series of antennas of no size at all which essentially means that the near field is somewhere inside the oven and the field drops off as you go farther and farther away. On the other hand, if you had a parabolic antenna the same size as the microwave oven you would have a coherent wave front and you would have a near field effect. Any microwave handbook will show you the near and far field data and I believe the Proceedings of the last Tri-Service Microwave Conference had curves of this data.

*Dr. Saul Rosenthal*: I would like to ask Dr. Hanlon a question. Everybody seems to agree when you pointed out there was at present no coordinated program for research to come up with the answers to all the questions. Is the role of the U.S. Government going to be to set up a program of coordinated research, and if so, when?

*Dr. Cleary*: Dr. Hanlon unfortunately has left. He asked me to direct any questions to him to Dr. Moore.

*Dr. Ray Moore*: In partial answer to the question, the Bureau of Radiological Health is doing what they can in this area through our consultants, our committees, and other activities. We are trying to come up with such a program. I will not promise you any immediate success in the type of coordinated program that I know that the questioner was suggesting other than to say that this is one of the goals.

*Dr. Rosenthal*: Let me ask another question. A number of organizations are interested in this area, for example the Army, the Navy, the Air Force, and the HEW. When I talk of a coordinated program we have to realize that there is only a limited amount of money and it would be sort of silly for each individual organization to go off on its own. Is that being coordinated in that sense?

*Dr. Moore*: We are trying to. We do have good and effective liason and consultation with the other agencies. We have representatives of the organizations you mentioned on our advisory committee. We serve as observers on many of their committees. The attempt is there. How successful we will be time will tell.

*Dr. Alan Shapiro*: I have a comment and that is that at microwave frequencies, when the wavelength is on the order of the overall dimensions of the body, I think the concept of depth of penetration has less significance. In particular in a portion of the body such as the cranium if you have the wavelength of the radiation on the order of the diameter of the skull you can have an induced field inside the skull which can be highly non-uniform. In fact the skull acts like a resonant cavity and there the depth of penetration can be very misleading since the main heat absorption need not be at or near the surface.

*Dr. Vogelman*: I carefully avoided resonance phenomena deliberately because the characteristics are so particularized to the kind of biological specimen you are dealing with that it takes a lot of effort and a lot of time to discuss each one. There are speakers at the Symposium who are going to deal with those specifics and I avoided them.

*Dr. Shapiro*: I wanted to make a distinction here between resonances. It seems to me that when you used the term "resonance" you talked about some molecular phenomena. Here I am talking about gross cavity effects and the concept of depth of penetration can, I think, be misleading in a very sensitive area like the skull.

*Dr. Vogelman*: You're still dealing with energy that is changed in amplitude by virtue of the depth of penetration. On top of this you are adding the resonance phenomena of the physical body and all you're doing is telling me that the field is distorted and I believe it. And I am hoping that somebody else deals with the details.

*Dr. Schwan*: We have discussed the subject matter before and we have published data which pertain to your question. I shall present data on two graphs which pertain to that. The relative cross section, typically of the head or of any object of biological interest, is indeed subject to resonances.

*J. R. Lott, North Texas State University*: As a biologist, I just attended a meeting of the Society of Biometeorology in Switzerland a couple of weeks ago and I see that perhaps I am listening to the same sort of discussion we had there, the main portion of which had to do with standardizaton. As a biologist we are at the complete mercy of the hardware people. Until these people can get together on standardized equipment for generating, aiming, and dimensionalizing in terms that everyone agrees upon, I think we biologists will be stabbing in the dark just as we did in ionizing radiation till we found out what a rad was. I hope that before this meeting is over some committee will be assigned the task of standardizing the procedures, standardizing terminology, and so forth. Other than that I think we will be full of words, full of theory, and sounding nothing.

*Dr. Schwan*: There are a number of standards already in existence. I think that we should not create new standards but modernize existing ones. As a matter of fact, the standards which exist in this country, such as those of the American Institute of Standards, the various military services, and the standards that are in existence in other countries, England, Germany, etc., are quite similar. So I repeat, if we discuss standards we should not neglect what we already have. We should discuss whether we want a change and, if so, why.

# INTERACTION OF MICROWAVE AND RADIO FREQUENCY RADIATION WITH BIOLOGICAL SYSTEMS

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I do not intend to discuss in detail the biophysical principles which pertain to the interaction of nonionizing electromagnetic radiations with biological systems. This we have done in the past, most recently at the meeting that took place in Surrey, England, January 1969. I shall cover the field only briefly but pay some attention to the problems that have not been entirely satisfactorily dealt with. I will particularly concentrate on some topics that are presently of particular interest.

Let me discuss first items that pertain to the biophysics of electromagnetic radiation.

*Dielectric properties of tissues observed at microwave frequencies.*

This area has been very well investigated in the past. We know today the electric properties of practically all tissues, and as a matter of fact, we understand the measured values in terms of structure and function of the tissues. There are only a few things that remain to be done and I will indicate them after I have shown a few typical results.

The dielectric behavior shown in Fig. 1 is typical for tissues of high water content. A decline in the dielectric constant $\epsilon$ with increasing frequency occurs at lower frequencies. Above 100 MHz the curve levels off and then eventually above about 10,000 MHz it drops off again very markedly. The change of $\epsilon$ at lower frequencies is well understood. It is due to the fact that cellular membranes with a capacity known to be about one microfarad per square centimeter of membrane surface affect the tissue impedance at lower frequencies. In the plateau region between 100 and 10,000 MHz the membranes are short circuited and, therefore, become electrically invisible at frequencies in excess of some 100 MHz. I shall remind you later of the fact that the curve comes to a plateau as the membranes are short circuited. The second decline of $\epsilon$ at high frequencies reflects that biological systems contain water and that the dielectric properties of water are subject to change with frequency. Figure 2 shows the specific resistance $\rho$ of blood as a function of frequency. The behavior is again typical of tissues of high water content with a small change of $\rho$ at low frequencies and a very pronounced one at high frequencies in excess of 1000 MHz. The sharp drop at very high frequencies is due to the fact that the conductivity of water changes very strongly at high frequencies.

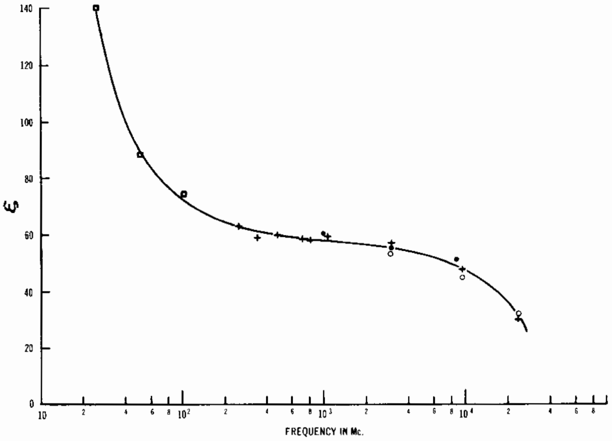

Figure 1. Dielectric constant $\epsilon$ of blood as function of frequency.

Figure 3 relates to fatty tissue. Fatty tissue, of course, has a low water content, and the dielectric behavior of fatty tissues is quantitatively not quite as well understood as that of tissues of high water content since the ratio of free and various types of bound water are not well established. The dielectric constant data are plotted versus the water content, with each point reflecting an experimental deter-

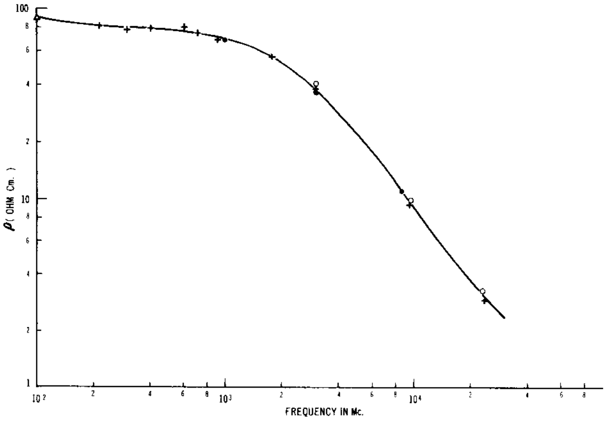

Figure 2. Specific resistance ρ of blood as function of frequency.

mination. The relationship between water content and the dielectric constant is apparent. This is anticipated since water has a high dielectric constant and fat a low one and as the water content of subcutaneous fatty tissue varies a corresponding variation in the dielectric constant must occur. The same arguments apply to the conductivity. In Fig. 4 the conductivity $K$ is plotted against water content with a clear indication of the relationship between water content and microwave conductivity. We have, of course, results as shown in Figs. 3 and 4 obtained at a variety of frequencies and the results are qualitatively always the same with due allowance for the frequency dependent properties of water.

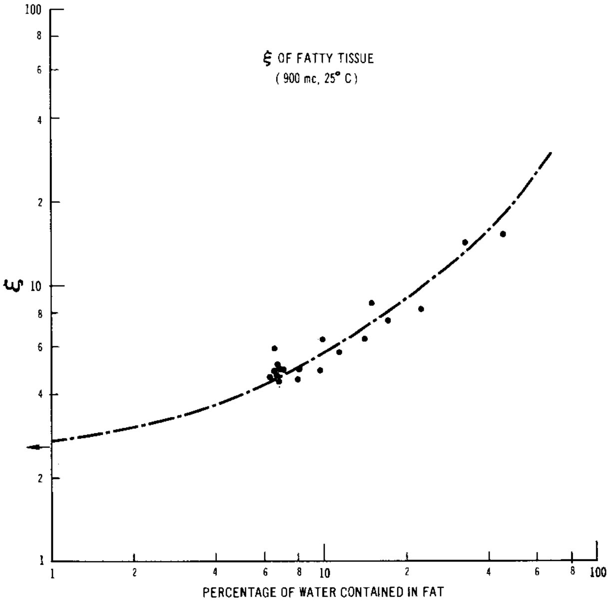

Figure 3. Dielectric constant of fatty tissue as function of its water content. Frequency 900 MHz.

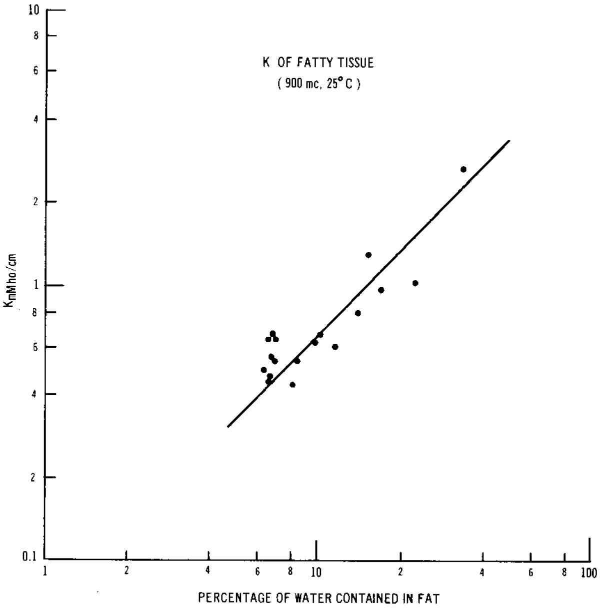

Figure 4. Conductivity of fatty tissue as function of its water content. Frequency 900 MHz.

There is hardly any need for further work on the dielectric properties of tissues at microwave frequencies. All that remains to be done perhaps, is to cast the total knowledge about electrical properties at microwave frequencies in some simple equations. It works out quite simply for tissues of high water content as shown in Fig. 5. Dielectric constant $\epsilon$ and conductivity $K_0$ is observed, say, at 1 or 10 MHz and depends on the salt content. $K_0$ has typically about half the value characteristic of physiological saline solution. Thus from wavelength and weight percentage of macromolecular components in the tissue dielectric constant and conductivity can be predicted at any frequency. The accuracy of the equations in Fig. 5 is better than 10 percent.

In the case of tissues of low water content, such as subcutaneous fat and both yellow and red bone marrow, we are not able, at the present time, to cast our knowledge in such simple equations. The reason is that in the case of lower water content we are not quite sure what the appropriate mixture formulas are or about the state of water. Various forms of water are known to be in existence in tissues, normal water as we know it and "bound"

$$\varepsilon = 5 + \frac{70 - p}{1 + (1.5/\lambda)^2}$$

$$K = K_0 + \frac{70 - p}{60\lambda}\,\frac{(1.5/\lambda)^2}{1 + (1.5/\lambda)^2}$$

Figure 5. Dielectric constant $\epsilon$ and conductivity $K = 1/\rho$ of tissue of high water content as function of free space wavelength $\lambda$. $p$ volume fraction occupied by macromolecules, conductivity $K_0$ at frequency 100 MHz largely reflects salt content.

$$D = \frac{\sqrt{\lambda\rho}}{17} \sim f^{-1/2}$$

for $60\lambda > \varepsilon\rho$

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$$D = \frac{\sqrt{\varepsilon\rho}}{377} \sim f^{-2}$$

for $60\lambda < \varepsilon\rho$

Figure 6. Depth of penetration $D$ of microwaves for tissues as function of free space wave length $\lambda$, dielectric constant $\epsilon$ and specific resistance $\rho$. For large wavelength $D$ varies with $f^{-0.5}$ and for small with $f^{-2}$ ($f$ frequency).

water which is attached to the surface of macromolecular components. Knowledge of the physical properties of bound water as found for instance in fatty tissue is at the present time virtually absent. Last but not least, it ought to be clearly stated, that the above reported behavior excludes any indication of any sort of resonance behavior.

*Depth of penetration.*

Dr. Vogelman (see this volume) has already briefly characterized the typical frequency dependence of absorption coefficients and various related quantities such as depth of penetration as a function of frequency. I have provided these data in the past. Absorption coefficients change with frequency and if one takes all of the results which are available for tissues of high water content and expresses them analytically in terms of $\epsilon$ and $\rho$, one can do so by formulating two very simple approximate expressions which are given in Fig. 6. For wavelengths such that 60 $\lambda$ is greater than the product of the dielectric constant $\epsilon$ and resistivity $\rho$ of tissue, the depth of penetration $D$ varies with the square root of $\lambda\rho$. That means, in view of the fairly frequency independent nature of $\rho$, that the depth of penetration changes at low frequencies $f$ with $f^{-1/2}$, i.e., slowly. On the other hand, if 60 $\lambda$ is smaller than $\epsilon\rho$, the depth of penetration is proportional to $(\epsilon\rho)^{1/2}$, and with due consideration of the frequency dependence of the resistivity $\rho$, proportional to $f^{-2}$. In other words, above approximately 300 MHz, the depth of penetration begins to change rather rapidly with frequency. It eventually declines to a value in the millimeter range at frequencies above 3000 MHz. The expressions in Fig. 6 are not experimental ones. They are mathematically derived with due consideration of actual values of conductivities and dielectric constants and at the same time they are in excellent agreement with known data. The conclusions that we need to draw from the absorption coefficient work are: At low frequencies electromagnetic radiation is fairly penetrating and changes only slowly with frequency, while at high frequencies much in excess of 3000 MHz, the total energy which is absorbed by the body is converted into heat in the skin. As a matter of fact, at about 10,000 MHz absorption coefficients apply which are similar to those for infrared. Indeed, data which have been obtained in the infrared region agree quite nicely with the extrapolated absorption coefficients above 10,000 MHz.

I should say that, in my opinion at least, no further work is needed with regard to absorption coefficients.

*Relative absorption cross section of man.*

The third topic of interest pertains to some questions that have been raised from the floor. What is the effective cross section of the human body to microwaves? This problem also has been studied in our laboratory. Some typical results of Dr. Anne's work are presented in Figs. 7 and 8. Here the relative absorption cross sections of a

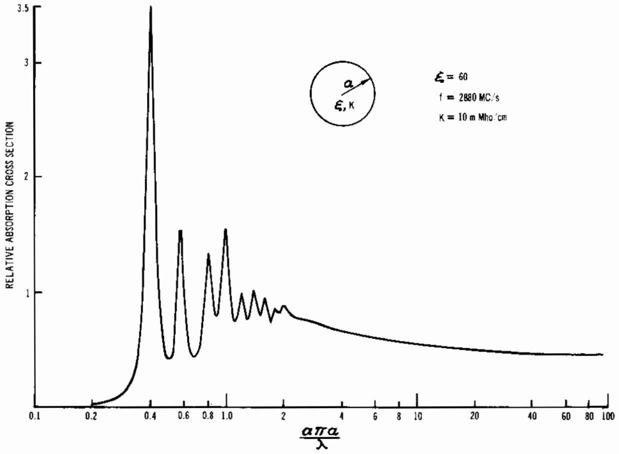


Figure 7. Relative absorption cross section of a sphere. The relative cross section is the ratio of absorbed to incident energy.

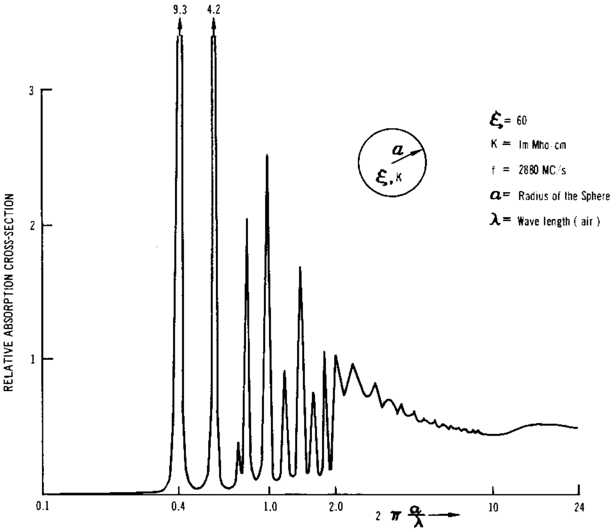


Figure 8. Relative absorption cross section of a sphere. The conductivity of the sphere is 1 mMho/cm while that of the sphere referred to in Fig. 7 was 10 mMho/cm. Note the stronger resonances in the case of the lower losses.

lossy sphere are plotted against its radius *a*. The dielectric constant of the sphere is assumed to be similar to that of tissue, namely 60, and the conductivity $K = 1/\rho$ is equal to 10 and 1 mMho/cm, respectively. The relative absorption cross section has a very low value for small sizes, and it goes through resonances for medium values of $2\pi a/\lambda$. These resonances are much more pronounced in the case $K = 1$ mMho/cm than for 10 mMho/cm. At higher values of $2\pi a/\lambda$ the absorption cross section levels out to a value close to 0.5.

The strongest resonance has a value of nearly 10 in the case of $K = 1$ mMho/cm and a value near 3.5 for $K = 10$ mMho/cm. Tissue conductivity values at 3000 MHz are typically near 25 mMho/cm and resonance behavior is further dampened. The two graphs suffice to illustrate the point that the sort of macroscopic resonance possible for lower $K$-values is fairly well dampened out by biological fluids and therefore, not of any great concern.

All of the work done so far pertains to the overall relative cross section of man. This cross section is defined as the ratio of the total energy absorbed by man divided by the incident energy. It does not indicate anything in regard to the distribution of energy inside man or inside the phantoms which have been used by us to simulate man. There is still after all a possibility that there may be, given proper excitation frequencies, selective hot spots which may be created somewhere inside the body, even though the relative absorption cross section of the body does not indicate a sharp resonance behavior. I believe that the reported cross section data strongly imply that we do not have to worry too much about structural resonances but we should check this possibility nevertheless, particularly at lower frequencies where depth of penetration values are larger, thus enhancing the possibility of states of resonance. A good deal of this work can be carried out by calculations for simple shapes such as cylinders or spheres, provided appropriate dielectric constants and conductivities are used. I believe that this, while not an extremely urgent task, is an interesting task and should be undertaken to determine whether there can be spatial resonances which lead to hot spots of energy at particular frequencies and particular parts of the body.

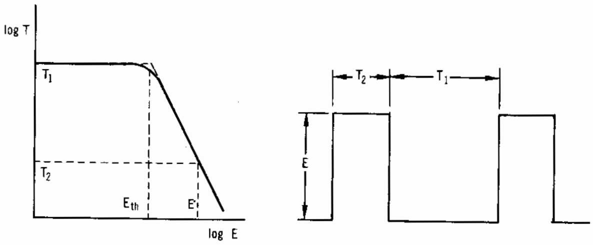
## NONTHERMAL EFFECTS

Some people feel that a definition is lacking regarding thermal and nonthermal effects. I believe the difference between thermal and nonthermal effects can be very simply stated. We deal with thermal effects of microwaves if the microwave field does not directly interact with the biological medium but merely heats it, i.e., interacts with the biological media via the thermal route. In other words, thermal effects are present if the heat, irrespective of its genesis, creates the biological effect and not the field itself. Nonthermal effects occur when the electric field or the accompanying magnetic field interact either on a molecular or a macroscopic level. The existence of nonthermal effects has been controversial. Many dubious results have been reported in the field. Starting some 40 years ago, the old Viennese school was interested in homeopathic treatment with diathermy and hundreds of papers have appeared that purport to report the existence of nonthermal effects. I think it is important to make sure that whatever work is done in this area is of good quality and instills confidence. It seems to me to merely expose a test animal or an enzyme at a particular frequency, or set of frequencies, and hope for some results is a shot gun approach. I think the past 40 years have clearly indicated that the statistical likelihood of hitting in the dark is extremely remote. What is needed is research probing into basic mechanism which might affect biological systems on a nonthermal basis, either on the microscopic or macroscopic level. I shall now report about some pertinent attempts in our laboratory.

*Field evoked force effects.*

We have been interested particularly in one class of effects, we call them field evoked force effects. Here we are concerned about the forces which are evoked by alternating electrical fields, acting on blood corpuscles, protein molecules, or whatever else it may be. It is well established that DC electrical fields can evoke forces. Thus, in several physics texts you can find formulas appropriate for the DC case. We have been able to extend this work to the AC case and discuss various manifestations of field evoked forces. It was an undertaking extending over 10 years and its results have been published and reported at several occasions. One outcome of this work was that we understand a variety of observations that have been made by various groups of investigators, as for example, the phenomenon of pearl-chain formation as observed for the first time in the 1920's and, more recently Heller's observation of the orientation of unicellular organisms in electric fields. On the basis of simple physical principles one can calculate the electrical potential energy that the particles are subject to. Evoking then the well known principle that any system will tend to minimize its potential energy, one is then able to predict precisely the sort of phenomena that have been observed, such as pearl-chain formation and orientation of particles. The outcome of this work is that for biological cellular particles, one needs fairly high field strength values to obtain a force effect, say of the order of 100 V/cm. For macromolecules even higher field strength values are required. This has to be compared to the tolerance standard of 10 mW/cm$^2$ which corresponds to 2 V/cm in free space or 0.2 V/cm in tissue. Clearly, at 100 V/cm, associated heating becomes excessive. Thus in the presence of a continuous alternating field one cannot obtain nonthermal field force effects at field strength values which are thermally insignificant.

There is one more problem, however, which has not been entirely dealt with in our presentations of the past. It is the question of whether there is a difference between pulsed fields and CW fields. Very recently we have been interested in relevant experimental research. Saito has estimated the speed with which systems respond to field force effects. He found that the speed associated with field force effects varies inversely with the square of the applied field strength as indicated in Fig. 9, provided that the field strength is larger than the threshold field strength $E_{th}$ which is needed to overcome Brownian disturbance. At lower field strength, the time constant $T$ characterizes the speed with which pearl-chains break up. In this case $E<E_{th}$, $T$ varies but little with $E$. Our recent work was experimental, checking whether the time constant which characterizes the speed of pearl-chain formation changes inversely with $E^2$ and the results are in excellent agreement with the theoretical prediction; the time constant varies indeed inversely with the square of the field strength. I would suspect that what we have observed in the case of pearl-chain formation is of rather general validity. After all, the product of $E^2T$ is the total minimal energy which has been applied in the presence of a field $E$ to affect the force effect of interest. It is proportional to the energy expended on the particles of interest and subjected to the force effect of interest, where the proportionality factor is only a function of particle geometry and electrical properties but not of $E$ and $T$. The energy expended on the particles should be independent of



$$E^2\ T_1\ \text{const.} \longrightarrow \frac{T_2}{T_1} = \left(\frac{E_{th}}{E}\right)^2$$

$$\text{Average Energy} \sim \frac{T_2\ E^2}{T_1+T_2} = \frac{1}{\frac{1}{E^2}+\frac{1}{E_{th}^2}}$$

$$E > E_{th} \longrightarrow \text{Average Energy} \sim E_{th}^2$$

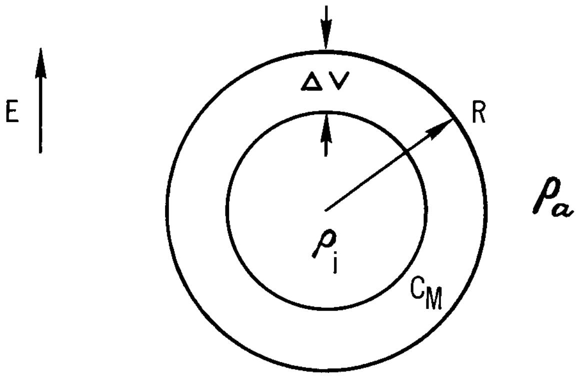
Figure 9. Upper left: Field strength dependence of the time constant $T$ which states how rapid a field force effect occurs. $E_{th}$ is the threshold field strength needed to evoke a field force effect. Upper right: A particular pulsing manner, where $T_1$ and $T_2$ are chosen equal to the time constants with and without field, will optimize the likelihood of a force effect without undue concomitant heating (see text). The equations indicate how in this case only the average energy determines the force effect.

$T$ and, hence, $E^2T$ should be constant. The consequences of this argument are far reaching as will be shown next.

We shall prove that as far as any field induced force effect is concerned, a pulsed field can be no more effective than a CW field of equal average power. We apply a pulsed field as indicated in Fig. 9. The ratio $T_2/T_1$ is given by $(E_{th}/E)^2$ provided we choose $T_2$ and $T_1$ to optimize our chances to get a nonthermal field force effect, and to minimize the likelihood of heating. We accomplish this by applying the pulse over a period $t_2$, where $t_2$ is to be chosen equal to the time constant $T$ that is needed to get the effect. If the time $t_2$ would be smaller than $T_2$ we could not obtain a force effect, since the time required for an effect would be longer than the time of applying the field. And if $t_2$ would be greater than $T_2$, needed energy would be wasted to heat. As the field induced force effect takes place we switch the field off and then let the system rest for a period of time $t_1$. $t_1$ is chosen equal to the time constant $T_1$ that corresponds to threshold field strengths; in other words, the time when the force effect just begins to disappear. Thus, we apply the field, and the moment we obtain the force effect of interest, we switch the field off. Then we wait so long that the effect just begins to disappear but before it does, we give the system another burst of energy. Clearly under such circumstances we get minimal heating and optimal likelihood for a sustained effect. Under such conditions it is easy to calculate the average energy as indicated in Fig. 9. It is, of course, given by $E^2T_2$ divided by the total time $T_1+T_2$. Since $E$ is greater than the threshold field strength, the average energy is simply proportional to the square of the threshold field strengths no matter how $T_1$ and $T_2$ are chosen; i.e., the field force effect is simply given by the rms value of the applied field. Since the times $t_1$ and $t_2$ were chosen to enhance the possibility of a field force effect without unnecessary heating, we conclude that one cannot increase the likelihood of field force effects by pulsing. Not much remains to be done in the area of field force effects. Perhaps the conclusion that pulsing does not enhance such effects needs to be checked experimentally. We also believe that the phenomena of RF-hearing is a field induced force effect, acting on the total head or on the macroscopic sized middle ear structure. It would be of interest to have this further investigated.

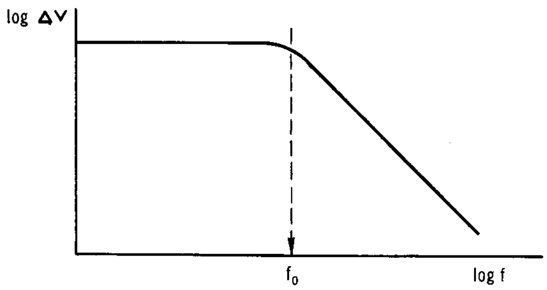
*Excitation of biological membranes.*

I alluded before to the fact that membranes are short circuited by currents of high frequency. Straightforward application of Laplace's equation permits the calculation of the potential $\Delta V$ evoked across the membrane of a nerve fiber in the presence of the field perpendicular to the direction of its axis. The result is given in Fig. 10. $C_M$, the capacity of the membrane, has the usual value of about 1 $\mu$f/cm$^2$, as is well established in neurophysiological work. Figure 11 shows the frequency dependence of the potential $\Delta V$ evoked across the nerve membrane. $\Delta V$ is frequency independent at low frequencies and decreases above a certain cut-off frequency. The cut-off frequency $f_0$ is given in Fig. 11. $f_0$ is usually smaller than 1 MHz. Introducing typical values of $\rho_i$, $\rho_a$, and $C_M$ one obtains potentials $\Delta V$ which are about $10^5$ or $10^6$ times smaller than the resting potential. According to all modern concepts of neurophysiology about excitation this just cannot stimulate nerves. Let me state it another way. The electrical field strength which exists in a nerve membrane is something like 500 kV/cm. The field strengths applied by a microwave field to the human body are infinitely smaller and, hence, cannot evoke stimulation.



$$\Delta V = \frac{2RE}{\sqrt{1+\left[\omega C_M R(\rho_i+\rho_a)\right]^2}}$$

Figure 10. Alternating potential $\Delta V$ evoked across a membrane by a field $E_0$ directed perpendicular to the axis of the membrane surrounded nerve cell. $\rho_i$ and $\rho_a$ specific resistances inside and outside the membrane, $C_M$ membrane capacitance per cm$^2$ surface area, $\omega$ angular frequency, $R$ cell radius.



$$f < f_0 : \Delta V = 2RE$$

$$f > f_0 : \Delta V = \frac{2E}{\omega RC_M(\rho_i + \rho_a)}$$

$$f = f_0 \longrightarrow \omega RC_M(\rho_i + \rho_a) = 1 \longrightarrow f_0 R \sim 500$$

Figure 11. Frequency dependence of $\Delta V$. At low frequencies $f<f_0$, $\Delta V$ can be some mV for a field $E_0=1$ V/cm and, hence, may excite upon appropriate rectification. However, at frequencies $f>f_0$, $\Delta V$ is very much smaller and excitation appears impossible. The equation for $f_0$ indicates a value below 1 MHz. For further details, see text.

*Macromolecular resonance.*

There are strong indications that macromolecules cannot be excited in tissue fluids. On the other hand their degraded state, resulting from the viscous damping and the electrical losses of tissue electrolytes, has been observed and discussed in great detail. Much is known about the relaxational behavior of cells, tissues, and macromolecules and its manifestations, frequency dependent dielectric constant and conductivity are well investigated. It has not so far provided a base for the postulate of destructive resonant effects caused by thermally insignificant fields.

We have shown above that mechanisms which come to mind are not likely to cause nonthermal effects on membranes, cells and biological macromolecules. This statement applies under conditions of practical interest, i.e., they pertain to biological structures in the human body, surrounded by biological fluids and electrolytes and they pertain to field strength levels which are not thermally dangerous and below very approximately 1 V/cm. However, convincing as these arguments may be, they cannot rule out the possibility of nonthermal actions based on principles not yet considered. Much work has been published in support of this contention, even though its quality leaves much to be desired and it has been subject of criticism. Some of this abundant work was conducted almost 40 years ago, other work rather recently. We do not propose that additional, poorly conducted work, be added to this literature body of doubtful value. But we do propose that an effort is made to duplicate some of this work, under conditions which inspire confidence. We specifically recommend that some of the Russian work be repeated in order to check the validity of the basis of the Russian low standards of exposure.

## STANDARDS OF SAFE EXPOSURE

Present western standards are all in terms of flux levels. I personally believe strongly in the validity of the 10 mW/cm² figure in far-field configurations and I have not seen anything to make me think it was a poor suggestion. In the presence of more complicated field geometries, of course, the concept of a flux breaks down. What is the hazard to a person near the foot of a perpendicular antenna where only a magnetic field but no *E*-field exists? And how do we deal with near-field configuration, or the hazard in fields resultant from several sources? I am prepared to present what appears to me the only rational approach to the problem. Whatever biological damage results on a thermal basis is, of course, caused by the currents which are induced in the biological system of consideration. Let us briefly indicate what current densities might be significant. A total body tolerance is implied by the 10 mW/cm² figure. We assume one side of the human body completely illuminated, i.e., about 1 m². Thus the total

Total body tolerance

$$10\ \mathrm{mW/cm^2} \times 10^4\ \mathrm{cm^2} = 100\ \mathrm{W}$$

$$= \sim 1\ \mathrm{mW/cc}$$

Heat generated by current equal if

$$j^2\rho = 10^{-3} \longrightarrow j^2 = 10^{-5} \longrightarrow j = 3\ \mathrm{mA/cm^2}$$

For $f < 100$ Kc: 1 mA/cm²

For $f > 1$ Gc: > 3 mA/cm²

TOLERANCE Current Density

$$\underline{\underline{3\ \mathrm{mA/cm^2}}}$$

Figure 12. Tolerance current density calculation. The calculation is based on a tissue resistivity of 100 Ohm-cm, typical for the frequency range between 100 and 1000 MHz. Different values apply outside this frequency range and necessitate different tolerance current levels below 100 KHz and above 1 GHz. For RF- and VHF-range a tolerance current density of 3 mA/cm² is suggested.

thermal load is about 100 W, or 1 mW/cm$^3$ body tissue. Now let us simply calculate what current density $j$ in tissues correspond to this. Quite obviously the product $j^2\rho$ ($\rho$ resistivity) has to be equal to 1 mW/cm$^3$. Introducing typical $\rho$ values, the current density derived is near 3 mA/cm$^2$. The total argument is summarized in Fig. 12. At frequencies below 100 kHz, the figure should be somewhat lower and for figures above 1 GHz it can be greater than that value. What I propose with regard to standard work is to set as a guideline the concept of a minimal permissible current density induced in tissue. Then for each field configuration of interest one can discuss what this implies with regard to external fields.

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Support for this extended systematic effort has been provided primarily by the Office of Naval Research (Contract Nonr 551-05). Without its continued interest this program would not have been possible. Air Force Contract AF 30(602) has aided us in undertaking the expensive work on relative absorption cross section studies. Much of the basic work on tissue impedance and on dielectric properties of macromolecules was supported by NIH Grant 1253.

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[1] The letter (S) indicates review and survey papers.

# HEAT STRESS DUE TO R. F. RADIATION[1]

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## SYMBOLS AND ABBREVIATIONS

$C$ = heat loss or gain due to convection, in watts
$E_{\max}$ = maximum evaporative capacity of a standard man, in watts
$E_{\text{req}}$ = actual heat load on a standard man, in watts
ET = effective temperature, °C
$f(W)$ = heat gain due to absorption of r. f. energy, in watts
HSI = heat stress index of Hatch, Belding, and Haines
$M$ = metabolism, in watts
$P$ = vapor pressure of the moisture in the air, in millibars
$R$ = heat gain due to radiation in the infrared and visible spectral regions, in watts
RH = relative humidity
RPG = radiation protection guide for r. f. radiation; presently 10 mW/cm$^2$ for normal environments
$t_d$ = dry-bulb thermometer reading, °C
$t_g$ = Vernon globe thermometer reading, °C
$t_w$ = wet-bulb thermometer reading, °C
THI = Thom's temperature-humidity index
$V$ = air velocity, in meters/min
$W$ = r. f. power density, in mW/cm$^2$.

## INTRODUCTION

Recently the United States of America Standards Institute published a standard (USAS C95.1-1966) relating to the Safety Level of Electromagnetic Radiation (10 MHz to 100 GHz) with Respect to Personnel. The sponsors were the U.S. Department of the Navy and the I.E.E.E.

The recommendations contained in the standard are consistent with previously established limits (1), with two new stipulations. One establishes a time period of 6 minutes over which the power is to be averaged. The other is qualitative rather than quantitative, and states that the "Radiation Protection Guide (RPG) number (10 mW/cm$^2$) should be appropriately reduced under conditions of moderate to severe heat stress."

It is the purpose of this paper to record the results of a brief study undertaken to evaluate in a quantitative way the heat stress due to microwave radiation. A further objective was to attempt to establish a simple, reasonable, and quantitative reduction factor for the RPG number under adverse thermal environmental conditions.

## SUMMARY

In the following paragraphs, the conclusions are stated first. The proposed reduction of the RPG number is based upon the temperature-humidity index (THI), which is then defined. A simple approximate formula for the THI based on the temperature and the relative humidity (RH) is presented.

The proposal is then examined in terms of the heat stress index (HSI) of Belding, Haines, and Hatch (2, 4), modified to take into account r. f. radiation.

Finally, the proposal is examined in terms of effective temperature (ET), and it is seen to yield a "safety factor" reasonably independent of temperature and humidity.

## CONCLUSIONS

The results may be presented briefly as follows:

### *Heating by r. f. Power*

1. 10 mW/cm$^2$: An incident power density of 10 mW/cm$^2$ will produce heat in a (standard)[2] person

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[1] This paper originally appeared in Proceedings of I.E.E.E., Vol. 57, 1969, and is being used with the permission of the Institute of Electronic and Electrical Engineers.

[2] A "standard" man is defined later.

at the rate of about 57.5 W if all the incident power is absorbed. This may be compared with the basal metabolic rate of 73–88 W for a person at rest, and with 293 W for a person engaged in moderate work.

2. 1 mW/cm$^2$: On the same basis, an incident power density of 1 mW/cm$^2$ is equivalent to 5.75 W. This is less than 10 percent of the average basal metabolic rate and, hence, may be considered almost insignificant from the standpoint of heat production.

### *Proposed Reduction*

With 1 mW/cm$^2$ as the lower guide number limit for hot environments and 10 mW/cm$^2$ as the upper guide number limit for normal environments, the proposed reduction for moderate to severe heat stress is based on the THI.

When the THI is 70 or less,

$$\text{RPG}=10\ \text{mW/cm}^2; \qquad (1)$$

When the THI is between 70 and 79,

$$\text{RPG}=(80-\text{THI})\text{mW/cm}^2; \qquad (2)$$

When the THI is 79 and greater,

$$\text{RPG}=1\ \text{mW/cm}^2. \qquad (3)$$

In other words, the RPG number is reduced by as many milliwatts per square centimeter as the THI exceeds 70. For example, if the THI were 75, the guide number would be 5 less than 10 mW/cm$^2$, or 5 mW/cm$^2$.

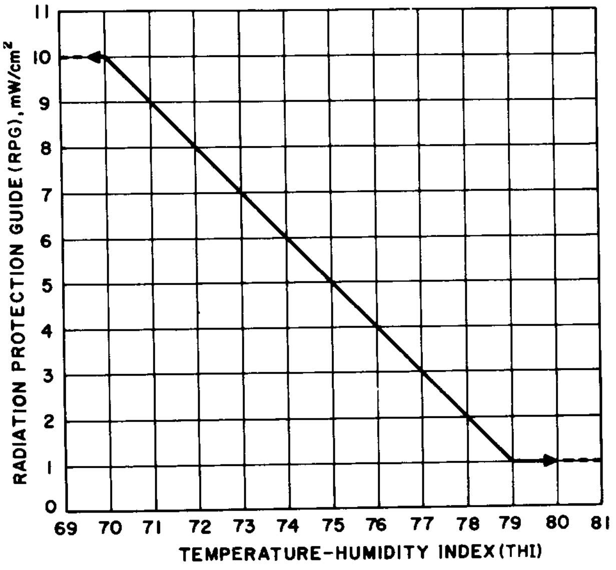

Figure 1. Proposed radiation protection guide versus temperature-humidity index.

A plot of this relationship is shown in Fig. 1. Note that below a THI of 70, the guide number is 10 mW/cm$^2$, and above 79 it is 1 mW/cm$^2$.

Note also that the time interval over which the power is averaged remains fixed at 6 minutes. This is shown graphically in Fig. 2, where the proposed RPG is plotted as a function of time for various temperature humidity indices.

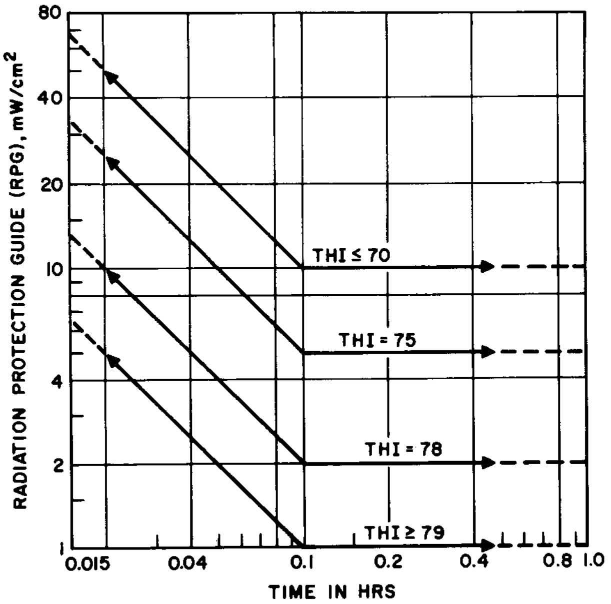

Figure 2. Proposed radiation protection guide versus time for temperature-humidity indices as indicated.

## TEMPERATURE-HUMIDITY INDEX (THI)

The temperature-humidity index was first proposed by E. C. Thom (3), Office of Climatology, U.S. Weather Bureau, Washington, D.C., and is considered a significant factor for the evaluation and monitoring of synergistic stress (11, 12). It seems to be the most widely quoted of all the indices that have been proposed to express human comfort. Thom originally defined the THI in terms of the dry-bulb and wet-bulb temperatures in degrees Fahrenheit, thus:

$$\text{THI}=0.4(t_{df}+t_{wf})+15. \qquad (4a)$$

Changing the temperature readings from Fahrenheit to Centigrade gives

$$\text{THI}=0.72(t_d+t_w)+40.6, \qquad (4b)$$

where $t_d$ is the dry-bulb temperature, and $t_w$ the wet-bulb temperature, both in degrees centigrade.

An approximate expression is derived in the Appendix to relate the THI to the relative humidity (RH), thus:

$$\mathrm{THI} = 1.44t_d + 0.1\ \mathrm{RH} + 30.6. \qquad (5)$$

This approximate expression is exact when the RH is 100 percent. At 50 percent RH, the error is less than 1 percent when the THI is between 70 and 80. At 30 percent RH, the error may be as high as 3 percent when the THI is 80. Another expression derived by Kahn et al. (11), which is more accurate at low humidities, is quoted in the Appendix.

## ASSESSMENT OF THE HEAT STRESS DUE TO ABSORPTION OF R. F. ENERGY

A general expression to characterize the heat stress of a particular individual would depend on the following factors (2):

$M$ = rate of metabolic heat production within the body
$D$ = rate of change of body heat content
$U$ = rate of heat exchange by respiration
$R$, $C$, and $E$ = rates of heat exchange with the environment by radiation $R$, convection $C$, and evaporation $E$.

Haines and Hatch (2) conclude that $D$ and $U$ are insignificant, and proceed to obtain mathematical descriptions of the remaining factors under specified conditions as functions of globe temperature, wind velocity, and rate of metabolic heat production. They ignore r. f. radiation, however.

To avoid the complication of body size, they define a standard man. To avoid the complex problem of the effects of clothing, the rate of heat exchange by evaporation is established for a nude standard man, completely wetted.

These mathematical descriptions are then used by Belding and Hatch (4) to propose a heat stress index (HSI) in terms of 1) thermal load which is imposed on a standard man, 2) capacity of the environment to accept the load, and 3) physiological capacity to meet the demands over a period of 8 hours. The standard man represents a composite of young, fit, acclimatized men who have been subjects of physiological investigation of the effects of heat in the laboratory and in the field. He is defined as having a total body area of 1.858 $m^2$ (applicable to a man about 1.73 m tall who weighs 69.85 kg), and having a skin temperature of 35 °C. The equivalent surface of the body from which heat is exchanged by convection and evaporation is 1.81 $m^2$, and by omnidirectional radiation 1.44 $m^2$. For unidirectional radiation, such as microwave radiation, the geometric cross-sectional area, or the projected area, is taken as $1.81/\pi$ $m^2$. This is quite appropriate, since the limbs and the torso of the human body are not too different from circular truncated cylinders with axes normal to the incident radiation (6).

The Belding–Haines–Hatch HSI is probably as good as any other index for the purpose of evaluating the heat stress due to r. f. radiation; it lends itself readily to a modification that includes the r. f. heating. It is defined as the actual heat load $E_{\mathrm{req}}$ expressed as a percentage of the maximum evaporative capacity $E_{\max}$.

The heat load includes body heat production resulting from metabolism $M$, heat loss or gain due to infrared and visible radiation $R$, and heat loss or gain due to convection $C$. Normally, for comfort, the heat load is zero. Since $M$ is always positive, then $R+C$ must be negative:

$$E_{\mathrm{req}} = M + R + C = 0 \text{ for comfort.} \qquad (6)$$

By making use of data taken at Fort Knox by Nelson et al. (5), and by making some simplifying assumptions, Belding and Hatch relate $R$ and $C$ to

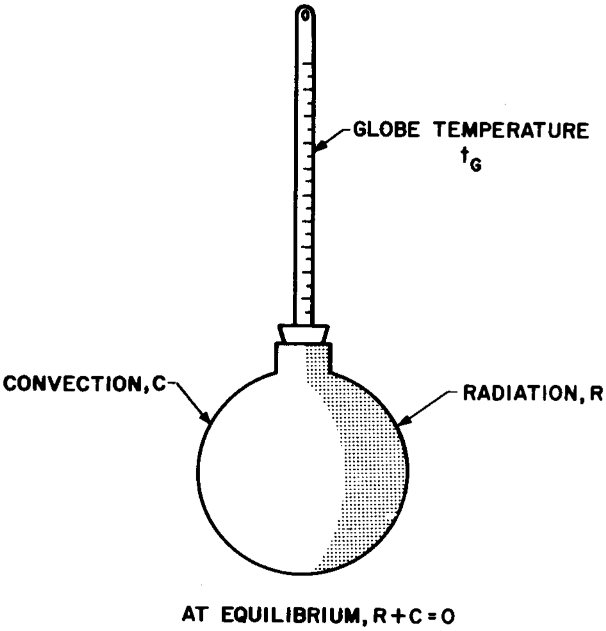

Figure 3. Vernon globe thermometer.

the globe temperature (when international units are used), thus:

$$R+C=[11.6+1.91(V)^{1/2}](t_g-35) \text{ watts,} \quad (7)$$

where

$R$ = heat radiation gain by the body (not including r. f.), in watts
$C$ = heat convection gain by the body, in watts
$V$ = air velocity, in meters/min
$t_g$ = globe temperature reading (including the effects of convection as well as heat and light radiation), °C. It is the air temperature if the surrounding walls and the air are at the same temperature and there are no other sources of radiation; and it consists of an ordinary thermometer encased in a spherical absorbing globe (see Fig. 3).

## MODIFICATION FOR R. F. RADIATION

If there is a source of r. f. radiation present

$$E_{\text{req}}=M+[11.6+1.91(V)^{1/2}](t_g-35)+f(W, S), \quad (8)$$

where $f(W, S)$ is the heating in watts due to absorption of r. f. radiation. It is a function not only of the power density $W$, but also of the relative absorption cross section $S$ of the subject. Here we are considering the subject to be completely immersed in the r. f. field, as one might be when exposed to the radiation from a large radar antenna. Localized exposures that do not exceed the RPG will surely result in less insult than total immersion.

Salati, Anne, and Schwan (6) have defined a relative absorption cross section $S$ as the ratio of the average power absorbed from the incident field by an object to the average power incident on the object's geometric cross-sectional area prior to its insertion into the field. From their theoretical and experimental work with artificial bodies representing men, they conclude that values of $S$ between 0.50 and 1.25 may be expected for man in the frequency range of biological interest, 300 MHz to 10 GHz. We shall assume an average value of 1.0 for $S$. Ordinary cloth fabric clothing will not alter this appreciably.

Taking $1.81/\pi$ or 5.575 m² as the equivalent surface of the body then yields

$$f(W, 1) \text{ in watts}=5.75W, \quad (9)$$

where $W$ is the power density in mW/cm². Then (8) becomes

$$E_{\text{req}}=\text{M}+[11.6+1.91(V)^{1/2}](t_g-35)+5.75W. \quad (10)$$

When $E_{\text{req}}$ becomes greater than zero, the body starts to dissipate the extra load through the evaporation of perspiration. By making some reasonable assumptions, Haines and Hatch (2) have established empirically the maximum evaporate capacity of a standard man in terms of the air velocity and water-vapor pressure. It is given by the relation

$$E_{\max}=3.52(V)^{0.37}(56.3-P) \text{ in watts,} \quad (11)$$

where

$V$ = air velocity, in meters/min
$P$ = vapor pressure of moisture in the air, in millibars
$E_{\max}$ = maximum evaporative capacity when man is completely wet and at normal temperature.

Hence, the total expression for the HSI becomes

$$\text{HSI}=\frac{M+[11.6+1.91(V)^{1/2}](t_g-35)+5.75W}{3.52(V)^{0.37}(56.3-\text{P})} \times 100. \quad (12)$$

To illustrate the effect of various factors on the HSI, a number of plots versus the THI have been prepared. Metabolisms of 292 W (corresponding to moderate work such as walking about, with moderate lifting or pushing) and 176 W (corresponding to light work such as standing at a machine or bench, mostly arm activity, with wind velocities of 61 m/min and 6.1 m/min, with and without r. f. radiation, are given as a function of the RH in Figs. 4 and 5. Here, the HSI is plotted versus the THI. The plots in Fig. 4 are for a wind velocity of 61 m/min. It is evident that the HSI depends rather strongly on wind velocity, and is not a strong function of RH for a given THI.

A r. f. power density of 10 mW/cm² is seen to affect the HSI appreciably at the lower wind velocities and high humidities when the THI is 80.

For example, at 60 percent RH with an air velocity of 6.1 m/min, our standard man working at the rate of 293 W when the THI is 80 would have a HSI of 106. Adding the r. f. radiation of 10 mW/cm² would increase the HSI to 134, an in-

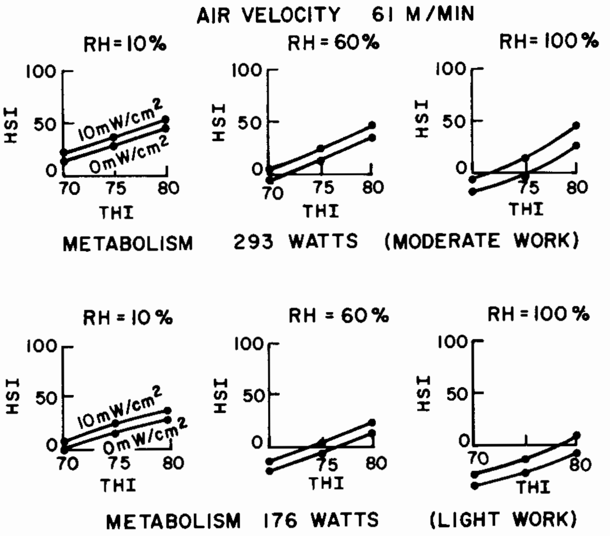

Figure 4. Heat stress index versus temperature-humidity index when air velocity is 61 m/min.

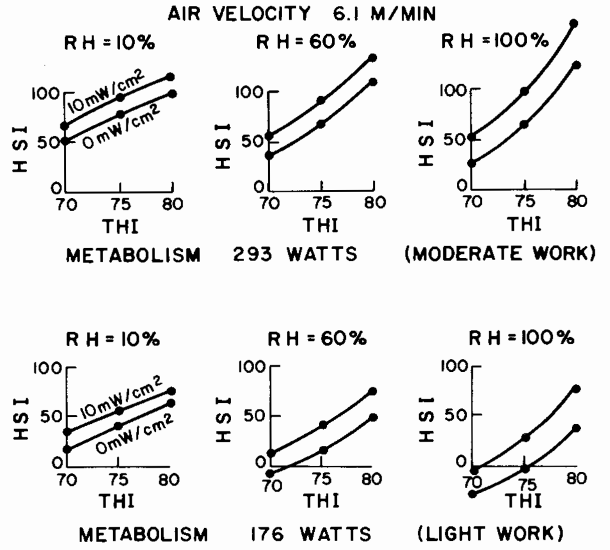

Figure 5. Heat stress index versus temperature-humidity index when air velocity is 6.1 m/min.

tolerable increase that would result in an increase in the body temperature if he did not stop working pretty soon.

It is evident from these plots that the RPG should be reduced when conditions of severe heat stress exist. Furthermore, it is seen that, when the THI is 70, the absorption of r. f. power having a power density of 10 mW/cm² by the standard man doing moderate work does not cause an intolerable increase in the heat stress.

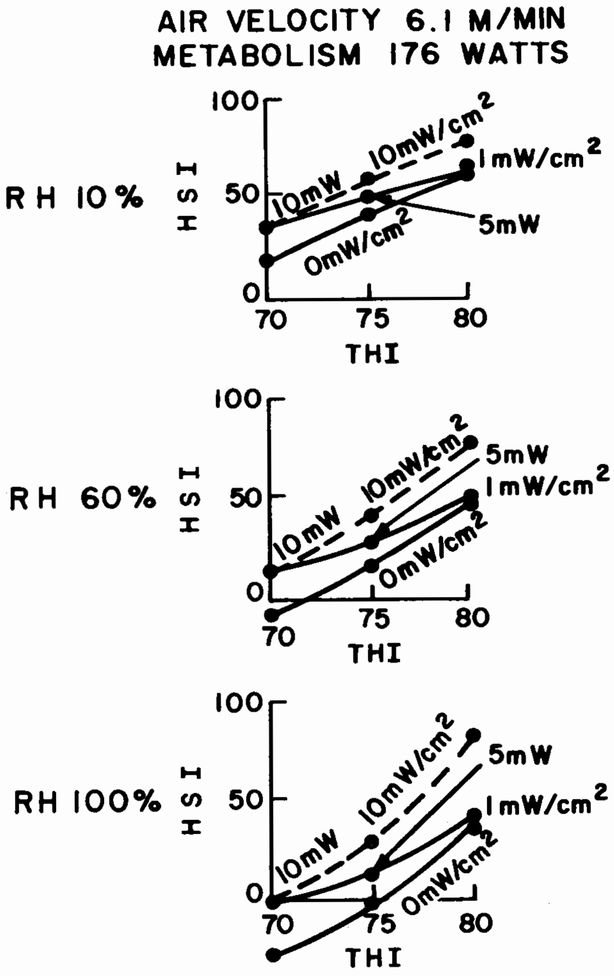

Figure 6. Heat stress index versus temperature-humidity index with proposed reduction in RPG.

In view of this, it seems reasonable to reduce the RPG from 10 mW/cm² at a THI of 70 to a low RPG at a THI of 80 in the simplest possible manner. This, in effect, is the underlying principle of the proposed reduction in the RPG for moderate to severe heat stress.

## LOW RPG FOR HOT ENVIRONMENT

For hot environments (THI$\geq$80), 1 mW/cm² is taken as the reasonably tolerable RPG number. It corresponds to 5.75 W absorbed in a standard man, or about 5 (kg) calories per hour. A few comparisons with familiar activities place this in its proper perspective. One peanut can provide the human body with 10 (kg) calories, so that eating half a peanut an hour would give 5.75 W. This corresponds to the

TABLE 1

*Globe temperature, wet-bulb temperature, and water-vapor pressure for THI of 70.75, and 80 and RH of 10.60, and 100 percent*

| THI | RH(%) | $t_g$(°C) | $t_w$(°C) | $P$(mb) |
|---|---|---|---|---|
| 70 | 10 | 28.44 | 12.38 | 3.87 |
| | 60 | 22.92 | 17.88 | 16.86 |
| | 100 | 20.8 | 20.8 | 23.98 |
| 75 | 10 | 33.3 | 14.44 | 5.14 |
| | 60 | 26.71 | 21.04 | 21.08 |
| | 100 | 23.9 | 23.9 | 29.75 |
| 80 | 10 | 37.4 | 17.33 | 6.41 |
| | 60 | 30.48 | 24.24 | 26.18 |
| | 100 | 27.36 | 27.36 | 36.41 |

work required by a person to climb a staircase at the rate of about three steps a minute.

For any of the conditions assumed in Figs. 4 and 5, 1 mW/cm² raises the HSI less than 5 points. Here we covered a rather broad range of environments, namely, an RH from 10 to 100 percent, THI from 70 to 80, metabolism from 293 to 176 W, and wind velocity from 61 to 6.1 m/min.

On the basis of a limit of 1 mW/cm² for a THI of 80, the simplest connection to 10 mW/cm² at a THI of 70 is a straight line. To further simplify the calculation, the limit of 1 mW/cm² is taken at a THI of 79 instead of 80 so as to produce a simple one-for-one reduction in RPG versus THI.[3]

In order to see how the HSI varies with the THI

TABLE 2

*HSI when r. f. power densities are 0, 1, 5, and 10 mW/cm², air velocity is 6.1 m/min, and metabolic rate is 176 watts*

| THI | RH(%) | HSI $W$ mW/cm² | | | |
|---|---|---|---|---|---|
| | | 0 | 1 | 5 | 10 |
| 70 | 10 | 19.15 | 20.76 | 27.18 | 35.2 |
| | 60 | −7.75 | −5.62 | 2.92 | 13.6 |
| | 100 | −28.1 | −25.5 | −15.06 | −2.05 |
| 75 | 10 | 42.4 | 44. | 50.6 | 58.8 |
| | 60 | 16.9 | 19.25 | 28.8 | 40.8 |
| | 100 | −3.04 | 0.128 | 12.8 | 28.7 |
| 80 | 10 | 62.8 | 64.5 | 71.3 | 79.7 |
| | 60 | 49.3 | 52.16 | 63.3 | 77.3 |
| | 100 | 37.6 | 41.8 | 58.7 | 79.9 |

TABLE 3

*HSI when r. f. power densities are 0, 1, 5, and 10 mW/cm², air velocity is 6.1 m/min, and metabolic rate is 293 watts*

| THI | RH(%) | HSI $W$ mW/cm² | | | |
|---|---|---|---|---|---|
| | | 0 | 1 | 5 | 10 |
| 70 | 10 | 51.8 | 53.4 | 59.8 | 67.8 |
| | 60 | 35.6 | 37.8 | 46.3 | 57. |
| | 100 | 24.8 | 27.4 | 37.8 | 50.86 |
| 75 | 10 | 75.8 | 77.5 | 84.0 | 92.3 |
| | 60 | 65.4 | 67.8 | 77.4 | 89.3 |
| | 100 | 61.4 | 64.5 | 77.2 | 93.1 |
| 80 | 10 | 97.1 | 98.8 | 105.5 | 114. |
| | 60 | 106.1 | 108.9 | 120.1 | 134.1 |
| | 100 | 123.6 | 127.9 | 144.8 | 166.0 |

TABLE 4

*HSI when r. f. power densities are 0, 1, 5, and 10 mW/cm², air velocity is 61 m/min, and metabolic rate is 176 watts*

| THI | RH(%) | HSI $W$ mW/cm² | | | |
|---|---|---|---|---|---|
| | | 0 | 1 | 5 | 10 |
| 70 | 10 | 0.23 | 0.915 | 3.65 | 7.1 |
| | 60 | −22.7 | −21.8 | −18.17 | −13.6 |
| | 100 | −40.6 | −39.5 | −35.07 | −29.5 |
| 75 | 10 | 16.0 | 16.7 | 19.52 | 23.0 |
| | 60 | −7.73 | −6.7 | −2.63 | 2.46 |
| | 100 | −27.9 | −26.5 | −21.1 | −14.35 |
| 80 | 10 | 29.8 | 30.56 | 33.4 | 37.0 |
| | 60 | 11.5 | 12.7 | 17.47 | 23.4 |
| | 100 | −8.39 | −6.58 | 0.64 | 9.68 |

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[3] The reviewers have observed that a curve based on a constant safety factor (below a damaging level) would have to be based on a more comprehensive index than the THI, and would probably not be linearly related to it. Figure 9 gives evidence in support of this observation.

TABLE 5

*HSI when r. f. power densities are 0, 1, 5, and 10 mW/cm², air velocity is 61 m/min, and metabolic rate is 293 watts*

| THI | RH(%) | HSI $W$ mW/cm² | | | |
|---|---|---|---|---|---|
| | | 0 | 1 | 5 | 10 |
| 70 | 10 | 14.14 | 14.8 | 17.57 | 21. |
| | 60 | −4.22 | −3.3 | 0.33 | 4.89 |
| | 100 | −18.0 | −16.9 | −12.5 | −6.95 |
| 75 | 10 | 30.27 | 31. | 33.8 | 37.3 |
| | 60 | 12.98 | 14. | 18.1 | 23.17 |
| | 100 | −0.39 | 0.96 | 6.37 | 13.13 |
| 80 | 10 | 44.5 | 45.2 | 48.1 | 51.66 |
| | 60 | 35.7 | 36.9 | 41.7 | 47.6 |
| | 100 | 28.3 | 30.14 | 37.4 | 46.4 |

for the proposed reduction rate, Fig. 6 was prepared. These graphs repeat the data given in the bottom three plots of Fig. 5. Points for 5 mW/cm² and 1 mW/cm² have been added at THI's of 75 and 80, respectively, in accordance with the proposed reduction of the RPG. The reasonable nature of the proposal is apparent.

Tables 1 through 5 list the data from which the curves of Figs. 4, 5, and 6 were plotted.

## RPG AS RELATED TO EFFECTIVE TEMPERATURE

Our first successful quantitative effort to establish the reduced RPG was associated with effective temperature (ET). This is another scheme for indicating the thermal significance of environments based on physiological reactions (7, 8). Test subjects were exposed to atmospheres with different temperatures, humidities, and air velocities, and asked to rate their comparative sensations of warmth and coolness. Nomograms were drawn to determine the ET in terms of the wet-bulb, dry globe thermometer readings, and wind velocity. For a wind velocity of 6.1 m/min, the ET is related to the globe temperature $t_g$ and the wet-bulb temperature $t_w$ by the relation

$$\mathrm{ET}=(34.4)\,\frac{t_g+0.210(t_g-t_w)}{t_g-t_w+34.4}\ (^\circ\mathrm{C}), \qquad (13)$$

when the wind velocity is 6.1 m/min.

A nomogram for ET is given in Fig. 7 for 6.1 m/min, and in Fig. 8 for 61 m/min.

We have already seen in (7) that the globe temperature is related to the incident radiation absorbed by a standard man by the relation

$$R+C=[11.6+1.91(V)^{1/2}](t_g-35)\ \text{watts.} \qquad (14)$$

We have also seen that the r. f. power density is related to the power absorbed by a man, thus:

$$f(W)(\text{in watts})=5.75W(\text{in mW/cm}^2). \qquad (15)$$

With these relationships in mind, we are able to relate a tolerable r. f. radiation (10 mW/cm²) at a THI of 70 to the radiation and convection which would bring the ET to 26.7 °C. Having established this fraction, which I shall call the reciprocal of the safety factor, we might then ascertain at other THI's the r. f. power densities that would yield the same safety factor.

Let us look at an example of this line of reasoning.

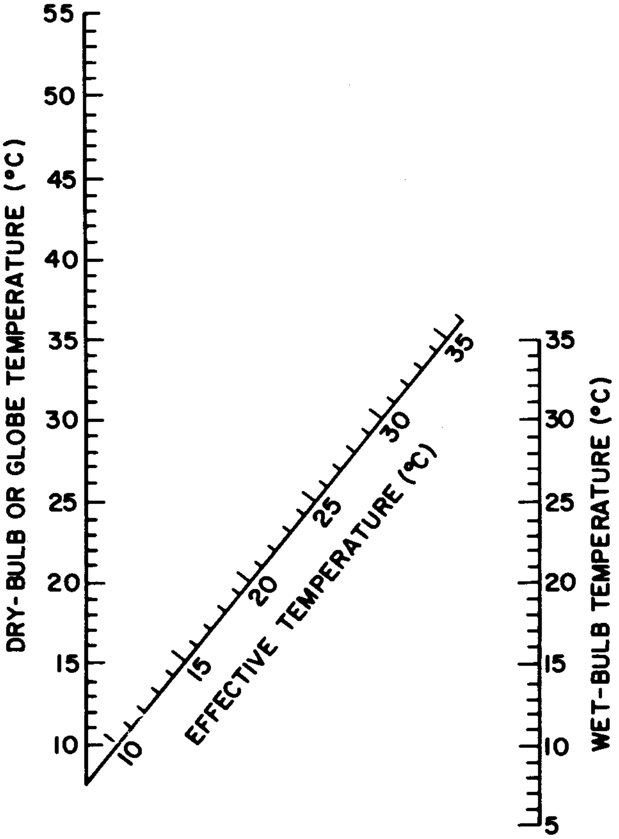

Figure 7. Effective temperature chart when air velocity is 6.1 m/min. (Data from Ref. 8.)

TABLE 6

*Safety factors and power densities for THI of 70 and 75 when RH is 10.60, and 100 percent and air velocity is 6.1 m/min*

| RH(%) | THI | ET(°C) | $\Delta t_g$(°C) | (watts) $\Delta(R+C)$ | (mW/cm²) $\Delta(W)$ | % | $W$ mW/cm² | Safety factor |
|---|---|---|---|---|---|---|---|---|
| 10 | 70 | 21.7 | | | | | | |
| | 82 | 26.7 | 16.71 | 273 | 47.3 | 21.1 | 10 | 4.73 |
| | 75 | 24.08 | | | | | | |
| | 81.5 | 26.7 | 9.2 | 150 | 26 | 21.1 | 5.5 | 4.73 |
| 60 | 70 | 20.95 | | | | | | |
| | 81 | 26.7 | 15.15 | 246 | 42.7 | 23.4 | 10 | 4.27 |
| | 75 | 23.98 | | | | | | |
| | 80.2 | 26.7 | 7.22 | 118 | 20.5 | 23.4 | 4.8 | 4.27 |
| 100 | 70 | 20.8 | | | | | | |
| | 80.4 | 26.7 | 14.35 | 235 | 40.7 | 24.5 | 10 | 4.07 |
| | 75 | 23.9 | | | | | | |
| | 79.7 | 26.7 | 6.38 | 104.5 | 18.1 | 24.5 | 4.4 | 4.07 |

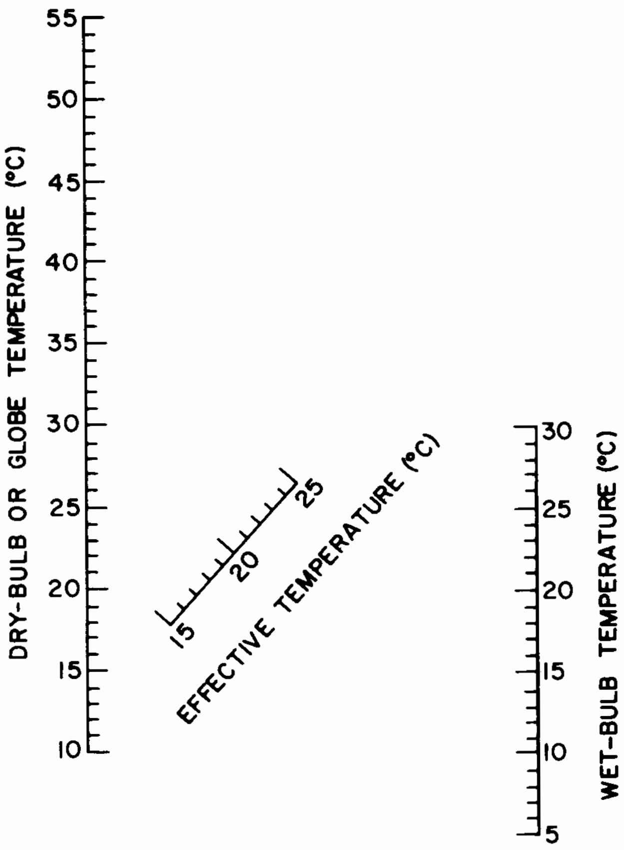

Figure 8. Effective temperature chart when air velocity is 61 m/min. (Data from Ref. 8.)

At a wind velocity of 6.1 m/min, THI of 70, RH of 10 percent, globe temperature of 28.44 °C, and wet-bulb temperature of 12.38 °C, the ET is 21.7 °C. To achieve an ET of 26.7 °C, $t_g$ would need to be raised to 45, 15 °C, an increase of 16.71 °C. From (14) it is seen that $\Delta(R+C)=11.6+1.91(V)^{1/2}\,\Delta t_g$, so that

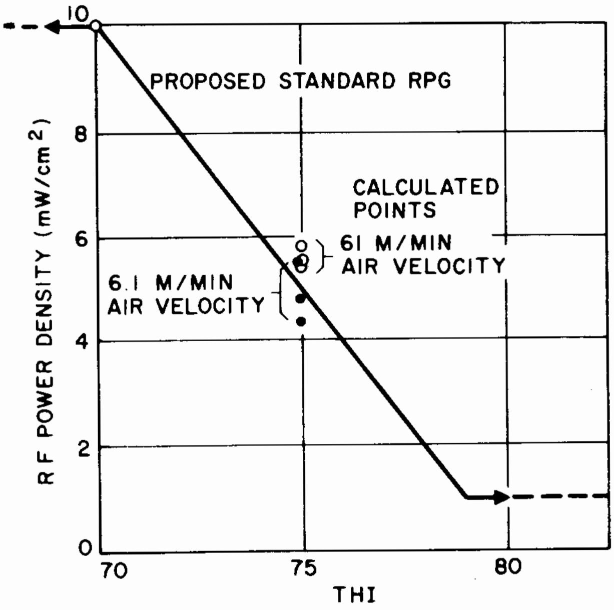

Figure 9. Comparison of proposed standard with calculated points based on effective temperature. Calculated points are based on the same safety factor at THI of 70 and 75 for a given air velocity and relative humidity.

TABLE 7

*Safety factors and power densities for THI of 70 and 75 when RH is 10.60, and 100 percent and air velocity is 61 m/min*

| RH(%) | THI | ET(°C) | $\Delta t_g$(°C) | (watts) $\Delta(R+C)$ | (mW/cm²) $\Delta(W)$ | % | $W$ mW/cm² | Safety factor |
|---|---|---|---|---|---|---|---|---|
| 10 | 70 | 20.8 | | | | | | |
| | | 26.7 | 16.67 | 442 | 76.7 | 13.04 | 10.0 | 7.67 |
| | 75 | 23.5 | | | | | | |
| | | 26.7 | 9.7 | 258 | 44.7 | 13.04 | 5.8 | 7.67 |
| 60 | 70 | 19.1 | | | | | | |
| | | 26.7 | 16.2 | 431 | 74.6 | 13.41 | 10.0 | 7.46 |
| | 75 | 22.5 | | | | | | |
| | | 26.7 | 8.83 | 234 | 40.6 | 13.41 | 5.44 | 7.46 |
| 100 | 70 | 17.93 | | | | | | |
| | | 26.7 | 15.98 | 424 | 73.5 | 13.6 | 10 | 7.35 |
| | 75 | 21.75 | | | | | | |
| | | 26.7 | 8.88 | 236 | 40.8 | 13.6 | 5.55 | 7.35 |

$\Delta(R+C)=16.33\Delta t_g$. This means that 16.33×16.71, or 273 W, would raise the ET to 26.7 °C; 273 W corresponds to the absorption of an r. f. power density of 47.3 mW/cm². The RPG of 10 mW/cm² at this THI is 21.1 percent of this. The safety factor is hence 4.73.

At a THI of 75, RH of 10 percent, globe temperature of 33.3 °C, and wet-bulb temperature of 14.44, the ET is 24.08. To achieve an ET of 26.7 °C, $t_g$ would need to be 42.5 °C, an increase of 9.2 °C. An increase of 150 W or absorption of 26 mW/cm² would do this. Now, 21.1 percent of 26 mW/cm² is 5.5 mW/cm². So, at a THI of 75, 5.5 mW/cm² corresponds to the same safety factor that 10 mW/cm² corresponds to at a THI of 70.

Tables 6 and 7 give similar results for humidities of 10, 60, and 100 percent, and wind velocities of 6.1 and 61 m/min. The points are plotted on Fig. 9, which shows how the calculated values of 5.5, 4.8, 4.4, 5.8, 5.44, and 5.55 mW/cm² compare with the proposed standard RPG of 5.0 mW/cm² at a THI of 75. In the worst case, i.e., $V=6.1$ m/min, RH = 100 percent, the safety factor for 10 mW/cm² at a THI of 70 is 4.07. The proposed standard RPG of 5 mW/cm² at a THI of 75 yields a safety factor of 3.6. Whether the safety factor is 3.6 or 4.07 is of little consequence compared with our concern for obtaining a simple expression for the proposed RPG number.

## APPENDIX

Mankind has long recognized that comfort during periods of warm weather depends not only upon the temperature but also upon the humidity and the circulation of air. Various schemes for devising a number that relates to our comfort have been suggested (3, 10). Names such as "humiture," "effective temperature," "discomfort index," and "temperature-humidity index (THI)" have been proposed for these schemes, all of which neglect the air velocity.

Of these, the temperature-humidity index, first proposed by E. C. Thom (3), Office of Climatology, U.S. Weather Bureau, Washington, D.C., under the less attractive and soon discarded name of discomfort index, seems to be most generally accepted by the public. It is quoted in radio and television broadcasts and tabulated in the local newspapers.

This index is obtained by a simple adjustment applied to the average of the dry-bulb and wet-bulb readings:

$$\mathrm{THI}=0.72(t_d+t_w)+40.6, \qquad (16)$$

when $t_d$ and $t_w$ are in degrees Centigrade.[4]

Quoting from Thom, "The index gives us a good

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[4] Thom's original expression was given in degrees Fahrenheit:

$$\mathrm{THI}=0.4(t_{df}+t_{wf})+15.$$

idea of the degree of discomfort. People feel discomfort as the index rises above 70, with over half uncomfortable with the index over 75. Everyone will be uncomfortable by the time the index reaches 79, most people feeling the discomfort acutely by this time. As the index passes 80 discomfort becomes more serious. When office conditions in the Washington Metropolitan area are such that the index becomes 86 or higher, for example, present government regulations permit supervisors to give consideration to the mass dismissal of the employees who are working under these conditions."

Whether or not Thom's THI is really indicative of comfort or discomfort is a moot point, since it neglects air circulation. One is usually more comfortable when the fan is on, yet turning on the fan has not changed the THI in the room.

At any rate, since the THI is quoted so often, it seems reasonable that we should be interested in calculating it in a simple way from temperature and relative humidity. Equation (16) is simple enough, but the wet-bulb temperature is seldom quoted although relative humidity is. Let us see if (16) can be given in terms of relative humidity.

Equation (16) may be rearranged thus:

$$\mathrm{THI}=1.44t_d-0.72(t_d-t_w)+40.6+15, \qquad (17)$$

where $(t_d-t_w)$ is the depression of the wet-bulb thermometer.

To express the THI in terms of relative humidity, we need an expression relating $(t_d-t_w)$ and RH. A first-order approximation may be derived by noting in the Weather Bureau tables that, at 28 °C (82.5 °F, which is in the temperature range of interest), a 5 °C depression of the wet bulb corresponds to 65 percent RH and that 100−RH is roughly proportional to the depression, as seen in Table 8. From this table we have

$$(t_d-t_w)^\circ\mathrm{C}=\frac{100-\mathrm{RH}}{7}. \qquad (18)$$

TABLE 8

*RH and temperature difference between dry- and wet-bulb temperatures ($t_d=28$ °C, 82.5 °F)*

| $(t_d-t_w)$°C | RH(%) | (100−RH)/$(t_d-t_w)$°C |
|---|---|---|
| 2 | 85 | 7.5 |
| 4 | 72 | 7.0 |
| 6 | 59 | 6.9 |
| 8 | 47 | 6.6 |
| | | Average 7.0 |

Putting (18) into (17), we have

$$\mathrm{THI}=1.44t_d-0.72\left(\frac{100-\mathrm{RH}}{7}\right)+40.6$$

$$=1.44t_d-\frac{72}{7}+40.6+\frac{0.72}{7}\,\mathrm{RH};$$

that is,

$$\mathrm{THI}=1.44t_d+\frac{\mathrm{RH}}{10}+30.6. \qquad (19)$$

The approximate expression for the THI is exact when the humidity is 100 percent, regardless of temperature. At 50 percent RH, the error is less than 1 percent when the THI is less than 80. At lower humidities, the error increases, especially when the THI is 80 or more. For example, when the temperature is 34 °C and the wet-bulb temperature is 21 °C, corresponding to an RH of 30.2 percent, the exact expression (16) gives a THI of 80.2, whereas the approximate Equation (19) gives a value of 82.5.

The error at lower temperatures and 30 percent RH is less. For example, when the temperature is 25 °C and the wet bulb reads 15 °C, corresponding to an RH of 32.5 percent, the exact expression (16) gives a THI of 69.4 compared with 69.85 by the approximate relation.

When the temperature is expressed in degrees Fahrenheit, (19) becomes

$$\mathrm{THI}=0.8t_{d(F)}+0.1\,\mathrm{RH}+5. \qquad (20)$$

Kahn, Nelson, Tomberg, and Puller (11) derive a similar expression, which is more precise at the lower humidities but less precise for the higher humidities:

$$\mathrm{THI}=0.73t_{d(F)}+0.16\,\mathrm{RH}+6.4. \qquad (21)$$

### *Acknowledgments*

This work was undertaken at the request of the Radiation Hazards Subcommittee of the American Telephone and Telegraph Co., R. H. Groom, Chairman. Several invaluable technical and practical discussions with G. M. Wilkening of Bell Telephone Labs, and V. B. Robinett of AT&T created the basis upon which the concept of relating the RPG to the

THI was chosen. The author is indebted to Mr. Wilkening for his support relative to the evaluation of the physiological effects of heat, and to Mr. Robinett for his encouragement and enthusiasm for seeking a practical, workable yet reasonable proposal.

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## DISCUSSION

*Dr. Frey*: Dr. Schwan, I feel that I cannot conclude whether r. f. energy affects nerves or does not affect nerves. I do not feel I have sufficient information. You have concluded that r. f. energy cannot affect nerves and I must compliment you on having constructed an elegant mathematical proof of this. However, this proof is based upon certain assumptions as to how nerves work and how they function. Your assumptions are critical and if your assumptions are not correct then your whole mathematical structure would fall. Thus, one might ask whether you can prove the truth of the assumption that you have gotten from authorities in biology. If these assumptions are true and we have such knowledge about nerves then possibly you can tell us how information is coded in the nervous system, how information is transferred in the nervous system, and how information is stored in the nervous system.

*Dr. Schwan*: I am not aware of any particular assumptions. The calculation to which Dr. Frey referred is elementary, to say the least. The application of Laplace's equation, to calculate the potential, across the membrane is quite easy. With regard to the membrane capacitance we use a very substantial body of information to arrive at these values. There is admittedly an assumption in assuming that an imposed microwave evoked potential has to be of an order of magnitude not too small by comparison with the resting potential. I think I was careful in stating that the present neurophysiological knowledge, due for example to the work of Hodgkins and Huxley, Cohen, and many others going back to Berstein, precisely states that you cannot excite a nerve unless you get up to a potential which is not vanishingly small by comparison to the resting potential. As I stated before, if we can prove the existence of microwave effects on nerves, this would be very, very interesting since clearly if we can establish this beyond a shadow of a doubt it would have tremendous impact in neurophysiology.

*Question from floor*: I would like to raise a question directed at the same issue. I think the question of an evoked potential or an effect in terms of changing the resting potential of nerves may be irrelevant. Have you considered the possibility of affecting conduction of an action potential through change in the state of hydration of ions crossing the membrane; or through a molecular resonance phenomenon changing the orientation mobility of particles making up the membrane? In other words, by changing the conduction velocity one could change the integrative function of the system tremendously, even though you might not see a change in the resting potential of any single fiber.

*Dr. Schwan*: Quite clearly what we must do is to investigate on the level of the brain as well as on a macromolecular level in order to achieve an end. I would like to make a few comments about the possibility of microwaves interaction with macromolecular entities and particularly like to consider the question of macromolecular resonance. I have mentioned already that a very substantial body of work has been done by renowned researchers concerned with dielectric properties of proteins, peptides, amino acids, and nucleic acids. All this work has been carried out over several decades and it is well established and well accepted. It can be briefly summarized by stating that the electrical properties of macromolecules are characterized by relaxation effects. In other words, if you measure the effective dielectric property of a macromolecule as a function of frequency, then you get a characteristic change with frequency such that the effects of capacity decrease with increasing frequency. Mathematically it can be shown that this relaxation behavior, where the molecules at low frequency vibrate with the field but eventually stop vibrating at sufficiently high frequencies, is a degenerate form of resonance behavior. In resonance behavior there is a peak in the response characteristic and in relaxation phenomena the response decreases as in the case where you excite a pendulum, first in a gas and then in a fluid which becomes more and more viscous, in which case you do not get that sharp resonance peak. There is a switch over from where the pendulum follows the excitation to a state where there is no longer a strong peak as a function of frequency; that is relaxation behavior. Now relaxation behavior has been observed and carefully studied. It is due to dipole moments of molecular constituents. At lower frequencies so-called counter-ion relaxation effects come into the picture as another relaxation effect and at higher frequencies we have shown some 10 years ago, that you get additional relaxation effects which are either due to partial orientation of polar sub-units of molecular complexes or macromolecules. But spanning the total frequency range all of the effects are relaxation effects. We understand relaxation effects quite well these days and there's no indication of resonance effects. Now, why isn't there any resonance? It is very simple since biological media imposes a very strong restriction on the movement of macromolecules due to the presence of water. Water has a high viscosity and thus the molecule responds analogously to a pendulum suspended in tar. It is the high viscosity of water which changes the resonance effect to a relaxation effect. We might consider a case where the molecule is so weakly coupled to the water environment that the so-called rotational diffusion constants do not count anymore and you might set up a resonance effect inside the molecule. Let me explain this possibility simply in terms of equivalent electrical circuits. Suppose you have a high *Q* circuit; an AC capacity combination which is characterized by a high *Q* or sharp resonance at certain properly chosen frequencies. Now if you place a low resistance across the circuit which absorbs energy then you kill the resonance and you cannot excite your *Q* circuit in a very selective fashion in the presence of low resistive elements, and that is what you do with a macromolecule if you put it in water. You might say you might decouple your molecule completely so that it is not subject to the rotational diffusion constant as determined by the viscosity of water. But, if you decouple them, you have trouble feeding the energy in and you have trouble observing from the outside. There is no escape from this dilemma that I can see.

*Dr. John Heller, New England Institute*: It is a pleasure to agree with Dr. Schwan since on past occasions we have not. In 9 years we have never seen anything work CW that did not work pulsed. However, I would like to talk to this preoccupation with thermal effects that we have heard something about. To use a 10 mW/cm$^2$ standard is as inapplicable as the old RBE was in early days of ionizing radiation. We will present indications tomorrow that one of the things that r. f. can do is cause mutations in plants, animals, and human materials. There is a frequency specificity at which this happens. We are not talking about heat.

*Gene Barron, John Hopkins University*: I think in line with Dr. Heller's comments there was a report published in about 1961 by a man named Turner that was essentially a translation of a book by several Russians in which they indicated that the Russians' safe level was 0.01 mW/cm$^2$ which is down by a factor of a 1000 from our safe level. Now this was based on nonthermal effects; physiological changes observed in human beings. Would either Dr. Schwan or Mr. Mumford care to comment on that?

*Dr. Schwan*: I have for many years made it a practice to study very carefully the work of our Russian colleagues. I have met with a number of them repeatedly about this. I must say that the publications I could lay my hands on are rather qualitative and I have trouble evaluating the quality of the work. I should also like to state that in personal discussions my personal curiosity has not been satisfied.

*Jim Treach, Motorola*: The proposal of a current density versus a power density seems to be getting more at the heart of the generating problem or the source. What type of model would we use to measure this current density?

*Dr. Schwan*: That is very difficult. I suggested the current density only as a general guide with regard to the sort of thing that we could do. Let me quote some typical examples, such as the case which I alluded to before. A person standing at the foot of a perpendicular antenna could be in a strong magnetic field. In this case something very different has to be done than under other conditions. In this case typically what could be done is to make a phantom model of the simplest case, a sphere. Give it the properties which are typical of an assumed human body and expose the sphere to the magnetic field and calculate what currents are induced by the magnetic field. But depending upon the field configurations you may have to do something different. I think there is no escape from it since the current does the heating and we must eventually come to grips with the problems involved with different field configurations even though they may be complex problems.

*Question from floor*: Would a thermal rise of some sort or a technique of measuring the temperature rise of the body indicate the power density or let us say the contribution due to the magnetic field?

*Dr. Schwan*: Not necessarily any more than you would find in a far field where the 10 mW/cm$^2$ flux pertains. What I did in arriving at this figure is to take the 10 mW/cm$^2$ figure and I asked myself what is the equivalent heat generation and on that basis, taking known tissue resistivities, I arrived at a guideline of 3 milliamp/cm$^2$.

*Roger Dickerson, FDA*: Mr. Mumford's paper involved a rather extensive heat transfer analysis relating humidity, temperature, etc., with thermal stress and it implies to me a heat source and a particular temperature of the heat source, I suppose specifically the material that is about to be damaged. Since this implies some maximum temperature in the tissue, do we know at what temperature damage occurs?

*Mr. Mumford*: I am not quite sure I understand your question but if I have understood it correctly, I can state that we all recognize that heat stress will, if extended for a period of time at high enough levels, cause a rise in the body temperature. The body temperature has to rise in order to dissipate the heat. Our limit that we have proposed is set at such a level that we do not under ordinary conditions expect a rise in the body temperature.

*Roger Dickerson*: Let me rephrase the question. To perform those heat transfer calculations that we saw the result of, you would have to know the temperature of the heat source and so evidently someone decided what this maximum temperature should be. Perhaps this is body temperature of 98 °F.

*Mr. Mumford*: For these heat stress index calculations the temperature of the skin from which the evaporation takes place was assumed to be 95.5 °F.

*Dr. Vogelman*: I would like to make one comment on the Russian literature. The Russian standards are set on the basis of statistics that are generated through interviews by medical people associated with people who would normally be exposed to microwave radiation. It is very difficult to determine whether they have introduced a factor of 10, 100, or 1000 in their statistics as generated in this kind of interview. There are therefore two things that are in question. One is how good is the interview and second is what is the correction factor.

I would like to ask Dr. Schwan a question. In your pulse calculations you have assumed that the effect requires the repetition of the pulses but as in the homemade *Q*-switched laser, one pulse and you have the hole already—you cannot reverse it. What about irreversible effects and pulse radiation?

*Dr. Schwan*: That is a very good question as a matter of fact and it is worth dwelling on. The statement that the rms value is only of significance pertains to field-evoked force effects as I tried to define them before such as the orientation of macromolecule or the alignment of blood cells. Excluded are all irreversible effects and whatever additional time constants may go into irreversible effects. That is the situation regarding high force effects and about this, frankly, we do not know anything at the present time.

*Mr. Griffy, Columbia Scientific*: I would also like to ask a question about this CW versus pulse calculation. Why is it you use the time $t_1$ for the time off? As I understand that is time necessary for the field just at threshold and has nothing to do with the relaxation time of the phenomena when the field is actually off.

*Dr. Schwan*: I tried to optimize the effect without involving thermal effects, therefore I had to apply the field for a sufficient time so that the effect takes place. Any effect requires time to take place. If you orient molecules you need a certain time to have it take place. This time is dependent on field strengths. Clearly if you apply a high field strength the forces are strong and it snaps rapidly into position, and for small field strengths it takes longer periods of time. So the time was chosen just to get the effect and no longer. If you apply it longer you might apply more heat than is needed to get the effect. We want to minimize the heat development.

*Mr. Griffy*: My question was concerned with the off time. I understand why you leave it on for time $t_2$.

*Dr. Schwan*: As you take the field off it takes a certain amount of time before the effect disappears. What you have is a competition between random thermal forces and the phenomena of pearl-chain formation, or in Heller's work the orientation of particles for example. Random thermal forces, Brownian movement acts after you switch off the field to eliminate the effect, and thus, if you get orientation or something like that, it disappears after a while. Quite obviously you should choose off time in such a way that you switch back the field just before the particles start to break apart.

*Mr. Griffy*: Yes, but I am not clear why this should be the time $t_1$ which corresponds to the threshold field value. It might be a completely different relaxation time than $t_1$.

*Dr. Schwan*: The calculations of Saito and the recent experimental work by Sharon Kresh have shown that the time which characterized the breakup is very close to the time which corresponds with threshold field strengths. That, of course, has already been experimentally substantiated. That is a very valid point in the argument.

# BIOLOGICAL EFFECTS OF MICROWAVE EXPOSURE[1]

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## THERMAL EFFECTS OF MICROWAVE EXPOSURE

The exact nature of the biologic effects of microwaves is not completely understood. It has been shown, however, that microwaves may affect a variety of organisms, from protozoa to mammals. Effects may occur at various frequencies and power densities characterized by responses that involve reaction of the entire organism to changes at the molecular level.

Although most of the experimental data support the concept that the effects of microwave exposure are primarily the result of local or general hyperthermia, there are large areas of confusion, uncertainty and actual misinformation.

It is important, therefore, to review the present state of the art of biologic effects of microwaves and attempt to decipher the known and substantiated from the speculative and unsubstantiated effects, in order that we may maintain a realistic perspective on the nature of microwaves and the possible effects of exposure to this form of energy. Unless this is done, the tremendous potential of electromagnetic energy in the microwave range for radar, communications, biomedical, industrial and consumer use and applications will be hampered.

### A. Biophysical Principles

When microwaves are absorbed by any material, the energy is transformed into increased kinetic energy of the absorbing molecules, which, by increased collision with the adjacent molecules produces a general heating of the entire medium. The energy value of 1 quantum of microwave (0.024–$4.0 \times 10^{-6}$ eV) is much too low to produce the type of excitation necessary for ionization, no matter how many quanta are absorbed. Chemical activations involving orbital transitions of electrons are rarely encountered with radiation of wavelength longer than ultraviolet or possibly visible light (1).

It has been determined that one ionization occurs on the average for every 34 eV of energy expended in air. The actual amount of energy needed to eject an electron from a molecule (ionization potential) ranges from 10 to 25 eV (2). The extra energy which is expended is used to form excited molecules. Where large molecules are involved, the energy is distributed through the entire molecule with too little energy concentrated at any one bond to cause its rupture. The energy is removed from the system as oscillation energy which becomes randomized and is converted to heat.

For the sake of comparison, it may be noted that the solar constant or the solar radiation just outside the earth's atmosphere is 139.6 mW/cm$^2$ (3). About two thirds of this gets through the atmosphere so that the typical solar radiation at the surface of the earth can be as much as 90 mW/cm$^2$, and perhaps more typically around 60 mW/cm$^2$. This radiation consists primarily of infrared, visible and ultraviolet components. Though the ultraviolet, in particular, has well-known important nonthermal effects, the total absorbed radiation acts to heat the surface of exposed skin.

Since the major effect of exposure to microwaves is thermal in nature, the general effects of hyperpyrexia must be understood. The reactions resulting from temperature elevation in the tissues, no matter what the cause, are similar to those observed after exposure to microwave energy of adequate power levels.

When considering the biological effects of microwave radiation, the wavelength or frequency of the energy and its relationship to the physical dimen-

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[1] This paper is based on work performed under contract with the U.S. Atomic Energy Commission.

sions of objects exposed to radiation become important factors. It has been determined that for any significant energy absorption, the physical size of the object must be equivalent to at least a tenth of a wave-length at the frequency of radiation.

The human body is composed of various tissues which may be considered as a transmission medium exhibiting the characteristics of a complex dielectric material.

The degree of temperature rise from exposure to microwaves is dependent on numerous physical and biologic factors:

1. Intensity or power density; the amount of heat produced is proportional to the power density as measured in mW/cm$^2$.
2. Duration of exposure; limited, however, by environmental and physiological factors.
3. Frequency or wave length of the radiation.
4. Size and dimensions of the exposed object.
5. Thermal regulatory capacity of the exposed subject.
6. Thickness of tissue.
7. Composition of tissue.

The biologic factors in temperature increase are mainly those related to the ability of the tissue to rid itself of excess heat. Heat transfer at a given body temperature is equal to the algebraic sum of the heat generation due to metabolic processes and heat loss from radiation and breathing. When heat loss predominates, normal temperature is restored. If, on the other hand, heat gain exceeds heat loss, the body temperature rises to the lethal temperature for the animal.

## B. Biomedical Principles

Detailed information on the thermal response to microwave exposure is available in several publications (see, e.g., Refs. 4–21).

In order to present some of the general principles of thermal effects of microwaves, results of some studies performed at the University of Rochester between 1957 and 1965 will be briefly described.

### *Materials and Methods*

Adult mongrel dogs were exposed to 2800 MHz (AN/FPS-6) or 1280 MHz (AN/FPS-8) pulsed microwaves. The units were operated at 360 pulses/sec with a 2–3 microsecond pulse width.

To simplify the determination of the power density and to aid in the interpretation of data, a microwave "free space" room was constructed for animal exposures (Fig. 1). This room, approximately 7×7×15 ft., was lined with commercial microwave absorbing material which permits a maximum of 2 percent of the incident energy to be reflected from its surface. Power density measurements were made with a Ramcor (R) Model 1200 densitometer. In the exposure chamber, power density varied between $2\times10^{-3}$ to 1.2 W/cm$^2$, depending on distance from the horn. The field pattern was relatively uniform across the animal's body during exposure, with the energy at the periphery differing by less than 20 percent from that at the center. A double Plexiglas cage was constructed to confine two animals during exposure, permitting one to serve as a control. Since the animals were free to turn to any position, rotation was not considered necessary.

Dogs were exposed at two power densities (100 mW/cm$^2$ and 165 mW/cm$^2$) for differing periods of time. A small number of rabbits and rats were also exposed for comparative purposes.

Additional exposures were performed utilizing an end-fire helical antenna, from a 200 MHz (CW) generating source, located in an anechoic chamber 42 ft. long by 10 ft. wide and 9 ft. high. The predetermined power density was 165 mW/cm$^2$.

Rectal temperature of dogs and rabbits exposed at 2800 MHz pulsed microwaves was monitored throughout all experiments, beginning 15 minutes prior to irradiation, with an electronic thermometer energized by a thermistor probe covered with

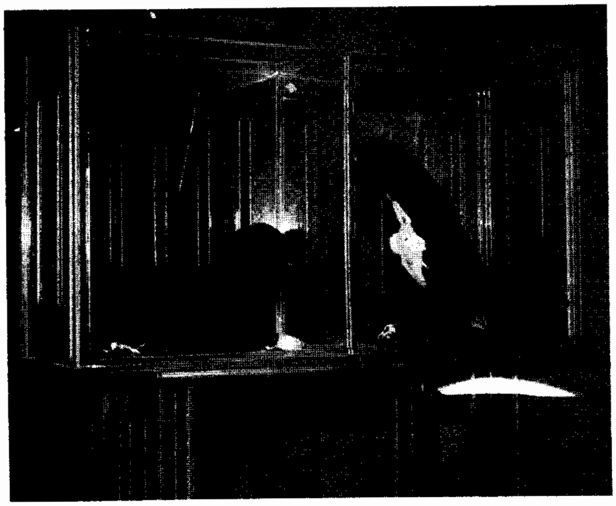

Figure 1. Microwave "free space" room for animal exposures.

Plexiglas and fixed in the rectum. Exposure was started when the measured temperature maintained a constant value. The animals' responses during the exposure were recorded. Blood samples were obtained by a single-stab jugular puncture before and within 1 minute following exposure. The dogs were weighed before and after each exposure. General appearance, alterations in behavior and gait, and desire for water at the conclusion of each exposure were recorded.

To assess the effect of anesthesia on the response to microwave exposure, several animals were injected intravenously with pentobarbital sodium and exposed at 2800 and 200 MHz.

Four dogs picked at random were exposed to 165 mW/cm², 2800 MHz, while under medication with pentobarbital sodium, morphine sulfate, or chlorpromazine, in order to determine the effect of sedation on the response to microwaves. A latin square experimental design was utilized. At least 1 week elapsed between exposures.

*Results*

a. *Temperature Response*—The thermal response in the dog exposed to 165 mW/cm², 2800 MHz pulsed microwaves at 30 percent humidity consisted of three distinct phases (Fig. 2). In phase I, initial thermal response, body temperature increases by 2–3 °F ½ hour after onset of exposure. In phase II, period of thermal equilibrium, rectal temperature stabilizes. This may last 1 hour, during which the temperature will cycle between 105 and 106 °F. In phase III, period of thermal breakdown, the temperature rises above 106 °F, continues increasing rapidly until a critical temperature of 107 °F, or greater, is reached. If exposure is not stopped, death will occur.

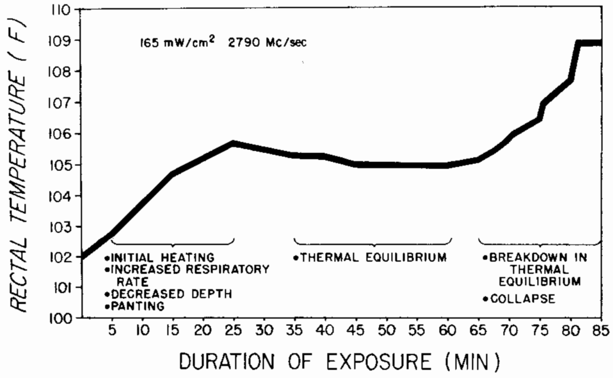

Figure 2. Thermal response of dogs to microwaves.

A critical rectal temperature with no equilibration is reached in 10 minutes in the rabbit and 20 minutes in the rat when exposed at 165 mW/cm², 2800 MHz. The influence of body size on the thermal response at this frequency is negligible. Fox terriers weighing 4 kg, which is equivalent to the weight of the rabbit, respond the same as medium sized dogs ranging in weight from 3 to 20 kg.

Exposure of dogs at 100 mW/cm² for periods up to 6 hours does not cause a critical rectal temperature. Initial heating is slight, the animal remaining in thermal equilibrium during the remainder of exposure.

At 200 MHz, 165 mW/cm², the dog equilibrates later than at 2800 MHz and remains in thermal equilibrium for a longer period before breakdown. Body size of the animal does not influence response. Equilibration is minimal in the rabbit, and critical rectal temperature occurs within 30 minutes. Rats exposed for 1 hour do not show evidence of thermal breakdown.

At 103.5–106 °F, 20 percent humidity, thermal regulation is adequate to maintain normal body temperature. Exposure to 2800 MHz microwaves at this environmental temperature results in increased rectal temperature, which is greater than that seen with microwave exposures at 72 °F, 30 percent humidity.

Temperature recovery assumes an exponential form for dogs exposed to 165 mW/cm² or 100 mW/cm². Pre-exposure level is reached within an hour.

In dogs that die during or immediately after microwave exposure, the liver, gall bladder, urinary bladder, stomach and lungs are 2–4 °F higher, while testes and the anterior chamber of the eye are 6 °F lower than simultaneously recorded rectal temperature, 15–60 minutes after death.

b. *Clinical Response*—Dogs exposed to 2800 MHz, 165 mW/cm² start panting shortly after irradiation starts. As exposure continues, the rate of panting increases and may stabilize only to increase again as the rectal temperature rises. Salivation occurs in many dogs, the amount increasing with the duration of exposure. Most animals display increased activity varying from restlessness to extreme agitation. The animals are alert throughout the exposure as long as they are able to maintain thermal regulation. Marked vasodilatation of the skin and mucous membranes is observed during prolonged exposure. The response is less marked with exposure at 100 mW/cm$^2$. Terminally, (4–6 hr. at 100 mW/cm$^2$ or 2–3 hr. at 165 mW/cm$^2$) weakness develops and, in extreme cases, the dog becomes prostrate. Recovery, when it occurs, is rapid.

Exposure of rabbits at 165 mW/cm$^2$ produces an extremely violent reaction. Within 5 minutes, desperate attempts are made to escape from the cage. Peripheral engorgement of all vessels yields an acrocyanotic picture. Forty minutes of exposure results in death. When rabbits are exposed at 100 mW/cm$^2$ for 1 hour, they become prostrate.

c. *Hematology*—Leukocyte changes in the dog reflected in distribution of the component cells indicate specific sensitivities related to frequency, power density, and duration of exposure. Lymphocytes and eosinophiles are decreased after 6 hours of exposure at 100 mW/cm$^2$, 2800 MHz. Total leukocytes and neutrophils are slightly increased at 24 hours (Fig. 3).

After 2 hours of exposure to 165 mW/cm$^2$, the total leukocyte count is slightly decreased. When the exposure is prolonged to 3 hours, leukocyte increase is observed, which is more pronounced at 24 hours. Lymphocyte and eosinophile changes are variable, but are decreased immediately or 24 hours after exposure.

d. *Effect of Premedication*—Anesthetization of the dog results in an increased thermal susceptibility to 2800 MHz (Fig. 4). Transient equilibration occurs when the animal is exposed to 200 MHz while under anesthesia.

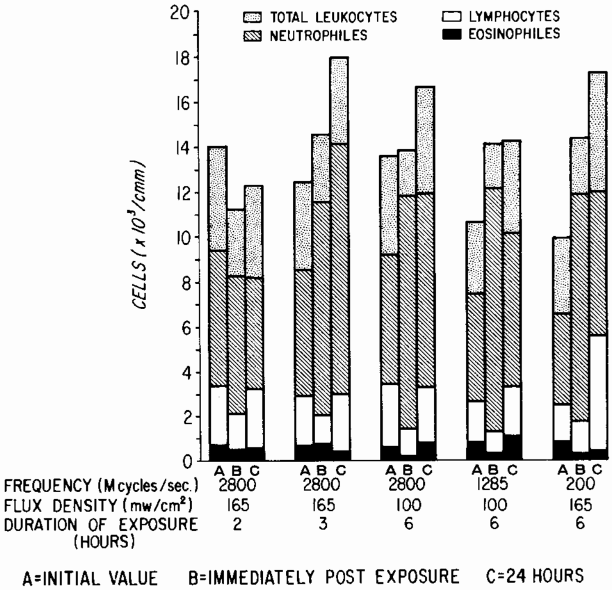

Figure 3. The effect of microwaves on leukocytes.

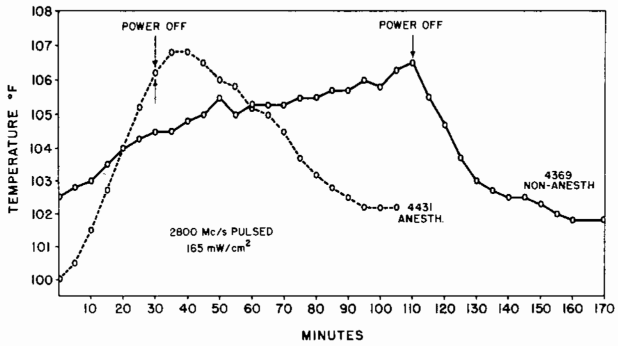

Figure 4. Thermal response to microwave exposure.

Anesthetization of the rabbit and rat, exposed to 2800 MHz, delays the time for reaching a critical rectal temperature. This probably results from the lower initial rectal temperature and peripheral vasodilation of the anesthetized animal. The anesthetized rat appears to be more sensitive than the nonanesthetized rat when exposed to 200 MHz.

Dogs that received pentobarbital sodium, morphine sulfate, or chlorpromazine responded with a higher rectal temperature than unmedicated animals (Table 1). The greatest rectal temperature increase, 4.56 °F, occurred in 30 minutes in animals that received pentobarbital sodium. Chlorpromazine premedication resulted in an increase of 2.5 °F and morphine sulfate in an increase of 2.13 °F in 30 minutes. The unmedicated dogs had a mean increase of 1.31 °F from the initial temperature in a comparable time period.

When pentobarbital sodium was used, the initial 4 °F increase occurred in 28.8 minutes; with morphine sulfate, 66.3 minutes; and with chlorpromazine, 108.8 minutes; compared with 172.5 minutes in unmedicated dogs.

The rectal temperature of pentobarbital-treated dogs did not start to decrease until several minutes after termination of the exposure. Thirty minutes postexposure, the rectal temperature of these animals dropped 2.25 °F. Morphine sulfate and chlorpromazine groups decreased 2.63 °F and 3.63 °F, respectively, compared with 3.75 °F for the unmedicated dogs.

Temperature changes were minimal for all groups when not exposed to microwaves. There was no apparent reaction from previous medication.

e. *Effect on Body Water*—The interrelationship of

TABLE 1

Thermal Response of Dogs Exposed to Microwaves After Medication Analysis of Variance

| Drug | Dose | Heating | | Cooling |
|---|---|---|---|---|
| | | Maximum °F Increase Initial 30 Min. Heating | Time (Minutes) For Initial 4°F Increase | Time (Minutes) For Initial 4°F Decrease |
| Control | — | 1.31 ± 0.47* | 172.5 ± 22.0 | 35.0 ± 8.45 |
| Pentobarbital Sodium | To effect ca. 30 mg/kg iv | 4.56 ± 0.47 | 28.8 ± 22.0 | 85.0 ± 8.45 |
| Chlorpromazine | 2 mg/kg im | 2.50 ± 0.47 | 108.8 ± 22.0 | 39.5 ± 8.45 |
| Morphine Sulphate | 4 mg/kg sc | 2.13 ± 0.47 | 66.3 ± 22.0 | 51.3 ± 8.45 |

* Mean ± Standard Error of the Mean

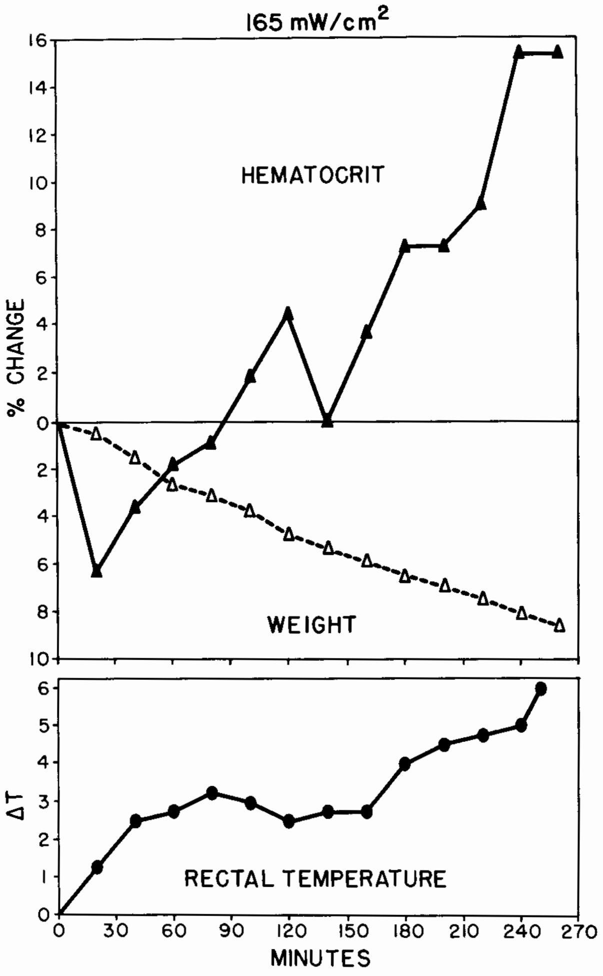

Figure 5. Physiologic response in normal dogs exposed to microwaves 2800 MHz.

hematocrit change, rectal temperature increase and weight loss in the dog exposed to microwaves is illustrated in Fig. 5. Hematocrit change is biphasic. Shortly after commencement of the exposure, hemodilution occurs followed by progressive hemoconcentration. A second attempt at hemodilution is noted at approximately 2 hours, followed by hemoconcentration. The dog loses its ability to hemodilute about the time thermal equilibration deteriorates. At this time, body weight loss is greater than 5 percent.

Dogs exposed at 165 mW/cm² show a body weight loss of 2.0 percent per hour. At 100 mW/cm², there is a weight loss of 1.25 percent per hour, and hemodilution occurs, as contrasted with hemoconcentration evident at 165 mW/cm².

f. *Adaptation*—Adaptation or an increase in the resistance of the animal is observed in the course of repeated irradiation (Fig. 6). The temperature equilibrium phase is prolonged and the animals endure longer durations of exposure.

g. *Burns*—Dogs may develop superficial burns on various portions of the body, but particularly on the thoracic cage. Five to six days following exposure, the affected skin sloughs, leaving a deep, clean, noninfected area identical in appearance with a third degree burn. The central portion appears to devitalize with development of a process not unlike dry gangrene. Scarring or keloid development was not noted.

h. *Late Effects*—All animals were normal after exposure. Periodic physical and eye examination by slit lamp and ophthalmoscope up to 1 year after

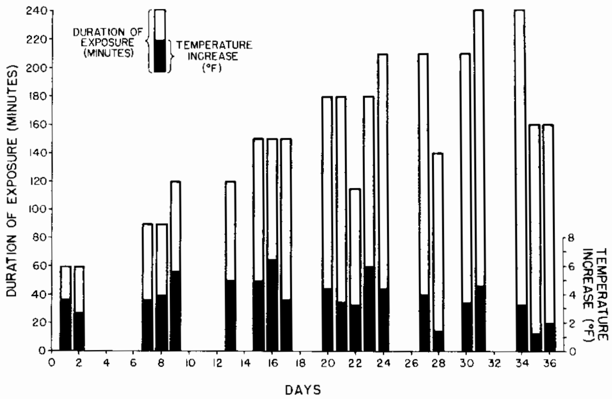

Figure 6. Development of microwave tolerance 2800 MHz, 165 mW/cm².

exposure failed to reveal any physiological decrements or lenticular changes.

*Discussion*

Exposure of various species of animals to whole-body microwave radiation at levels of 100 mW/cm² or more is characterized by a temperature rise which is a function of the thermal regulatory processes and active adaptation of the animal. The end result is either reversible or irreversible change depending on the conditions of the irradiation and the physiologic state of the animal.

The thermal response induced by microwave exposure in an animal with thermal regulatory capability comparable to that of man (such as the dog) is characterized by three phases: a) Initial thermal response, b) period of thermal equilibrium and c) period of thermal breakdown.

An excessive increase in body temperature produces damage indistinguishable from fever in general. The increase in temperature in irradiated tissues during local exposure occurs linearly for short periods (1–3 minutes) and is related to the quantity of the microwave energy absorbed. With exposures in excess of 3 minutes the magnitude of the thermal effect and distribution of heat in tissues is determined by heat-regulating mechanisms (22). At the same power density, intermittent exposure can be tolerated for longer periods than uninterrupted exposure because of heat dissipation. The rate at which the heat is dissipated will vary in different species depending on heat-regulating mechanisms or metabolic characteristics.

An early manifestation of acute heat stress for the mammal is hemodilution, which occurs during the first 30 minutes of exposure and before the body temperature increases. With prolonged exposure, hemodilution is reversed as a result of the dehydration, and hemoconcentration follows. The early hemodilution is no doubt due to an influx of extravascular fluid as a result of the extensive peripheral vasodilatation (23). The dog exposed to microwaves shows a similar physiologic response. Ambient temperature is critical in these experiments, inasmuch as the total water loss in warm expired air is greatly accelerated (24).

Alterations in leukocyte levels have been reported after exposure of the body to heat (25), and diathermy (26). Leukocyte levels are also altered by exposure to 2800 MHz pulsed microwaves, 100–165 mW/cm². The decrease in lymphocytes and eosinophiles seen after prolonged exposure to microwaves (100–165 mW/cm²) resembles that reported to occur after slow continuous ACTH injection and may be indicative of hypothalamic or adrenal stimulation. The suggestion that this effect is a manifestation of hypothalamic-hypophysial stimulation resulting in the well known adaptational "stress syndrome," has been questioned by Presman (27), who suggests that stress in reaction to microwaves of medium and high intensities arises from direct reaction of all skin receptors rather than heat receptors alone on brain structures, while the effect of radiation at low intensity involves only action on brain structures.

The greater thermal susceptibility of dogs to microwaves while under the influence of pentobarbital sodium, morphine sulfate, or chlorpromazine indicates impairment of the thermal regulatory mechanism. To what degree microwaves contribute to this effect is not clearly understood. When pentobarbital sodium is administered for surgical procedures, a decline in rectal temperature can result (28). Hemingway (29) reported a similar response in investigations conducted in a cool environment.

The reaction intensity in local irradiation has been estimated in humans in terms of the point of barely perceptible pain sensation (30). This happened when the skin was heated to a temperature of 46–47 °C which required a microwave intensity (at 3000 MHz) four times higher than for infrared rays (for the same duration of irradiation). This difference was explained by the different absorption and distribution of energy into the tissues from microwaves of this frequency range as compared with infrared. Experiments with shorter wavelength microwaves (24 GHz) (6) however, showed that an intensity of microwaves three times lower than infrared rays produced the same degree of heating of rat skin for the same duration.

The pain effect from direct irradiation of peripheral nerve in a cat by pulsed microwaves (2.5 and 10 GHz) has been studied in comparison with the effect of heating the nerve by infrared and convected heat (31, 32). Regardless of the type of agent, physiological reactions indicative of pain sensation (accelerated respiration and heartbeat, dilatation of the pupils, rise in blood pressure, etc.) were noted when the temperature of the nerve was raised to 46 °C.

When animals are subjected to prolonged irradiation by microwaves at high intensity, changes in tissues and organs such as hemorrhage, burns and necrosis may develop. This is no doubt the result of marked overheating of the tissues (33, 34).

The development of skin burns over the rib cage in dogs exposed to 2.8 GHz, 100 mW/cm$^2$ microwaves suggests a differential sensitivity of specific body areas. Because water readily absorbs microwave energy, the distribution of fluid in the exposed subject is an important factor in the development of burns. The possibility of a specific effect produced by reflection from the underlying bone is also suggested (18).

The extreme manifestation of the irreversible action of microwaves, or death, has been studied, but the criteria for lethal conditions of irradiation have not been established yet with sufficient precision.

The duration of irradiation by pulsed microwaves of various frequencies and intensities sufficient to kill the animal (immediately after irradiation or some time thereafter) has been estimated (6, 18, 35).

Deichmann et al. (5) investigated the thermal stress effects of exposure to an interrupted microwave field (simulating the continuous 360 degree sweeping action of a radar scanner). Using unprotected rats subjected to a constantly rotating microwave frequency of 24,000 MHz, 300 mW/cm$^2$ (average power density), they found that the ratio of exposure time to nonexposure time in the field, as the scanner completed its full circle, was critical to the length of total safe exposure. The animals survived 80 minutes of total exposure to the microwave beam during an eight hour period. The animals had a chance to dissipate some of the absorbed heat during the nonexposure intervals. Prausnitz and Susskind (36) have confirmed this with mice exposed to 10,000 MHz. They suggest that when the mice are out of the microwave field, the slight latent period before body temperature decreases, reduces their ability to dissipate heat if the exposure-nonexposure cycle is too rapid. This would result in a situation similar to almost continuous exposure.

Lethality depends on a number of conditions of irradiation and on the state of the animal. For a given intensity, a shorter irradiation is required to kill the animal when the temperature of the body and the environment is higher (37, 38).

Body temperature may be the determining factor as to when death will occur. Studies of survival time of rats in a 24,000 MHz microwave field at different ambient temperatures showed that all exposed rats died when the rectal temperature rose to approximately 44 °C (111.2 °F), regardless of the ambient temperature. The lower the ambient temperature, the greater the chance for thermal compensation and, therefore, the chance for survival (39).

There are no substantiated reports of death from exposure to microwave generating equipment under normal conditions of operation. Death of a man from radar exposure has been reported (40), however, no relationship was established between the death of this individual, who died of a post-surgical peritonitis, and his microwave exposure. There is no evidence of adverse effects from exposure to microwaves in human beings among the thousands of individuals who have worked with radar and radar unit components, even at levels far in excess of the 10 mW/cm$^2$ safety level (41).

### *Summary*

The knowledge gained from laboratory experience concerning the effects of radiation within the range of frequencies from 500 to 10,000 MHz (60 to 3 cm wavelength) can be summarized as follows (USAF T.O. 1967):

Radiation at frequencies below 1000 MHz causes heat to be developed primarily in the deep tissues as a result of the penetration of the energy.

Frequencies greater than approximately 3000 MHz cause heating of tissues in much the same manner as does infrared radiation or direct sunlight.

Radiation at frequencies between 1000 and 3000 MHz is subject to varying degrees of penetration and is absorbed in both surface tissues and the deeper tissues, depending upon the characteristics of the tissues themselves (thickness, dielectric constant, and conductivity) and the frequency of radiation.

When electromagnetic energy is absorbed in tissues of the body, heat is produced in the tissues. If the organism cannot dissipate this heat energy as fast as it is produced, the internal temperature of the body will rise. The body's ability to dissipate heat successfully, depends upon many related factors, such as environmental air circulation rate, humidity, air temperature, body metabolic rate, clothing, power density of the radiation field, amount of energy absorbed, and duration of exposure (time).

If only a portion of the body is exposed, the internal temperature of the portion irradiated may rise considerably above normal. However, if the exposure is not prolonged and the areas exposed have adequate blood circulation, the measured oral and rectal temperatures may remain completely normal. Where areas of the body are cooled by an adequate flow of blood through the vascular system, there is less likelihood of tissue damage resulting from abnormal temperature; in areas with relatively little blood circulation, the temperature will rise considerably, since there is little means for the interchange of heat. Consequently, tissue damage is more likely to occur in those areas where proportionately greater rises in temperature can occur. Thus the eyes and testes are readily susceptible to thermal damage, since these organs do not possess an adequate vascular system for the exchange of heat. Presently available information and experience indicate that the eyes and testes are the most vulnerable to microwave radiation.

The body's reaction to an abnormally high fever (hyperpyrexia) is essentially the same regardless of how the fever is produced, whether it is the result of hot baths, steam cabinets, heatstroke, diathermy, or absorbed microwave energy.

## CRITIQUE OF BIOMEDICAL INVESTIGATIONS INTO THE BIOLOGICAL EFFECTS OF MICROWAVES

### A. Experimental Design

Quantitation of the biological response to microwaves is a complex problem because of the wide frequency spectrum, the large number of physical and biological variables and the interrelationships of these variables.

The factors which have to be considered include: Frequency, intensity, waveform (continuous wave, pulsed, and modulated), animal orientation with respect to source, size of animal with respect to wavelength, portion of the body irradiated, exposure time-intensity factors, environmental conditions (temperature, humidity), and shielding. The condition of the exposed subject such as state of health, restraint, medication, etc. has important implications. These variables, individually and in combination, affect the biological response to microwaves.

Radiation in the millimeter range tends to penetrate only a few millimeters into the body, while radiation of longer wavelength penetrates progressively deeper; body size, therefore, becomes a considerable factor in any comparative evaluation. The inherent thermal regulation ability of the animal is also a factor in such biological responses.

One of the problems in studying biologic effects of microwaves, as in all biomedical investigations, is the selection of the most appropriate animal species for study. Animals are quite often selected only on the basis of convenience, economy or familiarity and without regard to their suitability to the problem under study. Because of the lack of awareness and concern in the selection of the experimental animal, many investigations have no inherent value insofar as extrapolation to man is concerned and, in some cases, have led to incorrect interpretations necessitating expensive, time-consuming attempts at confirmation or logical application of the data.

Definitive information concerning effects of microwaves in man can be obtained by extrapolation from animal experimentation and comparison with specific observations following human exposure. Because of the complex nature of the biologic responses to microwave irradiation, it becomes essential to investigate different species of animal under a variety of exposures before experimental results can be reliably extrapolated to man. Most of the earlier investigations of biologic effects of microwaves were conducted on static models or small laboratory animals such as mice, rats, or rabbits. In numerous instances, the exposures were performed while the animal was under the influence of anesthetics, sedatives, tranquilizers, or physically restrained, thus modifying the physiologic or biochemical response.

Before an investigation to elucidate biologic effects of microwaves can be undertaken, certain specific problems pertaining to animal variability must be appreciated. Numerous physiologic factors such as interspecies and interstrain variability in heat regulation and metabolic function must be recognized. Intraspecies body size variation, with resultant differences in the coefficient of heat absorption, cannot be ignored. The effect of previous medication coupled with the physical aspects of exposure, such as frequency or power density, as well as other experimental variables, must be considered.

### B. Effect on the Lens of the Eye

The eye is sensitive to many types of electromagnetic radiation. Certain parts of the eye are more susceptible to particular wavelengths than others. Longer wavelengths are readily transmitted through the globe of the eye with little if any absorption and do not give rise to any deleterious effects in the lens. Shorter waves, such as those in the centimeter range, however, can be harmful to the anterior half of the eye because of absorption and consequent heating effects (42).

According to Zaret (43), the initial site of the pathology is not in the lens substance itself, but in the capsule surrounding the lens at its posterior surface.

The lens is avascular, and is located at least 2mm or more from any blood supply, making it much less effective in dissipating heat as compared with most other tissues and organs. Since microwave absorption is associated with the production of heating, this may be an important factor in the greater susceptibility of the lens to certain forms of electromagnetic radiation. Another important consideration is the rather unique method of differentiation and growth which is present in the lens. The major metabolic activity, particularly oxidative respiration, occurs within the layer of epithelial cells located only in the anterior subcapsular region extending toward the equator.

Microwaves have been shown to produce cataracts in a variety of experimental animals (see, e.g., Refs. 44 to 55).

In several studies, exposure of animals to various frequencies ranging from 200–5500 MHz at field intensities up to 150 mW/cm$^2$ did not produce eye damage; most of these exposures were whole-body (7, 17, 62, 63). Lubin et al. (64) reported that lens changes did not occur in rabbits given 400 MHz whole-body exposure even if radiation times were extended to the lethal period. Addington et al. (62) did not find any eye changes in guinea pigs, dogs, sheep, or mice, from chronic whole-body exposures to 200 MHz (CW).

Whole-body exposure of dogs to 2800 MHz (pulsed) microwaves at an average power density of 165 mW/cm$^2$ for three hours in a single exposure or as long as six hours after daily exposures over a three week period did not produce any lenticular changes when eyes were examined regularly for several years after irradiation (18). In these exposures, the dogs could move around in their cages and their eyes were not exposed directly to the microwave beam for prolonged periods of time.

Richardson et al. (51) noted clouding of the lens after heating of rabbit eyes to 50 °C with 10,000 MHz. With this superficial energy the changes occurred in the anterior segment of the lens, with clouding of the cornea. Using pulsed or CW, 5500 MHz microwaves, Zaret (65) produced lens opacities in rabbits after exposure to 390 mW/cm$^2$ for 34–37 minutes.

Threshold for appearance of cataracts in the rabbit after a single exposure to 2450 MHz CW has been established by Williams et al. (66) to be 120 mW/cm$^2$ for 270 minutes and 600 mW/cm$^2$ for 5 minutes exposure.

Some biochemical changes have been noted when the eyes of rabbits were exposed to microwaves. Following microwave irradiation of sufficient intensity to result in early cataract formation, a loss of phosphatase activity of the lens occurs (67). At low exposure levels, with delayed cataract formation, no significant reduction of adenosine triphosphatase or pyrophosphatase is noted. Rabbits with alloxan induced diabetes are more susceptible to microwave induced cataract formation than are nondiabetic rabbits (49).

In man, Barron et al. (70) and Daily (136) did not find changes in eyes of persons working with radar. A case has been reported, however, where a technician developed bilateral cataracts while operating a radar unit in the 1500–3000 MHz range, with exposure to 100 mW/cm$^2$ for a one year period (58). The significance of this finding has been questioned. Cogan (57) does not believe that the microwave etiology of the cataracts was proven. Kalant (1) points out that "the lesions described are quite unlike those produced by microwaves in all the experimental studies, and the authors are careful not to claim that the lesions were caused by microwaves, but merely to urge caution." This "report gives insufficient information to permit even a guess concerning the actual intensity of exposure, and it seems improbable in the extreme that the lesions described were in fact caused by microwaves."

Zaret et al. (71) conducted an extensive study on the frequency of occurrence of lenticular imperfections in the eyes of microwave workers. A statistically significant difference between the eyes of microwave exposed and control populations was noted. Posterior polar lens changes were more prominent in microwave workers; the number of defects showed a linear increase with age. Although an apparent statistical difference in the score of lens changes between the exposed and control groups existed, the difference was considered not significant from a clinical standpoint. According to Zaret et al. (71), the extent of minor lenticular imperfections does not serve as a useful clinical indicator of cumulative exposure. A relationship can be established between the dose of microwave radiation delivered to the eye and the appearance of cataracts (72). From repeated exposure at 5 watts/cm$^2$, cataracts were formed in two months. At 500 mW/cm$^2$, several months elapse prior to appearance of posterior capsular opacification; at this level, several years are required for production of formed cataracts.

Cleary and his associates (73, 74) found that although repeated subthreshold exposures may produce minimal types of lens changes, it did not appear to increase the incidence of cataracts in Army and Air Force personnel following operational exposure. An analysis of the relative incidence of lens changes in a sample of microwave workers and a control sample revealed a statistically significant increase in rate of accumulation of specific types of defects in the lenses of microwave workers. It was also noted that specific areas of microwave work specialization differ in regard to incidence of lens defects and correlations with microwave exposure parameters. Since the number of defects increased significantly with age in the control group as well as in the group of microwave workers, this process may be interpreted as indicating lens aging. Occupational exposure to microwave radiation may be implicated as a stress that increases the rate of lens aging (74).

Damage to the lens is generally irreversible. Unlike other cells of the body, the transparent cells of the lens cannot be replaced by regrowth. When the cells making up the lens become damaged or die, a cataract eventually forms. Thus, it is not unusual to find cataracts developing many years after the occurrence of the event which produced the original injury. Some of the reported early lenticular opacities or cataracts may simply be due to tumescence of the lens fibers and is a reversible change. The mechanisms responsible for microwave cataractogenesis is believed to be mainly a thermal one in which the maximum heating effect is produced adjacent to or within the epithelial layer of the lens (42, 50, 52, 75).

The available information indicates that the initial effect of microwave irradiation is mainly directed towards the lens capsule resulting in a marked alteration in the permeability of that structure and impairment in metabolism. Studies employing $^{14}$C-labeled adenine in lenses from rabbits' eyes indicate an increase in turnover of the albumoid RNA fraction which is derived from soluble RNA of the lens (76). A significant increase in the permeability of the capsule occurs. Such effects appear to be thermal in nature.

It is quite likely that eye damage effects are related to frequency. At about 2450 MHz, the tissue focuses the electromagnetic energy to a point in the lens area. This is the area in which cataracts can take place. Below 1000 MHz, the energy is less sharply focused, and therefore, the hot spot in the eye will probably occur in the aqueous humor.

Microwave induced opacities in the posterior cortex may result as an interface effect at lens cortex-posterior capsule boundary or at capsule-vitreous body boundary, with concentration of the energy in the posterior cortex from reflection of microwaves. Thus the temperature could be higher in the cortex than in the vitreous immediately behind the lens where ocular temperatures are usually recorded.

The possibility of cumulative damage to the lens from repeated subthreshold exposures to microwaves has been suggested. In a series of studies by Carpenter and associates (45, 77), exposure of rabbits' eyes directly to 2450 MHz, 280 mW/cm$^2$, 5 minutes was the minimal single exposure period which would cause an opacity. With a "subthreshold" exposure of 4 minutes, opacities resulted when exposures were repeated at intervals ranging from 1 day to 2 weeks. Daily 3 minute exposures for 5 consecutive days caused opacities. Three minute exposures given at four day intervals resulted in opacities; when the interval between exposures was increased to 7 days, no opacities developed even after 5 such weekly exposures. Carpenter and VanUmmersen (47) note that the cumulative cataractogenic effect of microwaves, "involves initiation of a chain of events in the lens, the visible and end result of which is an opacity, and that this chain of events must be initiated by an adequate power density acting for a sufficient duration of time if it is to progress to the development of an opacity. If either the power density or the duration of the irradiation is below a certain threshold value, then the damage done to the lens is not irreparable and recovery can occur, provided sufficient time elapses before a subsequent similar episode." Most investigators agree that there is a critical intraocular temperature which must be reached before opacities develop. This temperature, as reported by various authors, ranges from 45 to 55 °C. Obviously, no cumulative rise in temperature can occur if the intervals between exposures exceed the time required for the tissue to return to normal temperature. The cumulative effect to be anticipated, therefore, is the accumulation of damage resulting from repeated exposures each of which is individually capable of producing some degree of damage (1).

It should be noted that in the studies by Carpenter et al. (45, 77) that "opacities occurred after 60 minutes or longer exposures of the eye to pulsed microwaves when the average power density was only 80 $mW/cm^2$ but the peak power was 400 $mW/cm^2$. A 45 minute exposure had no effect. It is significant that at the end of a one hour exposure period at this 80 $mW/cm^2$ power, the temperature within the eye had risen to 42.8 °C which is only 4 degrees above body temperature. Also significant is the fact that this same power has no effect when applied as continuous wave radiation for a one hour period. Indeed, daily exposure periods of this power and duration have had a cumulative effect on the eye only after 19 such periods. These results point to the peak power as being an important factor in causing opacities to develop when the eye is exposed to pulsed microwaves. Also, using the same time repetition factors and pulsed waves, but at a level of 40 $mW/cm^2$ no cataracts were obtained (45).

According to Zaret (78) these results do not necessarily indicate a nonthermal cumulative effect. Acute injury of the lens leads first to hydration, and this is reversible providing no lens protein denaturation has taken place despite the fact that banding, striations and opacification are evident. Hydration of lens fibres may last for many days. If the excess water leaves the lens before denaturation has occurred, no permanent residuum results. If another thermal injury intervenes, however, at a time when the lens is partially damaged, there may be a summation of effect. Baillie (79) used a hypothermic technique to investigate the postulated nonthermal mechanism for cataractogenesis from multiple microwave exposure at subthreshold levels. His data do not support the existence of a nonthermal cataractogenic property of microwave radiation. According to Baillie (79) the cataracts which developed during the course of his study can only be explained on the basis of thermal coagulation of lens protein. There is therefore, adequate evidence to incriminate heat as the initiating mechanism leading to cataract formation during or following a single exposure to microwave radiation. This study suggests that microwave cataractogenesis is, directly or indirectly, a thermal phenomenon. At subthreshold power levels, there is still some question regarding the cumulative effects on the lens. Differences in patterns of peak pulse levels and off time between pulses may be critical factors (80).

It should be understood that a cumulative effect is the accumulation of damage resulting from repeated exposures each of which is individually capable of producing some degree of damage. Since this has not been conclusively shown, the suggestion of cumulative effects is untenable.

It is important at this point to define the cumulative effect produced by ionizing radiation to put this question in its proper perspective. It has been suggested (and there are some experimental data to support the concept) that injury incurred from exposure to ionizing radiation is cumulative. This cumulative effect is a manifestation of the irrepairability of a certain fraction of ionizing radiation injury which has been designated as residual radiation injury. This component of residual radiation injury is additive with frequency of exposures and is not dependent on intervals between exposures once the full recovery potential has been realized (81).

### C. Effect on the Testes

The effect of microwaves on the testes is indicated in several studies (7, 82, 83, 33).

Exposure of the scrotal area results in varying degrees of testicular damage such as edema, enlargement of the testis, atrophy, fibrosis, and coagulation necrosis of seminiferous tubules in rats, rabbits, or dogs exposed to 2450, 3000, 10,000, or 24,000 MHz at power densities of about 10 to 15 mW/cm$^2$; these, however, were simply temperature increases rather than pathological changes (7, 83, 84, 85).

Testicular effects such as degeneration, and reduced sperm production have been produced experimentally at high power densities (>250 mW/cm$^2$) sufficient to produce a significant temperature rise (83, 86).

Ely et al. (7) using 2880 MHz, tried to determine the lowest power density which would produce minimal changes in the most sensitive animal in a group of dogs. They found 10 mW/cm$^2$ to be the "threshold" for testicular damage, for an indefinite exposure. When the testes of dogs were irradiated, it was found that the testicular temperature during irradiation varied from 36 °C to 44 °C. This temperature was maintained in most cases for 60 minutes. The authors point out, however, that the damage observed at such low power levels is slight, almost certainly fully recoverable, and the response of the testes to heating from a radar source is similar to that from other sources of heat. The same effect, which is reversible, can also be caused by a hot bath or constricted clothing and should therefore not be considered hazardous. It is questionable, therefore, whether such effects should be legitimately considered as a basis for appraisal of hazard from microwave exposure (1).

Whole-body exposure of dogs to 24,000 MHz (87) or guinea pigs to 3000 MHz (88) did not affect reproduction. Exposure to 3000 MHz, 8 mW/cm$^2$ did not affect mating of mice or rats (89).

Reports of sterility in the human from exposure to microwaves are questionable. Barron and associates (70, 90) found no evidence of fertility changes in their human surveys. Reports of altered fertility in man, even with unusually large exposures to microwaves are not available (91).

The testes are sensitive to temperature elevation because of their physical location relative to the body surface and poor ability to dissipate heat by means of the vascular system. "Any clothing that prevents maintenance of an intra-scrotal temperature that is at least 1 °C below body temperature will significantly lower sperm output. Daily wear of a well-fitting, closely knit jockstrap results in infertility after about 4 weeks. The better the insulation the more dependable the result. Normal output gradually is resumed after another 3 weeks without such interference" (92). Testicular reaction to heat injury resulting from r. f. radiation appears to be the same as the reaction to high fever associated with many illnesses.

Damage to the testes from r. f. radiation is considered to be completely reversible. Although a condition of temporary sterility and damage to seminiferous tubules may occur, the condition does not appear to be of a permanent nature and will ultimately correct itself. For that matter, temporary partial sterility can frequently be caused by tight-fitting clothing which does not permit freedom of movement and adequate air circulation for the dissipation of heat. Thus, a temperature rise in the testes approaching that of normal body temperature can occur, and in some cases this has been found to be above the minimum temperature threshold for thermal testicular damage. The normal temperature of the testes is below the normal body temperature, varies from individual to individual, and varies in the same individual from time to time, depending upon age and environment. For even the most severely exposed testes, it is almost certain that thermal damage is completely reversible; irreversible damage because of abnormal temperature in the human body is not likely to occur, since death of the individual would result from other causes long before the occurrence of irreversible damage.

Skillful cytological analysis is required to study cellular changes in the testes, experimental data therefore must be interpreted with extreme caution. In man especially, obtaining testicular biopsies imposes practical difficulties (93).

The biological hazard for the testes must be considered from three aspects: 1) Effect on mature stored sperm, 2) effect on developing spermatogonia, 3) the effect on the interstitial (Leydig) cells which are responsible for the secretion of androgenic hormone.

### D. Embryonic Development

There are some experimental data on the effect of microwaves on development of the chick embryo. VanUmmersen (94) investigated the effect of microwaves on development of the chick embryo using 2450 MHz CW (200–400 mW/cm$^2$) and found interference with cellular differentiation in the absence of effects on cellular proliferation.

Osborne (138, 139) found that at no stage of development was the chick embryo affected by long exposure to 200 MHz CW microwaves. In these experiments the temperature rise within the egg was never more than 1 °C.

Protein denaturation takes place in the neighborhood of 40–70 °C; anything which elevates the temperature to this region can start degradation of cell structures. The high power densities that were used in the experiments by Van Ummersen (94) are sufficient to cause protein denaturation on a thermal basis, since all embryos in which effects were produced reached a temperature of 55 °C.

(It should be noted, however, that one cannot compare 200 MHz with 2450 MHz microwaves in effect on developing chick embryos because of differences in wavelength and resultant energy absorption by an object the size of an egg.)

### E. Alteration in Electrophoretic, Immunologic and Enzymatic Activity of Proteins

Changes in the electrophoretic and antigenic reactivity of human gamma globulin and reduced reactivity of alpha-amylase have been reported by Bach (95) and Bach et al. (96). In the study on the effects on human gamma globulin, exposures were performed by using r. f. energy in a range of 10 to 200 MHz (most of them in the range from 10 to 40 MHz). Distinct effects attributed to harmonics of 6 MHz were noted, but not explored. Concentrated exploration for the effect was performed at 10 kilocycle intervals in the range of 13.04 to 13.39 MHz with the result that pronounced effects on antigenic reactivity were found at a power density of 13.4 mW/cm$^2$ using short duty cycle pulses in order to produce high electric field strengths. It was noted that the effect was highly frequency dependent, in the sense that a strong effect could readily be found 10 to 20 kc away from a frequency at which no effect was observed. The marked change in the antigenic reactivity could characteristically be observed at field strengths in the order of 25 V/m which agrees with the extrapolation by Saito and Schwan (97) on pearl-chain formation. The study on reduced activity of alpha-amylase (95), was performed using a kilowatt amplifier with a frequency of approximately 12 MHz.

No evidence has been obtained in viral, bacterial, tissue culture or whole animal experiments to show that these molecular effects can occur *in vivo*. They are so far strictly *in vitro* observations. Whatever these observations may mean in regard to human hazard is uncertain (95).

In studies on the effect of radiofrequency waves and biological macromolecules, Takashima (98) found that decrease in enzyme activity occurred only when the temperature in his preparation was allowed to rise. He concluded that the technique he employed, namely a 100 watt high frequency generator CW, 1 MHz to 6 MHz, had only a thermal effect on alcohol dehydrogenase. In his experiments performed with DNA, optical density (to detect strand separation) and viscosity were studied after irradiation between 10 Hz and 100 kHz; no change could be detected either in optical density or in viscosity.

### F. Decreased Incorporation of Labeled Amino Acid Into Liver and Testes

Suggestion of altered protein synthesis and protein catabolism as a consequence of microwave exposure is based on a study by Janes et al. (99). A careful analysis of this paper will reveal that a statement of altered protein metabolism after microwave exposure is not possible.

This study was performed in hamsters subjected to unspecified microwave power densities, which, however, were high enough to result in death due to hyperthermia. There was an apparent decreased amino acid incorporation in the liver 80 minutes after exposure, returning to normal at 20 hours. Protein synthesis in the testes rose significantly from 80 minutes to 20 hours postexposure.

The authors (99) qualify these results by stating: The findings of decreased amino acid incorporation into protein in liver and testes after microwave exposure cannot be equated to decreased protein synthesis without qualification. The mechanism may be mediated through rise in body temperature. It has been suggested that hyperthermia results in decreased protein synthesis and increased protein catabolism. Thus a definitive statement of the mechanism for the altered protein metabolism after microwaves or hyperthermia is not possible at this time.

### G. Genetic Effects

There is no direct or confirmed evidence of possible genetic effects due to exposure to microwaves. Heller and Teixera-Pinto (100) reported r. f. induced chromosomal abberations in garlic root tips growing in water when exposed for 5 minutes to 27 MHz radiation. This study has been subjected to criticism since thermal effects were not ruled out convincingly, leaving the possibility that the chosen parameters of the applied field caused biologically significant field induced-force effects (101). As noted by Kalant (1) "the authors did not state power levels and operated their instrument on a duty cycle of 0.004 to 0.009. Although the authors described their results as nonthermal no description is given of the methods of measuring the temperature. This is a particularly important omission since the electrodes were separated by a distance of only a few millimeters, much of which was occupied by glass insulation. The volume of water must have been very small indeed and the cooling relatively rapid on termination of radiation exposure. Under such conditions, accurate measurement of temperature change within the root tips must be an extremely difficult technical problem. In the absence of definite information, it would be well to reserve judgment on the question of whether or not the observed changes are truly nonthermal."

Janes et al. (99) also reported microwave induced chromosome effects in a study using hamsters. The authors did not designate power density measurements. The hamsters died between 5 and 30 minutes after onset of exposures with a considerable temperature rise indicating that a fairly high power density was used, probably in the range of 100 mW/cm$^2$ or more.

Sigler et al. (102) noted that there was a higher incidence of children with Down's Syndrome among fathers with prior occupational exposure to radar. This study has very questionable statistical validity and the conclusions are subject to criticism. It should be noted that the authors themselves only "suggested the relationship between mongolism and paternal radar exposure." Such an associative relationship has to be interpreted with extreme caution because of interacting variables, i.e., simultaneous exposure to ionizing radiation and excessively high power densities. Also, it is recognized that the appearance of this congenital malformation is closely related to the age of the mother, the incidence rising more than a hundred fold with increasing age of the mother from 15 to 45 years of age. Because the estimated overall "spontaneous" incidence of Down's Syndrome is about 0.15 in all births in Caucasoid populations, it is exceedingly difficult to relate any increased incidence to possible exposure history of the parent unless large numbers of well-documented cases can be correlated with precisely known exposures; this was not the case in the cited study.

Inferences of apparent genetic effects as a result of chromosome studies should be viewed with the understanding that there is extreme difficulty in relying on this type of work since chromosome scoring techniques are elaborate and require considerable skill. It is incorrect to suggest that these results are presumptive evidence of genetic effects of microwave irradiation. Cytogenetic studies are extremely difficult to perform. In general, these studies are extremely complex and conclusions made from fragmentary studies are fraught with danger.

In evaluating studies on isolated cell systems, it is often possible to measure changes in molecules when they are not a part of a living system; it is not always correct, however, to extrapolate these findings to living situations where the molecule may be in a different chemical form and may be surrounded by other molecules with differing sensitivities or protective capacities (93).

Although chromosome aberrations offer possibilities as early indicators of microwave-induced biological changes, such effects in tissue cultures may reflect total response of a specific tissue, but not genetic injury to the germinal epithelium where it is especially important. There are several sources of uncertainty or error in estimating chromosome aberration frequencies and in using the estimates to evaluate microwave exposures (see, e.g., Refs. 103 to 105). When cells are cultured *in vitro* aberration frequency may vary with time in culture (see, e.g., Refs. 104 to 106). There are also many variables in the tissue culture techniques used in various laboratories, which must be taken into consideration when comparing results. The possible influence of other agents such as viruses, heat, chemicals, etc., that are known to produce chromosome breaks should not be ignored (see, e.g., Refs. 107 to 109). In short, numerical data representing the various types of chromosome lesions, like any other type of biological changes in any type of disease, are significant only in the context of all other available information about the exposed individual (93).

It should be noted, that in the field of ionizing radiation, with the tremendous amount of work that has been done and the fairly convincing evidence of genetic effects as indicated by mutation studies in mice, it is still not possible to document exactly how effective ionizing radiation is in inducing mutation in man. The largest group of humans that is available for study is the offspring of individuals exposed to the atomic bombs at Hiroshima and Nagasaki, and as yet, no conclusion on mutational effects of ionizing radiation is possible.

It should be emphasized that little is known of the ionizing radiation dose mutation relationship for man, the validity of extrapolating from small animals to man, the importance of natural mutations in maintaining the incidence of hereditary conditions in the human population, or the relative mechanisms of selection and elimination of mutations in human populations. Estimates of mutational risk, such as those described for ionizing radiation, may be greatly in error in either direction, perhaps by an order of magnitude. Even in the study of radiation genetics in experimental mammals there are many complications which may tend toward error in estimation of the overall mutational effects of radiation. These include 1) selection of criteria, 2) the large variation in mutagenic effects, according to cell generation period at time of irradiation and 3) the radiation induced changes in the nature and behavior of the biologic material in which the mutation is being measured.

It is of interest that the Soviet investigators, in spite of their, what appears to us, despairing approach to microwave effects, do not report genetic damage.

The effects of microwaves on cells and tissues should be investigated by reliable techniques which are sufficiently sensitive to detect cellular damage over a wide range of power density and frequency. Such techniques should be as free as possible of interacting variables and should permit valid extrapolation to the whole organism with its multiple interdependent, integrated functions.

### H. Pearl-Chain Formation

The phenomenon of pearl-chain formation, which has been alleged to be indicative of nonthermal effects of microwaves is discussed by several investigators (101, 110).

In considering nonthermal effects of microwaves the excellent study by Sher (110) should be noted. He concluded that the "implications for pearl-chain formation are that on no account can biological pearl-chain formation occur for particles smaller than 3 μ (diameter) without risking overheating of the tissues. Particles smaller than about 30 μ (diameter) would not form pearl-chains; freely movable particles of this size are not available in the body. In conclusion then, it can be said with certainty that pearl-chain formation will not occur due to microwave irradiation (by usual pulsed or CW systems) of human beings who are even loosely observing the thermal tolerance threshold."

On the question of orientation of nonspherical particles, "consideration of time constants lead to the conclusion that such particles cannot respond to peak values of the field. It can be said that structures shorter than 15 μ will not be oriented by pulsed or unpulsed fields which do not overheat the tissues. It is unlikely that any histological structure exists which is superficial, sufficiently large and free to be oriented. Therefore, on the basis of the somewhat sparse data on orientation it can be said that significant biological orientation within human beings or large animals is very unlikely" (110). In discussing the study by Heller (111) on the effect of electromagnetic fields on unicellular organisms, Schwan (101) states that this orientation is caused by "the change in potential electric energy which occurs if a nonspherical particle is turned with reference to the applied field."

Roth (80) in his extensive and critical review states: The possibility of nonthermal effects has been the subject of much interest. However, a review of the literature, which claims the existence of such effects, fails to be quantitatively convincing. More research, especially conducted from a more quantitative point of view, is needed to clarify this point... no specific biological effects can be deduced . . . other nonthermal effects quoted in the Soviet and American literature are biologically interesting but have never been clearly shown to be related to symptoms in man.

### I. Soviet Investigations

The possibility that microwaves may interact with biological material without significant heating has been suggested by several Soviet investigators (see, e.g., Refs. 112 to 114).

Although some Soviet investigators describe the thermal nature of microwaves, the majority stress nonthermal or specific microwave effects at the molecular and cellular level. Studies performed in the United States generally reflect the physiologic response of the organism to the thermal burden imposed by microwaves.

A considerable body of literature has grown in the USSR on transient functional changes following low-dose 10 mW/cm$^2$ microwave irradiation studied by conditional response experimentation. The Soviets have strongly and repeatedly stressed that the CNS must be considered as being moderately or highly sensitive to radiation injuries. Their conceptual basis for this view is largely centered about Pavlovian "nervism." Very briefly this theory may be interpreted to mean that the central nervous system exerts a controlling influence over all types of reactions in the organism, including various local tissue reactions. Nonnervous reactions are considered as only of secondary importance because of the basic controlling role of the central nervous system in the whole organism. Thus, in considering microwave pathogenesis, Soviet physiologists have persistently sought the central nervous system mechanism that might be responsible for each microwave-induced phenomenon.

In general, the work of Soviet investigators in this area is subject to criticism because of limited statistical analysis of data, inadequate controls and lack of quantification of the results. Conditional response studies intrinsically do not lend themselves to objective interpretation.

It is of interest to note that one Soviet author (115) indicates there is evidence that microwaves may have a biological and especially a neural effect at field intensities which do not produce measurable thermal changes although specific, e.g., nonthermal microwave effects have not been experimentally verified. He reasons that, since biological objects are electrically heterogeneous and since microwave-range electromagnetic fields (EMF) have a known selective thermal effect on various tissues and organs, a difference between a microwave effect and a neutral heat effect is not necessarily due to an unknown extrathermal factor, but might well be a function of an uneven distribution of heat in the organism which could exert its own peculiar effect. The specific action of microwave EMF, in Osipov's view, should only be understood as a demonstrable transfer of EMF energy into nonthermal energy. He therefore feels that the many alleged "nonthermal" microwave effects (113, 116) may well be "microthermal" effects in the absence of conclusive experimental evidence to the contrary (112).

These low-level effects reported by Soviet investigators have not been confirmed outside of the U.S.S.R. One of the main difficulties in confirming this Soviet work is quantification. American investigators have not been able to obtain information on how these studies were conducted, even though attempts have been made.

The importance of the difference between the Soviet and Western views is readily apparent when it is realized that practical consideration of Maximum Permissible Exposure is based on the acceptance or rejection of nonthermal effects of microwaves as biologically significant.

The U.S. Department of Defense and the U.S.A. Standards Institute recommend the 10 mW/cm$^2$ level whole-body continuous exposure, but Soviet standards recommend considerably lower exposure limits.

One does not know how much confidence to put in the conclusions of the Soviet investigators. The results of Soviet experiments do not clearly indicate whether the changes produced by microwaves are due to generalized thermal effects or to more specific influences on particularly vulnerable tissues. The lack of precise temperature-measuring devices no doubt plays a part in the assumption of nonthermal "specific" microwave effects.

Although the Soviets recommend much lower limits than we do, there is no information presently available on how the lower limits prescribed by the Soviets are observed, if they are at all.

Osipov (115) in a review of neurologic responses to microwave exposure concluded that most subjective symptoms were reversible and that pathological damage to neural structures was insignificant. Only rarely were microwaves found to cause hallucinations, syncope, adynamia and other manifestations of the so-called "diencephalic" syndrome.

Livshits (117), another leading Soviet investigator, states the following: During the last 15 years, disputes among researchers studying the effects of radiation on the higher nervous activity by the conditioned reflex and zoopsychological methods have not ceased. In conditioned reflex investigations, it has been discovered that irradiation induces various disturbances of the higher nervous activity. It must be mentioned that such an effect of radiation is observed only in experiments conducted according to the schemes used by I. P. Pavlov and his followers.

Among the authors that have investigated the effects of radiation upon conditioned reflexes in different animals, there is no complete unanimity in the evaluation of the phenomena that they observed and the understanding of their mechanism.

The opinion of certain foreign researchers that the change in the latent period and values of the conditioned reflex expresses only or primarily a change in the excitability of the unconditioned reflex centers, in general contradicts the considerable material obtained in the laboratories of I. P. Pavlov and his followers. In radiation pathology, in particular, this question is complex and will require a special investigation.

Dodge (118), in his review of the Soviet research in this area, stated "An often disappointing facet of the Soviet and East European literature on the subject of clinical manifestations of microwave exposure is the lack of pertinent data presented on the circumstances of irradiation; frequency, effective area of irradiation, orientation of the body with respect to the source, waveform (continuous or pulsed; modulation factors), exposure schedule and duration, natural shielding factors, and whole plethora of important environmental factors (heat, humidity, light, etc.) are often omitted from clinical and hygienic reports. In addition, the physiological and psychological status of human subjects such as health, previous or concomitant medication, and mental status is also more often than not omitted. These variables, both individually and combined, affect the human response to microwave radiation."

Very intense microwave fields of up to 10 watts/cm$^2$ applied directly to the head have been shown to cause deterioration of conditioned reflex activity in dogs (119). This is hardly a surprising finding, and adds little to our knowledge since no measurement of cerebral temperature change was made, and no pathological studies of brain damage are quoted (1).

Causal relationships of such findings to microwave exposure have not been necessarily always established. Other work has been carried out studying changes in conditioned reflexes evoked by the radiation in animals. To the best of our knowledge, this work has not always been reported in great detail and has not been reproduced elsewhere (101).

### J. Central Nervous System Effects

It is known that an r. f. field can be reinforced in the region of peripheral nervous tissue causing a temperature rise, even while nearby muscle and skin show no measurable temperature effect. When peripheral nerves are heated above a minimum level they may trigger spontaneously. Evidence presented by McAfee (31, 32) convincingly indicates that it is thermal stimulation of the peripheral nervous system which produces the neurophysiological and behavioral changes observed. The interaction between the peripheral nervous system and the central nervous system would account for effect on heart rhythm, blood chemistry, etc. as reported by the Soviets.

An auditory response has been reported to occur at power levels below 1 mW/cm$^2$ of 200–300 MHz microwaves and is believed to be a direct auditory nerve response to microwaves (120). It should be noted, however, that significant though extremely inefficient rectification of microwave energy may be possible *in vivo* (121). Thus some of the nonthermal neurologically related observations can be explained, especially where one hears pulse repetition frequency.

There is no evidence that this auditory sensation constitutes a risk of injury. Considering that many sources of auditory sensation exist in the normal environment and are not considered hazards, more evidence of hazard is required.

It is noteworthy that a leading Soviet spokesman on biologic effects of microwaves has stated that the changes in the functions of the nervous system produced by microwaves are not specific (113). As is known, such changes are produced by any means of stimulation or variation of the excitability of the peripheral and central parts of the nervous system.

Hence, we can naturally assume that also the action of microwaves under this system is due to stimulation or variation of the excitability of the nervous tissues. The elucidation of the physical and chemical mechanisms of microwaves on excitable structures involves considerable difficulties, this is because the physical-chemical mechanisms of excitability of living tissue in general, is still far from clear.

### K. Cardiovascular Effects

Several investigators report that exposure of animals or man may result in direct or indirect effects on the cardiovascular system (122, 123, 124, 135). Some authors suggest that exposure to microwaves at intensities that do not produce appreciable thermal effect may lead to functional changes. These changes are observed with acute as well as chronic exposures (84, 125, 126).

Increased heart rate has been observed after exposure to power densities of 50–130 mW/cm$^2$ for variable periods of time ranging from 10–140 minutes (see, e.g., Refs. 122 to 124).

Slowing of the heart rate is reported by some Soviet investigators with low, or what they consider nonthermal, levels of microwaves (see, e.g., Refs. 127 to 129), although others have reported increased heart rate with low-level microwave exposure over the dorsal aspect of rabbits (130, 131). These discrepancies reveal several defects in some of the experiments which should be recognized, such as frequency, power density of microwaves, duration of exposure, animal restraint and inadequacy of statistical analysis.

Tolgskaya and Gordon (132) suggest that receptors of the reflexogenic zone of the curve of the aorta, the carotid sinus, and all layers of the auricular wall are highly sensitive to microwaves. They observed morphological modification of receptors after one exposure to microwaves; these changes decreased with repeated exposures. Levitina (133) suggests that reduced cardiac rhythm is initiated through stimulation of the skin receptors.

### L. Ionizing Radiation

It is essential that one distinguish between ionizing radiation effects and those effects produced by electromagnetic radiation in the microwave range.

Since microwaves do not cause ionization, those effects resulting from dissociation of chemical bonds, such as mutation effects, cannot be induced directly by microwaves as they can be by x-rays. Generally speaking, the effects of microwave exposure are not associated with the disturbing effects of ionizing radiation, including x-rays. The effects of microwaves are principally thermal. X-ray irradiation causes little thermal effect (2).

Reported cumulative effects of microwaves as indicated by cataract formation in rabbit's eyes (77) result from repeated subthreshold doses to fairly high power densities ($>80$ mW/cm$^2$) where insufficient time is allowed between exposures to permit tissue repair. This effect must be associated only with near-threshold exposures and has no general significance. It cannot be extrapolated to very low exposure intensities as one does in the case of x-rays.

The benefit vs risk philosophy first propounded by the Federal Radiation Council in the field of ionizing radiation is "predicated on the view that there is probably no threshold for biological effects from exposure to ionizing radiation." The recognition that microwave radiation is non-ionizing, does not exhibit low-level cumulative effects, and exhibits a threshold for its hazardous thermal effects has very important implications. It means that one cannot simply adopt the philosophy of radiation protection for x-rays which consists of weighing the benefits obtained from x-radiation against the risk involved in exposure.

### M. Perspective

A critical review of studies into the biological effects of microwaves indicates that many of the investigations suffer from inadequacies of either technical facilities and microwave measurement skills or insufficient control of the biological specimens and the criteria for biological change. Assessment of genetic and neurologic effects are most difficult because of the problem of differentiation between magnetic fields and thermal effects of microwave exposure. Not enough detailed systematic studies are available to determine the relationship of response to microwaves with differences in frequency, air temperature and humidity, clothing and other factors which affect microwave-induced temperature rise. Realistic safety standards for human tolerance to microwave radiation requires a more thorough analysis of the interaction of electromagnetic fields with the human body.

There is a serious philosophical question about the definition of hazard. One objective definition of injury is an irreversible change in biological function as observed at the organ or system level. With this definition it is possible to define a hazard as a probability of injury on a statistical basis. It is important to differentiate between the hazard levels at which injury may be sustained, and effect or perception. Safety levels with respect to whole-body radiation may be different and more stringent than safety levels corresponding to localized exposures of relatively nonsensitive body areas.

Except for the Soviet bloc literature, there is no evidence to support a requirement of less than 10 mW/cm$^2$. There is much to be critically reviewed in the current furor over the discrepancies between U.S. and U.S.S.R. safety standards on microwave radiation. One does not know how much confidence to put in the conclusions of the Soviet investigators. The results of Soviet experiments do not clearly indicate whether the changes induced by microwaves are due to generalized thermal effects or to more specific influences on particularly vulnerable tissues. The lack of precise temperature measuring devices no doubt plays a part in the assumption of nonthermal specific microwave effects.

Because of their conditional response studies, Soviet standards are based on effect rather than hazard levels. The low-level effects reported by the Soviet investigators have not been confirmed in this country and there is little effort in this direction at the present time. One of the main difficulties in confirming the Soviet work is quantification. American investigators have not been able to obtain information on how these studies are conducted. There is no information presently available on how the low limits prescribed by the Soviets are observed. As Westin (134) has pointed out, extrapolation to man "must be approached with great caution until further data become available. Until that time the present exposure criterion of 10 mW/cm$^2$ must be adhered to."

### N. Prospects

Although a considerable amount of work has been done to characterize and elucidate the interaction of microwave energy with biologic systems, these have been more or less of a qualitative nature. Little quantitative information is available at present. These studies have resulted in confusion as to the type and extent of microwave induced injury. It is essential to realize that there is no universally accepted single specific biologic indicator of exposure to microwaves other than the thermal response at higher field densities. There is no reason to believe that a single biological test would be a satisfactory indicator of microwave exposure.

The vast experience obtained in studies on the biologic effects of ionizing radiation and in space medicine can, within reasonable limits, be applied to all electromagnetic radiation. With these concepts in mind we can also develop criteria for hazard assessment. Proper investigation of the biologic effects of microwaves requires an understanding and appreciation of biophysical principles and comparative biomedicine. Such studies require the selection of biomedical parameters which should consider basic physiological functions and work capacity, identification of specific and nonspecific reactions, and differentiation of adaptational or compensatory changes from pathological manifestations. The most valuable parameters at present are those which, under normal conditions show self-regulatory properties, such as body temperature, neuroendocrine, central nervous system and cardiovascular responses.

Suggestions for studying ionizing radiation (93) can be applied to the analysis of effects from microwave exposure:

> The biological indicators of microwave response should express themselves in a reasonably short time.
>
> The technique of measurement preferably should not require exotic equipment.
>
> The microwave-induced biological changes should have a high probability of occurring.
>
> The range of normal values for the parameters selected should be well-defined and should have a relatively small range of variability. Ideally, the range of normal values for the individual in question, rather than the mean for a group, should be the reference value when evaluating post-exposure data.
>
> Anatomical studies should be done to look for morphological changes parallel to functional ones. Behavioral studies should be done to assess the degree of gross functional decrement associated with possible neurologic changes that may be observed.

Certain questions are highly pertinent to the selection of subjects for investigation when the central issue is effects on the human animal.

1. What are we trying to determine?

a. Does exposure to microwaves result in biologically measurable effects?

b. Are these effects harmful (or significantly so) e.g., are they likely to be more serious than effects of say, taking a new job in a very hot boiler room or trying to get a good sun-tan at the beach?

c. What kind of effects are they, e.g., are they acute and reversible such as sensation of heat, 1st degree burn; do they have genetic consequences; are they repairable in whole or in part?

2. What concepts and criteria should be used in selecting problems to study when the major concern is man?

a. Which systems would one logically expect to show changes of microwave exposure?

b. Of these, which ones are likely to show well defined and relatively narrow ranges of variability in unexposed animals so that relatively small changes will be recognizable as a result of microwave exposure.

3. What approaches are appropriate?

Any approach that provides reliable answers is acceptable.

The most sensitive criteria for judging the state of regulatory systems is the variability of physiological indices under conditions of perturbation rather than their absolute values at rest. Usually those changes that reflect degree of deflection from a balanced or steady state in response to a measured stimulus or alternatively, rate of return to steady state such as heating and cooling rate of animals exposed to specific frequencies and power densities are most reliable indicators.

4. What are the physiological, anatomical correlations between or among animal species that would bolster rather than weaken one's confidence when extrapolating from animal data to man? No single animal species can represent an ideal model and no experimental method is universally suited to all foreseeable uses. It is essential, therefore that a comparative approach be used in selecting the animal most appropriate for laboratory investigation of microwave effects. Such comparative approach requires identification of similarities and contrasts in microwave absorption and thermal regulatory capability in various animal species, if extrapolation to man is to have validity.

Extrapolating the results of microwave experiments from various species of animals to man has been done frequently without accounting for interspecies differences in mass and size, or inherent differences in thermal regulation. Experiments performed on rodents cannot be used to predict effects on humans unless the differences in body mass and thermo-regulatory capability are taken into account.

It is essential in designing experiments that the experimental subject be maintained in a relatively "normal" life situation and that restraints, tranquillizers or anaesthesia be avoided. Generally, larger animals are kept under a wider range of conditions than are the small laboratory species. The advantage of using the larger animals includes ability to obtain more and larger samples from one animal, and a single large animal can be studied in more detail over a longer period of time. The importance of body mass is also of consequence. Another important consideration is that work with larger species in addition to rodents extends our base and provides a firmer basis for extrapolation of certain findings to man, because so many metabolic correlations of body mass such as rate of oxygen consumption, pulse rate, neuroendocrine function, etc., are directly concerned in temperature regulation. This is central to the whole problem of microwave effects.

In general, there is little doubt that biomedical study of several species is required to provide the most reliable extrapolation to man. Ideally, one should choose taxonomically unrelated species to bring out generalizations, with the realization, however, that simply to study multiple species alone will not advance understanding. The main contribution of a comparative approach is not to record the same phenomenon in as many different animals as possible, but rather to select intelligently some that can serve for meaningful comparisons. From a spectrum of species, basic information on microwave effects can be acquired which in turn can be used to elucidate mechanisms of action. It should be emphasized, however, that studies on animal models should be complemented, when ever possible, by retrospective and prospective studies on man himself.

The greatest need today in the assessment of biological effects of microwave exposure is to maintain a realistic perspective on the nature of microwave fields and the possible effects from exposure. The mechanisms by which cell damage is produced, the biological tolerance of the most susceptible tissues and safe levels of intensity must be established in an organized fashion.

Because of the frequency dependence of biologic response to microwave exposure, it is unrealistic to extrapolate responses observed at one frequency to those which could occur at another until more basic information is obtained at various frequencies. Investigation of the variation of penetration depth with frequency is important. Consideration should be given to frequency effects and modulation effects, e.g., the differences between the effects of CW and pulsed irradiation.

To make the results of microwave investigations meaningful, the electromagnetic field patterns, both in and near the body structure that is exposed, should be established quantitatively as a function of frequency, source configuration and source location.

Field effects as opposed to thermal effects associated with pulsed microwave power are not understood but may be significant. Comparative studies should be performed to relate near-field and far-field responses as well as induction fields or non-radiation situations that would occur in near fields.

Important problems that have to be resolved are: the effects of electromagnetic fields on human tissues and the effects of tissues of complex geometric shapes on electromagnetic fields. Quantitative studies should be developed involving electrically equivalent phantom models, thermography, solid state electronics and computer technology integrated with sound physiological techniques (137).

The development of adequate and operable standards requires comprehensible evaluation of information obtained from animal experiments and surveys of individuals exposed either occupationally or while engaged in military activity. The criteria to be used in evaluating experimental results of microwave exposure and the interacting variables in such assessment requires the exercise of informed judgment. Since there is such a clear-cut dichotomy in the criteria used in the United States and the U.S.S.R., these have to be understood and evaluated. Although the hazard of microwave exposure has not become an ecological problem as with ionizing radiation, some consideration should be given to unifying concepts in the development of a realistic MPE for microwaves.

There is no doubt that the central nervous system effects must be resolved by quantitative experimentation and good biomedical investigation and the implications of such effects should be intelligently defined.

The questions of possible genetic effects from "low-level" microwave exposure and the resolution of the controversy concerning thermal, nonthermal and microthermal effects are extremely important in the development of realistic MPE and to avoid placing undue restrictions on industry and the military.

The problem is how to determine tolerance limits. The parameters that have to be studied include physical factors, such as frequency, average power, peak power, pulse repetition frequency, integrated exposure time, recovery time between exposures and biological characteristics of the test species and their relation to man. Some parameters may be irrelevant or of only minor importance compared to others. The substantial number of suitable parameters which may or may not be relevant to microwave exposure hazards dictates careful design of experiments, if significant information is to be obtained.

Many biological, chemical and physical phenomena have been noted in the past but are as yet inadequately understood and explained. Some of these phenomena, involving mechanical orientation of particles, or breaking of chemical bonds seem inexplicable on the basis of energy available from the microwave field. Many attempts over the past several years to devise a working hypothesis explaining these phenomena have been fruitless. A thorough understanding of the biological hazards due to r. f. fields may be achieved by an explanation of these physical and chemical phenomena which requires more detailed study of the various observed phenomena.

An aspect of the work that must be kept in mind in the planning of experiments on the biological effects of microwaves is the effect of temperature increase and a measure of the energy input into each experimental system. More sensitive instruments for measuring temperatures are required.

It is essential that studies be performed to determine the minimum exposure conditions which would produce an effect and the maximum exposure which will produce a reversible biological effect. We need to know more precisely what the threshold is for irreversible changes from microwave irradiation. The repairability of the biological damage should be determined. A comprehensive study would ultimately provide limits of exposure which would cause biological effects which are not permanent. If possible, experiments should be designed to simulate real-life situations of exposure. Ultimately, a clear definition of hazards and its relative importance must be made. In general, fresh approaches must be used to develop newer concepts and understanding of the biologic effects of microwaves.

Better controlled work on biological macromolecules and cells and their response to electromagnetic fields is essential to provide an answer to the question of whether there are nonthermal effects on biological matter and if they can be harmful. In particular, with regard to nonthermal effects, more basic work on the interaction of microwaves with biological and other particles is needed to find out if the demonstrated phenomena of "field induced force effects" can cause harm.

Well-controlled behavioral studies on animals should be performed. Conditional responses and their modification due to microwave exposure may be an excellent tool to study the more subtle effects of multiple exposures to low-intensity microwaves and the possibility that other than thermal effects can be harmful, but more objectivity is required.

Well-planned, controlled animal studies should be undertaken. Representative species of animals of different orders should be used to provide extrapolation factors for predicting the response of man. A number of microwave frequencies with carefully calibrated beams should be used. Such studies are best developed through direct collaboration of biomedical and engineering personnel.

Since evidence indicates that the eye and testis may be among the most critical organs in the assessment of possible microwave hazards, it is essential that the effects on these organs be critically and quantitatively evaluated on a sequential basis. Investigation of long-term effects on large enough numbers of suitable animal species is mandatory.

In conclusion, it should be emphasized that more sophisticated conceptual approaches and more rigorous experimental design must be developed. This will require increased and improved education and training in the biologic effects of microwave radiation. There is great need for systematic, quantitative investigation into the biologic effects of the whole electromagnetic spectrum on a comparative basis, in well-controlled experiments. This should be done by using sound biomedical and biophysical approaches at the various organizational levels from the whole animal to the subcellular level on an integrated basis with full recognition of the multiple associated variables.

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# THERMAL AND NONTHERMAL CATARACTOGENESIS BY MICROWAVES

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In 1926, Duke-Elder suggested that lens damage would occur as a result of irradiation with ultra-high frequency electromagnetic energy (1). This hypothesis was shown to be correct for microwaves by the demonstration in experimental animals of lens opacities following exposure to the radiation (2, 3). The confirmation and supplementation of these findings by others (notably: Osborne and Frederick, (4); Daily et al. (5); Richardson et al. (6); Daily et al. (7); Schwan and Piersol, (8); Williams et al. (9); Carpenter, (10)), have made the hazard of blindness a problem for those concerned with medical, industrial, research and other applications of microwave energy.

The information on microwave cataractogenesis to date may be summarized as follows. The lens opacity is usually subcapsular in the anterior or posterior polar position. Its onset may be immediate or delayed depending on the power density and the exposure time. The delayed opacity may develop after a single exposure if the exposure is longer than a particular threshold time which has a specific value at each power density. The delayed opacity will develop after multiple exposures when the exposures are shorter than this threshold, if they are made with sufficient frequency over an adequate period of time. In general the delayed opacity reaches its maximum density 7–14 days after a single exposure or at a similar time after the last of a series of multiple exposures. Finally, some degree of regression in the density of an opacity may occur. (For descriptive purposes an exposure equal to the single exposure threshold time at a particular power density will be referred to as a threshold exposure, and the lesion produced by multiple subthreshold exposures will be referred to as a cumulative microwave cataract).

The dissipation of microwave energy as heat during its passage through the eye has been held solely responsible for the cataractogenic effect. However, recent reports have suggested a supplementary nonthermal cataractogenic effect to explain the formation of cumulative microwave cataracts in certain cases where the measured intraocular temperature rise produced by each exposure has been insufficient to account for the lens damage on a purely thermal basis (11, 12). If this nonthermal cataractogenic effect exists, it constitutes an important occupational hazard. Conditions of frequent minimal exposure can be visualized (leakage, direct or reflected, from apparatus etc.) where there would be no thermal sensation to act as a warning.

The following study was designed to determine whether or not a cumulative microwave cataract could be produced when the exposures were made under sufficient hypothermia to prevent the lens temperature from exceeding normal body temperature. A cumulative microwave cataract developing under these conditions would support the hypothesis of a non-thermal cataractogenic effect of the radiation. The microwave frequency and the power density incident on the eye were kept constant so that exposure time was the only variable. The exposure times were short to minimize heat loss during irradiation and a random field was used to simulate reflection from multiple surfaces.

## APPARATUS AND METHODS

The microwave apparatus was a 7′×3′×3′ cavity which was energized at a nominal frequency of 2.5 GHz as shown in Fig. 1. It contained a rotating reflector to prevent the formation of static points of focal concentration in the random field formed by

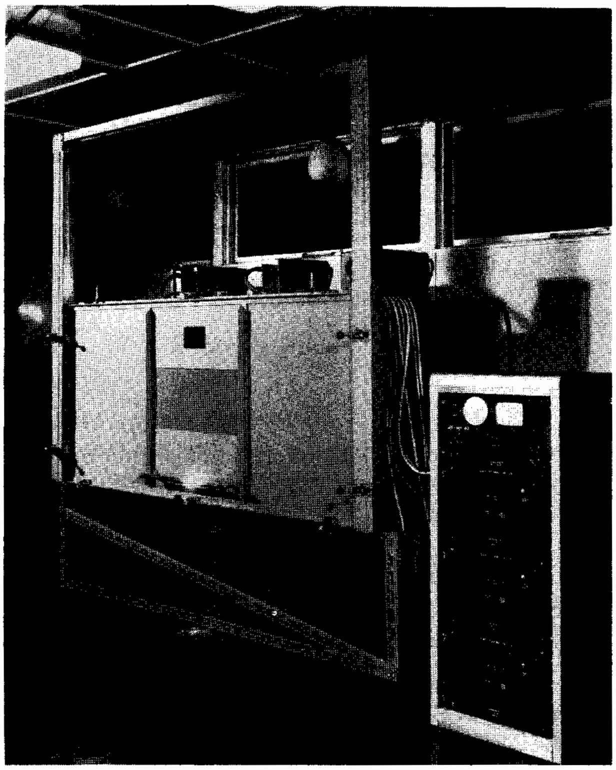


Figure 1. On the left: the cavity with the microwave generators (three water cooled magnetrons) located on its upper surface. The front wall is detachable and can be slid upwards for gaining access to the interior. On the right: the control console.

reflection from its metallic confines. A preliminary study using water loads demonstrated that the field in the working area in the center of the cavity produced uniform dielectric heating power of 4.5 kW. A further preliminary study using a coaxial wavemeter, demonstrated that the frequency of the microwaves in the cavity corresponded to a free-space wavelength of 12.4 cm.

An aluminum box (2′8″×1′×2′) was placed in the cavity to shield the body of an experimental animal from the field. The box had an aperture in its upper surface and the aperture was covered with an aluminum plate (thickness, $\frac{1}{16}$″) which had a 2.5 cm hole bored in its center. The hole allowed part of the field to leak into the interior of the box. The power output of the cavity was adjusted so that the power density inside the box, 2 mm below the plate, was 5 watts/cm$^2$ as measured by calorimetry. The box contained polystyrene blocks to support the animal so that one eye could be positioned with the cornea 2 mm below the hole in the plate. Anesthetic gas supplies were led into the box and expiratory gases were conducted away from it by tubing passing through the side of the cavity as shown in Fig. 2.

Fifteen adult mongrel dogs, each weighing approximately 13 kg, were used. All experimental procedures were performed under general anesthesia with positive pressure respiration. The anesthetic technique has been described elsewhere (13). Full pupillary dilatation of both eyes was produced in each animal prior to all maneuvers by instilling mydriatic drops (homatropine 5% and cocaine 2%) into the conjunctival sac. In preparing an eye for exposure, stay sutures of 0000 braided silk were inserted through the tendons of the recti muscles and loosely secured to the plate around the hole. The sutures were then tightened so that the center of the cornea was immediately below the hole, in the plane where the power density was 5 watts/cm$^2$ when the apparatus was energized. In those animals where hypothermia was used, cooling was produced by immersing the body up to the neck in ice water. Water at 40 °C was used for rewarming. Body temperatures were monitored using esophageal and rectal thermocouples. On those occasions where the temperature of specific tissues was recorded, a fine thermocouple needle was used. The hypothermic technique was varied as required, according to the clinical state of the animal. This was aided by estimating the pulse pressure in the groin and observing the electrocardiograph displayed on an oscilloscope. When hypothermia was prolonged, the aortic pressure was monitored using an indwelling cannula connected to a pressure transducer. Also, with prolonged hypothermia, the animal's blood gases and acid-base state were monitored and maintained within normal limits as described elsewhere (13).

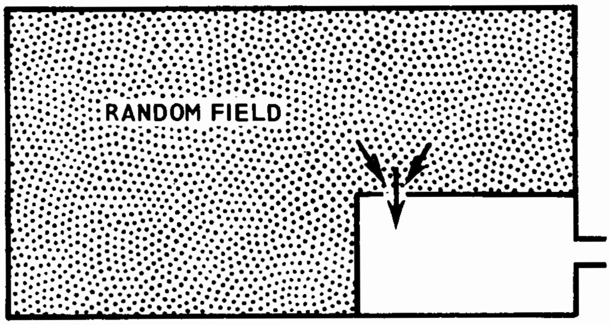


Figure 2. Diagram of the microwave cavity containing the aluminum box. The position of the hole in the plate is indicated by the arrows. The opening for the anesthetic gas pipes is on the right.

A single exposure was made into the right eye in the first five dogs. The left eye was left untreated to act as a control. The exposure with the first animal was 45 seconds. With each subsequent animal the exposure was increased by 10 seconds. The eyes were examined by direct observation and by ophthalmoscopy, every day, over a period of 14 days. At the end of the 14 day period, the animals were killed. The lenses of both eyes were then excised, examined and photographed. The threshold exposure, under the experimental conditions, was established from this part of the study.

Two thermocouple needles were inserted into the right eye of the sixth dog. One of the needles was advanced into the substance of the lens and the other was positioned in the vitreous humour close to the posterior pole of the lens. The needles were firmly secured in these positions by suturing them to extra-orbital structures. The animal was then cooled to 22 °C. From similar preliminary studies this temperature had been estimated as the protective temperature. (The protective temperature is that which would prevent microwave heating of the lens in excess of normal body temperature following a threshold exposure). During cooling, the relationship between the general body temperature and the general intraocular temperature of the right eye was observed. When the protective temperature was reached, a threshold exposure was made into the left eye. The various regions of this eye were then explored using a thermocouple needle and the intraocular temperatures were recorded. The time taken for the maximum intraocular temperature to return to its pre-exposure value was also recorded. The animal was then rewarmed sufficiently to allow further comparison between the general body temperature and the general intraocular temperature of the right eye. When these observations had been made the animal was killed.

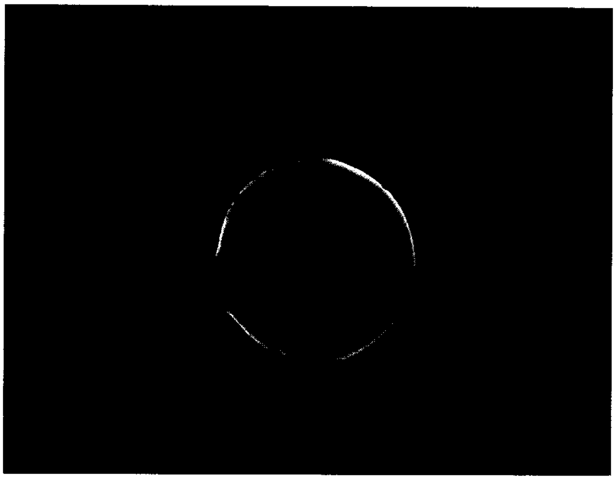
The right eye of the seventh dog was exposed without cooling using the threshold exposure. The eye was then explored with a thermocouple needle and the time required for the maximum intraocular temperature to return to its pre-exposure value was recorded.

The exposures with the eighth, ninth, tenth, and eleventh dogs were respectively 50%, 58%, 66%, and 75% of the threshold exposure. The procedure with the eighth and ninth dog was as follows. The right eye was exposed once at normal body temperature, then the animal was cooled. When the protective temperature was reached, the exposure was repeated on the left eye. Then the animal was rewarmed and allowed to recover from the anesthetic. This procedure was repeated every two or three days over a period of fifteen days, the total number of exposures in each eye being seven. With the tenth and eleventh dog, ten exposures were made into the right eye at normal body temperature, allowing sufficient time between exposures for the intraocular temperature to return to its pre-exposure value. Then the animal was cooled. When the protective temperature was reached it was carefully maintained within a limit of plus or minus one centigrade degree while ten exposures were made into the left eye. Once again sufficient time was allowed between exposures to insure that the intraocular temperature would return to its pre-exposure value. When the tenth exposure had been completed, the animal was rewarmed and allowed to recover from the anesthetic. The eyes were examined by direct observation and by ophthalmoscopy, every day, over a period of 14 days. On the fourteenth day the eyes were photographed and the animals were killed. The lenses were then excised, examined and photographed.

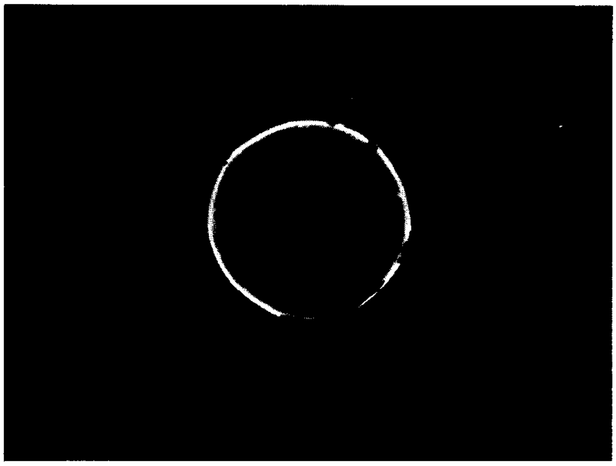
The right eye of the twelfth, thirteenth, and fourteenth dog was exposed once at normal body temperature. The exposures for these animals were respectively 50%, 75%, and 90% of the threshold exposure. The fifteenth dog was cooled to the protective temperature. Then ten exposures were made into the right eye using 75% of the threshold exposure at intervals which were sufficient to allow the eye temperature to return to its pre-exposure value. The animal was then rewarmed and allowed to recover from the anesthetic. These four animals were transferred to the long-term observation accommodation.

## RESULTS

The results of the single exposure of the right eye at normal body temperature in the first five dogs were as follows. The 45 second and 55 second exposures produced no visible effect. The lenses remained perfectly normal in appearance throughout the observation period. The 65 second exposure produced a fine "feather" opacity in the lens which appeared on the 7th day. A slight increase in the density of this opacity was noted over the remainder

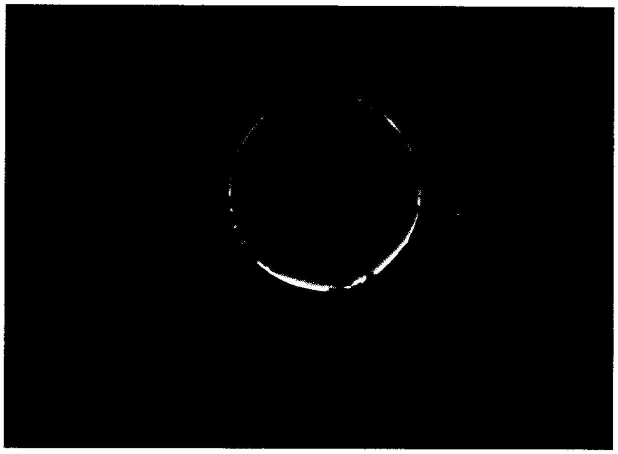


(a) 55 second exposure—normal appearance.



(b) 65 second exposure—"feather" cataract.

(c) 70 second exposure—dense cataract.



(d) Control.
(Threshold exposure—60 seconds.)

Figure 3. Lenses excised on the 14th day following a single microwave exposure made at normal body temperature. Photographs using dark field illumination.

of the observation period. The 70 second exposure produced a patchy generalized opacity in the lens which appeared between the 2nd and 4th days. This opacity also increased in density but in this case a maximum density was reached on the tenth day. The 75 second exposure produced a dense opacity which was evident immediately after the exposure. This opacity remained unaltered throughout the observation period. From these findings the threshold exposure under the experimental conditions was fixed at 60 seconds (Fig. 3). Other findings were as follows. Photophobia of 2–3 days duration was noted following the 65, 70, and 75 second exposures. Diffuse corneal clouding was observed following the 70 and 75 second exposures. The corneal clouding resolved completely by the 8th day in the eye which was exposed for 70 seconds. Periorbital edema of 3–5 days duration was also noted following the 70 and 75 second exposures. This was associated with a small third degree burn of the lower eye lid in the eye which had received the 75 second exposure. The burn was excised and the wound was sutured on the fourth day.

During the cooling and rewarming of the sixth dog, a close relationship was noted between the general intraocular temperature of the right eye and the general body temperature. A maximum temperature of 38 °C was recorded in the left eye of this animal at the anterior surface of the lens, following the threshold exposure made at the protective

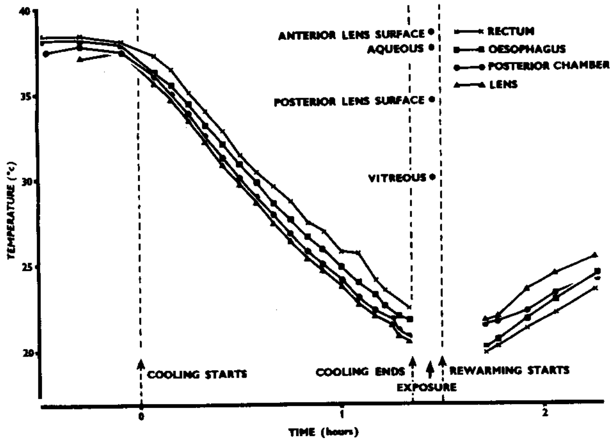
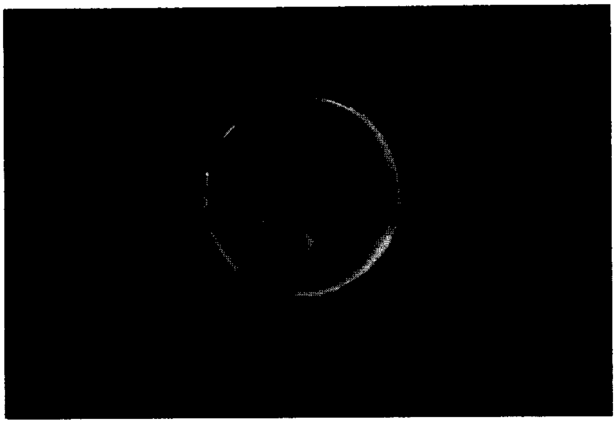


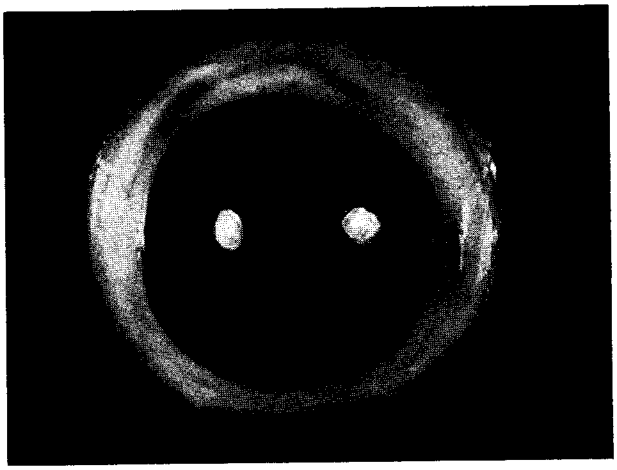
Figure 4. Cooling and rewarming charts showing temperatures recorded in the right eye, esophagus and rectum. The temperatures recorded in the left eye following the threshold exposure made under hypothermia are shown in the area between the cooling and rewarming charts.

temperature (Fig. 4). These observations confirmed that 22 °C was the protective temperature under the experimental conditions.

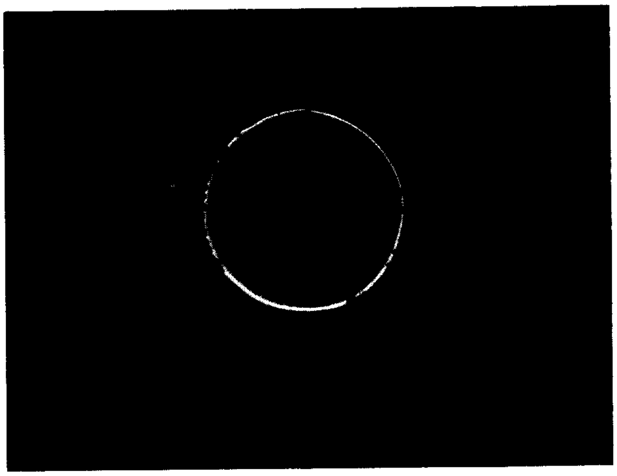
A period of 7 minutes was required for the intraocular temperature to return to its pre-exposure value following the threshold exposure made into the left eye of the sixth dog (at the protective temperature) and the right eye of the seventh dog (at normal body temperature). The maximum intraocular temperature in the left eye of the seventh dog was 52 °C. On the basis of these findings it was decided that the minimum time between exposures would be 10 minutes in the experiments on the eighth, ninth, eleventh, and fifteenth dog.



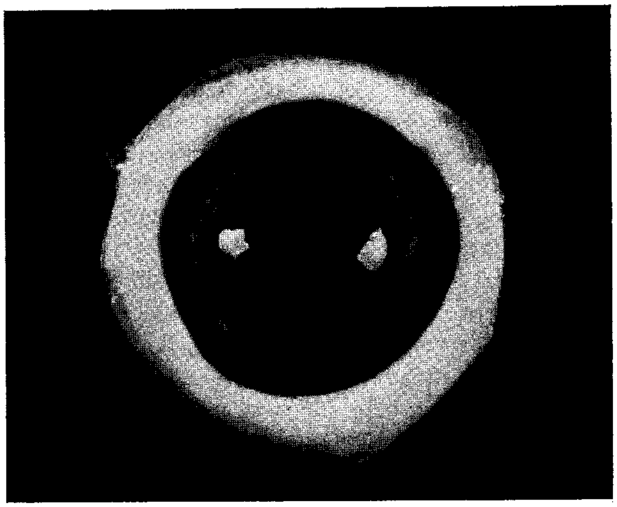
(a) Right lens (normothermic)—
a dense cumulative microwave cataract.



(b) Right eye (normothermic)—diffuse corneal clouding.



(c) Left lens (hypothermic)—normal appearance.



(d) Left eye (hypothermic)—normal appearance.

Figure 5. The excised eyes and lenses of the eighth dog.

The effects of the exposures on the eyes of the eighth, ninth, tenth, and eleventh dogs were all exactly the same. A dense cumulative cataract developed in the lens of the right (normothermic) eye during the observation period. This was associated with a moderate degree of corneal clouding. The lens of the left (hypothermic) eye was perfectly clear throughout the observation period. The general appearance of this eye remained normal (Fig. 5).

The twelfth, thirteenth, fourteenth, and fifteenth dogs, which form the long-term control for the study, have been examined at regular intervals to the time of writing (4 months). There has been no evidence of cataract and the general appearance of the eyes has remained normal.

The examination of the cataractous lenses produced in this study revealed that the opacities were, in general, patchy and disposed evenly throughout the cortical area.

## DISCUSSION

The cataract which developed during the course of microwave irradiation can only be explained on the basis of thermal coagulation of lens protein. According to unpublished work from this laboratory, dog lens protein coagulates at approximately 60 °C. This agrees with results published elsewhere (3).

The eyes which developed a cataract as a result of a single exposure, showed other evidence of tissue damage. This ranged from changes producing photophobia to tissue destruction. The minimum intraocular temperature following exposure in these cases, must have been greater than 52 °C as this was the temperature of the lens following the threshold exposure made at normothermia. There is therefore adequate evidence to incriminate heat as the initiating mechanism leading to cataract formation during or following a single exposure to microwave radiation.

The heat induced disturbance, which led to the development of the delayed cataracts following single exposure to the radiation, has not been identified. It must be an upset in a vital process because the cataracts appeared after an interval of 2–7 days, at a time when the lens temperature was normal. An upset in enzyme systems, such as those involving adenosine triphosphatase and pyrophosphatase, may be part of this disturbance (14).

The maximum intraocular temperature produced by each exposure in the eyes which developed a cumulative microwave cataract, must have been less than 52 °C in view of the experimental findings. As a general body temperature in the range 43 °C–52 °C is not compatible with life, some upset in the vital processes of the lens and related structures would be expected when the eye temperature is raised to a level within this range.

When microwave heating produces an intraocular temperature rise which does not exceed 43 °C, the vital processes of the lens and related structures should not be unduly affected. If a cumulative microwave cataract developed under these conditions, an upset in a vital process initiated by a nonthermal effect of the radiation must be postulated. If this nonthermal effect were to exist, it would increase as the exposure was increased, but it would be masked by the thermal effect when the exposure produced an intraocular temperature in excess of 43 °C.

The exposures which were made under hypothermic conditions in this study were designed to unmask any non-thermal effect of the radiation. These exposures did not produce cumulative microwave cataracts.

An investigation on the intraocular temperature patterns produced under the conditions of this experiment will be presented as a separate study.

## CONCLUSION

This study suggests that microwave cataractogenesis is, directly or indirectly, a thermal phenomenon.

### *Acknowledgments*

The advice and criticism of Professor A. M. Boyd is gratefully acknowledged.

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# STUDIES OF BIOLOGICAL HAZARDS FROM HIGH POWER HF BAND TRANSMITTERS

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The radio frequency biological hazards which have received the most intensive attention in the past have been those due to energy in the UHF and SHF portions of the spectrum where the predominant effects appear to be thermal. Resonant heating of the more sensitive exposed organs such as the eye and testes has been shown to be the greatest hazard at these frequencies.

In the latter part of the 1950's serious consideration began to be given to the biological hazards to human beings in the immediate and near vicinities of high power HF transmitters. The HF band (3 to 30 MHz) has for many years been utilized widely for relatively reliable, consistent communications over long distances. In order to insure a satisfactory signal-to-noise ratio at the receiving end, in spite of adverse effects of ionospheric variations, a combination of high power and high antenna gain is used for the transmitter. Due to the effects of heavy communications traffic, which may be considered as an externally induced increase in an undesirable noise level at the receiver, and to radio jamming, the net effect is a requirement that the transmitter power be increased. The future power levels cannot be predicted but the possibility for greater and greater transmitter power must always be taken into account in planning for future operations. Thus it is all the more important to study the biological effects of this radiation in the 3 to 30 MHz range. To do this a laboratory was set up with facilities for the irradiation of animals in known electric and magnetic fields for controlled periods. The animals were observed during and after the irradiation. Facilities were available for microscopic observation and interpretation of the tissues from the gastrointestinal tract, for blood studies and for physical measurements (weight, etc.) of the irradiated and control animals.

## LABORATORY IRRADIATION INSTRUMENTATION

A HF transmitter capable of delivering 200 W continuously was constructed by Ark Electronics Corporation. The transmitter operates in the frequency range of 3 to 30 MHz with good frequency stability. The amplifier output could be either capacitively or link coupled to the load. The induction load consists of an air-wound solenoid on a 5½-inch diameter Plexiglas form 10 inches long, which provides a concentrated relatively pure magnetic field inside an enclosed animal cage. The capacitive load consists of a pair of 6-×10-inch parallel plate electrodes separated by a 6-inch gap which will generate a concentrated relatively pure electric field in the enclosed volume. The irradiation unit was placed in a copper screen enclosure 8×8×8 feet. The voltages across the irradiation solenoid and the plate electrodes were measured and monitored with a Tektronix oscilloscope connected to a capacitor voltage divider. The voltage pattern on the oscilloscope indicated a pure sine wave when modulation was not used. The *Q* of the coil or of the plate electrodes with the animal in place was measured with a Boonton *Q* meter. The impedance of the solenoid was obtained and from the rms voltage across the solenoid the current was calculated.

The power absorbed by the rat during irradiation is obtained as the product of the reflected resistance of the rat, in series with the inductance of the solenoid, by the square of the rms current. In a similar way the power absorbed by the rat between the plate electrodes is obtained from the equivalent shunt resistance $R$ produced by the presence of the rat and the rms voltage across the electrodes by the relationship $P=V^2/R$. The electric field within the volume between the electrodes is given by $E=V/D$ volts per meter, where $V$ is rms voltage across the electrodes and $D$ is the distance in meters between the two electrodes. The theory and measurements were checked by successive temperature measurements in a volume of Ringer's solution placed in the $H$ field and in the $E$ field. The heating of the solution in each case agrees satisfactorily with that calculated from the $Q$ measurements.

## EXPERIMENTAL PROCEDURES

The adult male albino Wistar rat was used as the test animal. Data were obtained on 115 rats. After a shipment was received the rats were placed in cages in a well regulated animal room and were left for at least 2 weeks to stabilize and to eliminate unhealthy animals. The rats to be irradiated were picked at random from the rat colony except in those cases where rats of a given weight-range were needed to explore the effects of a given parameter.

Several experimental variables were studied in the 6 MHz and 14 MHz regions. Among these were:

### *Irradiation Frequency*

The objective was to determine the effect of frequency of irradiation on biological parameters of the rats, for a constant radiation dosage. In this series, dosage, irradiation time, and type of r. f. field (electric or magnetic) were held constant and differences in evidence of biological damage were sought. There was little significant physiological evidence of any difference in the effects at the two frequencies as far as weight change, water intake, or fecal count are concerned. There was appreciable evidence of pathological effects at the two frequencies. The effects were observed in thin tissue section slides of myocardium, lung, liver, stomach, small and large bowel, pancreas, kidney, testis, and spleen. Quantitative comparisons between tissues such as these are very difficult but it appears that the changes are about the same for 15 watt-seconds per gram at 14 MHz as they are for 35 watt-seconds per gram at 6 MHz for either type of field.

### *Irradiation Intensity, Time, and Size of Specimen*

Experiments were done to assess the biological responses when equal total dosages were employed. It seems axiomatic that a biological effect must be produced by energy absorbed in the tissues. It is therefore logical to believe that this factor should be employed in the establishment of a radiation safety standard, at least in the 3 to 30 MHz range. The unit would be watt-seconds or joules per unit weight. This appears to be appropriate in the HF band where the RF energy completely penetrates the body so that all organs are exposed and resonance heating does not occur. On the other hand the power density in terms of watts per unit area is not as good a unit because it does not tell enough about the total absorption in the body and on this basis is not realistic. It is clear that a very high amplitude wave will produce damage after only a very short elapsed time, measured in seconds. For lower levels of incident HF power over reasonable periods of time it is expected that the power integrated over exposure time (energy) is the important factor. Our experimental results indicated conclusively a good correlation of biological damage with exposure in terms of watt-seconds per gram absorbed in the rat.

The survival after high field-strength irradiation was not observed to be dependent on rat size or weight when the same dosages were given in terms of the energy absorbed per unit weight.

The effect of extremely low level irradiation for very long periods of time could not be investigated by us at this time.

It was noted that the pathological findings revealed less damage in the older and heavier rats than in the younger ones. The conclusion is that the older rats had developed physiological systems that were more resistant to the effects of irradiation.

### *Electric and Magnetic Field*

The effect of type of r. f. field, electric or magnetic, was explored. For comparison of these factors dosage and time were held within narrow limits. The field intensities used were one or more orders of magnitude higher than those corresponding to the far field microwave safety limit of 10 mW/cm$^2$.

Forty-five of the irradiated rats survived for over 30 days (at which time they were sacrificed) while the remaining 37 died during irradiation. These were high intensity fields compared to the microwave safety limit. Although magnetic field strengths of 0.51 ampere per meter represent the latter limiting safe *H* component, a significant fraction of the rats exposed to fields as high as 200 amperes per meter survived with little evidence of damage. Correspondingly, the 10 mW/cm$^2$ *E* field component is 195 V/m. A significant number of rats showed no signs of biological damage (up to 30 days when they were sacrificed) after being irradiated in electric fields exceeding 8 kV/m, for 5 to 15 minutes. These fields were applied separately. No attempt has been made so far to irradiate simultaneously with both *E* and *H* fields.

The mean pathological index from the tissue slides per unit dose for rats irradiated at 14 MHz was 50 percent greater than that for rats irradiated at 6 MHz, while at 6 MHz in the electric field it was triple that in the magnetic field. Thus the higher frequency and the electric field were more damaging.

It was important to study any effects which might be produced on the blood-forming organs. Instead of studying the bone marrow directly it was more meaningful to count the cells per cubic millimeter of blood. Control (nonirradiated) rats were used to find the base line and the variability of the individual cell counts. To get a safer base line many of the rats were studied before, and then after irradiation. The following trends were observed. There was little effect on the red cell count and on the hemoglobin. The white cell count on the other hand dropped in one day after the irradiation to about half of its original value. It then rose in a steady fashion until it reached the preirradiation value in about 30 days. The platelet count was not statistically affected.

## CONCLUSIONS

In our experiments on rats with HF radiation using the *E* and *H* fields separately it appears that the appropriate basis on which to compare biological effects is net energy absorbed by the body. Further research is under way to investigate the thermodynamic balance equation for the rat. The ultimate set of recommended levels may thus be a combination of electric field intensity *E*, magnetic field intensity *H*, and absorbed power *W* or total energy absorbed. The last named quantity would be computed. One of the ways to specify dosage would be in terms of watt-seconds per gram. A time factor would also be specified.

From tissue slides the pathological damage appeared to be on the order of 50 percent greater at 14 MHz than at 6 MHz. The *E* field seemed to produce about 3 times the damage produced by the *H* field for the same dosage.

One of the most sensitive indications of damage from irradiation that we found was the lowering of the white cell count. This resulted very soon after rather intense irradiations. In many cases it might be worthwhile to check the white count in the blood of individuals who were exposed to high levels of radiation near antennas emitting high power radiation. Since the cell count has the ability to quickly reestablish its normal level it is unlikely that it would show significant change after low-level, long-term irradiation.

For the type of animals tested (200 to 350 gram adult male albino Wistar rats) the following order-of-magnitude levels of *E* and *H* fields were established as threshold levels of tolerability:

Magnetic field = 1 to 10 A/m for exposures not exceeding 0.1 hour.

Electric field = 400 to 4000 V/m for exposures not exceeding 0.1 hour.

It is realized that it is not valid to make an analytical extrapolation from rat to man. However, as a starting point, the threshold levels shown above may be adopted cautiously to man and to grazing animals in the radiation field of high power HF band transmitters.

It has been the sponsoring agency's basic intent that we derive an interim standard level (which would be progressively refined). The time schedule made it impossible to use larger numbers of rats in order to obtain better statistical accuracy. A follow-on program has just gotten under way, for the fundamental purpose of carrying on the work of the original program using statistical design and control of experiments and a correspondingly far larger number of animals.

In the original program a parallel study of measurements in the transmitter field was undertaken together with the laboratory work with the ultimate objective of being able to relate the results of the two investigations. A clear relationship exists in the fact that $E$ and $H$ fields were measured in both places. The fact that a complicated combination of $E$ and $H$ fields prevails at the antenna site while only relatively pure $E$ and $H$ fields were obtained in the laboratory, militates against directly relating the two sets of data. Also, the field parameter of power density (in watts per unit area) and the laboratory parameter of power or energy (watts or joules) are not consistent, and this remains an area for further investigation.

### *Acknowledgments*

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# NONUNIFORM BIOPHYSICAL HEATING WITH MICROWAVES

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## INTRODUCTION

Our studies on the interaction of microwaves and biologic systems has centered on studies of rats and dogs exposed to 2450 MHz radiation. The research had been concerned with elucidating the mechanism or mechanisms involved in the death of rats and in the change in their behavior when exposed to sublethal dosages of microwaves. Specifically, rats exposed to lethal doses of microwaves display respiratory collapses 2–3 minutes before cardiac arrest. After exposure to sublethal dosages, rats demonstrate hyperactivity and belligerent attitudes toward the animal handler. Rats exposed to conventional heating (a hot plate was used to raise body temperature to the same temperatures and at the same rate as those of the microwave exposed animals) demonstrated no change in behavior patterns. Finally we irradiated dogs in whose head a steel plate had been placed and we attempted to reproduce a reported somnorific effect of microwaves (1).

Initially, we assumed that the microwave director would produce a doughnut-shaped field. In these studies and others we have become aware that the position of the animal relative to the director alters the response. Our studies then became centered in determining exactly the microwave pattern.

## METHODS

Various biological materials, such as a combination of fat and muscle, have been used to map a microwave field (2). The major disadvantage of this method, however, is the heterogeneity of the media. We had initially tried a concentrated albumin solution but it did not give an accurate reading of the microwave pattern, due to convection currents that were produced by the microwave heating. A solid medium that was nevertheless sensitive to temperature changes, appeared to be necessary.

A gel composed of cornstarch and water was found most effective in mapping a microwave field. Cornstarch, 240 mg, was combined with 1600 cc of warm water. If the effects of color were to be studied, food coloring was placed in the solution. The solution was stirred and poured into a 6×6×3 inch acrylic container. The gel was left overnight before use and was never used more than two days.

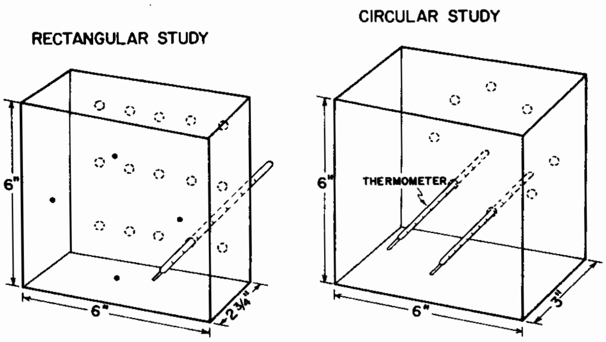

Figure 1. Containers for temperature distribution measurements.

Two different types of containers were used (Fig. 1). One had holes drilled so that the thermometers inserted would correspond to the circumference of the director. The other had holes arranged so that thermometers would map the microwave field in a rectangular fashion. The gel was solid enough to allow thermometers to be fixed at predetermined places.

The director was a hemispheric reflector Type "A" (diameter approximately 9.3 cm), which is reported to have a field pattern the shape of a doughnut (2, 3). The gel was irradiated for 10 minutes. Microwaves were produced by a Raytheon

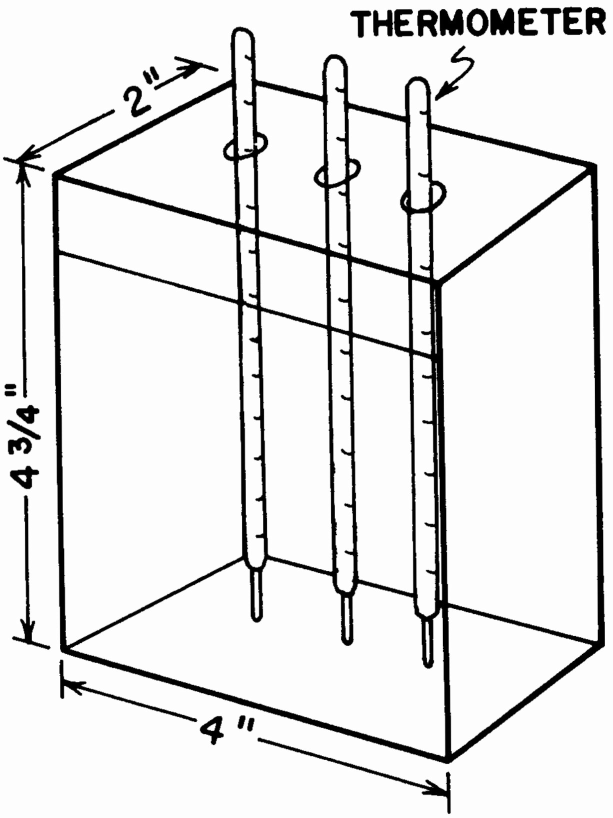

Figure 2. Temperature measuring apparatus (water load) for microwave generator calibration.

Model CMD4 12.25 cm, 2450 MHz, continuous waveform generator, reportedly capable of delivering an output of 125 watts. The generator was calibrated by a water load (4) consisting of a square acrylic receptacle with a 100 cubic cm frontal surface. Irradiations were delivered over a 10 minute period at 5 cm from the wave director. Temperatures were measured by three thermometers placed in 500 ml of water (Fig. 2).

Various materials have been proposed to attenuate microwave penetration (4). To test this hypothesis, aluminum foil, $\frac{1}{8}$ inch, grounded, was placed in front of the gel. The shielded gel was then irradiated.

## ANIMAL STUDIES

Once the hottest spots of the director were determined by the gel studies, rats were selectively irradiated. Albino male rats were anesthetized with sodium pentobarbital and placed in a supine position. The director was placed 5 cm away from the chest and the rats were irradiated until death occurred. Shields made of $\frac{1}{8}$ inch, grounded aluminum, were selectively placed at different areas of the body, to ascertain whether certain areas were heated more quickly.

Electrocardiograms, rectal temperatures and surface temperatures of the neck and the inguinal region were recorded. The surface measurements were taken by shielded thermistors.

## RESULTS

The water load study showed that the microwave director was able to consistently produce an increase of 6.43±1.1 °C equal to 21.33 W (0.1233 W/cm$^2$). This energy level was employed during the gel and animal studies. The effective maximum position (flush) showed 28 effective watts (0.28 W/cm$^2$). Thermometers placed in an empty acrylic container did not register any temperature increase.

In those acrylic boxes in which the thermometers were arranged in a circle of the same circumference as the director 5 cm away, there was no uniform

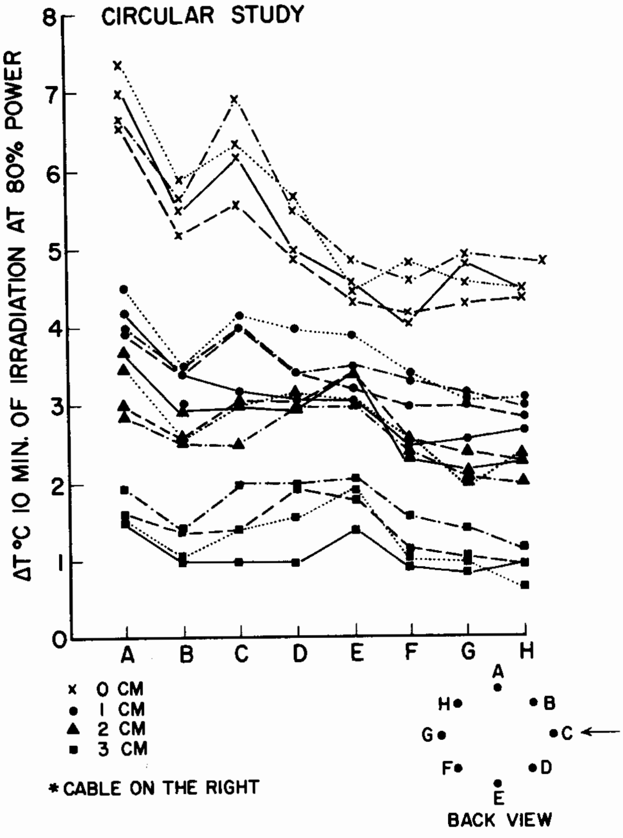

Figure 3. Temperature distribution for circular array of thermometers.

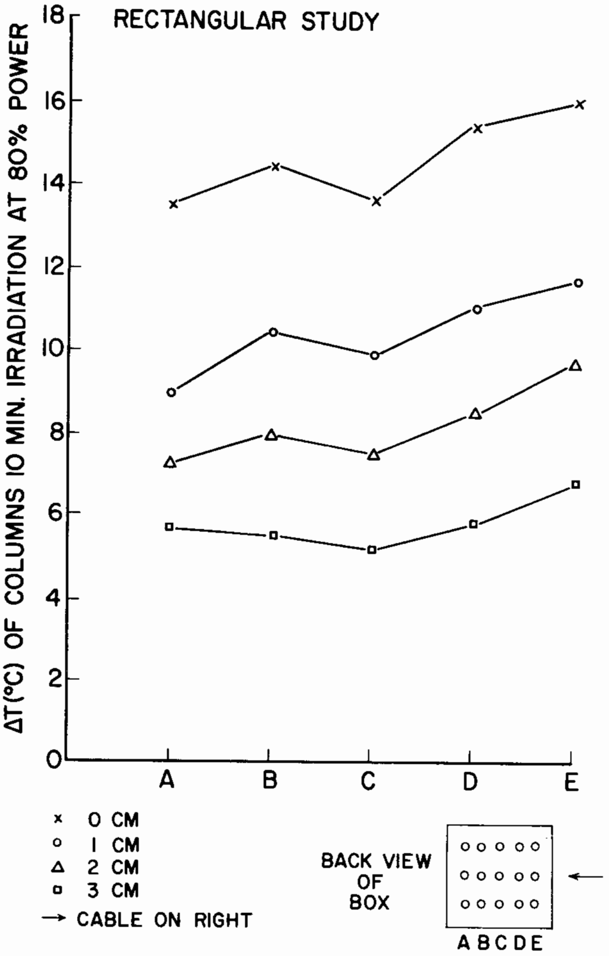

Figure 4. Temperature distribution for rectangular array of thermometers.

circular heating (Fig. 3). Flush on, 3 cm in the cornstarch, however, there was a uniform pattern, since the variation of temperature in any of the thermometers was not more than 0.4 of a degree. All other measurements showed that there was no isothermal circle.

TABLE 1

*Shielding study at 2450 megacycles.*
*Aluminum foil, $\frac{1}{8}$ inch, grounded*

| Nonshielded Gel | Shielded Gel |
|---|---|
| 73.5 °C | 15.0 °C |

Temperatures are those summed from the columns of the rectangular study.

In the rectangular study, with the director 5 cm away, the temperature pattern was such that the side toward the waveguide was consistently 9° higher than that at the far side of the box (Fig. 4). Flush on, however, the highest temperatures were recorded from the sides of the director (Fig. 5). These results were reproducible from one gel study to another.

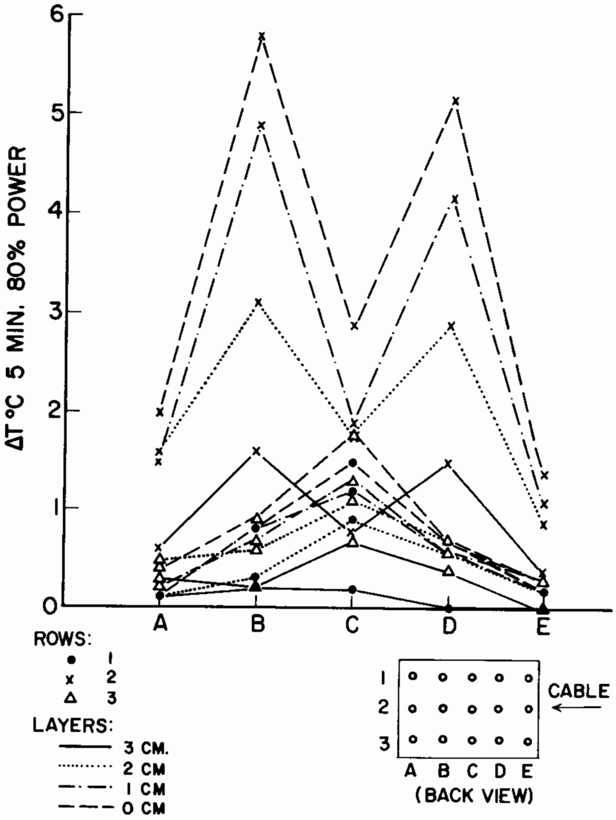

Figure 5. Temperature distribution for rectangular array, flush on.

Since the rectangular study was more sensitive to temperature increases than the circular study, the penetration pattern of irradiated gel (rectangular study) was investigated with the director 5 cm away. The temperature changes of the rows were compared to the columns. The top and bottom rows showed both the highest temperature and highest temperature increase (Fig. 6). The bottom row eventually had the highest over-all temperature. This was true if the temperatures recorded at different depths were summed. There was always a sharp drop in temperature in the first cm of irradiated gel.

The temperature changes recorded from the summing of the columns showed that the columns closest to the coaxial cable produced the most heat (Fig. 7).

Colored cornstarch (red, blue, black) yielded the same temperature gain. However, if the initial temperature of the gel varied, then the cooler gel always registered high temperature gains. These findings were similar for the noncolored (white) gel.

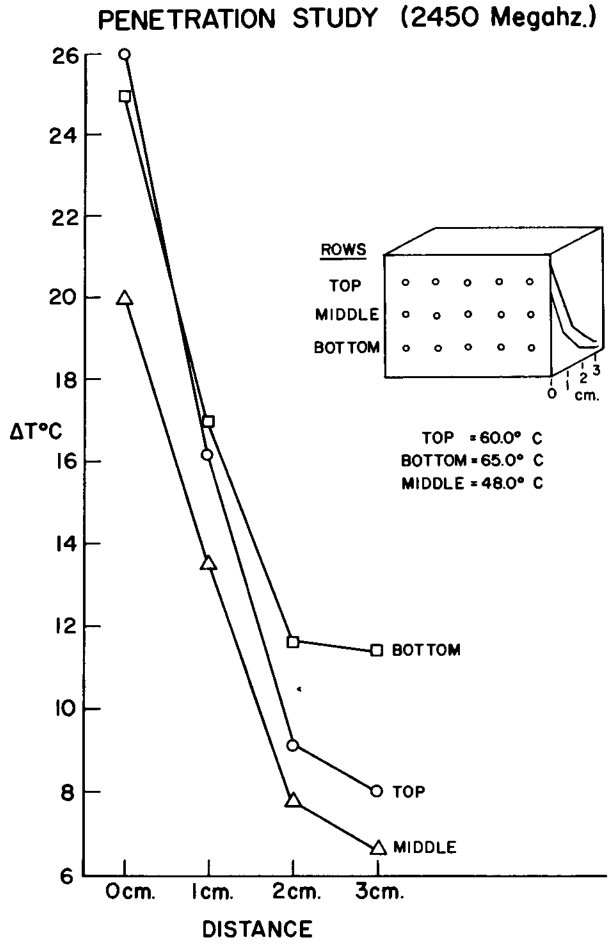

Figure 6. Temperature variation with depth of absorber at various positions in the absorber.

Aluminum foil placed in front of the gel allowed a rise in temperature only 20 percent of that occurring in control situations where the gel was not shielded (Table 1).

Table 2 shows the effect of shielding the throat of two albino rats. The results have been duplicated in 5 animals for each study. The non-shielded animals displayed greater variations in heart rate and the surface temperature of their throat was always greater than that of the chest and even the inguinal region.

TABLE 2

*Comparative effects of shielding the throat*

Rat with shielded throat

| Time (min) | Rectal temp. (°C) | Heart rate (beats/sec) |
|---|---|---|
| 0.0 | 37.5 | 8 |
| 1 | 38.0 | 9 |
| 2 | 39.0 | 9 |
| 5 | 40.0 | 9 |
| 6.5 | 41.0 | 9 |
| 7.0 | 42.0 | 10 |
| 9.0 | 44.0 | 9 |
| 10.0 | 45.0 | 9 |
| 11.0 | 46.0 | 10 |
| 12.0 | 47.0 | 10 |
| 13.35 | 48.0 | 11 |
| 14.00 | 48.0 | 1 |

Rat without shielded throat

| Time (min) | Rectal temp. (°C) | Heart rate (beats/sec) |
|---|---|---|
| 0.0 | 37.5 | 8 |
| 1.4 | 38.0 | 8 |
| 2.0 | 39.0 | 10 |
| 2.5 | 40.0 | 10 |
| 3.0 | 41.0 | 10 |
| 4.0 | 42.0 | 11 |
| 5.0 | 43.0 | 10 |
| 6 | 43.8 | 12 |
| 7 | 44.0 | 10 |
| 8 | 45.5 | 10 |
| 9 | 46.5 | 8 |
| 10 | 47.5 | 7 Death |

| Time (min) | Rectal temp. (°C) | Temperature without shield | |
|---|---|---|---|
| | | Throat | Chest |
| 0.0 | 37.4 | 32.7 | 32.7 |
| 1.10 | 38.0 | 36.0 | 34.1 |
| 3.38 | 39.0 | 37.5 | 35.2 |
| 4.14 | 40.0 | 39.0 | 36.7 |
| 5.08 | 41.0 | 40.0 | 36.7 |
| 6.00 | 42.0 | 41.0 | 37.4 |
| 7.00 | 43.0 | 42.0 | 37.6 |
| 9.00 | 44.0 | 42.4 | 38.3 |

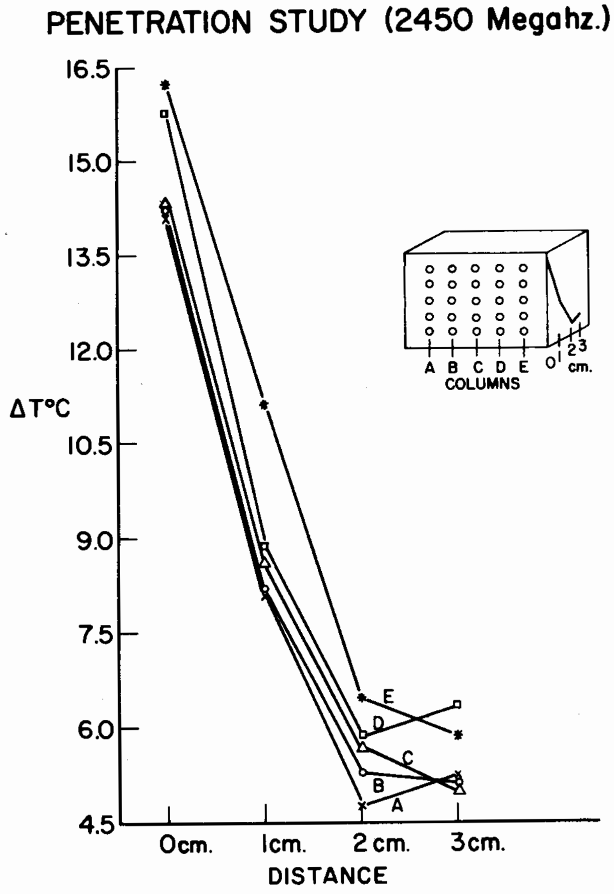

Figure 7. Temperature variation with depth of absorber at various positions in the absorber.

## DISCUSSION

The penetration and frontal patterns of microwaves have certain direct applications. Although the use of microwaves as a clinical tool is successful, its heating pattern has not been successfully mapped. Rae et al. (2), using 2453 MHz, showed that the frontal pattern of microwaves was in the shape of a doughnut. The higher temperatures were not in the center of the field with the A and B director. These temperature measurements were taken, however, after the muscle and fat had been irradiated. Further, they showed that at depths of 3 cm there was a 2 °C rise in temperature. Lehmann (5), using 2450 MHz, irradiated a muscle-fat mass and found that the distribution of temperature was not symmetrical. He also showed that the highest temperatures occurred in the layer of subcutaneous fat if it was 1 cm or less in thickness.

Our results show that with the generator consistently producing about the same amount of energy, an A director does not produce a uniform distribution of temperature. Also, monitoring the circular path of the director is not as sensitive as making a rectangular study. We could have been led to the faulty conclusion that a circular pattern of heating was taking place. In the rectangular studies, with the director flush against the gel, the greatest amount of heat was produced from the sides of the director rather than from the top or bottom.

In our penetration studies a marked decrease in temperature occurred 1 cm away from the director. It would seem that microwaves when used to irradiate patients are acting mainly to raise the temperature of the first 1 cm, but actually there is a certain amount of heating that takes place 3 cm away. Extrapolating the results from the gel to the animal studies, it was found that by selectively shielding certain areas, especially the throat, animals survive longer than the controls ($p<0.01$). Further, surface temperatures more proximal to the center of the director (chest area) were always cooler than those of the neck region.

It is clear that placing an object in a microwave field affects the heating pattern. However, since somewhat the same hot spots were obtained in both the gel and the irradiated rat, one may place confidence in using the gel as a potential tool for monitoring the microwave pattern. Finally, we have constructed rat models made of cornstarch, irradiated the models and monitored their temperatures. Though this work was done on only four phantoms, the results in every case agreed with the data from our live animal studies.

The conclusion is reached tentatively that microwaves may selectively heat the rat faster on the neck and also in the inguinal region. High temperatures in the intestines may conceivably trigger increased breathing by exciting thermoreceptors postulated in the intestine (6). Such sensors could drive the respiratory center to increase ventilation and thus increase cooling. Increased heating in the intestinal region may be responsible for the high incidence of intestinal ulceration observed in rats irradiated with sublethal microwave power. The heating of the throat may explain the observation that blood entering the brain cannot be cooled as effectively as blood in other areas of the body.

## SUMMARY

1. A gel composed of cornstarch and water was capable of monitoring microwave irradiation.

2. The gel is relatively inexpensive and the results are reproducible. Further, the gel is of such a consistency that thermometers can be placed in any area. Hence penetration studies and frontal pattern studies of microwaves may be undertaken.

3. The gel is not plagued by the problems of heterogeneity found in the common biological tissues that have been used to monitor microwaves.

4. Using an "A" director, a doughnut-shaped distribution of microwave heating was not observed when the whole radiation field was considered.

5. The pattern of temperature rise was greatest on the side of the coaxial cable, with the director two inches away from the acrylic container.

6. There was a sharp temperature drop 1 cm into the cornstarch. Hence, microwaves of 2450 MHz selectively heat the first cm of the substances they are irradiating.

7. Irradiation of rats may produce hyperventilation because of differential heating of the neck and intestines. Death may ensue.

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# EXPERIMENTAL MICROWAVE CATARACT: A REVIEW

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Experimental microwave cataracts have been produced by a number of investigators and have resulted from exposure of eyes to several different microwave frequencies. Daily et al. (1–3) employed 2450 MHz radiation; Richardson et al. (4, 5) used both 2450 and 10,000 MHz; Williams et al. (6, 7) worked at 2450 MHz; Belova and Gordon (8) at 3000 MHz; Carpenter (9–11); Carpenter et al. (12–14) and Carpenter and Van Ummersen (15) at 2450 MHz, 8236 MHz, 9375 MHz, and 10,050 MHz; Michaelson et al. (16) at 2800 MHz; and Birenbaum et al. (17) at 5500 MHz. On the other hand, whole body exposures of guinea pig, dog, and sheep at 200 MHz by Osborne and Addington (18) and of rabbits at 385 MHz and 468 MHz by Cogan et al. (19) failed to demonstrate an effect upon the lens.

In many of the above-cited experiments, the animals were exposed to radiation for various periods of time and at various power levels. Attempts to establish time-power combinations as thresholds for the production of opacities were made by Williams et al. (7) and by Carpenter (9, 11). Although the resulting threshold curves were not coincident, probably because of differences in the methods employed to measure power levels, they were similar in shape over three different frequencies (2450, 8236, and 10,050 MHz). The threshold curve for 5500 MHz obtained by Birenbaum et al. (17) was also in agreement.

When the eye is exposed to continuous wave radiation, there is only one power level to be considered. However, when the radiation is pulsed (5, 9, 11, 13, 15–17, 20) there are two power levels to be taken into account: peak power and average power. The question of which of these is the significant factor in the induction of microwave cataracts has long been a vexing one but it now seems to have been resolved in favor of average power. Although the results of earlier experiments by Carpenter (11) and Carpenter and Van Ummersen (15) were equivocal, both Birenbaum et al. (17) and Fisher (20) have more recently presented data indicating that average power rather than peak power is the significant parameter in the induction of lens opacities by pulsed microwave.

Cataracts have been induced in experimental animals not only by single exposures but also by multiple ones. In the latter instance, there might well be demonstrated a cumulative effect of r. f. energy on the eye but only if it were first clearly established that a single one of the exposures was clearly below the cataractogenic threshold dose and hence was by itself incapable of causing opacity formation. In a number of the experiments (1–4, 8), this condition was not met, but when threshold curves for a particular animal species had been experimentally established, then it became possible to test the effect of repeated subthreshold radiation doses.

Experiments on the rabbit eye (13–15) clearly demonstrated a cumulative effect. For example, at a power density of 280 mW/cm$^2$, five minutes was found to be the shortest single exposure which would cause a lens opacity to form. With the exposure period reduced to three minutes, daily exposures for five consecutive days or even three exposures given at four day intervals caused opacities to form in all cases. However, when the interval between irradiations was extended to seven days, no effect upon the lens could be seen after five such exposures. It therefore seemed that the low-level three minute exposure, although insufficient to induce an opacity, nevertheless did cause some harm to the lens, even though the harm was not apparent. A seven day interval between exposures was long enough to enable the lens to recover but a four day interval was not, so that when the next exposure occurred, the lens was still under the effect of the damage previously inflicted. The multiple exposures could thus act in a cumulative manner and cause a cataract to form. When the power was reduced to

80 mW/cm$^2$, a single exposure of 1 hour duration had no observable effect but the same dose, given daily for ten consecutive days, evoked opacity formation.

It must be concluded therefore, that the effect of microwave radiation on the eye can be cumulative, so that episodes of irradiation which are not harmful when experienced only once may become hazardous if they are repeated frequently enough.

The cataractogenic threshold curve is not a straight line, so that the cataractogenic radiation dose, considered as the product of power density and duration of exposure, is not a constant. At lower power levels, the minimal duration of exposure which will cause opacity formation is disproportionately long compared to threshold exposures at higher power levels. Investigating this matter by experiments focused upon two different dose levels, Fisher (20) found that lower doses, in terms of watt-minutes, induced opacities at the higher power level while high doses at the lower power level were ineffective.

Biological tissues become heated as they absorb microwave radiation. This is true of both living and dead tissues and forms the basis for microwave diathermy and microwave cooking. The eye is no exception and the lens is particularly subject to microwave heating, inasmuch as it has no blood supply and can dissipate heat only through the adjacent fluid aqueous humor and jelly-like vitreous body. Temperature increases in the eye during or immediately after microwave irradiation have been measured by several investigators, including Richardson et al. (4), Osborne and Frederick (21), Daily et al. (2), Williams et al. (7), Ely and Goldman (22), Carpenter (9), and Imig and Searle (25). They were in general agreement that the higher the power, the more rapid is the temperature rise and the higher is the level it reaches before tending to stabilize.

Recalling that the higher power levels cause lens opacities even though the single exposure may be of relatively brief duration, it is not surprising that there has been some tendency to conclude that lens opacities are a result of microwave heating. Schwan and Piersol (30) have suggested that 45 °C is the intraocular temperature above which lens damage can result. However, upon critical evaluation of our data, we (9, 13) were led to suggest that some factor other than a thermal one might be responsible for the induction of lens opacities. It seemed reasonable to expect that if the higher intraocular temperature was the determining factor, then it should be possible to identify some critical temperature below which no lens opacities would be caused and above which they would be produced. Our data yielded no evidence to support such a view.

For example, at a power level of 280 mW/cm$^2$, the minimal exposure which would induce a lens opacity was five minutes, an exposure period which resulted in an intraocular temperature of 49.3 °C. A single exposure of three minutes at this power raised the intraocular temperature to 47.2 °C and no opacity was caused but three such exposures, at four day intervals, were cataractogenic. To cite another example: at 120 mW/cm$^2$, the intraocular temperature rose to 44.2 °C during a 35 minute exposure period which caused opacity formation. At the same power, an exposure of 25 minutes resulted in an intraocular temperature of 44 °C but no opacity. There thus arises the curious situation by which microwave irradiation accompanied by a rise in intraocular temperature to 44 °C does not cause lens opacities; with a rise to 44.2 °C it does cause them; but with a rise to 47.2 °C it does not, unless the irradiation and accompanying temperature increase occur three times at four day intervals. With the intervals stretched to a week, five such incidents left the transparency of the lens unaffected.

It seemed obvious that the induction of microwave cataracts was independent of any fixed critical temperature as well as of the amount of increase in intraocular temperature. We therefore suggested (9) that microwave cataracts were not merely the result of microwave heating but were attributable to some other property of this radiation.

The time period intervening between irradiation of the eye and the first sign of opacity formation constitutes a latent period, which in the case of microwaves, is from one to eight days, with an average of 3.5 days. This is a much shorter latent period than is the case with radiation cataracts caused by x rays, which have a latent period of 25 to 30 days, according to D. Cogan and Donaldson (23) with radiation of 1500 to 3000 R given to ten-week old rabbits. They found also that the latent period was affected by the age of the animal, for with doses of 1500 R, cataracts appeared in 15 to 20 days when three-week old rabbits were irradiated but only after 100 to 150 days when the animals were three years old. In contrast, Van Ummersen and F. Cogan (24) concluded from 163 experiments that in the case of microwave cataracts, the age of the animal has no bearing on the latent period and that there is no significant relationship between the age of the animal and the susceptibility of its lens to damage by radiation.

Although microwave cataracts and x-ray cataracts have differing latent periods, they exhibit a number of features in common. Typically, both develop in the posterior subcapsular cortex and their onset is marked by the appearance of small granules or vacuoles in the region of the posterior suture of the lens. Often they appear at the ends of the suture and progress axialwards. With both microwave and x-ray cataracts, peripheral changes may also occur, consisting of granular opacities and vacuoles which are immediately subcapsular and which have a striated or feathery appearance corresponding to the orientation of the lens fibers. These striate opacities, concentric with the lens equator, subsequently migrate axialwards to form ring-shaped cataracts.

Histopathologically, microwave and x-ray cataracts share several similarities, the most notable of which are a piling up of swollen epithelial cells at the lens equator and migration of many of these cells beneath the lens capsule toward the posterior pole. The cell nuclei become pyknotic and in many cases disappear, leaving small globular masses which stain acidophilically. In other cases, the cells may swell sufficiently so as to burst and spherical fluid-filled spaces containing cell debris are seen in the posterior cortex beneath the capsule. Cogan et al. (26) state that among the lens changes occurring in radiation-induced cataracts, "what appears to be specific for the radiation type is the early migration of cells beneath the posterior capsule." Although they were referring specifically to cataracts caused by ionizing radiation, the statement appears to be equally applicable to microwave cataracts. It is also true that the posterior ends of many of the already formed lens fibers become hydropic and swollen.

That the changes leading to formation of opacities are the effect of the microwave radiation acting directly on the lens tissue seems to have been clearly demonstrated by Keene (27), who removed lenses from the eyes of rabbits immediately after cataractogenic irradiations and cultured them in vitro for periods ranging from one to nine days. In 17 cases, cataracts developed in the irradiated lenses while the control lenses, from the nonirradiated left eyes, remained clear. The opacities invariably developed in the posterior subcapsular cortex and varied from vesicular to crescent-shaped and fibrous ones. They were similar to those which developed in vivo after similar exposures to radiation but the latent period was shorter by about two days.

In connection with experiments on the cumulative effect of repeated subthreshold exposures, we suggested (13) "that the cataractogenic effect of microwave radiation involves initiation of a chain of events in the lens, the visible end result of which is an opacity, and that this chain of events must be initiated by an adequate power density acting for a sufficient duration of time if it is to progress to the development of an opacity." To look more closely into the "chain of events," we enlisted the help of Dr. Jin Kinoshita of the Howe Laboratory of Ophthalmology, Harvard Medical School and the Massachusetts Eye and Ear Infirmary. He and his associates studied some of the biochemical changes taking place in the lens following microwave irradiation; results have been reported in papers by Merola and Kinoshita (28) and Kinoshita et al. (29).

Briefly, the method employed was to irradiate the right eye of rabbits with 8 minute cataractogenic dose at 2450 MHz. Both eyes were removed for study at various times after irradiation, in most instances before any sign of opacification had appeared in the right eye. The lens of the non-irradiated left eye served as the control.

The first detectable change to occur in the lens following microwave irradiation was found to be a marked lowering of the ascorbic acid level, which 18 hours after exposure was 23 percent lower in the irradiated lens than in the nonirradiated control lens. This decrease occurred before there was any indication of opacification and also before any change in glutathione concentration in the lens. Ascorbic acid and glutathione are two reducing substances occurring in high concentrations in the lens. It is known that in the case of experimental diabetic cataracts and in those caused by ionizing radiation, a decrease in lens glutathione is the first observable change. In the development of microwave cataracts, the early drop in ascorbic acid appears to be the distinguishing feature.

To ascertain whether the change in ascorbate was due simply to microwave heating, eyes were exposed to the same radiation dose and then were removed for lens ascorbic acid analyses at various post-irradiation periods. No change in ascorbic acid level could be detected a half-hour after exposure or even six hours after exposure. The change must therefore take place sometime between 6 and 18 hours following irradiation, a fact which would seem to rule out the possibility of its being a thermal effect. In another experiment, isolated rabbit lenses were exposed for eight minutes to the same temperature as occurred in the eye during irradiation for a similar period. In no case was there a change in the normal level of ascorbic acid.

In view of the generally accepted opinion that ascorbic acid is not synthesized in the lens but most probably is taken up from the aqueous humor, there remained the possibility that the change in lens ascorbate was simply the reflection of a decrease in the level of ascorbic acid in the aqueous humor. Analysis of the two, however, disclosed that in irradiated eyes the ascorbic acid level was maintained at normal levels in the aqueous humor while undergoing a marked decrease in the lens.

Some five or six days after irradiation, opacities become visible in the lens and at this later stage, another chemical change is evident in the form of a change in cation distribution. There is a loss in potassium and a gain in sodium, with a noticeable net increase in total electrolytes. At the same time, there is an increase in water in the lens. As the cataract matures, there occurs a large increase in water and a marked rise in total cations, the latter accounted for by the large increase in sodium rise and as the cataract progresses, the increase in chloride concentration roughly parallels the increase in water.

The swollen cells and lens fibers seen histologically in the development of microwave cataracts have already been commented upon. The biochemical findings suggest as a most likely possibility that microwave radiation in some way damages lens membranes and thus causes an increase in permeability.

Another biological effect of microwave radiation on the lens occurs within the first few days after exposure as an inhibition of DNA synthesis and mitotic activity in the lens epithelium. This topic will be presented at this Symposium by Dr. Claire Van Ummersen, who, with Dr. Frances Cogan, conducted the investigations on which the report is based.

In connection with the decrease in lens ascorbic acid, an observation by Keene (27) is of interest. In an earlier study of microwave induced cataracts (9), it was pointed out that the earliest visible change in the lens—and one which could be observed only by slit-lamp examination—occurred in the posterior cortex as a series of concentric bands of slightly milky appearance separated by bands of clear lens substance. According to the number of bands, the condition was termed double or triple "cortical banding." This early banding usually disappeared within a week or two, irrespective of whatever other changes ensued in the lens.

Keene used a histochemical test for ascorbic acid to determine the distribution of this substance in the irradiated lens. The method employs silver nitrate and depends upon the fact that ascorbic acid reduces silver to produce a greyish-brown stain wherever there is a concentration of ascorbic acid. The lenses were studied in histological sections prepared after Parlodian embedding. Keene's findings were:

1. In the normal lens, there was a uniform distribution of ascorbic acid in the cortex, with none evident in the nucleus;
2. In a lens removed and fixed immediately after irradiation, the same picture was seen;
3. In a lens removed 18 hours after irradiation, the staining pattern showed the ascorbic acid to be concentrated in parallel band-like zones in the posterior cortex, with low concentration areas between them;
4. In a lens removed immediately after irradiation and cultured in vitro for 18 hours, four parallel zones were evident, with two zones of lesser concentration and homogeneous distribution. In the anterior cortex, the ascorbic acid was uniformly distributed and thus resembled the condition in the normal lens;
5. Irradiated eyes in which double or triple banding could be seen by slit-lamp examination were removed a week after irradiation for histochemical identification of ascorbic acid. In the cases of double banding, the ascorbic acid zones were present in the peripheral posterior cortex but not in the axial region. In those lenses which displayed triple banding, the ascorbic acid zonation was spread across the entire posterior cortex from the equator inwards.

Although these experiments suggested the possibility that the earliest radiation effect to be seen in the lens may be the result of a change in ascorbic acid distribution, following a decrease in the amount, it was not possible to correlate the widths of the ascorbic acid zones and the widths of the bands seen in the lens by slit-lamp.

## SUMMARY

1. The lens is highly susceptible to damage by microwave radiation at several different frequencies, as it is also to damage by ionizing radiation.

2. Lens opacities have been induced by irradiation of the eye at frequencies from 2450 MHz to 10,000 MHz, continuous or pulsed wave.

3. Microwave cataracts may result from a single incident of exposure or they may develop as the cumulative effect of repeated exposures at power levels low enough so that no single exposure is itself harmful.

4. The radiation dose required for opacity induction, expressed as power density times duration of exposure, is not a constant.

5. Irradiation causes a rise in intraocular temperature which is related to the power density. However, the induction of lens opacities is not dependent upon a critical temperature.

6. Following irradiation and before opacities appear in the lens, there is a latent period which varies from one to six days. In the case of ionizing radiation, the latent period is 25 days or more. The susceptibility of the lens to damage by microwave radiation is unrelated to the age of the animal, as is also the length of the latent period. With ionizing radiation, the younger the animal, the shorter is the latent period.

7. In their development, morphology and histopathology, microwave cataracts are similar to those induced by ionizing radiations. They represent a permanent alteration of lens transparency.

8. Inasmuch as opacities will develop in lenses removed immediately after irradiation and cultured in vitro, it appears that microwave cataracts develop as a direct effect of the radiation on the lens rather than as a result of a change in its intraocular environment.

9. During the latent period preceding onset of an opacity, two specific biological effects which can be identified in the lens are an early marked reduction in ascorbic acid level and an inhibition of DNA synthesis and cell division in the lens epithelium.

10. At the time when opacities first become apparent, there occurs an increase in lens electrolytes and water, suggesting that one result of microwave radiation is an increase in membrane permeability in the lens.

11. There is evidence to suggest that the double or triple "cortical banding" seen by slit-lamp examination as the first visible change in the lens following irradiation may be related to a change in ascorbic acid distribution in the lens cortex.

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# CLINICAL MICROWAVE CATARACTS

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To date, 44 cases of microwave cataract have been reported. The first case was described by Parker and Hirsch (1) in 1952, the second by Shimkovich and Shilyaev (2) in 1959 and the remaining 42 by Zaret (3) in 1969. The criteria for establishing this diagnosis will be presented. Also, a typical retrospective environmental exposure history, which is unique in its completeness, will be detailed.

All of the cases occurred in individuals working in the immediate vicinity of microwave generating or propagating equipment. Most were engaged in research, development, testing or maintenance of high-power radar systems. They were known to have had multiple exposures to power densities far exceeding 10 mW/cm$^2$. Many of these people have had repeated exposure at several different frequencies. At any rate, regarding medical history, they all worked in microwave environments either for the Army, Navy, Air Force, NASA, or industry.

Other features of history were shared. As a group, the men were too young for naturally occurring cataracts, they averaged 40 years of age at onset. No factor of senility, congenital anomaly, family history nor intercurrent disease process was associated with the eye pathology.

In order to understand the pathogenesis of microwave cataract it is necessary to be familiar with a normal lens. In the human eye, the lens is a transparent, biconvex tissue enclosed within a very thin, transparent capsule. Ordinarily, cataractogenesis takes place within the lens substance, which becomes opaque in the process, while the capsule remains transparent. The reverse of this, opacification of the capsule with a transparent lens substance, is known to occur in environments of excessive infra-red radiation where it is recognized as the earliest permanent finding of thermal injury to the lens. After capsular opacification becomes extensive, the lens substance also becomes opaque and this results in a reduction of visual acuity.

Capsular opacification was observed in all of the cases reported above. This resembles the infra-red cataract except for the location where opacification first appeared. For microwaves the process begins in the posterior capsule; with infra-red irradiation, it begins in the anterior capsule. Both types appear to be thermal in nature, the difference being that with infra-red radiation the thermal gradient is highest at the anterior surface of the lens and decreases to the posterior surface; whereas, with microwave radiation, the eye is heated uniformly and, as the iris located in front of the lens serves as a heat sink, the temperature gradient is highest at the posterior surface of the lens and diminishes to the anterior surface.

There is usually a long latent period, lasting from months to years, between exposure and the earliest evidence of microwave cataract. Pre-clinical signs of microwave injury were described by Zaret (4) in 1969 as consisting of roughening, thickening, and minute areas of opacification in the posterior capsule. However, although some of the cases reported above only exhibited minimal findings when examined originally, none was considered to be a clinical microwave cataract until it had progressed to the stage where the capsular opacification was readily demonstrable and vision began to fail.

Occasionally, an individual received a massive dose of microwave radiation directed into one eye as in looking through a window cut into a section of wave guide. In such a case, there would be a marked difference in the course of cataract formation between the two eyes. In one such instance the individual developed an acute fulminating cataract in a matter of days. Moreover, all of the tissues of the anterior segment of the eye displayed evidence of thermal injury. Keratitis and iritis developed simultaneously with an acutely formed cataract. Here, the cataract did not develop secondary to the other inflammation; instead, it appeared as if the entire anterior half of the eye were partially burned. Many months later, the other eye exhibited preclinical changes in the posterior capsule. Now, many years after the episode, the lens changes have progressed to the stage of incipient microwave cataract.

The factors of microwave cataractogenesis were reported by Zaret (5) in 1964. The pathognomonic features of this condition were documented in such detail that the lens can serve as a cumulative tissue dosimeter, qualitatively indicating radio-frequency injury. The human data available at that time was evaluated and a crude relationship was presented between the power density of microwave radiation believed to have been delivered to the eye and the time of occurrence of cataract formation: repeated exposure to 5 W/cm² produced a cataract within two months; whereas, repeated exposures to 500 mW/cm² were followed by a latency of many months before posterior capsular opacification appeared and many years before the cataract was fully formed.

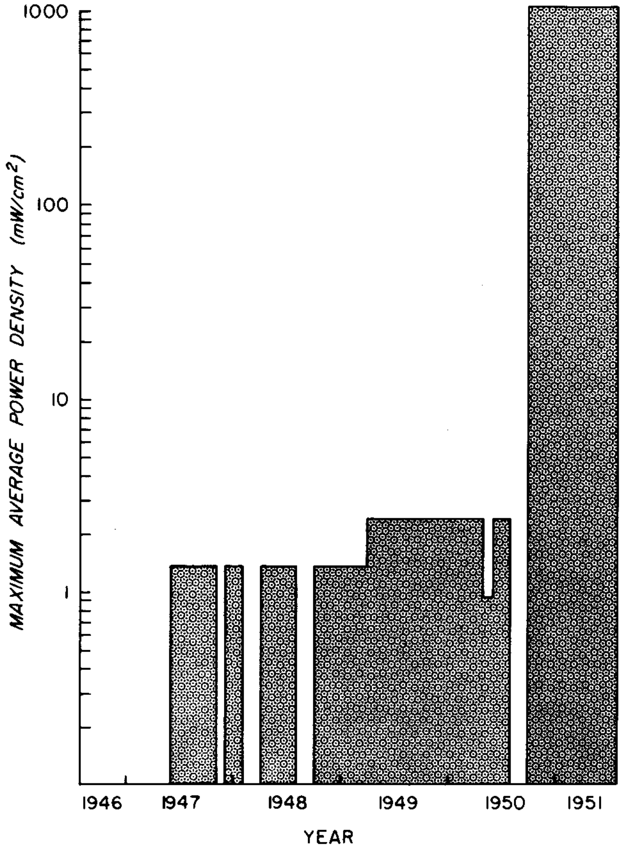

Figure 1. Maximum average power density as a function of months of exposure.

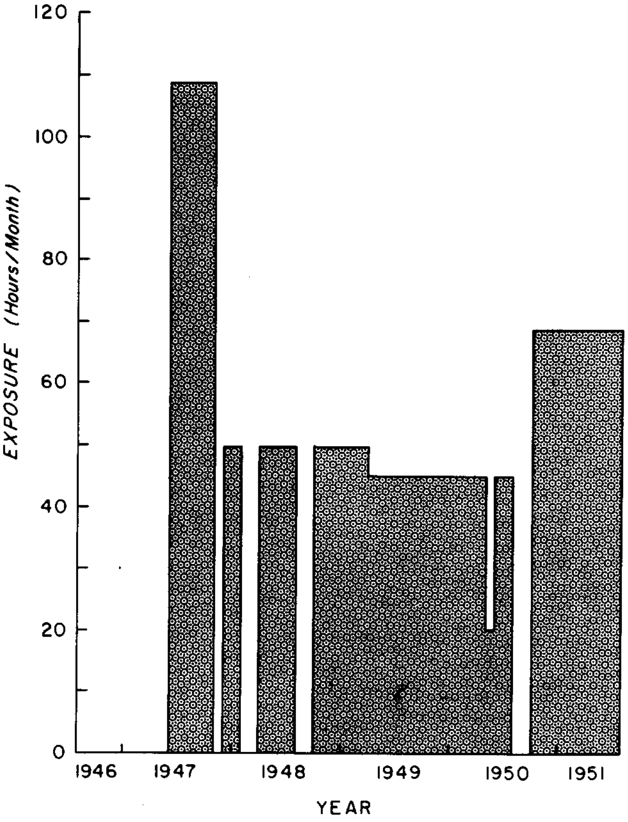

Figure 2. Average duration of exposure to microwave radiation as a function of time.

In 1964, only five documented cases of human microwave cataract were known to exist. Since that time, the 39 additional cases have been reported (2). Unfortunately with one exception, records of work history were either unavailable or inadequate to permit accurate reconstruction of dose rates and exposure durations.

Fortuitously, the one patient who did keep a log of his work history while in the service also became proficient in microwave theory and was able to accurately reconstruct the radio-frequency fields in which he worked. The data and computations describing his exposure history fill two volumes. The salient features of this body of data have been summarized in the following table and graphs.

Certain aspects of this specific case are typical of the group as a whole. This individual was a troubleshooter. His work involved all portions of the r. f. spectrum. He had many exposures to power densities of about 1 W/cm².

TABLE 1

*Microwave radiation exposure record in U.S. Navy*

| Months in Navy (60) | Maximum average-power density (mW/cm$^2$) | Exposure time (hours/month) |
|---|---|---|
| Aug. 1946–May 1947 (10) | 0 | — |
| Jun. 1947–Oct. 1947 (5) | 1.36 | 108.76 |
| Nov. 1947 (1) | 0 | — |
| Dec. 1947–Jan. 1948 (2) | 1.36 | 50.0 |
| Feb. 1948–Mar. 1948 (2) | 0 | — |
| Apr. 1948–Jul. 1948 (4) | 1.36 | 50.0 |
| Aug. 1948–Sept. 1948 (2) | 0 | — |
| Oct. 1948–Mar. 1949 (6) | 1.36 | 50.0 |
| Apr. 1949–Apr. 1950 (13) | 2.40 | 45.0 |
| May 1950 (1) | 0.96 | 20.0 |
| Jun. 1950–Jul. 1950 (2) | 2.40 | 45.0 |
| Aug. 1950–Sept. 1950 (2) | 0 | — |
| Oct. 1950–Jul. 1951 (10) | 1072.00 | 68.6 |

Following this exposure, more than a decade passed before his vision became impaired and ophthalmic consultation was sought. At that time, in 1964, the visual acuity of his right eye was correctable to 20/40 and his lens exhibited advanced capsular opacification characteristic of microwave cataract. The vision of his left eye was 20/20 and his left lens displayed minimal pre-clinical signs of microwave injury. During the past 5 years he has been examined repeatedly and the changes in both eyes cannot be corrected beyond 20/200 and opacification of the lens substance is imminent. Visual acuity of the left eye remains correctable to 20/20 and the posterior capsular changes are demonstrable by slit-lamp examination.

Microwave cataract is a preventable, environmental disease. However, it will be controlled only if health-safety programs are rigidly enforced and appropriate applied research is performed. Health-safety measures must include a continuing surveillance of generating systems, thorough investigation and documentation of accidental exposures and periodic eye examinations of personnel working in microwave environments. In addition, the requirement for pragmatic research to establish cataractogenic thresholds for high power microwave systems is self-evident and it behooves the users to ensure that this specific knowledge is acquired for the equipment they operate.

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# THE DISSIPATION OF MICROWAVES AS HEAT IN THE EYE

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## INTRODUCTION

A previous communication described two distinct types of microwave cataract, a coagulative type produced by thermal denaturation of lens protein, and a delayed type which was presumed to be caused by a derangement of a vital process in the lens or in a structure related to the lens. The initiating mechanism of the process leading to the formation of the delayed type of microwave cataract was investigated using a hypothermic technique and it was concluded that this mechanism was entirely thermal (1).

The harmful effect of microwave heating on the eye has been recognized from the time the first studies were made demonstrating microwave cataractogenesis (Daily et al. (2), Richardson et al. (3)). In these and subsequent studies (Osborne and Frederick (4); Daily et al. (5, 6, 7); Williams et al. (8); Richardson et al. (3, 9); Addington et al. (10); Carpenter (11, 12); Carpenter and Van Ummersen (13)) temperature measurements were restricted to the aqueous humor or vitreous humor at the lens interface or in close proximity to the lens.

Further research is required on the temperature patterns produced in the eye by the dissipation of microwave energy. The following study is an initial investigation on this problem. The in vivo experiments were not extended to include observations on microwave cataractogenesis because interference with the interior of the eye by the insertion of thermocouple needles would have predisposed to traumatic and other forms of cataract. Also, irradiation of dielectric materials was not undertaken with a thermocouple needle in situ because the concentration of the field around the tip of the needle would have led to increased heating in that area. This "end concentration" observed with lengths of metal in a microwave field has been described in detail elsewhere (Baillie et al. (14)).

## APPARATUS, METHODS AND MATERIALS

The first part of this study used a 4.5 kW microwave cavity which produced a random field of energy with a wavelength of 12.4 cm. A modification enabled the cavity to be used for irradiating the eye of a dog at a power density of 5 watts/cm$^2$ on the corneal surface. The apparatus and the modification have been described elsewhere (Baillie (1)).

The second part of the study used a waveguide type of microwave test bench which was aligned vertically with an accuracy which would permit measurements on an air to liquid interface.

A mechanically driven thermocouple needle connected to a recording apparatus was used to determine the temperature pattern in the interior of dielectric samples which had been exposed to the field in the cavity (Fig. 1). Each recording was started 15 seconds after the end of the exposure. A detailed description of this apparatus, including the electric circuit, is being prepared for publication.

The dissipation of microwave energy as heat in various dielectric fluids was compared by simply measuring the temperature rise in 500 ml samples of the fluids after exposure in the center of the microwave cavity. The exposures were made under identical conditions using a thin glass beaker as a container. The post-exposure temperature of each sample was recorded 30 seconds after the power had been turned off. This allowed 15 seconds to open the cavity and a further 15 seconds in which to stir the liquid and measure the temperature.

A dielectric fluid, which could be set as a jelly and which had similar microwave dissipating properties to those of vitreous humor, was chosen. Ten 12 cm cubes were molded from this material. Each cube was covered on all surfaces but one with aluminum foil and exposed to the microwave field in the center of the cavity. The pattern of the temperature rise

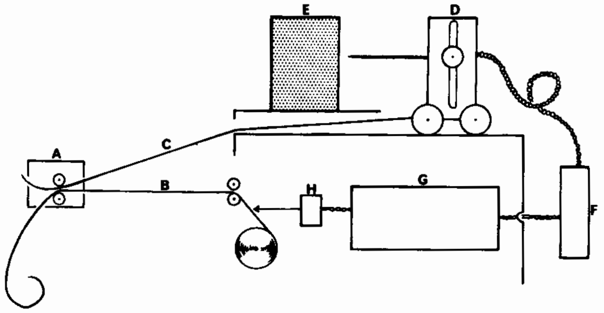

Figure 1. The mechanically driven thermocouple needle. (a) Drive motor: 5 mm/sec. (b) Recording paper. (c) Needle drive paper. (d) Needle holder on wheels. (e) Dielectric sample. (f) Preamplifier. (g) Main recording amplifier. (h) Ink recorder.

along the line perpendicular to the exposed surface and passing through the center of the cube was recorded.

Two types of eye model were prepared from the chosen material. The first type was a 2 cm diameter sphere (the approximate size of a dog's eye) recessed into a block of the same material. The second type was simply a flat surfaced block (Fig. 2). These two types of eye model were exposed in the modified cavity with the effective corneal surface in the plane where the power density was 5 watts/cm². Traces were then made of the pattern of the temperature rise along the optical axis of the model.

A further exposure was made on the effective corneal surface of an eye model which had been allowed to equilibrate with room temperature. Traces of the temperature pattern along the optical axis were recorded at intervals over a period of 4 minutes while the model cooled. The decay of the temperature recorded at the lens position was used to estimate the temperature at this position at the moment the microwave power was switched off. This was repeated six times for each of the exposures: 30 seconds, 45 seconds, 60 seconds, 72 seconds, and 85 seconds. A graph was then constructed for predicting lens temperature from exposure time.

An in vivo check on the predictions of the graph was made using 4 dogs. The anaesthetic technique and the method of preparing the eyes for exposure have been described elsewhere (Baillie (16, 1)). A single exposure was made into the right eye of each of the four animals at a power density of 5 watts/cm² on the corneal surface. The exposure times with the first, second, third, and fourth animals were, respectively, 30 seconds, 45 seconds, 60 seconds, and 75 seconds. Immediately after the exposure a thermocouple needle was passed through the cornea and anterior chamber to the lens. It was then advanced into the substance of the lens using a screwing motion. The correct positioning of the needle in the lens was aided by observing the halo produced by the refractive disturbance around the advancing point. The temperature of the lens was recorded and compared with the predicted temperature in each case.

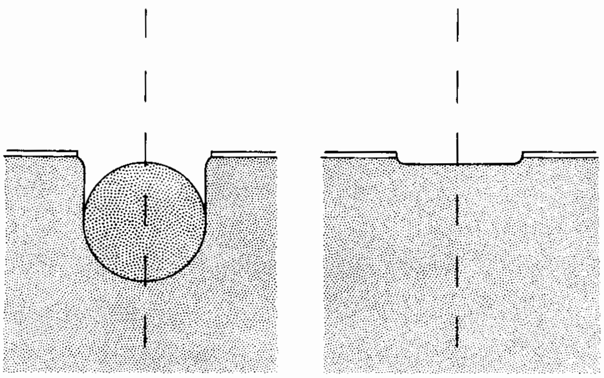

Figure 2. Spherical and flat eye models. The 2.5 cm diameter hole in the metal plate covering each model (part of the modification of the cavity) permits the random field to irradiate the effective corneal surface. The optical axis is indicated by the dotted line.

The effect of exposing 25 ml samples of fresh cow lens and vitreous humour in the center of the cavity, using a thin glass test tube as a container, was observed.

The relative permittivities and attenuation constants of fresh samples of cow lens and cow vitreous humour were deduced from standing wave measurements which were made on various depths of sample using a modification of a standard method (Roberts and von Hippel (15)).

## RESULTS

The temperature rise produced by the microwave irradiation of the dielectric samples varied by a maximum of 8% of the mean temperature rise of the group with the exclusion of egg yolk and the sugar solutions (Table 1). Agar (5% weight for volume with water) was chosen as the material for making the eye models. This particular agar solution sets firmly after heating and is suitable for moulding into firm shapes.

The temperature patterns recorded in the ten agar cubes following exposure in the microwave field were almost identical. There was a sub-surface peak which occurred in each case within a depth limit of 5–10 mm. With increasing depth, beyond this sub-surface peak, the temperature fell off rapidly towards the pre-exposure temperature of the cube. This deeper portion of the curve was exponential in character. The temperature curve suggested by isolated temperature readings recorded in the eye of a dog which had been exposed to the field during a preliminary study, was similar to the temperature curves of the cubes (Fig. 3).

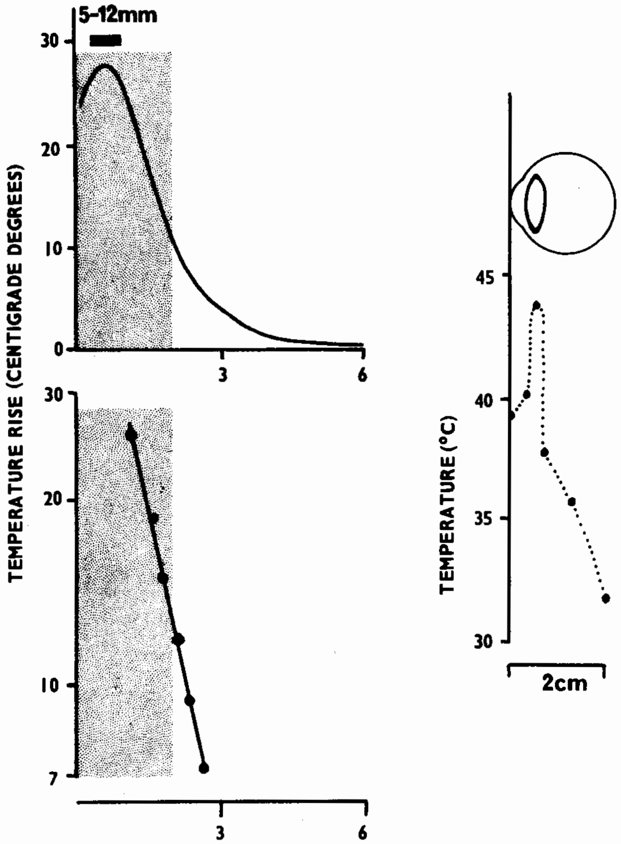

Figure 3. *Left upper:* Temperature pattern in an agar block. The range of the sub-surface temperature peak in 10 blocks is marked. *Left lower:* The temperature recordings deep to the sub-surface peak-log/linear scale. The shade area corresponds to the optical axis of a dog's eye. *On the Right:* Temperature pattern suggested by observations with a dog's eye following exposure. (The dog was cooled to 30 °C to prevent thermal destruction of the eye.)

The shape of the temperature curves with the two types of eye model were so similar that the flat type of eye model was used, for convenience, throughout the remainder of the study (Fig. 4).

TABLE 1

*Temperature rise in 500 ml samples of various materials exposed in the microwave cavity under identical conditions*

| Sample | Temperature rise (centigrade degrees) |
|---|---|
| Distilled water | 23.5 |
| Tap water | 22.0 |
| | 23.0 |
| Normal saline (0.9% w/v) | 24.0 |
| Dextrose solution (5% w/v with water) | 27.5 |
| "Dextran 110"* | 26.5 |
| Dried human plasma (reconstituted) | 22.0 |
| Albumin (5% w/v with water) | 25.0 |
| Egg white | 25.0 |
| Egg yolk | 32.0 |
| Agar (5% w/v with water) | 22.0 |
| | 24.0 |
| | 23.5 |
| | 23.0 |
| Vitreous humour | 22.0 |
| | 22.0 |
| | 22.0 |
| | 23.0 |

* A plasma expander M.W. = 110,000. Dextrans: 6% w/v with normal saline.

The observations with the eye models indicated that the decay of the sub-surface peak temperature towards the pre-exposure temperature was exponential in character. The estimation of the temperature at the lens position of the model, when the microwave power was switched off, was made

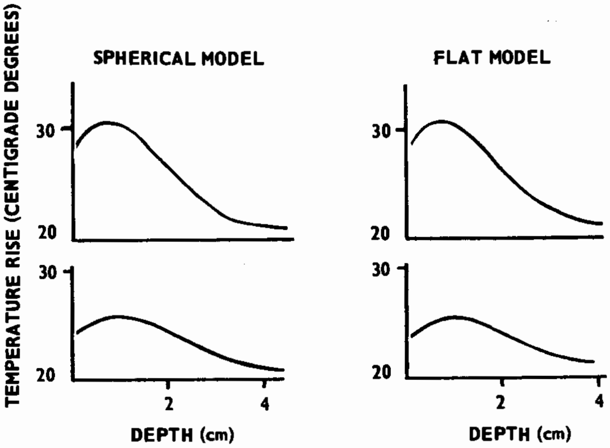

Figure 4. Temperature pattern along the effective optical axis of eye models following microwave exposure. Spherical model, Upper pattern—45 seconds: Lower pattern—3 minutes. Flat model, Upper pattern—45 seconds: Lower pattern—3 minutes.

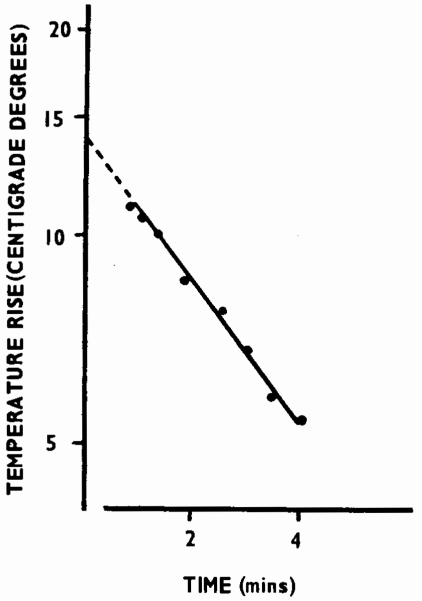

Figure 5. Decay of sub-surface temperature peak following exposure. Dotted line: the projection used for estimating the temperature at the lens position at end of microwave exposure.

by extrapolating the log-linear line to the ordinate (Fig. 5).

The relationship of the mean values of the estimated lens temperatures at the end of the exposure times: 30 seconds, 45 seconds, 60 seconds, 72 seconds, and 85 seconds to these exposure times was linear (Fig. 6).

The observations with the dog eyes indicated that the rise in lens temperature predicted by the graph was, on the average, low by approximately 40% (Table 2).

The ratio of the temperature rise in the 25 ml samples of lens and vitreous humor exposed in the microwave cavity under identical conditions was 2 to 1.

TABLE 2

*Table comparing lens temperature and estimated lens temperature for exposure times. The estimated lens temperature was obtained by adding the predicted temperature rise to the normal body temperature of a dog: 38 °C*

| Exposure time (sec) | Lens temperature | Estimated lens temperature |
|---|---|---|
| 30 | 49 | 44.2 |
| 45 | 54 | 48.2 |
| 60 | 58 | 50.5 |
| 75 | 62 | 52.0 |

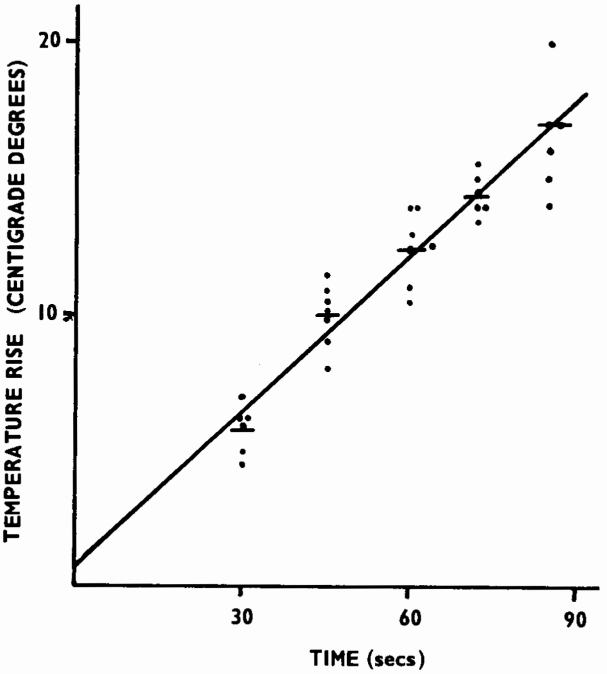

Figure 6. Graph of estimated lens temperature rise and exposure time. (•) Experimental values; (—) mean values.

The waveguide studies demonstrated that the relative permittivities of lens and vitreous humor were approximately 35 and 75, respectively. The ratio of the attenuation constants of lens and vitreous humor was 1 to 1.9.

## DISCUSSION

This similarity of the temperature pattern in the agar blocks to the temperature pattern suggested by the isolated readings made in the eye of the dog during the preliminary study, indicate the comparable nature of these curves at least in terms of shape. Similar patterns were suggested in another study but the temperature gradients were not nearly so steep (Richardson et al. (9)). On the basis of the temperature pattern alone, these studies indicate that the position of the sub-surface temperature peak produced by microwave irradiation is extremely close to the lens if not within its substance.

The similarity between the temperature patterns of the spherical eye model and the flat eye model suggest that the curvature and area of the cornea in the spherical eye model were insufficient to produce significant optical concentration of the microwaves at the frequency employed.

The rapid exponential decay of the sub-surface peak towards the ambient temperature indicates the difficulty of making a reasonable estimation of the sub-surface temperature peak value at the time the microwave power is turned off. On consideration of the mechanism of this decay and the straightness of the log-linear graph of sub-surface temperature peak value and time, the linear extrapolation which was made to estimate the sub-surface peak temperature at the end of exposure, is probably justified. The straightness of the line on the prediction chart can also be taken as reasonable justification for this extrapolation.

In a previous study (Baillie (1)), 60 seconds was established as the threshold exposure for cataract formation in the dog following a single exposure under these experimental conditions. The prediction graph indicates that this exposure should produce a lens temperature of approximately 50 °C. This temperature has been quoted, with reservation, as the critical temperature of the thermal cataractogenic effect of microwave radiation (Carpenter (11)).

The discrepancy between the predictions of the graph and the findings of the in vivo studies may be explained on the basis of the difference in the dielectric properties of lens and vitreous humor. This postulated difference was confirmed by the fact that a greater amount of heat was generated in lens than in vitreous humor during the test tube experiments. The waveguide studies suggest that these differences may be due, in part, to the superior reflecting property of vitreous humor as the powers which could pass into lens and vitreous humor were calculated to be in the ratio 1 to 0.7.

## CONCLUSIONS

This study indicates the possible fallacies of drawing conclusions about the mechanisms of microwave cataractogenesis on the basis of temperature measurements made in the eye at positions other than the interior of the lens. It also draws attention to the fact that the eye does not have uniform dielectric properties and that intraocular temperature decay must be considered seriously when estimates of temperature at the end of exposure are being made.

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# REVIEW OF STUDIES OF PEOPLE OCCUPATIONALLY EXPOSED TO RADIO-FREQUENCY RADIATIONS[1]

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There is increasing evidence that radio-frequency radiations can affect biological organisms, even at relatively low intensities, particularly under conditions of chronic exposure. A substantial number of observations have been made at intensity levels below those presently accepted as tolerable for continuous exposure in the United States and most of Western Europe.[2] To date, the deleterious effect of radio-frequency fields, particularly of microwaves, at relatively high intensities, e.g., 50 mW/cm$^2$ or greater, has been recognized and attributed to heating. However, biological hazards may exist at lower levels, extending well below 10 mW/cm$^2$, and effects at both high and low intensities may be attributable to more complex modes of interaction. At low intensities effects may be subtle, impairing performance; chronic, affecting general mental and physical health and longevity; and may also be mutagenic, affecting succeeding generations. In addition, any biological damage occurring coincident with radio-frequency exposure can lead to medical-legal problems which would be difficult, if not impossible, to adjudicate on the basis of present knowledge.

Direct data on human response is almost exclusively derived from clinical studies of occupationally exposed workers. These occupational exposures encompass various frequency regions and are characteristically of relatively low intensity. Supplementary data have been derived from collateral animal experiments and an occasional human experiment. Animal data are indirect, with problems of extrapolation.

Almost all of the large-scale, long-term clinical investigations of exposed people and, therefore, information in this area, comes from the Soviet Union and Eastern European countries. In these countries, a great deal of emphasis is placed on occupational health and industrial hygiene. Many institutes and their affiliated clinics have participated in studies of the effects and potential hazards of r. f. radiations.

In the Soviet Union, recognition of subjective complaints, symptoms, and cases of impaired performance of exposed workers, led to a focus on research at low radiation intensities. By contrast, in the United States primary concern has been with the thermal hazard of these radiations and consequently with studies at considerably higher intensity levels (see, e.g., 85, 86, 88, 105). Few studies of exposed populations have been conducted in the United States and this class of effects (the so-called "clinical syndrome") is not generally recognized or accepted as attributable to r. f. radiations; particularly, not at the low intensities reported in Soviet studies ($<$10 mW/cm$^2$).

There has been considerable controversy and skepticism in the West about the health hazard of prolonged low-intensity exposures and the validity of the foreign observations. There are several reasons for this. The complaints of occupationally exposed workers are primarily amorphous and neurasthenic, and nonspecific in that they can be produced by stresses other than radio waves.

At least in the early stages, reported symptoms are mild and generally not sufficient to cause an individual to seek medical attention or to be disabling, even through alertness and efficiency may be impaired. For the most part, disturbances lie within clinical norms or tolerances.

In most cases, symptoms are functional and are not accompanied by severe pathological change. Typically, they disappear when the individual is removed from the exposure environment, with occasional reports of exceptions involving individuals showing very pronounced symptoms, usually re-

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[1] This paper is based in part on material compiled with the support of U.S. Army Medical Research and Development Command Dept. of the Army.

[2] Ten milliwatts/square centimeter.

sulting from long-term exposures and/or intensity levels above those permissible under Soviet standards (e.g., 10 $\mu$W/cm$^2$) (20, 21, 23, 81, 84, 95).

Additional uncertainty stems from difficulties in measuring some of the extremely low-intensity levels reported (e.g., microwatts/cm$^2$) particularly under nonexperimental conditions (e.g., people often move about in facilities where objects and various configurations of the surroundings can produce reflections and standing waves).

Some confusion has ensued from the classification of effects as "thermal" or "nonthermal," presumably (and perhaps prematurely and erroneously) according to causative mechanism. The lack of a proven biologically significant mechanism for "nonthermal" interaction became another basis for skepticism over the existence of effects at very low-intensity levels.

Furthermore, differences in investigating and reporting methods and the lack of ready access to details of foreign experiments have compounded our difficulties in interpreting, evaluating, and reproducing experiments and results. As reported, the studies vary in quality with respect to statistical methodology, use of controls, dosimetry, preexisting health status, and attention to other environmental factors. However, some studies are quite attentive to these considerations. While it is difficult to assess the statistical methodology in detail from these reports, standard statistical methods such as the Student t test for level of significance are frequency used.

Efforts are being made to elevate the level of technological sophistication of controls and measurements for the collection of quantitative and definitive data (36, 39, 64, 72, 90). For example, with respect to dosimetry, the Leningrad Institute of Labor Protection has been concerned with the development of precise instrumentation and standardization for field measurements (55). Two widely used field measurement devices: one for the microwave range (PO-1-MEDIK) and one for lower frequencies (IEMP-1) are described in the literature (28, 39, 55, 67).

Even allowing for a substantial error in dosimetry, there is evidence of biological effects[3] in response to chronic low-intensity exposures. In many cases, those indices which appear affected by r. f. exposures in clinical examinations of humans have been investigated in more controllable laboratory experiments with animals which have produced supporting data.

Furthermore, the existence of effects can be established independent of questions of clinical significance, hazards, or even of mechanisms. The full clinical significance and the hazard potential of the effects (individually and collectively) are not fully understood and require further assessment. Nonetheless, these effects are indicative of a disturbance of normal condition and a process of change. As such, they should not be dismissed prematurely.

There has been a steady expansion of research at low intensities in the Soviet Union in the directions of both larger-scale and longer-term clinical studies of people and more elaborate animal experiments. A number of extensive clinical studies have been conducted over a period of 20 years at various Soviet and Eastern European Institutes (39, 43, 49, 59, 60, 67, 70, 71, 81, 100, 101, 108). The Institutes of Labor Hygiene and Occupational Diseases in Moscow and Leningrad have been particularly active in this area. The Gorky Institute has done work with emphasis on lower frequencies. Institutes in Czechoslovakia and in Poland are also active in this area. As an example, the Moscow Institute conducted a 10-year study of over 1000 individuals exposed in various occupations over periods from months to as long as 20 years (20, 39, 59, 94). The study included investigation of symptoms associated with chronic, long-term low-level exposures that "do not produce a thermal effect." Effects of various frequency bands were compared from below the high-frequency (HF) band up through the superhigh frequency (SHF) band. A large portion of the work was done in the centimeter range with reported exposure intensities of 1 mW/cm$^2$ and below. Even at these low intensities, systematic, long-term exposures were reported to produce symptoms. Similar observations have been made at these and lower frequencies extending into the ELF region. (For example: VHF (30, 31, 35, 70, 81), HF (30, 31, 45, 70, 81), MF (50, 81), LF (81, 101), and ELF (4, 45).

It is also of interest that in Soviet studies of people occupationally exposed to pulsed and static mag-

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[3] The term "biological effects" is used in this paper to refer to biological changes or shifts associated with conditions of irradiation and does not contain any necessary or inherent implication of either clinical significance or hazard value.

netic fields of hundreds to a few thousand oersteds, symptoms were observed similar to those produced by r. f. exposures and maximum permissible exposure levels were proposed (111–113).

In the United States, only isolated studies of this nature exist, such as those of Barron (6) and Daily (18), and the ocular studies of Cleary (16, 17) and Zaret (117). For example, Barron et al. (6) in the 1950's examined 226 radar workers grouped by years of exposure and by two intensity ranges (below approximately 13 mW/cm²). They conducted follow-up studies on approximately 100 individuals 6–9 months later. Their primary finding was changes in blood composition, most notably in the leukocytes. Also mentioned were occasional complaints of headache, fatigue, aching eyes, and occasional cases of sound and warmth sensations under some conditions.

In the Russian literature, reference is made to the "stereotype-nature" of complaints and to the "pattern" of complaints of radio-frequency exposed workers. It is interesting that as early as 1933, a report referring to two workers exposed to r. f. fields refers to their having "complaints which are common to that occupation" (97). Several Soviet investigators comment on the stimulating effect of early observations of subjective complaints on subsequent research programs. For example, Obrosov (79) states that early awareness of the symptomatology led to a formal request being submitted to the State Institute of Physiotherapy in 1942 to investigate the complaints of radar workers, which, in turn, led to investigations of therapeutic applications.

The symptomatology associated, in the Soviet literature, with prolonged exposure most commonly includes headache, increased fatiguability, diminished intellectual capabilities, dullness, partial loss of memory, decreased sexual ability, irritability, sleepiness and insomnia, emotional instability, sweating, and hypotension. Shortness of breath (dyspnea) and pains in the chest region are also reported. Symptoms of disturbance of the vegetative nervous system including sinus arrhythmias, a tendency toward bradycardia, and other vagotonic changes are common observations. There appears to be a certain commonality and consistency to the symptomatology for exposures in the various frequency bands, although some distinctions have been suggested (37, 38, 59, 81). Various Soviet investigators have grouped symptoms into clinical syndromes which vary in number and terminology, but are essentially similar (22, 23, 84). For example, based primarily on data from the centimeter range, investigators at the Moscow Institute of Labor Hygiene define 5 specific syndromes related to the stages of the condition (22, 23). (Mild exposures result in the "vegetative" and "asthenovegetative" syndrome; and in the acute stage, the "angiodystonic" and "diencephalic" syndromes are described.) The two more severe syndromes include symptoms described as emotional instability, weakened memory, cardiovascular problems, severe seizure-like headaches, fear, and shivering. At this stage, the condition is described as disabling, requiring removal from work and hospitalization. These more severe conditions are not frequently seen.

The most commonly reported objective physiological changes are neural, cardiovascular, blood compositions, and endocrine functions. Objective measurements carry more weight than subjective symptoms, and some attempts have been made to correlate the rather amorphous symptoms of the "clinical syndrome" with objective measurements such as electroencephalography. Although time will not permit detailed discussion of individual studies, certain general results can be noted.

Nervous system effects, to be discussed in some detail tomorrow, will only be briefly mentioned here. These effects are prominent among reported observations. A substantial body of data (human and animal) indicates that the nervous system (particularly the central nervous system) reacts to intensities of radiation below the threshold of response of other body systems and reacts sooner (37, 38, 40, 48, 51, 52, 87, 92). There is a majority opinion among Soviet investigators that of all body systems, the nervous system is most sensitive to these radiations. The emphasis placed on the prominent role of the nervous system in these reactions is consistent with the Soviet view and reflects the influence of Pavlovian teaching.

At low intensities, neural changes, like other reported biological shifts, are typically functional, are not accompanied by distinct pathological change, and disappear after the subject is removed from the radiation environment. Nervous system response is expressed in the electroencephalogram (EEG) and by altered response times. Commonly, responses are characterized by initial excitation followed by subsequent inhibition. Other reported changes include threshold shifts generally in the direction of increasing thresholds for sensory perception, increases in the latent period of the conditioned-reflex reaction, and disruption of vegetative system regulatory and compensatory functions.

Various biochemical, neurohumoral and metabolic disruptions have been observed which can affect neural and other body functions (7, 13, 38, 119). Changes in histamine in the blood (generally increases) have been reported (22, 23, 32, 33). Decreased cholinesterase levels are frequently reported in exposed people and also in animals where they have been observed in connection with altered neural response (13, 31, 38, 74, 75, 102, 106).

EEG changes have been observed in some occupationally exposed people at microwave and lower frequencies (12, 21, 24, 25, 27, 34, 45, 52, 109, 114). These changes are reported to be early occurring and often appear before other changes are detectable in the organisms. They are frequently reported to persist after the cessation of irradiation. The changes are generally polymorphous, and are not necessarily unique as they can be observed in response to other factors.

In general, reported effects in the EEG are characterized by predominance of the slow rhythms (alpha and theta rhythms). Most frequently, changes occur in the amplitude characteristics of both fast and slow waves. Paroxysmal bioelectric activity is reported such as spasmodic spike-type discharges, etc. This activity is noted most often during sensory stimulation. In more severe cases, more pronounced epileptiform bioelectric activity may also be observed.

A Czechoslovakian study of persons exposed to cm wave radiations reported finding certain correlations between EEG activity and other clinical observations and subjective complaints (52). The investigators feel that this indicator can point toward more serious changes than were ascertainable from clinical evidence only, and that the observed EEG activity was useful in further localizing the disruptions which, they feel, are mesodiencephalic. They regard EEG shifts as a kind of early-warning system for detection of organism response to r. f. radiation on a very subtle level.

Similar observations were made at 500–2400 Hz, 3.5 MHz, and with occupational magnetic-field exposures (45, 112, 113).

EEG reactions (with rhythmic light stimulation and hyperventilation) were studied in individuals occupationally exposed to centimeter and lower frequency radiations who showed various degrees of the "clinical syndrome" (34). Individuals were grouped by length of service, which extended up to 20 years. Disturbances were observable in the slow rhythms. The degree of manifestation appeared related to the degree of the clinical syndrome. Radiations in the VHF/HF range were reported as more effective in producing shifts than those in the SHF/UHF region. The EEG was one of the factors used by this group in their categorization of specific syndromes (22).

Changes in the function of the visual, auditory and olfactory modalities have been reported in man and in experimental animals, under a variety of irradiation conditions, including low-exposure densities ($\ll 10$ mW/cm$^2$) (9, 11, 14, 29, 62, 68, 102). Functional changes in sensory systems and conditional reflex behavior at these intensity levels have been found to be accompanied by slight and reversible histological disruptions in the receptor apparatus in some animal studies (60, 106, 107). Olfactory and auditory perception disturbances generally take the form of a depressed reaction or response, increased thresholds and increased latent period of response to stimuli. There are reports of alterations in pain sensitivity in the direction of increasing the threshold (reduced sensitivity), (20, 49) and indications of stimulation of cutaneous thermoreceptors (47) by extremely low-intensity radiations. In one study, the administration of caffeine was found to temporarily increase the depressed olfactory sensitivity leading the investigator to implicate functional shifts in the cortical portion of the olfactory analyzer (29).

A U.S. study of auditory thresholds at intensities of 0.5 mW/cm$^2$, 1.0 mW/cm$^2$, and 1.5 mW/cm$^2$, exposed people with normal hearing to CW (1000 MHz) radiation with and without sinewave modulation (at 400 and 1000 Hz) for two minutes prior to and during presentation of various auditory stimuli (11). A significant decrease in auditory thresholds was reported for 5000 Hz auditory stimulation which was proportional to the magnitude of the average power density. Also, the thresholds were significantly lower with 1000 Hz than with 400 Hz modulated radiation. This increased sensitivity is interesting in contrast to the decreased sensitivity reported by Soviet investigators in subjects who had experienced long-term exposures. It would be interesting to see whether this effect would persist under chronic exposure conditions or eventually shift in the opposite direction.

Numerous Soviet studies cite cardiovascular disturbances which they widely regard as the predominant vegetative response to radio-frequency irradiation (19, 20, 26, 40, 54, 74, 78, 80, 81, 83, 95, 110). In general, cardiovascular responses are characterized by hypotension, dystonia, and vagotonic reactions. Electrocardiographic (EKG) studies of exposed people and of animals, report a predominance of bradycardia, arrhythmia, and particularly sinus arrhythmias. Depressed intracardial conduction, commonly intraventricular, and lowered EKG waves, particularly T-waves, are also reported. Shifts are reported more often in persons with long histories of occupational exposure. Some examinations suggest a heightened susceptibility of persons with predisposition to, or a history of, cardiovascular disease. In the interest of occupational hygiene, many Soviet investigators (and at least one U.S. researcher) have recommended that cardiovascular abnormalities be used as screening criteria to exclude people from occupations involving radio-frequency exposures (1, 69, 80, 110).

An extensive examination program was conducted by the Institute of Labor Hygiene and Occupational Diseases, Moscow, involving over 500 individuals, periodically exposed for periods up to approximately 10 years to cm and longer wave radiations at low intensities (e.g., below 1 mW/cm$^2$, and up to several mW/cm$^2$) (20, 23, 54, 74, 80, 93, 95). This program revealed a variety of cardiovascular shifts predominant among which were bradycardia and vascular hypotension. Differences in responses to acute exposures of higher intensities and longer term chronic exposures at lower intensities were noted. Although these effects are generally reported to be reversible, a few exceptions are noted for certain individuals chronically exposed over many years, who showed pronounced pathological conditions (20, 21, 23, 95).

In the blood, alterations have been reported in the protein fractions, ions, histamine content, hormone and enzyme levels, and immunity factors, but most frequently reported are changes in cellular composition (5, 7, 13, 15, 22, 23, 32, 33, 42, 56, 65, 81, 103, 105, 116). These changes are somewhat variable, but are most commonly characterized by instability of leukocyte indices. Leukocytosis is often seen and leukopenia also occurs, sometimes preceding a shift to leukocytosis. Leukocytosis may vary in type; e.g., monocytosis, lymphocytosis, and eosinophilia. Cases of shifts in other formed elements also have been reported, including reticulocytosis and thrombocytopenia. Changes in erythrocytes and hemoglobin concentration are less frequently reported. These shifts often lie within clinical tolerances, and are a common response to various physiological stressors. They do, however, indicate a reaction to r. f. radiation.

Increased thyroid gland activity and sometimes enlargement is the most commonly reported endocrine response of exposed people (19, 21, 23, 81, 93, 99, 119). Adrenal changes are also reported (3, 53, 61, 119).

A few occupational studies have suggested possible disturbances in some reproductive system functions (22, 44, 81). Several foreign low-intensity animal studies report reproductive system disturbances and cases of adverse effects on progeny (10, 40, 58, 77, 89), although contradictory evidence has also been reported (46). Of particular significance are possible genetic changes which might occur in large populations over long periods of time. Very little genetic data exists, although one U.S. study suggested a possible relationship between paternal radar exposure and mongoloidism (98).

Ocular changes, including "turbidities" or cloudiness of the crystalline lens and cataracts, which can result from microwave exposures, have been thoroughly discussed here today. The majority of existing experimental and clinical evidence on this type of ocular effect indicates that radiation damage to originally healthy eyes does not generally occur at intensities much below 100 mW/cm$^2$. There is, however, some limited evidence from a Soviet study which suggests that for workers having small lenticular opacities, continued work under low-intensity microwave fields (at "several mW/cm$^2$") can cause progressive development of the opacity formation (8).

A 1967 Polish paper (118) discussing ophthalmological aspects of safety standards for workers during operation of electromagnetic-field generators in military installations, indicates concern for workers with some eye ailments when working in microwave fields as low as 0.01 mW/cm$^2$. On the basis of ophthalmological examinations, workers are categorized into four groups for which maximum permissible exposure conditions are rigidly prescribed, including total exclusion of one group.

Differences in Soviet and U.S. programs are further reflected in the development of safety criteria and standards. No universal, uniform or legal standards exist in the United States and in most other Western countries. In the Soviet Union, however, comparatively stringent legal standards have been established.

In the United States, safety criteria are based upon considerations of thermal stress and damage that can occur when the average power density of these fields exceeds 10 mW/cm². This level, which presumes a margin of safety, is the recommended and most generally agreed upon criteria for indefinite exposure to microwaves in the United States and Western Europe (96). Insufficient attention has been paid to the lower frequency bands (ELF, LF, MF, HF, VHF) and to possible differences in their hazard potential. Also, no differentiation is made between pulsed and continuous wave radiation.

There is general agreement among Soviet and Eastern European investigators that systematic chronic exposure to low-intensity radiations (around 10 mW/cm² and lower) can have an adverse effect on health. Their standards are more restrictive than those of the United States by several orders of magnitude (e.g., 10 μW/cm² for continuous daily microwave exposure) (67, 96). Furthermore, separate standards exist for various frequency ranges below the microwave region (e.g., 60 kHz–30 MHz, and 30–300 MHz) (2). In Czechoslovakia maximum permissible exposures distinguish between pulsed and continuous-wave radiations and are more restrictive for the pulsed case (0.025 mW/cm² vs 0.01 mW/cm²) (67).

Regulations have been developed in Eastern European countries for screening people for work entailing r. f. exposures (1, 2, 28, 39, 82, 118). Schedules for regular periodic examinations of occupationally exposed personnel have been legally established, with special attention to ocular, neural, and cardiovascular disorders. In addition, there are regulations governing safety procedures such as shielding, and personal protection, and for appropriate work/rest cycles, vacation and sick leave policies, and workers' compensation.

In summary, considerable investment of time, money and talent have been made in foreign programs to study the effects of low-intensity occupational radio-frequency exposures in man. These studies have resulted in the accumulation of a large body of research data, which in aggregate cannot be ignored even though in many details it must be substantiated. Furthermore, these clinical studies have had a substantial influence on the overall research direction in Soviet and Eastern European countries as reflected in the large number of extended clinical studies and controlled laboratory investigations with animals at low-intensity levels. Concurrently, additional research into therapeutic applications and the development of more precise instruments for dosimetry were stimulated.

This body of data deserves serious evaluation by U.S. researchers to further clarify the implications of this research. Analogous broad clinical and epidemiological studies should be undertaken, as well as related, carefully controlled animal experiments at low radiation intensities. These foreign studies can provide valuable background and guidelines for planning future research—research which is clearly necessary and warranted on the basis of current evidence.

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# INTERACTION OF MICROWAVE AND RADIO FREQUENCY RADIATION WITH MOLECULAR SYSTEMS

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The interaction of electromagnetic radiation with molecules has been studied extensively and over a wide frequency range for many decades. Many informative reviews of the subject are available in the literature. Although most interaction phenomena are quite well understood in terms of dielectric constants and dispersions, there remain some as yet unexplained observations which may be due to the electrical and thermal properties not of individual molecules but assemblies or molecular systems.

Some interesting effects are observed even at very low frequencies (10 Hz–0.00625 Hz), notably a phenomenon termed dielectric diffusion (1). When an electric field of low frequency interacts with a medium of inhomogeneous dielectric constant such as layered detergent solutions, there is a flow of matter in the direction of increasing dielectric constant.

More interesting phenomena are centered around the megahertz region of radiofrequency radiation. A resonance type phenomenon has recently been found by Wilkins and Heller (2) who observed changes in the electrophoretic mobility of polystyrene latex spheres after exposure to radiofrequency fields. In all of the above observations a rather sharp frequency dependence is noted while no measurable increase in the temperature of the medium could be discerned.

One is therefore lead to believe that these resonance type phenomena show some kind of nonthermal interaction between the incident electromagnetic field and the molecular system under study. There are, however, in principle two ways in which thermal energy influences a system of molecules: one effect is an increase in the temperature of the system, the other is a change in phase of the system from solid to liquid or liquid to gas. This second effect of thermal energy has been consistently overlooked in interpretations of the influence of electromagnetic energy on molecular systems, probably because there was no reason to suspect the existence of a solid phase which could undergo a phase change.

The only likely candidate for such an occurrence in biological systems, solutions of macromolecules, or suspensions of colloid particles is the ill defined substance called bound water. I would like to suggest here that the assumption that bound water is identical with *doped* ice type I leads to a consistent set of interpretations of the above mentioned phenomena. Such an assumption, furthermore, if extended to macromolecules and membranes, would predict a variety of effects which are nonthermal by the previously adopted definition, but nevertheless have a profound influence on the performance of biological systems.

The best example is the suspension of polystyrene latex spheres. The low frequency dispersion of these colloidal particles has been measured by Schwan, Schwarz, Maczuk, and Pauly (3) and interpreted by Schwarz (4). Wilkins and Heller (2) used the same system in their studies of the reduction of electrophoretic mobility after exposure to megahertz radio frequencies. Sieglaff and Mazur (5, 6) studied the mobility of an almost identical colloidal system and arrived at some estimates of the surface charge density. The numerical estimates range from $5 \times 10^{13}$ charges/cm$^2$ to $1.9 \times 10^{13}$ charges/cm$^2$. It is thought that these surface charges, mostly due to carboxyl groups, induce a structural change in the surrounding water. In our model we assume that the surface charges promote the formation of a hydrogen bonded layer of water, approximately 100 Å thick due to inhomogeneities in the spherical surface. The resulting ice structure has, however, electrical properties which are modified by the presence of the surface charges. Steinemann and Gränicher (7) and Gränicher (8) have developed a theory of the electrical characteristics of pure and mixed ice crystals which fits very closely the observed data. Whenever impurities are placed in the lattice substitutionally, new lattice defects are created and the conductivity, dielectric constant and relaxation time change. Since the electrical properties of ice are explained by the interaction of four different types of defects (two ionic defects and two orientational defects) a great variety of frequency dependent and concentration dependent data with differing activation energies could be explained.

If one assumes that the carboxyl groups on the surface of the polystyrene latex spheres act as substitutional lattice defects in an ice shell 100 Å thick, one may use Steinemann's data to predict the values of the relaxation times and other dielectric properties of a suspension containing those particles. For a surface charge density of $5\times10^{13}$ charges/cm² and a layer thickness of 100 Å, we arrive at a defect concentration of $N_D=5\times10^{19}$ ch/cm³ and a conductivity $\sigma_s=1.6\times10^{-15}\ (N_D)^{1/2}$ according to Steinemann (7). Substituting $N_D$ we find the dc surface conductance of $\sigma_s=1.12\times10^{-5}$ $\Omega^{-1}$ cm$^{-1}$ which is very close to the estimate given by Schwarz. In this relatively high volume concentration of defects the majority carriers are $L$ defects with a mobility of $\mu_L=2\times10^{-4}$ cm²/V sec which is also almost identical to that assumed by Schwarz (4) for the mobility of the counterions in the hydration shell of the particles.

Since it seems that some major data points and theoretical values of the colloidal suspension fit the assumption of a doped ice layer on the surface of the polystyrene latex particle, we may inquire what changes in the electrophoretic mobility of these particles can occur when they are exposed to radiofrequency radiation.

The simplest form of the electrophoretic mobility of a particle is based on Stokes law of motion of a spherical particle through a viscous medium. The mobility is given by

$$U=Ze/6\pi\eta r \tag{1}$$

where $Z$ is the number of charges on the particle, $e$ is the electronic charge, $\eta$ is the viscosity of the medium, and $r$ is the radius of the particle.

The number of charges on the particle can be obtained from the estimated charge density $n=5\times10^{13}$ charges/cm² and the surface area of the particle: $4\pi r^2$. We find therefore that

$$Z=n\cdot4\pi r^2 \tag{2}$$

Substituting into Eq. (1), the mobility becomes

$$U=ne4\pi r^2/6\pi\eta r=\tfrac{2}{3}(ner/\eta) \tag{3}$$

Wilkins and Heller (2) observed that if the colloidal suspension was exposed to radio frequencies of 16 MHz for spheres of 1.17 μ diameter at 500 V/cm and 10 μsec pulses at a pulse repetition rate of 500 for one minute a maximal reduction in the electrophoretic mobility was found. Since only the total energy put into the system was the deciding factor in the mobility reduction (it could be achieved with pulses or CW radiation as long as the total exposure time was 0.3 sec) a conversion of this energy into a form that produced the observed phenomenon is indicated. If ice is indeed the material covering the surface, we may assume that the energy deposited in the system is used to effect a phase change in the ice, converting it to liquid water. The radius of the particle will therefore be reduced by the thickness of the ice layer, and consequently by Eq. (3) the mobility of the particle will be reduced. The maximal reduction in mobility will occur when all the ice changes phase. The maximal reduction in radius is therefore 100 Å.

Since

$$\Delta U=\tfrac{2}{3}(ne/\eta)\Delta r \tag{4}$$

and $n=5\times10^{13}$ charges/cm², $e=1.6\times10^{-19}$ coul/charge, and $\eta$, the viscosity of water is $10^{-2}$ g/cm sec or $10^{-7}$ newton sec/cm² we find

$$\Delta U=53.2\times10^{-6}(\text{cm}^2/\text{V sec})\cong0.5\times10^{-4}(\text{cm}^2/\text{V sec}) \tag{5}$$

which is a typical value for the reduction in mobility given by Wilkins and Heller (2).

The determination of the electromagnetic frequency at which this reduction of electrophoretic mobility occurs is slightly more complicated. The current density along the surface of a conducting spherical particle is higher at the points which are perpendicular to the direction of current flow. One expects the maximum heating of the shell to occur at those points, changing the sphere into a spheroid by melting the ice structure. As a result a dipole moment appears, leading to the phenomenon of pearl-chain formation which is also observed at this frequency. If the spherical shell were exposed uniformly to the electric field the rate of change of the phase boundary would be given by

$$L\rho4\pi r^2(dr/dt)=q_{\text{in}}-q_{\text{out}} \tag{6}$$

where $4\pi r^2(dr/dt)$ is the rate of volume change and $L\rho$ the latent heat of fusion, $q_{\text{in}}$ is the rate of heat generation in the spherical shell due to its conductance, $q_{\text{out}}$ is the rate of heat loss through the surrounding phase boundary. The rate of heat generation is further given by

$$q_{\text{in}} = \int_0^t v \cdot i \, dt = \int_0^t Zi^2 \, dt \qquad (7)$$

where, $v$ is the applied voltage at the surface, $i$ the current through the surface, $Z$ its impedance, and

$$q_{\text{out}} = 4\pi r^2 h_0 \Delta T \qquad (8)$$

where $h_0$ is the thermal transfer coefficient across the phase boundary and $\Delta T$ is the average difference in temperature between the shell and the surrounding medium. The exact equation is similar to two coupled second order differential equations, but its solution is not yet available.

An order of magnitude estimate of the exposure time necessary to achieve maximum reduction in mobility is possible if a uniform temperature increase of the shell is assumed. Following London and Seban (9) we find

$$t \cong L\rho\delta/\Delta T h_0 \cong 0.13 \text{ sec} \qquad (9)$$

where $\delta$ is the thickness of the spherical shell. This figure is to be compared with the 0.3 sec which Wilkins and Heller found in their experiment.

The above assumption of a spherical shell of ice whose conductivity is determined by the concentration of surface charges seems to provide an adequate explanation of the observed reduction in mobility of polystyrene latex particles. If one tries to apply the same reasoning to protein solutions, one finds again a satisfactory agreement between observed relaxation times of, for example, the bovine serum albumin solutions studied by O'Konski (10). The relaxation times at 1 °C are 1.59 and 0.28 $\mu$sec and at 25 °C are 0.74 and 0.14 $\mu$sec. These times correspond to a highly doped ice crystal with $3.9 \times 10^{19}$ defects/cm$^3$. Using the dimensions of the molecule one finds that such a defect concentration implies the existence of 4 carboxyl groups/molecule in agreement with estimates derived from the amino acid content of the molecules and a hydration layer of approximately 3 Å thickness. The corresponding hydration value is 0.378 g $H_2O$/g protein.

In the above two examples, I have attempted to show that the identification of the hydration layers of particles or proteins as an impure ice type structure provides a consistent interpretation of available data. The implications of such an interpretation have to be explored more fully.

It would seem that the commonly accepted definition of nonthermal effects has to be reevaluated to include the thermal effect of phase change. The possible effect of dehydration on macromolecules should be explored further since Bach's (11) observations of the reduction of the mobility of human $\gamma$-globulin due to exposure to radio frequency fields indicates a type of resonant phenomenon similar to that found also in polystyrene-latex sphere systems where it is ascribable to a change of phase of the hydration layer. Other macromolecules of biological importance may undergo a similar change if exposed to the correct frequency for a sufficient length of time.

One of the most important structures for the maintenance of a cellular system is the cell membrane. There is evidence that the membrane controls the flow of materials across it by means of pores consisting of hydrated protein tubes. The growth of tissues, regeneration, and signal transmission, indeed the survival of each individual cell depends on the integrity of its membrane structure.

If a phase change can occur in the water of hydration of the tubular protein structures of membranes, a profound influence on the transport properties of the membranes would be exerted. Since it is possible that transformations of the hydrated water phase of globular proteins can occur, one cannot rule out a similar phenomenon for proteins with a different symmetry, such as tubular structures. The exact frequency of the electromagnetic radiation as well as the power levels necessary to influence the hydration layers have not yet been explored; the possibility of an interaction with membrane structures cannot be ruled out at this time.

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# EFFECTS OF MICROWAVES ON OPTICAL ACTIVITY

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## INTRODUCTION

The effects of microwave irradiation on optical activity are under investigation at the Southeastern Radiological Health Laboratory with the overall objective of developing a chemical dosimeter based on changing the optical activity of a compound with microwave irradiation. The initial phase of this study was to determine if microwave irradiation would in fact produce a change in the optical activity of a compound. Van Everdingen (1) showed that starch and glycogen solutions can be altered by microwave irradiation to produce complete optical inactivity in both systems. Preliminary data from this SERHL study indicate the presence of specific optical rotation changes as a result of microwave exposure, the optical activity being reduced in proportion to the amount of microwave exposure.

A number of optically active compounds have been evaluated. It was found that the optical rotation of sucrose in a mixture of Triton N-101[2] and water could be altered. Also, the optical activity of sucrose in a mixture of glycerin and polyvinylpyrrolidone could be altered. In both cases the optical activity of sucrose was reduced in proportion to the amount of microwave irradiation. The effect of heat was compared to that of microwave exposure on each mixture and experimental data are presented.

## EXPERIMENTAL

All microwave exposures were done with a microwave oven with a frequency of 2450±50 MHz. The magnetron was pulsed at 60 Hz with pulse duration on the order of 5 msec. The oven was allowed to stabilize (or "warm up") thirty minutes prior to sample irradiation.

Samples (liquids in 50-ml pyrex volumetric flasks, solids in plastic dishes) were placed approximately in the center of the oven for each irradiation. Prior experiments determined that the central area of the oven received maximum irradiation. Solid samples were given continuous microwave irradiation, whereas liquid samples, which absorbed microwave energy more readily, were subjected to irradiation for one to one and one-half minute intervals or less to avoid excessive heat buildup. Samples were allowed to cool to room temperature between each exposure. Approximately 50 optically active compounds including several proteins, sugars, steroids, amino acids, hormones, enzymes and others were irradiated in their natural state for prolonged periods of time. Some were irradiated for as long as one hour. The minimum exposure time was 15 minutes. No changes in the optical activity of these compounds were observed.

These compounds were then solubilized prior to irradiation. Compounds that were soluble in water and/or glycerin were dissolved, Triton N-101 being added to the water solutions to adjust the viscosity. Triton N-101 is one of the alkylphenoxy polyethoxy ethanol series of surface-active agents.

Van Everdingen (1) pointed out the importance of the viscosity term in Debye's equation for relaxation times of polar particles in a viscous medium, reasoning that at a certain combination of viscosity and frequency, maximal energy absorption would occur.

The optical activity of the compounds dissolved in glycerine remained unchanged after prolonged irradiations, however, sucrose in a Triton N-101-water mixture exhibited a change in optical activity. The ratios of the three components (sucrose, water and Triton N-101) were then varied to determine the optimum proportions that would allow a maximum change in optical activity in relation to microwave exposure. A mixture consisting of 20 grams sucrose, 20 grams water, and 60 grams Triton N-101 resulted in a maximum change.

Temperature determinations were made immedi-

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[1] Now located at Southwestern Radiological Health Laboratory. P.O. Box 15027, Las Vegas, Nevada, 89114.

[2] Trade mark, Rohm and Haas Co.

ately after removal of the sample from the oven. Temperatures of the samples after a one-minute exposure ranged from 95° to 107 °C using a thermistor for temperature determinations.

To compare the effect of heat versus microwaves, samples identical to those irradiated in the oven were heated in a mineral oil bath at 125 °C for one-minute intervals which allowed the samples to reach approximately the same temperatures as reached during microwave exposure.

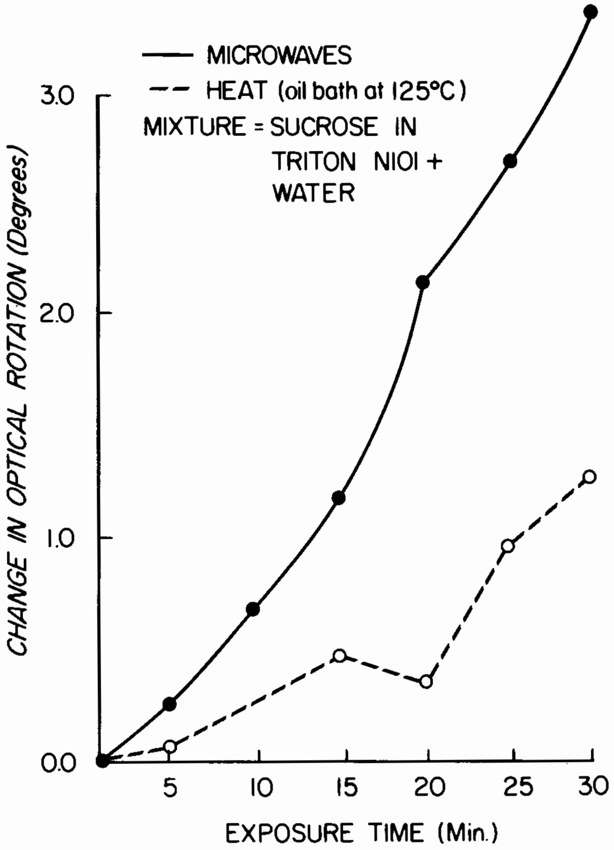

Figure 1. Changes in optical rotation as a function of heat and microwave exposure.

Figure 1 shows a comparison of sucrose-water-Triton N-101 samples heated in an oil bath versus samples exposed to microwaves. Both heat and microwaves altered the optical activity of sucrose, however, microwaves have a more pronounced effect.

Attempts to reproduce results with several lots of Triton N-101 or with similar detergents were unsuccessful. It was then decided that some impurity in the Triton N-101 was responsible for the change in optical activity. Other viscosity modifiers were tested.

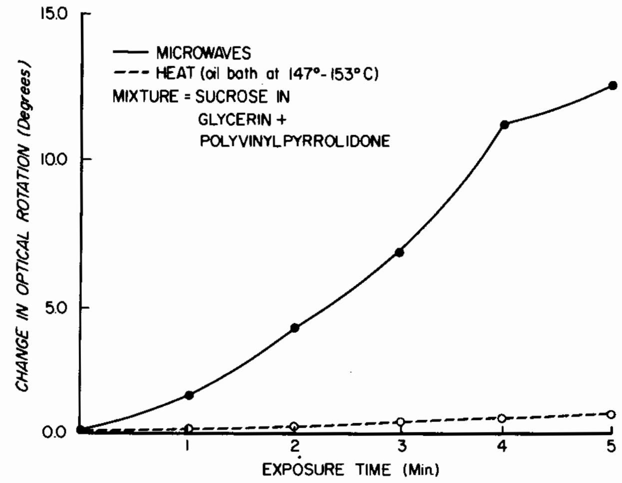

Figure 2. Effects of heat and microwave exposure of the sucrose in glycerin and polyvinylpyrrolidone mixture.

Replacement of the Triton N-101 and water with polyvinylpyrrolidone and glycerin resulted in changes in optical rotation upon microwave exposure. Pronounced changes were noted after a 30-second exposure period. The mixture consisted of 20 grams sucrose and 1 gram polyvinylpyrrolidone per 100 ml of glycerin. The pH of the mixture prior to microwave exposure was 5.4 and dropped to 4.3 after 5 minutes of irradiation. Temperatures of the samples upon removal from the oven ranged from 142–144 °C.

Samples of the same mixture were also heated in an oil bath to temperatures of 147–153 °C. Figure 2

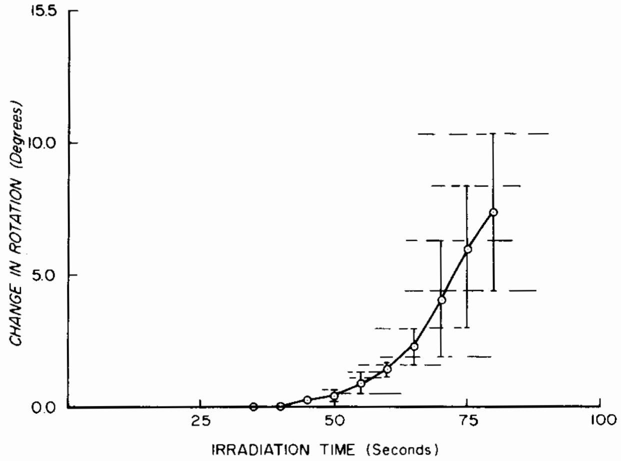

Figure 3. Reproducibility of optical rotation changes induced by microwave exposure of the sucrose in glycerin and polyvinylpyrrolidone mixture.

illustrates results of the heat versus microwave exposure on the glycerin-polyvinylpyrrolidone-sucrose mixture. Heat had very little effect on the optical activity, whereas, microwaves had a very pronounced effect. It may also be noted that the effect of microwaves on the sucrose-polyvinylpyrrolidone-glycerin was much more pronounced than that of the sucrose-detergent-water mixture.

Reproducibility of the experiments was difficult to achieve due to the variables associated with the procedure. Everything was kept as constant as possible, including the load, placement of samples in the oven, sample size and geometry. However, the power output of the oven varied appreciably.

To determine the variation of the power output, one-liter containers of water were irradiated for two-minute intervals. The variation in temperature rise of the water was used to determine the variation in power output. Overall, the power output decreased with intermittent oven usage, however, the power output would increase slightly during a period of continuous use.

A series of replicate samples of sucrose-polyvinylpyrrolidone-glycerin was irradiated for intervals ranging from 35 to 80 seconds. Ten samples were irradiated for each time interval. Results of this experiment are shown in Fig. 3. The averages of the ten samples for each time interval are plotted and show a decrease in optical rotation with increased microwave exposure. The ranges of the data are indicated by the vertical lines showing variations obtained.

The total energy absorbed from the microwave radiation field in the microwave oven by the samples used in these experiments is not known, therefore, the functional relationship between changes in optical activity and absorbed microwave energy has not been determined. A microwave radiation field of known power density will be used in future experiments to study this relationship.

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# STUDIES ON THE EFFECT OF 2450 MHz MICROWAVES ON HUMAN IMMUNOGLOBULIN *G*

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## INTRODUCTION

Changes in the paper electrophoretic pattern and in the antigenic reactivity of human gamma globulin (HGG), presumably Cohn Fraction II, have been reported for HGG solutions irradiated at specific frequencies within the 10–200 MHz range at 37.5 °C (1). Changes in the solubility of bovine gamma globulin, presumably Cohn Fraction II, were reported for irradiation at 13.1 MHz at 25 °C in a study supported by the U.S. Army (2). The simplest effect accounting for both these observations is aggregate formation. We report here a series of experiments we performed to determine if similar effects could be produced in solutions of human immunoglobulin *G* (IgG) by irradiating them at 2450 MHz.

Polymeric aggregates can be produced by heating human IgG solutions. The aggregated material increases from 0.2% at room temperature to 12.9% at 63 °C in 1% human IgG solutions heated for 10 minutes (3). However, heating may not be required for aggregate formation. Skvaril (4) discovered that the single immunoelectrophoretic line for IgG is split when IgG samples which had been stored for several months between 0–4 °C were analyzed. James, Henney, and Stanworth (5) observed a similar splitting in the immunoelectrophoretic line when IgG samples heated at 37 °C for 20 hours were analyzed. James and co-workers (5) propose that the structural changes which occur in human IgG during storage at 4 °C and at 37 °C are due to the same mechanism, namely, formation of a 10S dimer followed by proteolytic degradation which produces a 5S component. The 5S component appears after 20 hours at 37 °C at which time splitting of the immunoelectrophoretic line can be demonstrated. The presence of proteolytic enzymes in IgG preparations is supported by the work of Robert and Bochman (6). Since HGG prepared by cold ethanol fractionation (Cohn Fraction II) contains, in addition to IgG with a sedimentation value of 7, dimeric 10S and polymeric aggregates with S values between 20 and 40 (7), the IgG used in our experiments was isolated from HGG by column chromatography.

The IgG aggregates have a number of biological activities that are not demonstrable in pure preparations of native 7S IgG. Aggregated IgG binds rheumatoid factor (8), can provoke skin reactions in guinea pigs (9), and fixes complement (10).

## MATERIALS AND METHODS

### *Human Immunoglobulin*

The human IgG was isolated from HGG (Cohn Fraction II, lot 31, Pentex, Inc., Kankakee, Ill.)[1] by diethylaminoethyl (DEAE) cellulose chromatography (11). The fraction eluted with 0.0175*M* phosphate buffer, pH 6.3, was collected, concentrated with polyethylene glycol 20,000 (Fisher Scientific Co., Fairlawn, N.J.), and stored until use at −84.4 °C in plastic vials. Seven separate runs were made over a period of 5 months. The purity of the first 3 runs was determined by column chromatography and analytical ultracentrifugation. The purity of human IgG obtained from subsequent DEAE-cellulose runs was monitored by immunoelectrophoresis employing either rabbit antiserum against human gamma globulin (Cohn Fraction II) maintained at 50 °C for 30 minutes by cycling the microwave generator.

### *Microwave Irradiations*

Irradiations were performed at 2450 MHz with pulsed waves either from a microwave oven (Amana

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[1] The use of commercial products or mention of private firms in no way constitutes endorsement by the U.S. Public Health Service or its affiliates.

Radar range, Model RR-1) or from a microwave generator equipped with a standard gain horn (Model PPS-2.5AS, Varian Inc. Microwave Systems, San Carlos, California). For the oven irradiations, the IgG samples in polystyrene tubes, were suspended outside the oven in air 16 cm in front of the oven cavity. The power density was estimated to be 1350 mW/cm$^2$ at 16 cm. For irradiations with the microwave generator, the IgG or Cohn Fraction II samples in polystyrene tubes were placed in a polystyrene foam block 53 cm in front of the horn. The power density measured in air along the principle axis with a 9.1 cm dipole and power meter (model No. 413 C, Hewlett Packard Inc., Palo Alto, Calif.) was 450 mW/cm$^2$ ($\pm 10\%$) at 53 cm. Both sources were operated intermittently. Between the microwave pulses, the average temperature of the samples was read to ±0.1 °C with a nylon coated thermistor probe with a time constant of 3 seconds (Series 423, Yellow Springs Instrument Co., Inc., Yellow Springs, Ohio). The samples were stirred with the thermistor probe before recording the temperature and the probe was removed during irradiation.

### *Fractionation of HGG by Gel Filtration*

The HGG (Cohn Fraction II) was analyzed by fractionation on a 43×4.7 cm column of Sephadex G-200 (Pharmacia, Uppsala, Sweden). The human IgG was analyzed by fractionation on a 42×5 cm column of Sepharose 4B. The eluting buffer for both columns was $0.01M$ phosphate buffer pH 7.6 containing $0.15M$ NaCl. The eluate was collected in 6 ml fractions and their absorbance at 280 nm was determined with a Beckman model Du spectrophotometer. For each peak the fractions were pooled, concentrated by polyethylene glycol 20,000 and stored at −84.4 °C until use.

### *Protein Concentration*

The concentration of IgG was determined by measuring absorbance with a Cary model 15 recording spectrophotometer, taking $E_{280\ \mathrm{nm}}^{1\ \mathrm{cm}} = 1.4$ for a 1 mg/ml solution.

### *Analytical Ultracentrifugation*

The sedimentation coefficients ($S_{20,w}$) of human IgG were determined with a Spinco model E ultracentrifuge equipped with a Schlieren optical system operated at 59,800 rpm at 20 °C.

### *Preparation of the Antisera*

The antisera were prepared in rabbits against native HGG (Cohn Fraction II) or against HGG (Cohn Fraction II) maintained at 50 °C for 30 minutes by cycling the microwave generator (actual irradiation time 9 min). Equal volumes of Freund's complete adjuvant (Difco Laboratories, Detroit, Michigan) and of approximately 1.0 g % antigen solution in 0.85% NaCl were emulsified together to give a water-in-oil emulsion. Rabbits were immunized by injecting 1.0 ml emulsion intramuscularly at several sites twice per week for one month. Seven days after the last injection, the rabbits were test bled (about 10.0 ml) from a marginal ear vein, the serum was separated and the antibody titer was tested by the precipitin test (12).

### *Immunoelectrophoresis*

Immunoelectrophoretic analysis was performed by the method of Grabar and Williams (13) using $0.1M$ barbitone buffer, pH 8.2.

### *Isolation of Aggregates*

Human IgG in $0.0175M$ phosphate buffer, pH 6.3 was maintained at 50 °C for 40 minutes by cycling the microwave generator (actual irradiation time 10.5 min). It was allowed to cool to room temperature and then centrifuged at 105,000 g at 4 °C for 90 minutes using a Spinco rotor 40.3 in a Beckman Model G Ultracentrifuge. The supernatant was carefully withdrawn with a Pasteur pipette. The pellet containing the aggregate was resuspended in $0.1M$ barbitone buffer which was acidified with HCl to pH 5.0.

## RESULTS

The elution pattern of unirradiated HGG (Cohn Fraction II) on Sephadex G-200 (Fig. 1) showed significant amounts of higher molecular weight material than the 7S IgG. The 7S IgG was isolated by DEAE cellulose chromatography as described in the section on Materials and Methods. Seven separate runs were made over a period of 5 months. A composite sample of the first three runs (DEAE cellulose chromatography runs No. A, B, and C) eluted as a single peak from a column of Sepharose 4B (Fig. 4a).

Two IgG samples were irradiated with the microwave oven and their elution profiles on Sepharose

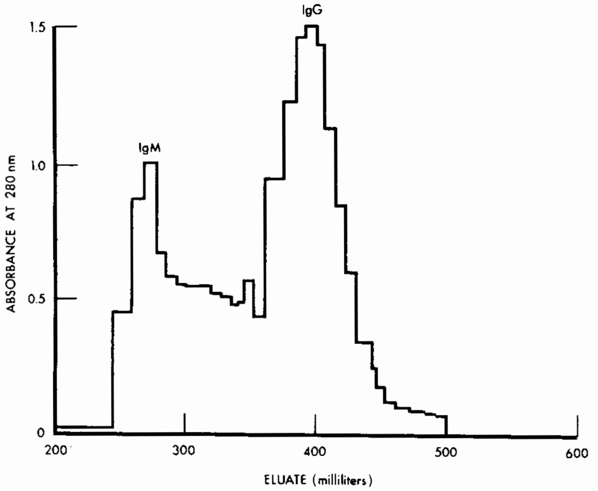

Figure 1. Fractionation of human gamma globulin (Cohn Fraction II) on Sephadex G 200. Eluting buffer: 0.01*M* phosphate pH 7.6, containing 0.15*M* NaCl. Column size: 43.0×4.7 cm.

4B columns compared with those of unirradiated IgG and with IgG which had been heated in a water bath at 50 °C for 30 minutes. Both samples were irradiated intermittently over a period of about 30 minutes for a total irradiation time of eight minutes. During irradiation one of the samples was cooled with a stream of cold nitrogen. Figure 2 shows the irradiation time and temperature profile of the sample irradiated at room temperature. With the indicated pulse duration and repetition rate, the temperature rose to 50 °C within the first 6 minutes and dropped to about 40 °C after 25 minutes. Figure 3 shows the irradiation time and temperature profile of the nitrogen cooled sample. The temperature of the cooled sample decreases to about 5 °C after 25 minutes. The elution profiles of the irradiated, unirradiated, and water bath heated

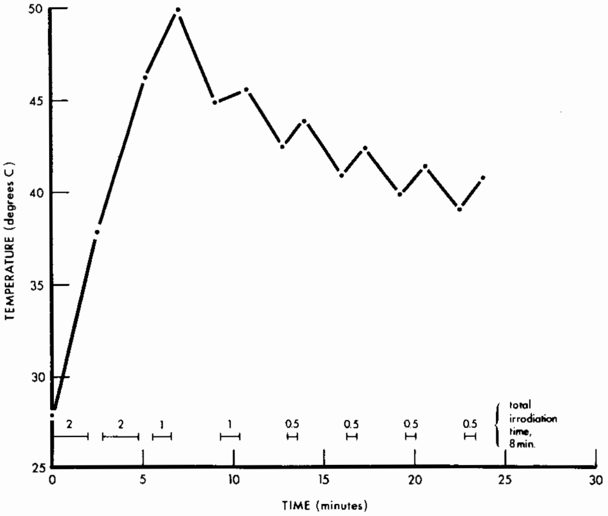

Figure 2. Temperature of microwave irradiated human IgG solution. IgG solution in polystyrene tube was suspended outside the oven in air 16 cm in front of the oven cavity. The duration of microwave pulses is indicated by the horizontal cross bars.

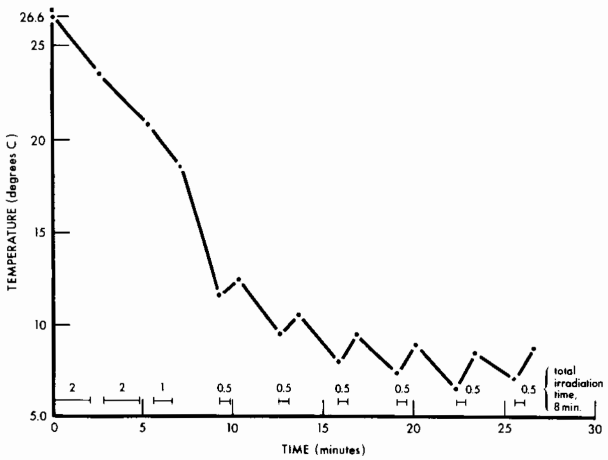

Figure 3. Temperature of microwave irradiated human IgG solution cooled with nitrogen. Irradiation conditions were as described for Fig. 2. The duration of microwave pulses is indicated by the horizontal cross bars.

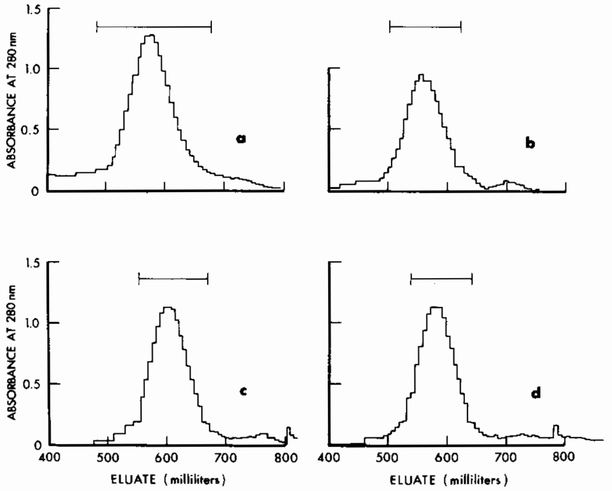

Figure 4. Fractionation of human IgG on Sepharose 4B: (a) No irradiation. (b) Irradiated as described in Fig. 2. (c) Irradiated as described in Fig. 3. (d) Heated for 30 min in 50 °C water bath. All samples were composites from DEAE-cellulose chromatography run No. A, No. B, and No. C. Concentration of each sample was 20.0 mg/ml in 0.0175*M* phosphate buffer pH 6.3. Eluting Buffer: 0.01*M* phosphate, pH 7.6, containing 0.15*M* NaCl. Column size: 42.0×5.0 cm. The sedimentation coefficients for the fractions under the cross bars are given in Table 1 and their ultracentrifugation patterns are given in Fig. 5.

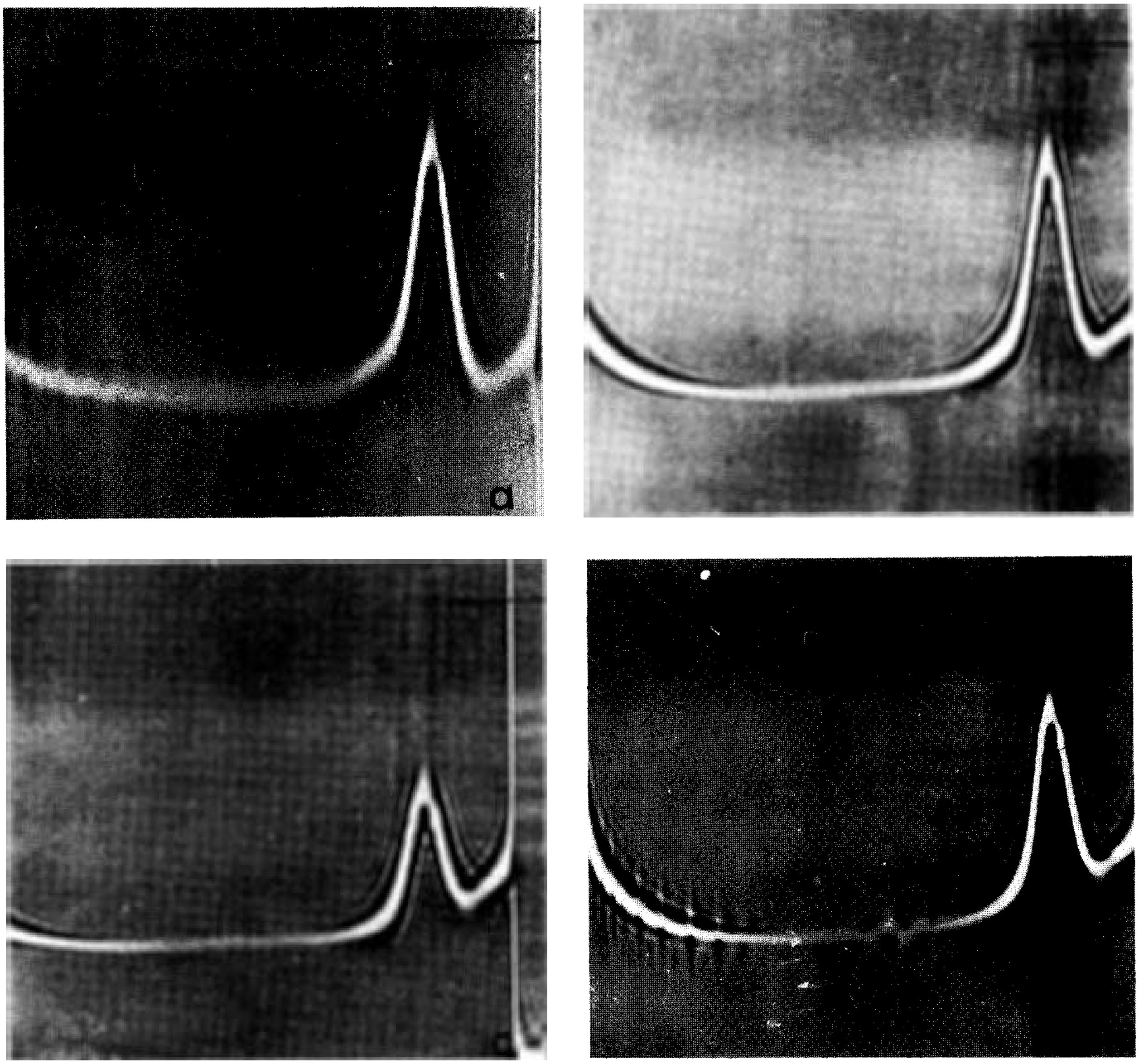

Figure 5. Analytical ultracentrifugation patterns of Sepharose 4B fractions shown in Fig. 4. Speed: 59,800 rpm. Temperature: 20 °C. Solvent: 0.01*M* phosphate buffer pH 7.6 containing 0.15 NaCl. Photographs shown are those that are taken at 16 minutes after attaining a speed of 59,800 rpm.

samples are shown in Fig. 4. Because of the small variability in the position of the eluate peaks, *S* values for the material in the main chromatographic peaks were determined. The results are presented in Table 1. The sedimentation patterns are shown in Fig. 5. The faster sedimenting shoulder, probably 10S, seen in the original material (Fig. 5a) is either absent or its concentration is too low to be detected in the other patterns. The ultracentrifuge pattern of the IgG sample heated in the water bath shows a small amount of aggregated material sedimenting ahead of the 7S component (Fig. 5d).

Samples of IgG purified by DEAE cellulose chromatography (run No. D) were irradiated with the microwave oven for 8.5, 7, and 5.5 minutes fractionated respectively over 30, 20, and 10 minute intervals. The samples were irradiated with the same pulse duration and distribution as was used in irradiating the nitrogen cooled sample (Fig. 3) except that the exposures were terminated at the

TABLE 1

*Sedimentation coefficients for human immunoglobulin G*

| Treatment | Protein conc. (mg/ml) | $S_{20,w} \times 10^{13}$ |
|---|---|---|
| a* Untreated | 4.2 | 6.3 |
| b Irradiated at 2450 MHz with rise in temperature | 3.9 | 6.1 |
| c Irradiated at 2450 MHz with no rise in temperature | 6.5 | 6.0 |
| d Heated in water bath (50 °C, 30 min) | 5.9 | 5.7 |

* Letters correspond to samples in Fig. 4.

given elapsed times. The temperature profiles of the samples did not differ significantly from those shown for the oven irradiated sample (Fig. 2) for equal time periods. The irradiated samples were compared to unirradiated material by immunoelectrophoresis using rabbit anti-HGG (Cohn Fraction II) sera. The immunoelectrophoretic pattern is shown in Fig. 6. In addition to the strong precipitin line given by IgG there was an additional line in the unirradiated material which indicates the presence of some impurity. Additional faint lines were noted in the irradiated material.

Samples of IgG purified by DEAE cellulose chromatography (run No. E) were heated in a water bath for 30 minutes at temperatures of 40, 50, and 60 °C respectively and compared to unheated IgG by immunoelectrophoresis. The immunoelectrophoretic pattern is shown in Fig. 7. The untreated sample from this DEAE cellulose run shows the splitting that is correlated with the presence of lower molecular weight material but appears to be free of the impurity seen in the earlier preparation (see Fig. 6). Additional precipitin lines are not seen in the patterns of the heated material.

Four human IgG samples purified by DEAE cellulose chromatography (run No. F) were irradiated with a microwave generator for 7.0, 8.0, 9.0, and 10.5 minutes fractionated respectively over 10.0, 20.0, 30.0, and 40.0 minute intervals. The temperature profile of the IgG sample irradiated for 10.5 minutes fractionated over a time interval of 40.0 minutes is shown in Fig. 8. The irradiations

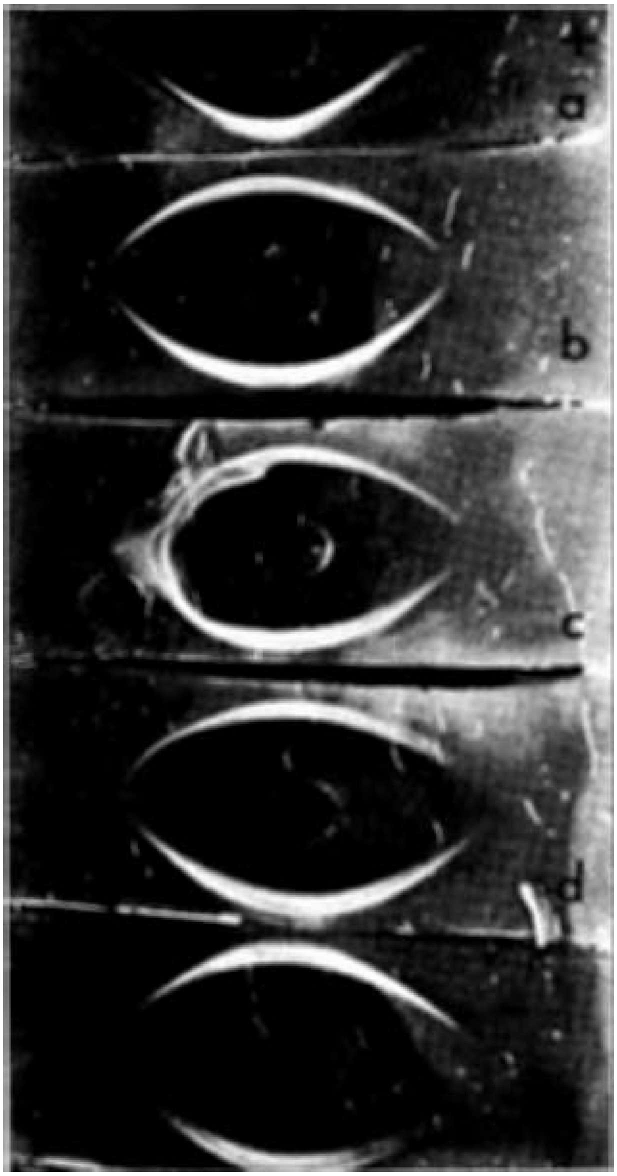

Figure 6. Immunoelectrophoretic patterns of microwave irradiated (2450 MHz) IgG. (a) and (b), no irradiation, (c) 8.5 minutes irradiation fractionated over 30 minutes, (d) 7 minutes irradiation fractionated over 20 minutes, (e) 5.5 minutes irradiation fractionated over 10 minutes. The irradiation conditions are the same as described in Fig. 2. The source was pulsed as shown in Fig. 3 except that the exposures were terminated at the given elapsed times. The temperature profiles were similar to those given in Fig. 2 over equal time intervals. All samples were from DEAE cellulose chromatography run No. C. The concentration of the samples was about 20 mg/ml in $0.0175M$ phosphate buffer pH 6.3. Antisera: Rabbit anti-Cohn Fraction II.

of 7.0, 8.0, and 9.0 minutes were performed with the same pulse duration and distribution as was used for irradiating the 10.5 minute sample (see Fig. 8) except that the exposures were terminated at the given elapsed times of 10.0, 20.0, and 30.0 minutes, respectively. The temperature profiles of these samples did not differ significantly from that shown in Fig. 8 for equal time periods. The immunoelectrophoretic patterns of the irradiated and the unirradiated samples using rabbit antiserum against irradiated HGG (Cohn Fraction II) are shown in Fig. 9. Only one precipitin line, migrating toward the cathode, is seen for the irradiated and unirradiated samples. The splitting of the single IgG line did not occur in these samples.

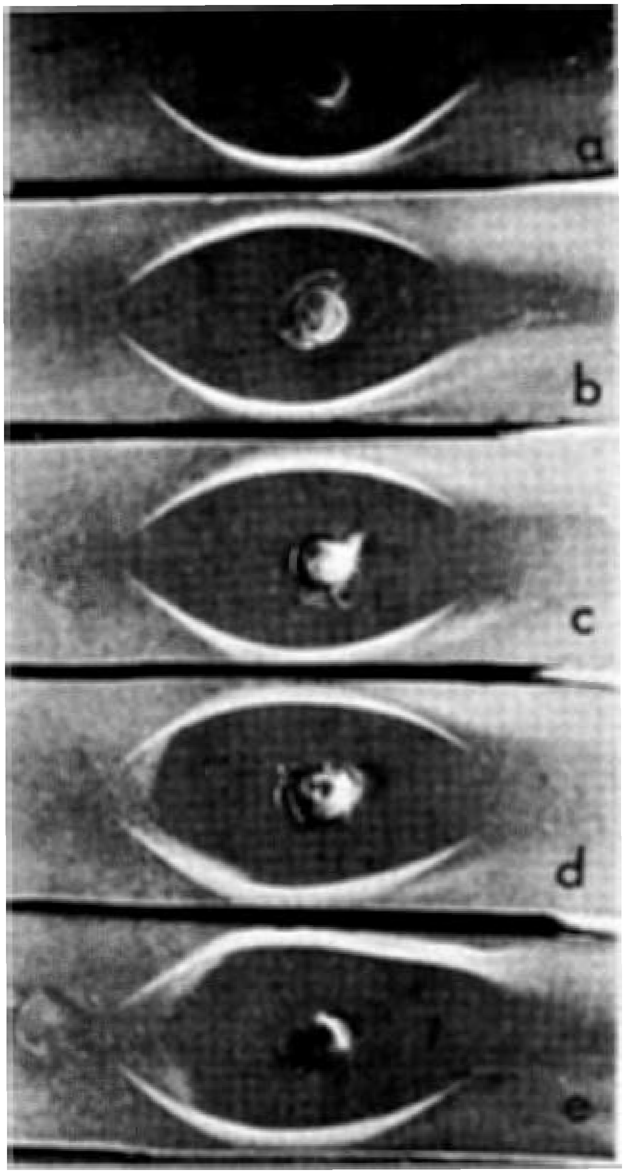

Figure 7. Immunoelectrophoretic patterns of water bath heated human IgG. (a) and (b) no irradiation. (c) heated at 60 °C for 30 minutes. (d) heated at 50 °C for 30 minutes. (e) heated at 40 °C for 30 minutes. All samples were from DEAE cellulose chromatography run No. E. The concentration of the samples was 20.0 mg/ml in 0.0175*M* phosphate buffer pH 6.3. Antisera: Rabbit anti-Cohn Fraction II.

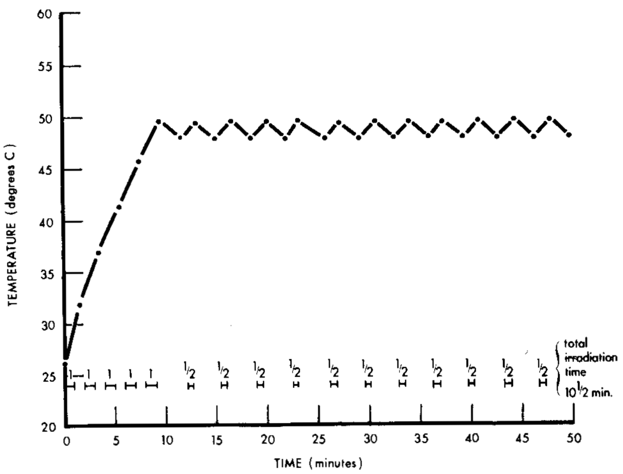

Figure 8. The temperature of microwave irradiated human IgG solution. The IgG samples in polystyrene tubes were placed in a polystyrene foam block 53.0 cm in front of the horn of the microwave generator. The duration of microwave pulses is indicated by the horizontal cross bars.

A sample of human IgG (DEAE cellulose chromatography run No. G) was irradiated with a microwave generator for 10.5 minutes fractionated over 40.0 minutes. The pulse duration and distribution were the same and the temperature profile essentially the same as those shown in Fig. 8. The sample was fractionated as described under "Isolation of Aggregates" in the section on Materials and Methods and compared immunoelectrophoretically to unfractionated irradiated and unirradiated IgG using rabbit antiserum against HGG (Cohn Fraction II). A single precipitin line, migrating toward the cathode, is seen for both the unfractionated irradiated and unirradiated IgG samples. The splitting of the IgG line did not occur in these samples. The electrophoretic mobility of the supernatant separated from the irradiated IgG is similar to the mobility of unirradiated IgG and the mobility of the aggregate is less than the mobility of the unirradiated IgG. The immunoelectrophoretic patterns of these samples are shown in Fig. 10.

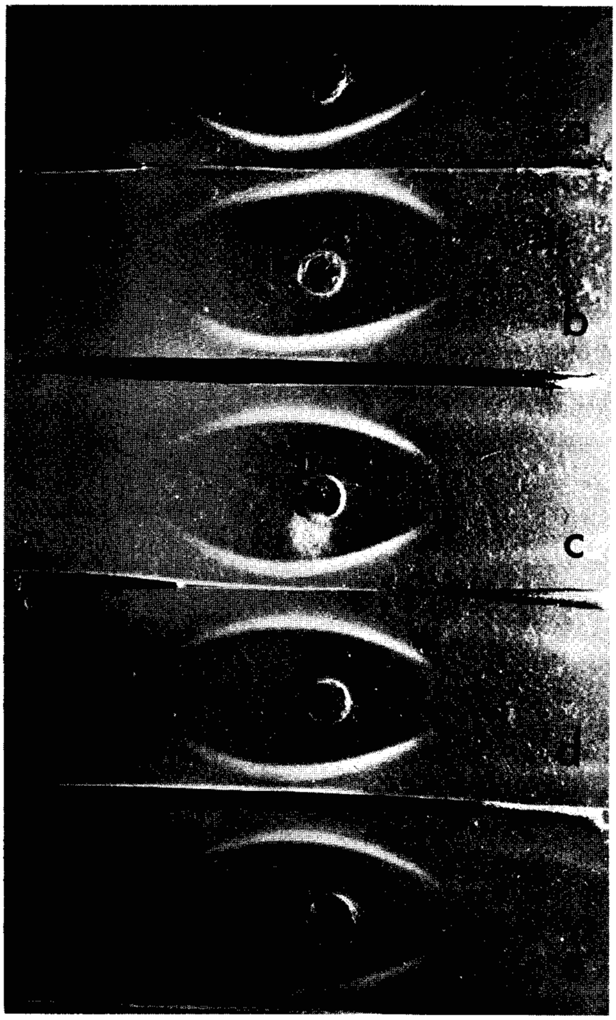

Figure 9. Immunoelectrophoretic pattern of microwave irradiated human IgG. (a) No irradiation. (b) 7.0 minutes irradiation fractionated over 10 minutes. (c) 8.0 minutes irradiation fractionated over 20 minutes. (d) 9.0 minutes irradiation fractionated over 30 minutes. (e) 10.5 minutes irradiation fractionated over 40 minutes. The microwave source was pulsed as shown in Fig. 8 and the temperature profiles were similar to that given in Fig. 8 over equal time intervals. All samples were from DEAE cellulose chromatography run No. F. The concentration of the sample was 20.0 mg/ml in 0.0175*M* phosphate buffer pH 6.3. Antisera: Rabbit anti-irradiated Cohn Fraction II.

## DISCUSSION

The results of this study indicate that there is no qualitative difference between the effects observed when IgG is heated either with microwaves or with a water bath. Microwave heating of IgG solutions causes the formation of aggregates.[2] Solutions of IgG ($c = 20$ mg/ml) which are initially clear become turbid after being heated at 50 °C for 40 minutes with microwaves. Initially clear IgG solutions also become turbid when heated in a water bath. The aggregates are insoluble, i.e., a precipitin line for

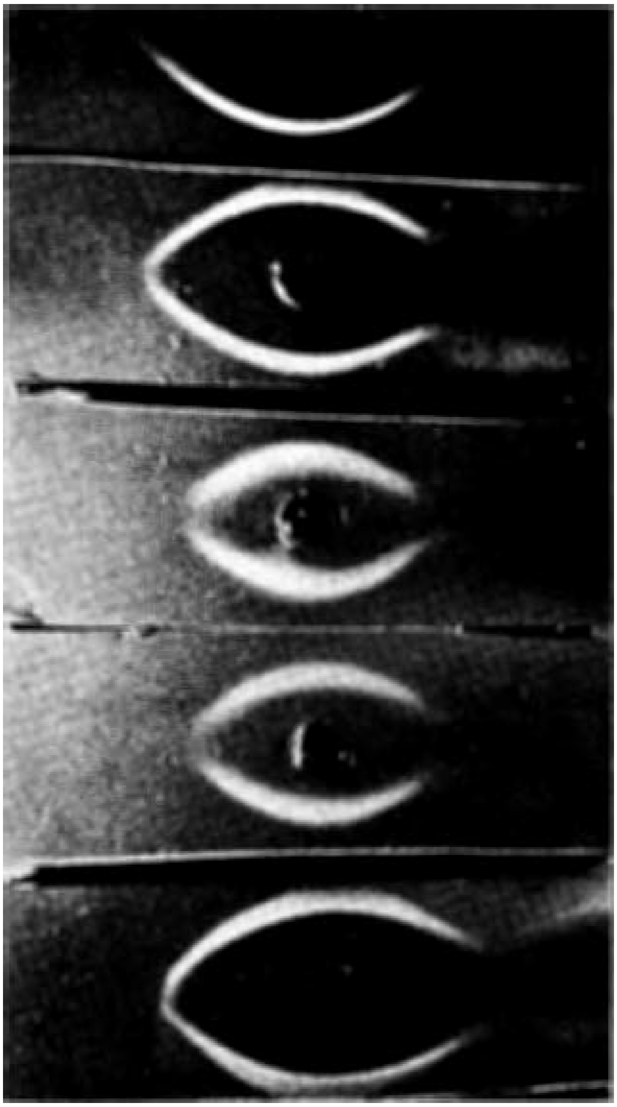

Figure 10. Immunoelectrophoretic pattern of microwave irradiated human IgG. (a) No irradiation. (b) 10.5 minutes irradiation fractionated over 40 minutes. (c) Aggregate. (d) Aggregate. (e) Supernatant after aggregate removal. The microwave source was pulsed as shown in Fig. 8 and the temperature profiles were the same as that given in Fig. 8 over equal time intervals. All samples were from DEAE-cellulose chromatography run No. G. The concentration of the sample was 20.0 mg/ml in 0.0175*M* phosphate buffer pH 6.3. Antiserum: Rabbit anti-Cohn Fraction II. Aggregate was isolated by centrifuging the irradiated IgG at 105,000 g at 4 °C for 90 minutes in Spinco rotor 40.3.

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[2] Restall et al. (14) have suggested the use of 2450 MHz microwaves to warm human blood from its storage temperature of 4–6 °C to 35 °C.

the aggregated material is seen only when the aggregates are isolated by ultracentrifugation, redissolved, in acid and then subjected to immunoelectrophoresis. Insoluble aggregates are not eluted from columns of Sepharose 4B. Therefore the similarity of the elution profiles and the $S_{20,w}$ values suggests that no gross changes occur in the structure of the soluble fraction. The small amount of material, probably 10S, seen in the ultracentrifuge pattern of untreated DEAE cellulose purified IgG and the small amount of faster sedimenting material seen in the ultracentrifuge pattern of the water bath heated material were not resolved on the respective Sepharose 4B chromatograms.

Chromatographically homogeneous preparations of IgG may still contain small amounts of aggregates, presumably 10S dimer as is indicated by the shoulder in the ultracentrifugal pattern of IgG eluted from a column of DEAE cellulose (see Fig. 5a). Impurities which give additional immunoelectrophoretic lines may also be present (see Fig. 6a). Out of the three DEAE cellulose purified IgG preparations analyzed by immunoelectrophoresis with rabbit antisera against HGG, two samples showed the splitting of the immunoelectrophoretic line that is concomitant with the appearance of lower molecular weight material (5S) while the third sample did not. Thus the very faint additional precipitin lines seen in the immunoelectrophoretic patterns of IgG irradiated with the oven may be due to impurities. No additional lines were observed in a subsequent sample irradiated with the microwave generator where splitting did not occur in the pattern of the unirradiated material. The heating curves of these two samples were somewhat similar (compare Figs. 2 and 8) though the microwave exposure probably differed by a factor of three (about 1350 mW/cm$^2$ vs. 450 mW/cm$^2$).

*Acknowledgment*

The authors wish to express their thanks to Mr. Richard A. Tell, Mrs. Mary K. Howes, and Mr. Thomas P. Abbott, Bureau of Radiological Health and Mr. Robert I. McCleskey, Laboratory of Immunology and Infectious Diseases, National Institutes of Health, for their excellent technical assistance. We are indebted to Dr. Ralph A. Reisfeld, Laboratory of Immunology, National Institutes of Health and to Dr. George N. Catravas, Armed Forces Radiobiology Research Institute, for the use of their analytical model E ultracentrifuges and to Dr. Moris L. Shore, Bureau of Radiological Health, for his encouragement throughout the work.

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# MOLECULAR MECHANISMS FOR MICROWAVE ABSORPTION IN BIOLOGICAL SYSTEMS

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## INTRODUCTION

Recent advances in the elucidation of the structure of molecules of biological interest, as well as the continuing refinement of their description in terms of quantum-mechanical models, invite the reexamination of experiments which suggest the existence of specific biological effects arising from exposure to electromagnetic radiation. The present treatment is a heuristic attempt to categorize the salient features of the diverse mechanisms of interaction which may be predicted on the basis of such models.

## THE UNPERTURBED SYSTEM

Consider the following schematic model of a biological system, whose interaction with electromagnetic radiation we wish to explore. The system consists of a complex mixture of small molecules, primarily $H_2O$, and various types of biopolymers, whose structure may be defined at the primary-secondary and tertiary levels, for the purpose of this analysis. We differentiate between a system of water molecules essentially associated with each other, mono-$H_2O$, and the system forming a sheath about the helical portions of the biopolymer, poly-$H_2O$; these relationships are depicted schematically in Fig. 1. As an example of the molecular structure in one layer of associated base-pairs within the helical structure of a biopolymer, consider the structure of the A–T and G–C base-pairs in DNA, Fig. 2.

The degrees of freedom of motion in the system just defined are myriad; our interest in the subsequent discussion will be which of these are related to absorption of r. f. and microwave electromagnetic radiation, and, specifically, which of the latter may be considered to lead to effects of biological importance. The specific descriptions of these motions are deferred to that discussion.

In the absence of external electromagnetic fields, the (unperturbed) system is nevertheless under the influence of thermal perturbations. It is of interest to assess this effect, which exists as a background to any external perturbations. Although the total contribution to the thermal energy of translational, rotational and vibrational degrees of freedom is of the order of $kT$ (where $k$ is the Boltzmann constant and $T$ the absolute temperature), the distribution of thermal energy in the limit, $h\nu \ll kT$, appropriate to frequencies $<285$ cm$^{-1}$ at 300 °K, falls off as $\lambda^4$, where $\lambda$ is the wavelength. In fact, at microwave frequencies, thermal or Johnson noise goes as $kT/(\delta\nu)$, where $\delta\nu$ is the frequency interval being considered. For $\delta\nu = 1$ MHz, $kT/(\delta\nu) = 5 \times 10^{-14}$ watt (MHz)$^{-1}$, a power level far below any experimentally useful microwave source. Furthermore, owing to the low frequencies relative to electronic transitions—involved in r. f. and microwave problems, the probability of spontaneous emission, $A_{mn} = B_{mn}h\nu^3/c^2$ (where $B_{mn}$ is the probability of photon-induced absorption or emission, $h$ is the Planck constant, and $c$ is the velocity of light), is very small $\sim 10^{-7}B_{mn}$. The primary processes, of any magnitude, of importance in this region of the electromagnetic spectrum are therefore photon-induced absorption and emission and collision-induced absorption and emission. In fact, these two processes compete in the dense gas and in the liquid state to produce relaxation-type phenomena for all processes having natural frequencies below the far-infrared. Photon-induced rotational transitions are proportional to terms $[\mu_0 \langle m/f(\beta)/n \rangle]^2$, where $\mu_0$ is the permanent dipole moment of the molecule, $\langle m/$ and $/n\rangle$ are rotational wavefunctions for the states $m$ and $n$, and $f(\beta)$ is a function of the angles between the molecular axis and the electromagnetic field axis; collision-induced rotational transitions for the case of a system of identical polar molecules go like $[\mu_0^2/R_0^3 \langle m/f'(\beta)/n \rangle]^2$, where $R_0$ is the distance of closest approach and $f'(\beta)$ is an angular function of the same order of magnitude as $f(\beta)$ above. Numerical evaluation of these terms leads to the conclusion that the two effects have the same order of magnitude in the liquid state; this is attested to by the fact that the rotational fine-structure of vibrational transitions is erased by collisional perturbations in the liquid. As a result, the pure rotational absorption spectrum in the dilute gas becomes pressure-broadened in the dense gas and is converted into a relaxation spectrum in the liquid phase. Whereas in the gas-phase collisions are sudden, with an interaction time much less than the period of rotational transitions, so that the system can be treated within the framework of the sudden-perturbation approximation of quantum-mechanics (1), in the liquid these sudden fluctuations are immersed in an ambient potential due to the average potential energy of the surrounding molecules.

In the limit of zero electric-field strength, the unperturbed system remaining essentially intact, we may describe its interaction with the field by means of a complex dielectric constant: $\epsilon^* = \epsilon' - i\epsilon''$, $\epsilon'$ relating to the dispersive and $\epsilon''$ to the absorptive part of the interaction. In the liquid, $\epsilon'(\nu)$ undergoes a relaxation and $\epsilon''(\nu)$ exhibits a broad maximum around the frequency corresponding to the relaxation time of the phenomenon being examined. The function $\epsilon^*(\nu)$ provides fundamental information on the interaction of the system with radiation; however, it may be difficult to define adequately processes $i$ such that $\epsilon^*(\nu) = \sum_i \epsilon_i^*(\nu)$, a procedure that is requisite in the treatment of mixtures and/or systems with more than one mechanism of interaction with the external field—as in the present case.

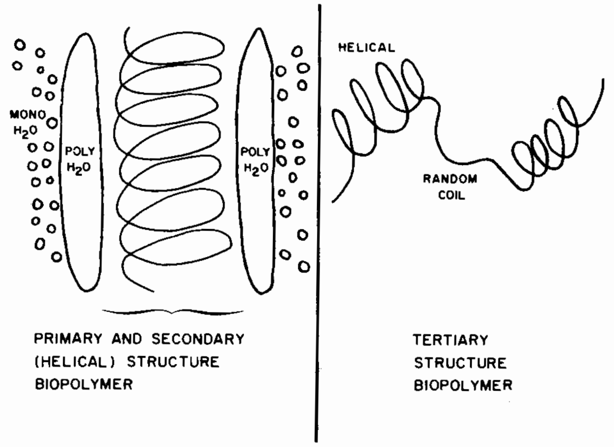

Figure 1. Schematic representation of protein structures and the associated mono- and poly-$H_2O$.

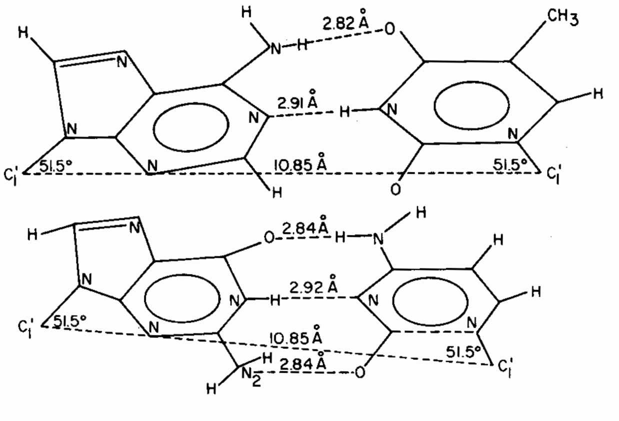

Figure 2. Nucleotide base pairing involving hydrogen bonding within the helical structure of DNA.

## MECHANISMS OF INTERACTION WITH RADIATION

1. The preponderant part of the microwave absorption of biological systems, i.e. corresponding to a maximum value of $\int \epsilon_i''(\nu)\, d\nu$, is the rotational relaxation of mono-$H_2O$, which accounts for 75 percent of cellular material by weight. Although the detailed mechanism of dielectric relaxation in mono-$H_2O$ is patently very complex (2), the much-studied function $\epsilon''(\nu) = f[\epsilon'(\nu)]$ for this system exhibits a form which closely resembles that predicted for a process with a single relaxation time. The large value of $\epsilon_{max}''$ and the wide frequency distribution, characteristic of relaxation phenomena, makes the mono-$H_2O$ in biological systems a very effective broadband attenuator for microwave radiation. While the rotational excitation of cell mono-$H_2O$, which may be converted into translational and vibrational excitation by collisions, leads to an increase in the statistical temperature of the cell, no specific biological effects are expected from this mechanism. Only at reasonably large microwave powers will rotational relaxation of mono-$H_2O$ lead to irreversible alterations in the biological structure, owing to essentially heating effects.

2. Another mechanism as a consequence of which no specific biological effects are expected is the overall rotational relaxation of biopolymer molecules. For this type of system, if the proper components of the overall dipole moment in the three-dimensional molecule-fixed axes are chosen, the

Debye theory of dielectric relaxation should be most appropriate: the rotation of a large mass-distribution against a fine-grained (quasi-hydrodynamic) medium. However, it must be pointed out that this formulation suffers from the fact that it may be in conflict with relaxation of $\epsilon'(\nu)$ associated with the migration of small ions to and from the macromolecules (3). The latter effect makes the definition of the dipole moment components, $\mu_s$ ($s=x$, $y$, $z$), of the macromolecule dubious; nonetheless, no direct biological effects are envisioned for this type of relaxation mechanism.

3. Segmental rotations of random-coil sections of biopolymers must be considered as a superposition of many relaxation-type processes, with a complicated distribution of relaxation times. Results on analogous systems (alkyl halides and long-chain alcohols) (4) have been analyzed with a variety of semi-empirical distribution functions for $\epsilon''(\nu)$, for the cases in which measurements of $\epsilon''(\nu)$ are available for a sufficiently wide range of frequencies $\nu$. It is clear that sufficiently large field strengths of r. f. and/or microwave radiation will lead, for this mechanism, to a deviation of the system from statistical equilibrium relevant to unperturbed conditions, in the sense that fluctuations from the equilibrium distribution of tertiary structures are expected as a result of the interaction. Presumably, if deviations from equilibrium become sufficiently large, interaction due to radiation may interfere with metabolic or replicative processes. The frequency distribution of this mechanism is expected to be rather broad, owing to the large spread of relaxation times associated with specific segmental rotations.

4. Internal motions within the framework of the biopolymers must be considered next, especially within the context of the following remarks. Although collisional interactions in a gas or a liquid are chaotic, the internal (primary and secondary) structure imposed upon biopolymers by stabilization of electronic states (through H-bonding and the strong van der Waals interactions between the highly polarizable layers of base-pairs within the helix) is effectively shielded from collisional perturbation by translational motion. However, electromagnetic radiation, although its intensity is modified through the internal-field effect, can penetrate into the secondary structure of biopolymers and potentially cause transitions which may alter this structure. Such a process may have as an effect the cumulative destruction of the substrate structure requisite for biochemical reactions; ultimately, this, as mechanism 3 above, may lead to the disruption of the (oscillatory) replicative and metabolic cycles in the cell.

One may differentiate between several possible internal motions in biopolymers, induced by electromagnetic radiation in the r. f. and microwave spectrum:

(a) terminal group rotation [—OH, —$NH_2$, etc.]
(b) inversion [—$NH_2$] and ring deformation [nonplanar ring systems]
(c) proton tunneling in H-bonded systems

Considerable evidence (4) exists concerning the existence of terminal group rotation in liquid dielectrics; these processes are invariably associated with a short relaxation time, and hence will be initiated primarily by high-frequency microwave radiation. To the extent to which group rotation within the structure of biopolymers is hindered by participation of the group (such as —$NH_2$) in H-bonding, it is difficult to estimate the relaxation time for such a process.

One of the best characterized molecular phenomena in microwave spectroscopy is the inversion transition in $NH_3$ (5); the vibrational levels of this nonplanar molecule are split by the double-minimum potential into doublets, and the $a \leftrightarrow s$ transition in the ground vibrational state occurs at $\sim 1$ $cm^{-1}$; inversion transitions and ring deformations (ring-puckering, etc.) have been observed in the millimeter and far-infrared regions of the spectrum (4). It is expected that similar transitions exist in biopolymers.

A significant portion of the stability of biopolymers is due to the existence of H-bonds connecting the pairs of associated bases in the helical- and double-helical structure of biopolymers. Considerable effort has recently gone into the elucidation of the electronic structure of H-bonded systems; in particular, one may inquire concerning the potential energy surface, provided by the electronic motion plus the nuclear repulsion, for rotational and vibrational motion of the proton. The results of such an inquiry depend, in their details, upon the sophistication of the quantum-mechanical description for the electronic states employed, but have provided, in every case (6), evidence for the existence of a double-minimum for proton motion in H-bonded systems. The results of such a calculation are depicted in Fig. 3, for the N—H···N bond of the C–G pair in a biopolymer (7). The Morse-type anharmonic-oscillator curve for the vibrational displacement of the proton in the N—H bond (dotted line in the figure) is considerably modified by the interaction of the H with the nonbonded N via a hydrogen bond; in fact, the system results in an asymmetrical double-minimum potential. The vibrational states of the N—H and the N—H···N system have been entered into Fig. 3; above the barrier, the energy levels for the systems in the two wells eventually must coalesce, but detailed information is not available. Because of the considerably higher barrier in the N—H···N hydrogen-bonded system, as compared to the $NH_3$ inversion problem, the splittings in the former situation are considerably smaller. Employing the methods of a square-well potential (asymmetric) with the general features of the N—H···N double-minimum well as discussed above, one arrives at an inversion frequency of $10^5$ $sec^{-1}$, in the r. f. region, as compared to the $NH_3$ frequency $10^{10}$ $sec^{-1}$. The extent to which proton tunneling, induced by r. f. radiation, alters the equilibrium of tautomers will be reflected in specific biological effects since proton exchange in the bases of a biopolymer alters its replication characteristics.

5. A further expected mechanism for absorption of electromagnetic radiation is the quasi-rotational or librational motion of the (highly structured) poly-$H_2O$ sheath around the biopolymer. Since the structure of poly-$H_2O$ is still being debated, experiments of the microwave absorption of poly-$H_2O$ are indicated. Energy absorption by the quasi-lattice of the poly-$H_2O$ surrounding the primary and secondary structures of biopolymers may be important in the labilization of those structures.

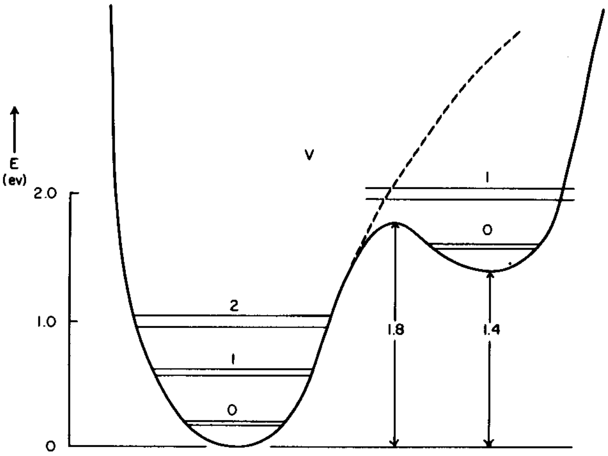

Figure 3. Potential energy curve for the N—H···N bond of the C–G pair in a biopolymer.

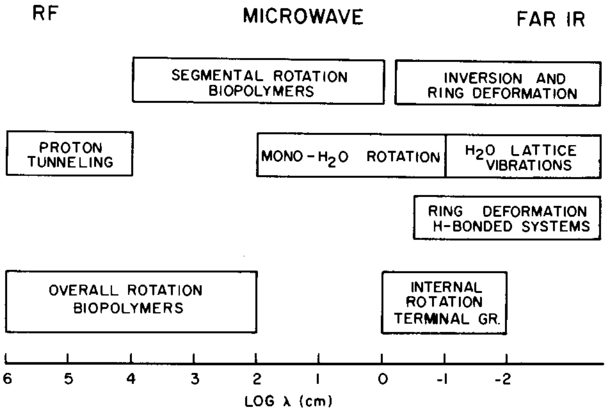

Figure 4. Summary of the expected frequency domains of various types of r. f. or microwave-induced interactions in biopolymers.

One concludes that radiative effects in the r. f. and microwave spectrum of biological systems may involve, in the case of specific biological consequences whose emergence may be a cumulative effect of long-term exposure at low power levels, segmental rotational relaxation of biopolymer sections, internal motions in biopolymers, and librational motion of the poly-$H_2O$ sheath surrounding the primary and secondary structures of biopolymers. Figure 4 summarizes the expected frequency domains of the interaction mechanisms discussed above.

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# CELLULAR EFFECTS OF MICROWAVE RADIATION[1]

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## BIOLOGICAL STUDIES

Extensive experiments at the New England Institute since 1958 have demonstrated previously unsuspected but highly significant "nonthermal" biological effects of radio frequency fields (1–6). We have shown that such fields:

(1) orient free-swimming protozoans (highly frequency-specific);
(2) inhibit cell division temporarily in cells grown *in vitro*;
(3) induce genetic changes (mutations and chromosome abnormalities in living cells, both plant and animal, including human);
(4) induce crossing over in male germ cells of Drosophila; and
(5) stimulate breaking of dormancy in gladiolus bulbs.

Since heat from such sources is a function of average energy input, we undertook experiments using small, intense pulses of radio frequency energy. Sufficient intervals between pulses made the overall rise in temperature insignificant, substantially ruling out the effect of heat.

Figure 1. Multiple chromosome bridges at anaphase in a dividing garlic cell treated with radio frequency at 21 MHz.

In experiments with colloidal particles, bacteria, and protozoa (1), remarkable events were seen under the microscope, not related to or accompanied by production of heat. For instance, at certain specific frequencies (5 to 7 MHz) motile protozoa could be constrained to migrate solely parallel to the electrical component of the radio frequency field. At other frequencies (27 to 30 MHz), they were constrained to swim perpendicular to the initial orientation.

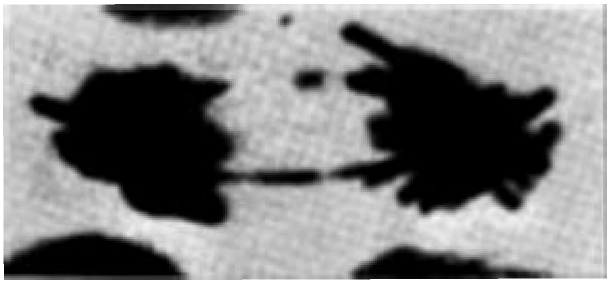

Figure 2. Another garlic cell showing anaphase chromosome bridging and chromosome fragments.

Even more intriguing was the effect of radio frequency on intracellular organelles, where similar orientation to specific frequencies occurred (1). It was obvious that, if r. f. could interact on this level, it might play a significant role in mitosis with consequent implications of importance in genetics and in biology and medicine. In experiments using garlic root tips (2, 3, 5), a great variety of chromosome aberrations occurred,[2] including bridging, fragmentation, micronuclei, etc. Figure 1 shows multiple chromosome bridges at anaphase in a dividing garlic cell; Fig. 2 shows another bridge

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[1] This work has been supported in part by the Office of Naval Research (Contract No. NR 101-756) and by the John A. Hartford Foundation, Inc.

[2] The conditions of treatment covered a wide range: frequencies from 5 to 40 MHz, pulse duration from 15 to 30 microseconds, repetition rates from 500 to 1000 per second, and voltages from 250 to 6000 peak-to-peak per centimeter. The most effective frequency was 21 MHz.

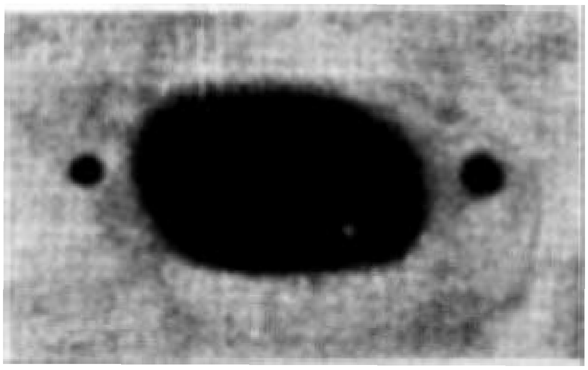

Figure 3. Garlic cell with 2 micronuclei, one on each side of the nucleus.

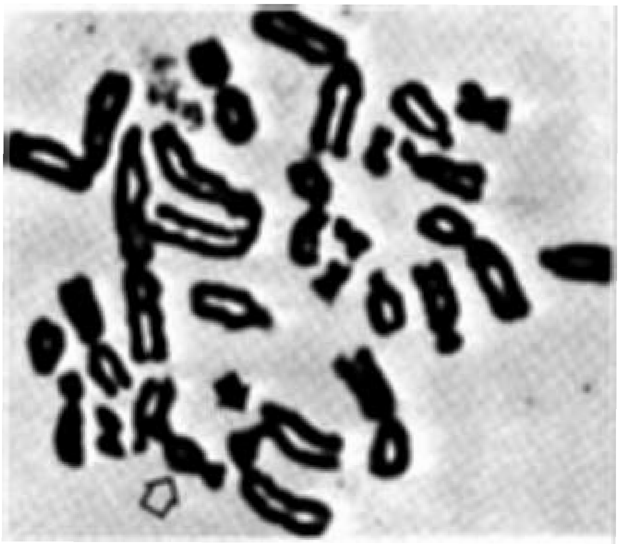

Figure 6. A Chinese hamster cell treated in tissue culture with radio frequency showing a dicentric chromosome (hollow arrow) and a chromatid break (solid arrow) lying adjacent to each other.

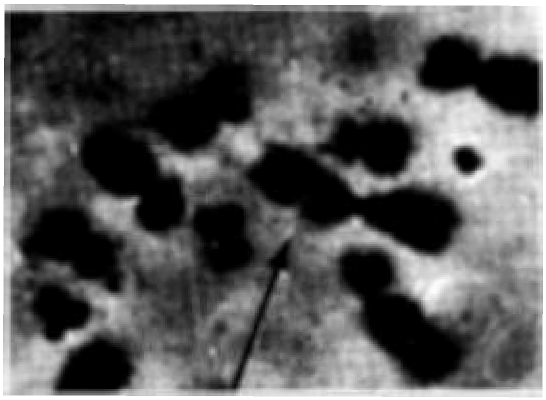

Figure 4. Cultured human lymphocyte showing a chromatid break following radio frequency treatment at 21 MHz.

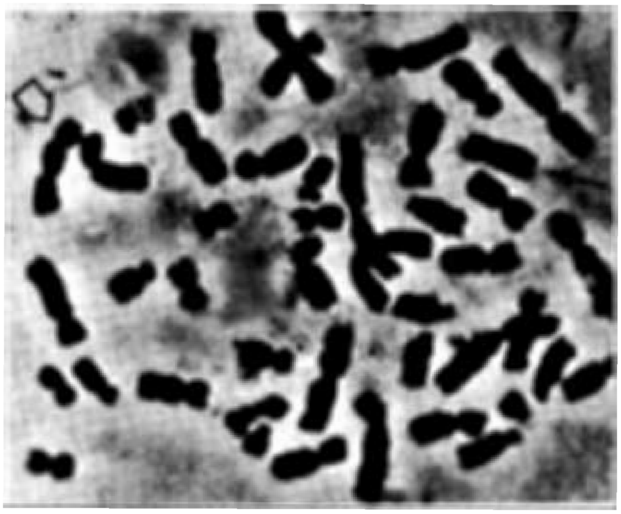

Figure 5. Another human lymphocyte after radio frequency treatment showing both a dicentric chromosome (hollow arrow) and an acentric fragment (solid arrow).

Figure 7. A Chinese hamster cell in tissue culture following treatment with radio frequency. The cell contains 23 chromosomes instead of the normal number of 22, and one is a ring chromosome.

TABLE 1

*Results of treatment of cultured human peripheral lymphocytes with pulsed radio frequency at 21 megacycles*

| Type of culture | Number of cells scored | Aberrations* | | | | | | Mean abn./cell | $\chi^2$ | *P* value |
|---|---|---|---|---|---|---|---|---|---|---|
| | | a | c | d | e | f | p | | | |
| Control | 600 | | 6 | | | 6 | 4 | 0.016 | | |
| Fixed immediately | 500 | 4 | 2 | | | 6 | 12 | 0.036 | 5.2 | 0.02 |
| 24 hours recovery | 2000 | 11 | 24 | 8 | 9 | 19 | 60 | 0.056 | 16 | <0.01 |
| 36 hours recovery | 850 | 4 | 10 | 3 | 8 | 8 | 41 | 0.077 | 24 | <0.01 |

* a = chromosome break.
c = chromatid break.
d = dicentric chromosome.
e = endoreduplication figure.
f = acentric fragment.
p = polyploid number chromosomes.

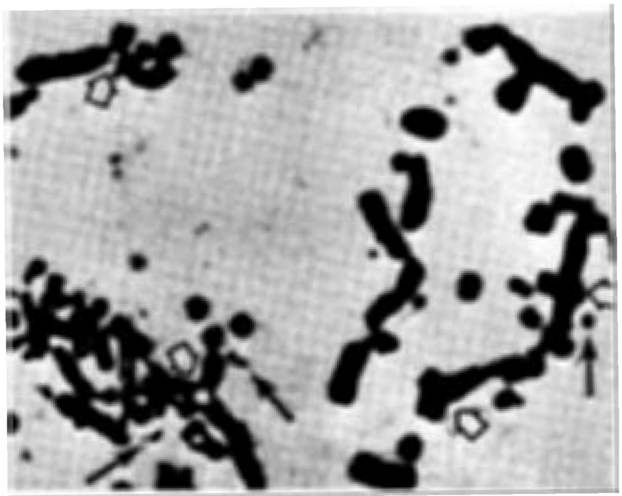

Figure 8. Parts of two Chinese hamster cells showing numerous fragments (solid arrows) and translocations (hollow arrows).

and fragments; and Fig. 3 shows a cell with two micronuclei, one on each side of the nucleus.

Human lymphocytes separated from peripheral circulation were placed in culture and stimulated to transform and undergo mitosis by means of phytohemagglutinin. After two days in culture, the cells were subjected to pulsed radio frequency at 21 MHz.[3] Following the experimental treatment, the cultures were either fixed immediately or allowed to recover for periods of 24 to 36 hours before fixation. Standard air-dry films were stained with aceto-orcein and scored for types of mitotic or chromosome aberrations.

Results are summarized in Table 1. The incidence of chromosome abnormalities in the experimental groups was significantly greater than in the controls. Chromosome damage ranged from single chromatid breaks through dicentric chromosomes to occasional severe erosion of all chromosomes within a given cell. Varying degrees of pycnosis of nondividing nuclei were evident. Figure 4 shows a chromatid break, and Fig. 5 shows both a dicentric chromosome and an acentric fragment in the same cell.

Cultured lung cells from Chinese hamster, when treated with radio frequency in a similar fashion to the human lymphocytes, produced significant num-

TABLE 2

*Crossing over induced in male germ cells of* Drosophila melanogaster *by r. f. treatment*

| Expt. No. | Experiment agent | No. tested | Cross over events | Percent of cross over |
|---|---|---|---|---|
| 1 | r. f., 20 MHz | 3116 | 6 | 0.19 |
| 2 | r. f., 20 MHz | 1110 | 2 | 0.18 |
| 3 | r. f., 20 MHz | 1045 | 2 | 0.19 |
| 4 | Heat, 4 hrs. | 1851 | 0 | 0 |
| 5 | Heat, 1 hr. | 2210 | 0 | 0 |
| 6 | Control | 4358 | 0 | 0 |
| 7 | Cold | 20,107 | 0 | 0 |
| 8 | r. f., 27 MHz | 7829 | 2 | 0.0255 |
| 9 | r. f., 30 MHz | 2758 | 2 | 0.072 |

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[3] Five hundred volts peak-to-peak per centimeter, distance of 2 cm between electrodes, 10 microseconds per pulse, 100 pulses per second for 30 minutes. Temperature was controlled at 27 °C.

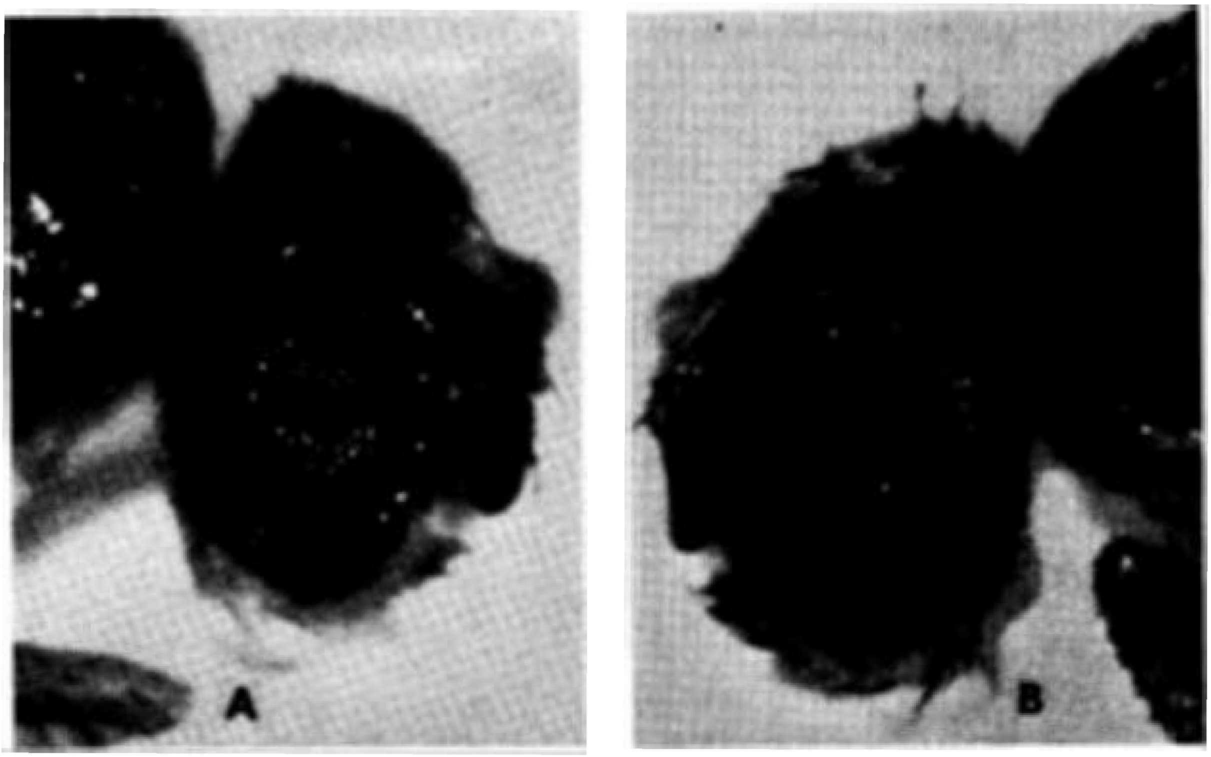

Figure 9. *Drosophila melanogaster* mutant eye (spotted) induced by radio frequency treatment, A; normal or wild-type eye, B.

bers of chromosome aberrations. Figure 6 shows a chromatid break and a dicentric chromosome in one cell. Figure 7 shows a ring chromosome in a cell with 23 chromosomes rather than the normal number of 22. Figure 8 shows a plethora of chromosome fragments and translocations.

Pulsed radio waves[4] applied to the mature germ cells of male Drosophila (5) resulted in the production of numerous visible mutations; some were sex-linked (white eye, singed bristles, yellow body, etc.), others were autosomal (blister wing, spotted eye); some were dominant, and some recessive; and many were sex-linked recessive lethals. Figure 9 shows the mutant spotted eye (A) compared to a normal eye (B). A mutant wing (blister wing, A) and a normal wing (B) are shown in Fig. 10. A sex-linked recessive visible mutant, singed bristle, is illustrated in A of Fig. 11, and the normal or wild-type bristles are shown in B.

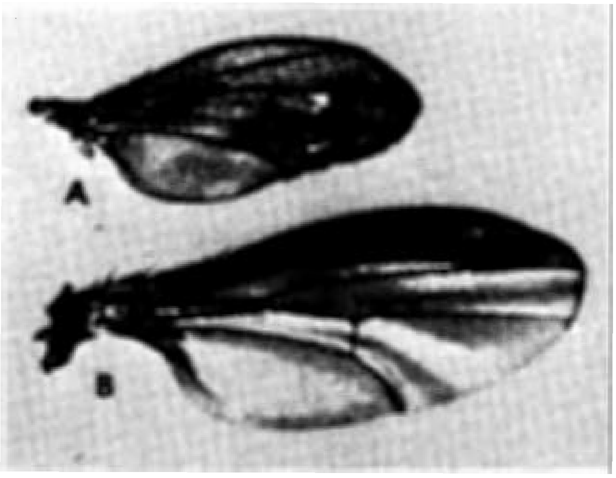

Figure 10. Drosophila mutant (blister wing) resulting from radio frequency treatment, A; normal or wild-type wing, B.

Furthermore, radio frequency energy induces "crossing over" in the germ cells of male Drosophila (4, 5), a phenomenon which naturally occurs only in the female fly. Table 2 summarizes results of these experiments. These genetic effects resemble those resulting from application of ionizing radiations, which have tremendously greater energy levels. The rate of crossing over induced by radio

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[4] The length of treatment varied from 5 minutes to 1 hour; the pulse width, from 30 to 50 microseconds; the most effective frequency was 21 MHz; the repetition rate was 500 to 100 per second; and the voltage, from 500 to 1000 peak-to-peak per centimeter. The flies were placed in a plastic compartment 1 $cm^3$ and were treated in air.

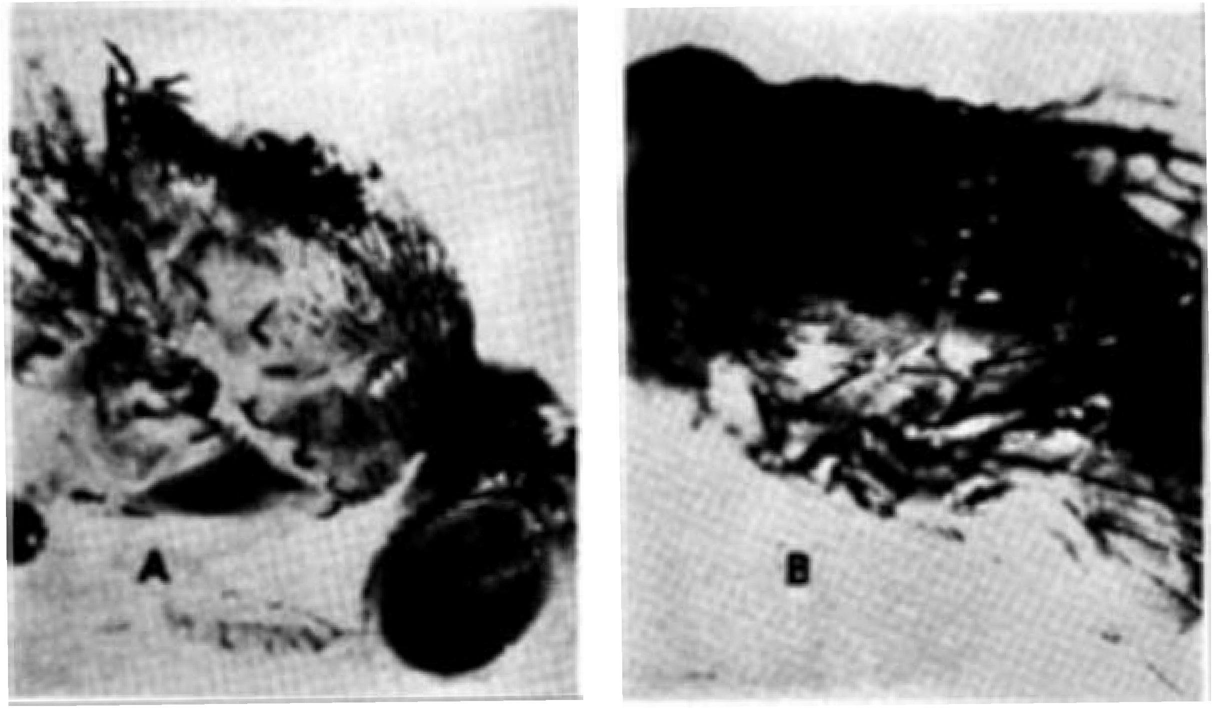

Figure 11. Drosophila sex-linked recessive visible mutant (singed bristles) resulting from radio frequency treatment, A; normal or wild-type bristles, B.

frequency treatment[5] in these experiments is equivalent to that produced by about 250 r of x-rays.

Treatment of gladiolus bulbs (6) with radio frequency of 21 MHz stimulated breaking the dormancy period and produced larger and more vigorous plants which bore more flowers than the other groups.[6] Normal emergence for these bulbs is about 40 to 50 percent; the value of 96 percent emergence for the bulbs treated with 21 MHz is much higher than the next value of 80 percent. The average height of the 21-MHz group was approximately twice that of any other group.

## NONBIOLOGICAL STUDIES

While we were actively pursuing these biological studies, we also undertook to secure basic physical data on the marked effect of radio frequency on the zeta potential of polystyrene colloids, demonstrating for the first time the fact that pulsed radio frequency waves could alter the charge on inert materials (7–9).

A monodisperse system of polystyrene was prepared by emulsion polymerization. It was dialized for 5 days against running distilled water. The electronegative zeta potential on these particles was on the order of 40 to 45 millivolts negative. These charges are due to the carboxyl and sulphate groups on the surface. These groups are covalently bonded to carbon atoms of the polymeric chain. There is about one charge to every 500 square angstroms of surface. A cuvette was filled with about 15 milliliters of polystyrene colloid. Two platinum electrodes were on either side of the cuvette. As a function of particle size, there was an interaction with an r. f. field. This is at a specific frequency for a particle size. Negative charges appeared to be "stripped" from the surface. There was about a 25 percent reduction of electronegative charge on the polystyrene. Different-sized monodisperses responded to different frequencies. The threshold voltages were of the order of 100 volts peak-to-peak per centimeter, with a maximum effect being found at 1000 volts peak-

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[5] The most effective frequency was 20 MHz. Other parameters were the same as above for mutations.

[6] The frequencies ranged from 11 to 41 MHz, at 1-MHz intervals. The chamber in which the cormels were treated measured 6×5×3.5 cm, which accommodated 25 cormels at a time. Other parameters were: 10 minutes' treatment, pulse width 30 microseconds, repetition rate of 1000 pulses per second, peak-to-peak voltage ranged from 12,500 to 15,000.

to-peak per centimeter. This effect reversed itself spontaneously with time. The response, however, was very slow, requiring 4 hours to regain its initial zeta potential. The rate of return was linear.

Other colloids also were examined, ranging from starch granules, where the charge is not ionogenic but adsorbed to spores of various fungi. All manifested the same phenomena. There was no evidence of an increase of ionic groups in the solution in which the colloids were suspended, and certainly the impressed r. f. field was trivial in comparison with circa 3 electron volts needed to break a covalent bond. As yet, no effective explanation of this phenomenon is available.

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# EFFECTS OF MICROWAVE RADIATION ON LENS EPITHELIAL CELLS
## (Summary)

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It is well established that exposure of the eye to microwave radiation can cause within a few days the formation of opaque areas, or cataracts, in its normally transparent lens. These posterior subcapsular cataracts are similar in appearance to those induced by ionizing radiation except that, in the latter case, weeks or months are required for the cataract to develop. With respect to its latent period the microwave cataract is similar to the galactose induced cataract, in which equatorial opacities appear after two days of galactose feeding.

Several investigators have shown that ionizing radiation and galactose feeding affect the lens epithelial cells, from which the lens fibers differentiate by a process of elongation. For this reason the present experiments were conducted with microwave radiation to determine whether this form of radiation has an effect upon the lens epithelium and, if so, whether the effect is similar to that of ionizing radiation or galactose feeding.

The right eyes of adult New Zealand white rabbits were exposed to cataractogenic doses of CW radiation at 2.45 GHz; the nonirradiated left eye served as the control. At post-irradiation intervals varying from six hours to one month the animals were sacrificed. One hour before sacrifice, tritiated thymidine (a radioactive form of the thymine incorporated by cells synthesizing DNA in preparation for mitosis and cell division) was injected into the anterior chambers of both eyes. This autoradiographic technique was utilized so that every epithelial cell which was preparing to undergo mitosis could be identified as well as those in active mitosis. By counting and comparing the number of such cells in both the irradiated and the control lenses the effect of the radiation could be determined.

Characteristically the irradiated lenses showed an initial pronounced suppression of both DNA synthesis and cell division. This gradually diminished during the ensuing two weeks, by which time these activities had recovered and by one month post-irradiation they were proceeding at a slightly accelerated rate. This sequence of events parallels closely those observed in the lens epithelium after exposure of the eye to ionizing radiation.

In twenty of the irradiated eyes, however, there was superimposed upon the usual course of recovery a precipitous rise in DNA synthesis occurring on the fourth to fifth day after irradiation. In all of these irradiated lenses equatorial vesicle strings had begun to develop in the superior temporal quadrant on the third day post-irradiation. The counts made on these epithelia revealed that the increased activity was localized in the quadrant of the epithelium lying directly in front of the vesicle strings. This sharp rise in DNA synthesis is similar to that which is observed in galactose fed rats where hydration of the lens occurs in the form of equatorial vesicles which seem to stimulate the overlying epithelium to proliferate at a greatly accelerated rate. The same stimulus may be responsible for the greatly increased rate of DNA synthesis in the microwave irradiated lenses in which equatorial vesicles are formed.

# EFFECTS OF 2450 MHz MICROWAVE RADIATION ON CULTIVATED RAT KANGAROO CELLS

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## INTRODUCTION

Microwave radiation has been reported to produce adverse effects in a variety of biological systems. Most significant are the microwave-induced lenticular changes resulting in cataracts in the eyes of humans (5, 14, 37), rabbits (7, 25, 29, 35), and dogs (6). Microwave-induced seminiferous tubular atrophy and necrosis, interstitial edema, and hypospermia have been observed in the testes of humans (26) and rats (12, 16, 28). In the hematopoietic system, microwave radiation has been observed to cause leukocytosis, lymphocytosis, and neutrophilia in rats (8, 34) and dogs (22), and has induced a degenerative giant form of mast cells in rats (33). Human lymphocytes *in vitro* (31) have undergone lymphoblastoid transformation, and the cell size, dry mass, and sodium $S^{35}$-sulfate uptake of rat mast cells *in vitro* (27) have been reduced after microwave irradiation. Microwave radiation has been shown to activate peripheral nerves causing behavioral, cardiovascular, and hormonal changes (21), and to deactivate the enzyme alpha amylase (1), reduce protein synthesis in liver and testes (17), and reduce ascorbic acid levels in eye lens (19).

The present study investigates the effects of microwave radiation on cell proliferation and on the induction of chromosome aberrations in cultured cells derived from rat kangaroo tissues. An appropriate dose of microwave radiation appears to promote cell proliferation slightly, but a large radiation dose disrupts ribonucleic acid synthesis, protein production, and inhibits cell proliferation or destroys the cells. Microwave-induced chromosome aberrations observed in cell cultures are of the same types as those produced by ionizing radiations.

## MATERIAL AND METHODS

Serially cultivated cells derived from choroid and bone marrow tissues of the rat kangaroo (*Potorous tridactylus apicalis*) were used in this study. The choroid cells initiated in October 1968 were subcultured through 25 passages, and the bone marrow cells initiated in August 1966 were subcultured through 88 passages. The choroid cells were used for cell-proliferation experiments, since they dispersed easily in the solution used for cell counts. The bone marrow cells were used for chromosome aberration studies because most of the cells were diploid.

The cells were cultivated in Falcon[1] plastic T-30 flasks for 24 hours in nutrient medium 199, supplemented with 20 percent fetal bovine serum, 10 percent NCTC-109 medium, 2 mM L-glutamine and 1 mM sodium pyruvate, plus 100 units of penicillin and 100 μg equivalents of streptomycin per milliliter of medium. Before irradiation, the nutrient medium was decanted and the cells were washed with Hanks' balanced salt solution. The flasks then were placed upright at 10 to 50 cm in front of an open microwave oven or microwave generator antenna, and irradiated for 5 to 30 minutes.

After irradiation, fresh medium was added to the flasks and the cultures were incubated at 37 °C. The nutrient medium was changed every 24 hours after irradiation through 144 hours. Cells for the chromosome aberration studies were fixed with methyl alcohol and acetic acid (3:1) at 8, 24, 48, 72, and 96 hours after irradiation. The cells were air dried and stained with Giemsa before microscopic observation with a Zeiss Photomicroscope II. Some choroid cell cultures were treated with actinomycin-D to study the effects of microwave irradiation on RNA synthesis; some bone marrow cultures were treated with 5-bromodeoxyuridine to evaluate

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[1] The use of commercial products or mention of private firms in no way constitutes endorsement by the U.S. Public Health Service or its affiliates.

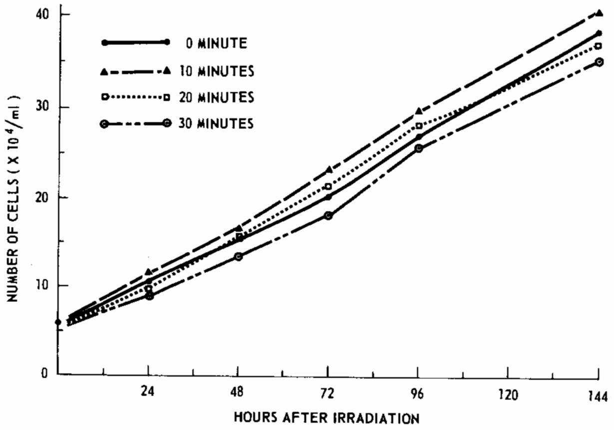


Figure 1. Number of cells in cultures irradiated at 50 cm from antenna.

the sensitivity of chromosomes to microwave radiation.

The microwave radiation used in the experiments emanated from a 2450 MHz microwave oven and also from a 2450 MHz microwave generator. The power density of the oven measured at 50 cm from its open front was 0.2 W/cm². The power density of the generator was adjusted to match that of the oven. A thermistor attached to a remotely controlled 9 cm dipole antenna was used in measuring the power density. All cell exposures and power density measurements were conducted in an anechoic chamber.

## RESULTS

### *Effect on* In Vitro *Cell Proliferation*

In preparing the cell cultures, approximately an equal number of cells was contained in the suspension allotted to each flask. After 24 hours of incubation and at the time of irradiation, cells in three flasks were counted and the average was used as the initial count. The cultures were irradiated at 10, 25, or 50 cm from the antenna for 10, 20, or 30 minutes. Every 24 hours after irradiation, cells in one flask of each treatment were treated for 5 minutes with 0.15% trypsin (Difco 1:250) in calcium- and magnesium-free salt solution, plus 0.2% Versene (EDTA—disodium salt), to detach the cells from the plastic surface. The cells were dispersed with a capillary Pasteur pipette, and counted with a hemacytometer.

Three repeated experiments were conducted. The average initial cell count was $5.7 \times 10^4$ per ml. After 24 hours of growth, the average cell count of the nonirradiated control cultures increased to $10.5 \times 10^4$ per ml, and at 144 hours the count was $38.2 \times 10^4$ per ml. The cultures are considered to be a slow growing cell line.

The cultures irradiated at 50 cm from the antenna grew well. Cell counts of the cultures irradiated for 10 minutes were in all cases greater than the unirradiated control; those irradiated for 30 minutes were less than the control counts as illustrated in Fig. 1. The microwave dose level at 50 cm appeared to be slightly beneficial to cell proliferation when the cultures were exposed for 10 minutes. Microwave exposures longer than 30 minutes slightly reduced cell proliferation.

Microwave radiation at 25 cm from the antenna depressed cell proliferation when the cultures were exposed longer than 20 minutes as illustrated in Fig. 2. For the cultures exposed for 10 minutes, the depressing effect appeared by 72 hours after irradiation.

Most cells in the cultures irradiated at a distance of 10 cm seemed dead. After trypsinization the cells did not "round-up" well; many of them remained flat or in the same shape as when attached on the plastic surface of the flasks. Cell counts declined during the first 24 hours after irradiation, and diminished steadily until they were about 10 percent of the control count as shown in Fig. 3. There was no cell proliferation and probably no surviving cells after the exposure.

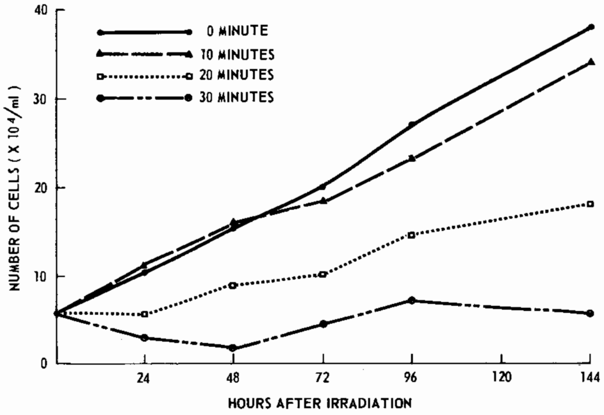


Figure 2. Number of cells in cultures irradiated at 25 cm from antenna.

### *Effect on Ribonucleic Acid (RNA) Synthesis and Protein Production*

Based on the results obtained in the above experiments, an experiment was designed to examine the effects of microwave radiation on RNA synthesis and on subsequent protein production and cell proliferation. The cultures were treated with an RNA synthesis inhibitor, actinomycin-D (11), and then exposed to the microwave radiation at a distance of 15 cm for 15 minutes. Cell counts were made at 48 and 96 hours after irradiation. Three controls were used: (1) cultures without irradiation or actinomycin-D treatment, (2) cultures without irradiation but treated with actinomycin-D, (3) cultures irradiated but without actinomycin-D treatment. The concentration of actinomycin-D was 3 μg per ml of medium and the cultures were treated for 16 hours before irradiation. The results are illustrated in Fig. 4. The depressing effects of actinomycin-D and microwave radiation on the cell proliferation appear to be independent and somewhat additive. Microwave radiation might also react in some way to disrupt RNA synthesis and reduce protein production and cell proliferation as does actinomycin-D.

### *Effect on Genetic Material—Chromosome Aberrations*

The cells used in the chromosome aberration studies were rat kangaroo bone marrow cells. A karyotype of the normal rat kangaroo chromosomes is presented in Fig. 5. The chromosomes in the cells exposed at a distance of 25 or 50 cm from the oven for 20 or 30 minutes appeared normal. Chromosome aberrations were observed only in cells exposed at 10 cm from the open front of the oven for 10 minutes or longer.

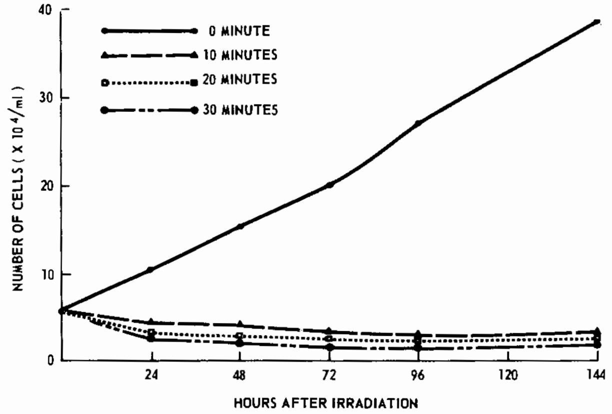


Figure 3. Number of cells in cultures irradiated at 10 cm from antenna.

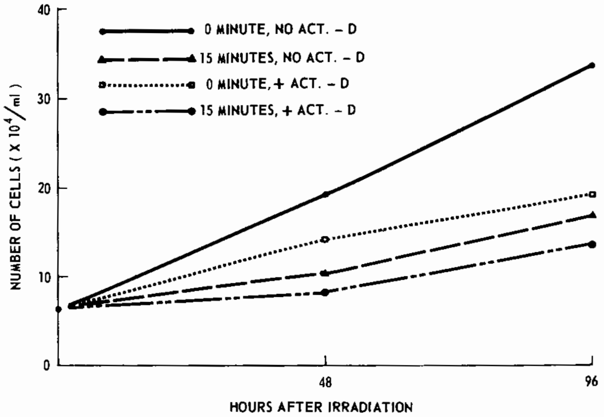


Figure 4. Number of cells in cultures treated with actinomycin-D and microwaves and irradiated at 15 cm from antenna.

The types of chromosome aberrations observed in this study are the same as those induced by ionizing radiation in other organisms including humans (3). They are chromatid breaks (Figs. 6–8), isochromatid breaks (Figs. 9–12), dicentrics (Figs. 13–16), chromatid exchanges (Fig. 17) and rings (Figs. 18–20). The number and types of aberrations in the irradiated cells are presented in Table 1. Chromatid breaks appeared in the cells as late as 48 hours after irradiation, while isochromatid breaks appeared at 8 hours after irradiation. The number of breaks per cell seems to be correlated with the length of exposure—the longer the exposure the greater the number of breaks per cell. However, the average number of chromosome breaks per cell per minute of exposure is approximately 0.005. The peak number of chromosome aberrations appeared at 48 to 72 hours after irradiation (Table 2). Since the male rat kangaroo cell has a diploid number of 10+X, $Y_1$, $Y_2$, and each chromosome can be identified without difficulty, aberrations on individual chromosomes were recorded and presented in Table 3. Chromosomes No. 1 and No. 2 had the greatest percentage of breaks (64%). Of all the chromosome break incidences, 58 percent were isochromatid breaks and 24 percent were dicentrics.

### *Electromagnetic Chromosome Deterioration*

Aside from the conventional types of chromosome aberrations described above, a number of mitotic cells showed severely damaged chromosomes. The

TABLE 1

*Microwave-radiation-induced chromosome aberrations in rat kangaroo bone marrow cells*
(10 cm from the open front of the oven)

| Minutes | No. cells observed | Chromatid breaks | Isochromatid breaks | Dicentric | Ring | Total no. breaks* | No. breaks per cell | No. breaks per cell per min. |
|---|---|---|---|---|---|---|---|---|
| 0 | (400) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | (150) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 50 | 0 | 1 | 1 | 0 | 3 | 0.0600 | 0.0050 |
| 15 | 333 | 3 | 15 | 3 | 1 | 26 | 0.0780 | 0.0052 |
| 18 | 150 | 3 | 5 | 1 | 0 | 10 | 0.0667 | 0.0037 |
| 20 | 111 | 1 | 8 | 1 | 0 | 11 | 0.1000 | 0.0050 |
| Total | 643 | 7 | 29 | 6 | 1 | 50 | 0.0778 | |

* Each dicentric, ring, or chromatid exchange is counted for two breaks.

TABLE 2

*Number of chromosome aberrations observed at various intervals after irradiation*

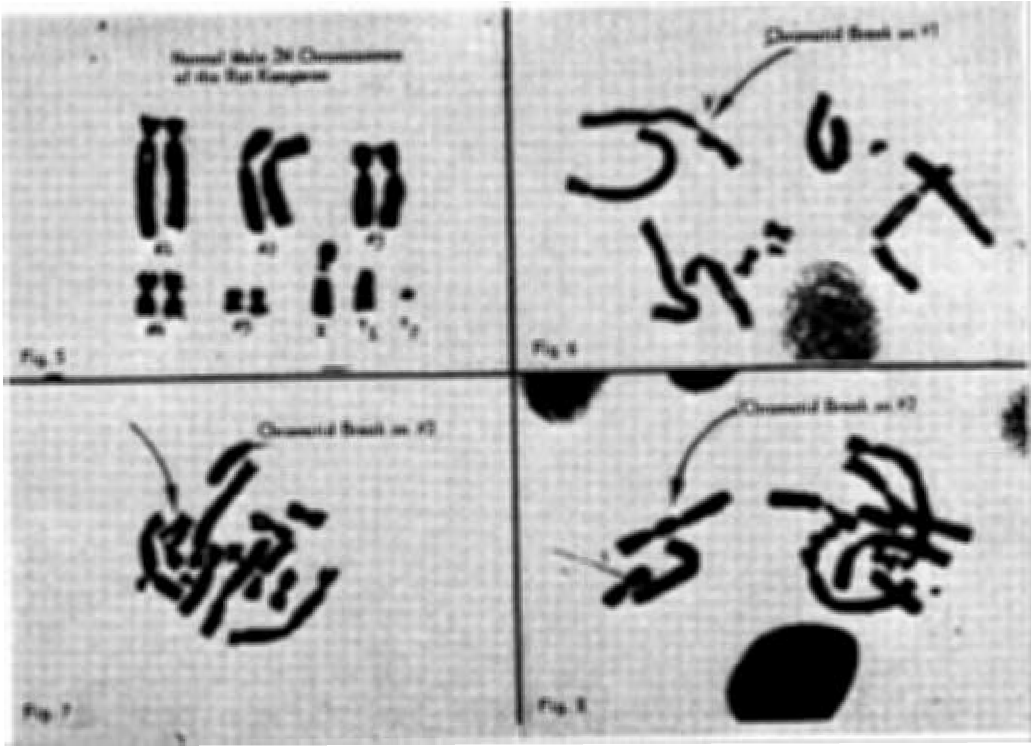
| Hours | No. cells observed | Chromatid breaks | Isochromatid breaks | Dicentric | Ring | Total no. breaks* | No. breaks per cell |
|---|---|---|---|---|---|---|---|
| 8 | 50 | 0 | 1 | 0 | 0 | 1 | 0.0200 |
| 24 | 50 | 0 | 2 | 0 | 1 | 4 | 0.0800 |
| 48 | 293 | 2 | 17 | 4 | 0 | 27 | 0.0923 |
| 72 | 150 | 3 | 7 | 2 | 0 | 14 | 0.0933 |
| 96 | 100 | 2 | 2 | 0 | 0 | 4 | 0.0400 |
| Total | 643 | 7 | 29 | 6 | 1 | 50 | 0.0778 |

* Each dicentric, ring, or chromatid exchange is counted for two breaks.

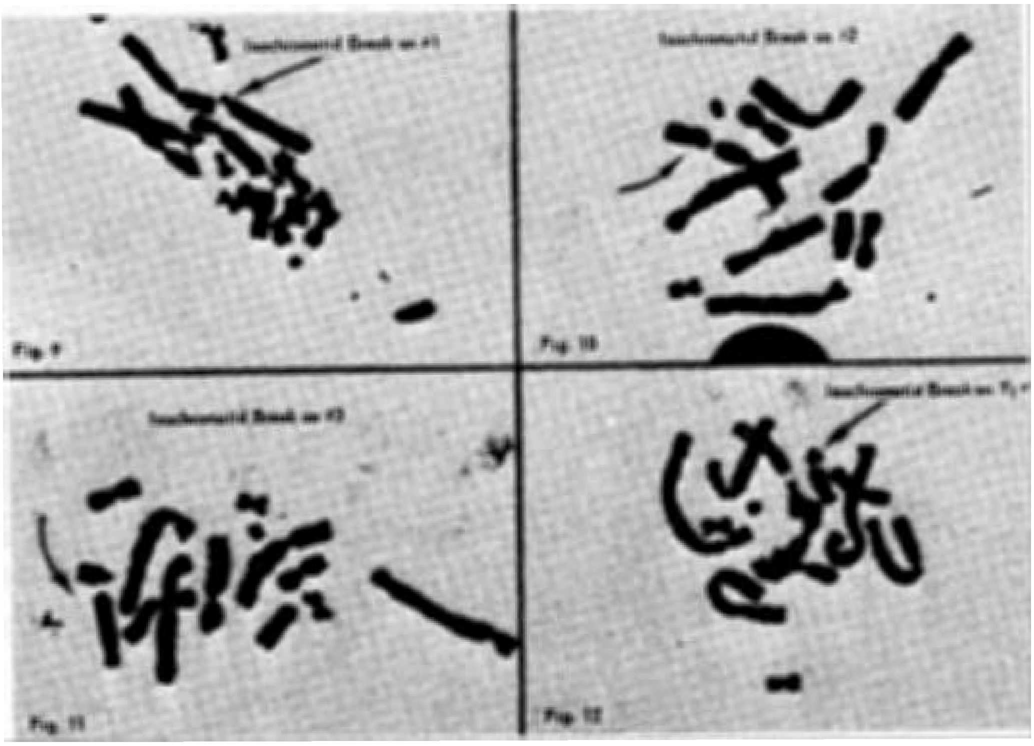
TABLE 3

*Number of chromosome aberrations on individual chromosomes*
(643 cells)

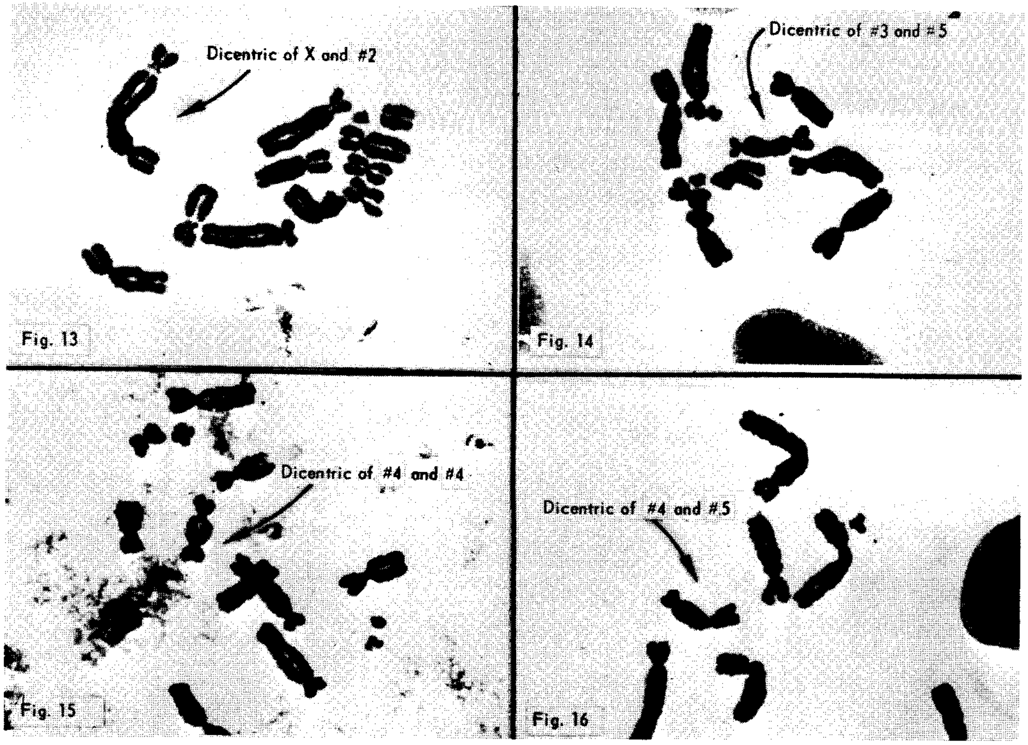
| Chromosome | Chromatid breaks | Isochromatid breaks | Dicentric (break) | Ring (break) | Total no. breaks |
|---|---|---|---|---|---|
| 1 | 3 | 10 | 1 | 0 | 14 |
| 2 | 3 | 10 | 4 | 0 | 17 |
| 3 | 1 | 2 | 0 | 0 | 3 |
| 4 | 0 | 1 | 2 | 2 | 5 |
| 5 | 0 | 0 | 4 | 0 | 4 |
| X | 0 | 4 | 1 | 0 | 5 |
| $Y_1$ | 0 | 2 | 0 | 0 | 2 |
| $Y_2$ | 0 | 0 | 0 | 0 | 0 |
| Total | 7 | 29 | 12 | 2 | 50 |



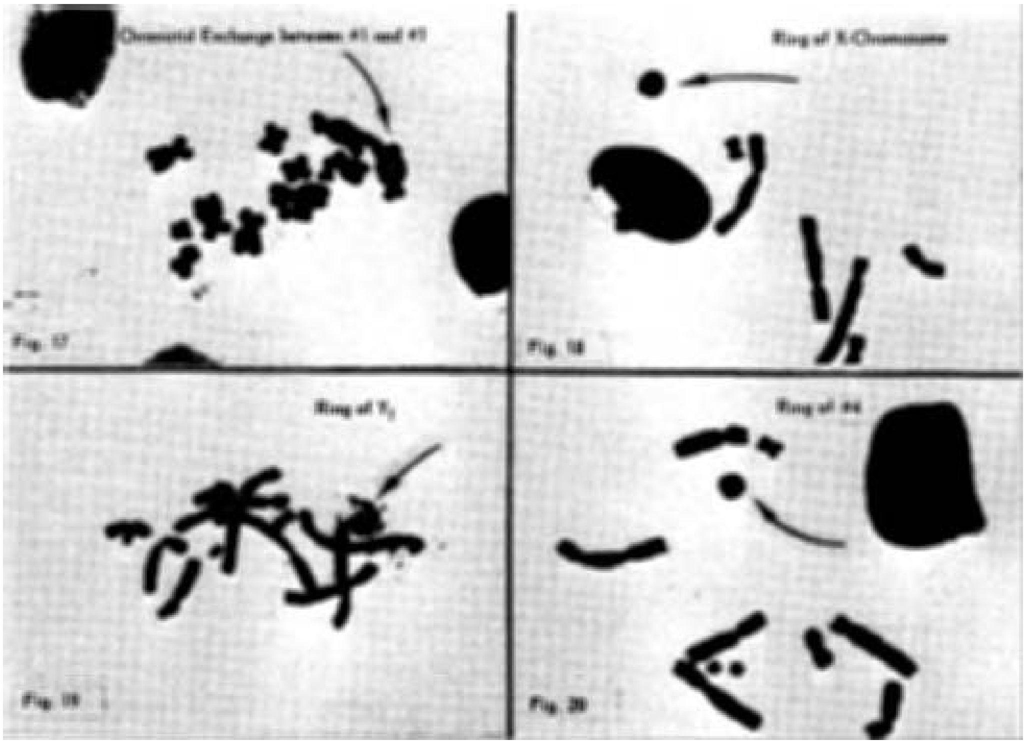
Figures 5–8. Normal rat kangaroo chromosomes and chromatid breaks.



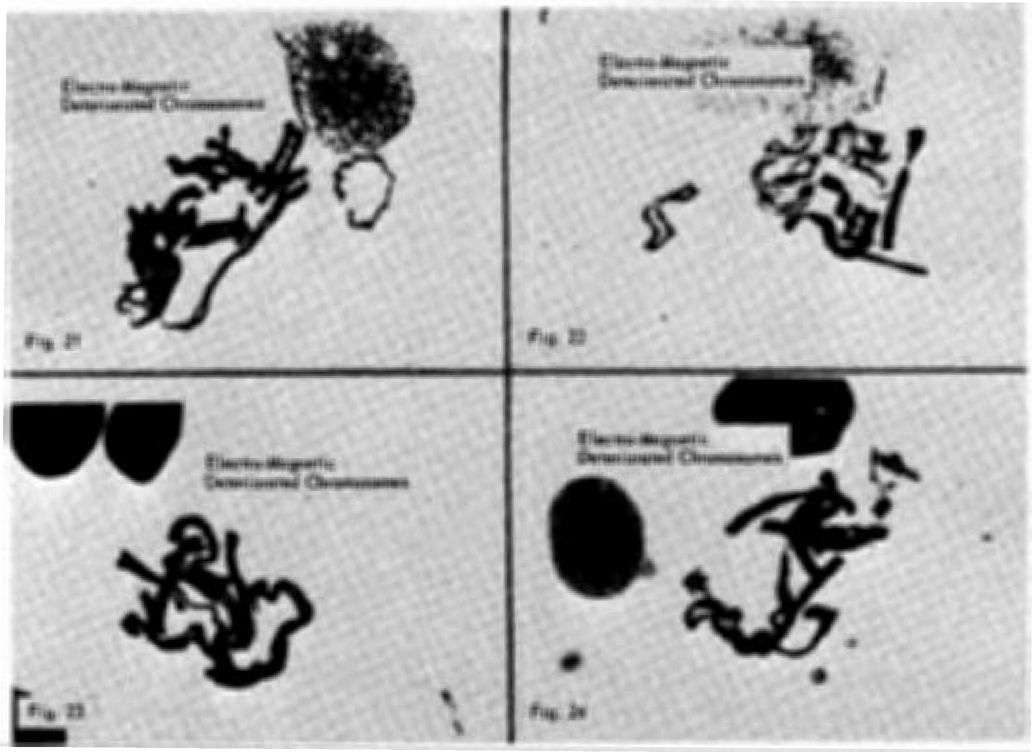
Figures 9–12. Isochromatid breaks.



Figures 13–16. Dicentrics.



Figures 17–20. Chromatid exchange and rings.



Figures 21–24. Microwave radiation damaged chromosomes.

damaged chromosomes had the appearance of uncoiling, stickiness, and dilation, which might be evidence of mass chromosome destruction (Figs. 21–24).

In order to quantitatively analyze electromagnetic chromosome deterioration, 200 mitotic cells were observed in each treatment including the controls. The percent abnormal cells are presented in Table 4. A small percentage of the unirradiated mitotic cells were abnormal. Among the cultures exposed for 12, 15, 18, and 20 minutes there was no significant difference in the average percentages of abnormal cells. The percentage of abnormal mitotic cells was the highest (22.0%) at 48 hours after exposure, but declined to 3.7 percent at 96 hours after irradiation.

### *Effect on Chromosome Radiosensitivity*

The thymidine analogue, 5-bromodeoxyuridine (BUDR) is known to incorporate into deoxyribonucleic acid (DNA) and increases chromosome radiosensitivity (10, 15). In our experiments, the rat kangaroo bone marrow cultures were pretreated with BUDR at a concentration at 25 μg per ml of medium for 16 hours before the cells were exposed to microwave radiation. After exposure the cells were incubated in fresh medium which contained an additional 5 μg per ml of thymidine. The cells were fixed at 48 or 96 hours after irradiation, and processed for chromosome aberration study.

The number of different types of aberrations incurred by the pretreatment and microwave radiation are presented in Table 5. Dicentrics occurred most frequently. The average number of breaks per cell per minute, 0.015, is three times greater than that of the cells not treated with BUDR.

The number of different types of aberration in individual chromosomes is presented in Table 6. Chromosome No. 4 was greatly sensitized by BUDR pretreatment, and again dicentrics occurred most frequently. The number of breaks on $Y_1$ chromosome was also increased.

## DISCUSSION

### *The Experimental Cells*

Rat kangaroo choroid and bone marrow cells, after being transplanted into plastic flasks, attach individually on the bottom of the containers, and

TABLE 4

*Percentage of abnormal mitotic cells*
(200 mitotic cells each treatment)

| Minutes of irradiation | Hours after irradiation | | | | Total | Average |
|---|---|---|---|---|---|---|
| | 24 | 48 | 72 | 96 | | |
| 0 | 0 | 4 | 3 | 2 | 9 | 2.3 |
| 12 | 10 | 16 | 12 | 3 | 41 | 10.3 |
| 15 | 5 | 26 | 22 | 6 | 59 | 14.8 |
| 18 | 11 | 23 | 19 | 4 | 57 | 14.3 |
| 20 | 12 | 23 | 18 | 2 | 55 | 13.8 |
| Total | 38 | 92 | 74 | 17 | 221 | |
| Average of irradiated cells | 9.5 | 22.0 | 17.8 | 3.7 | 13.3 | |

become flat and grow to form a monolayer. Before irradiation these cells were washed with Hanks' salt solution to reduce proteins or other nutrient elements which might have a radioprotective effect on the cells (20, 36). At the time of exposure, the flasks were placed upright to drain residual liquid from the cells and diminish the possibility of accumulating heat in the vicinity of the cells. At the distances and exposure times used in the study, microwave radiation will boil balanced salt solution or cell nutrient medium. If the solution or medium were to remain in the flasks, the accumulated heat in the liquid would have undoubtedly killed the cells.

Since the cells are flat and thin, each exposes a large surface to the microwave radiation that readily penetrates the cells. At the same time, the cells can dissipate the microwave-generated heat through this large exposed surface, although the cells may absorb a small amount of energy flux due to transparency to microwaves. These aspects might have increased the ability of the cells to tolerate the high microwave power density as demonstrated in our experiments.

### *Cell Proliferation Effect*

For the cell proliferation study, the cultures were irradiated at 10, 25, or 50 cm from the antenna. The radiation patterns at these three positions differ greatly (2). For the present we have no device available for measuring power density in the near field, that is 10 or 25 cm from the antenna. The

TABLE 5

*Microwave-radiation-induced chromosome aberrations in the BUDR-pretreated bone marrow cells*

| Minutes | No. cells observed | Chromatid break | Iso-chromatid break | Dicentric | Ring | Chromatid exchange | Total no. breaks* | No. breaks per cell | No. breaks per cell per min. |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 71 | 2 | 1 | 3 | 1 | 0 | 11 | 0.1549 | — |
| 15 | 50 | 1 | 2 | 2 | 2 | 0 | 11 | 0.2200 | 0.0147 |
| 20 | 100 | 2 | 2 | 9 | 3 | 1 | 30 | 0.3000 | 0.0150 |
| Total | 221 | 5 | 5 | 14 | 6 | 1 | 52 | 0.2353 | — |

* Each dicentric, ring, or chromatid exchange is counted for two breaks.

TABLE 6

*Number of BUDR-chromosome aberrations on individual chromosomes*

(221 cells)

| Chromosome | Chromatid breaks | Isochromatid breaks | Dicentric (break) | Ring (break) | Chromatid exchange (break) | Total no. breaks |
|---|---|---|---|---|---|---|
| 1 | 2 | 1 | 5 | 0 | 2 | 10 |
| 2 | 1 | 1 | 0 | 0 | 0 | 2 |
| 3 | 1 | 0 | 0 | 0 | 0 | 1 |
| 4 | 0 | 0 | 21 | 2 | 0 | 23 |
| 5 | 0 | 0 | 2 | 0 | 0 | 2 |
| X | 1 | 3 | 0 | 2 | 0 | 6 |
| $Y_1$ | 0 | 0 | 0 | 8 | 0 | 8 |
| $Y_2$ | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 5 | 5 | 28 | 12 | 2 | 52 |

power density at 50 cm was measured with a remotely controlled 9-cm dipole and a thermistor and found to be 0.2 W/cm$^2$. The power densities at 25 and 10 cm were calculated to be approximately 1 and 5 W/cm$^2$, respectively.

At a power density of 0.2 W/cm$^2$, the proliferation of the cultures exposed for 10 minutes increased but those irradiated for 30 minutes reacted adversely. Searle et al. (28) reported that the growth of larvae of the common fruit fly was not affected by microwave radiation at field intensities of 0.3 W/cm$^2$ or 1 W/cm$^2$. De Seguin et al. (9) reported that microwave irradiation significantly increased the growth of embryonic chicken heart explants. The proliferating cells might have migrated to the periphery of the explant where there was free space for expansion and growth. This dimensional increase in the irradiated tissues may have been counted as a favorable reaction of the explants to the microwave radiation.

The cells in our experiments grew as individual cells on the surface of plastic flasks. During exposure, there was no medium or other liquid around the cells to accumulate heat. The cells showed a beneficial as well as an adverse response to microwave radiation. Pincus and Fischer (24) heat treated cultures of chick osteoblasts and observed only thermal destruction at temperatures exceeding 50 °C. Microwave radiation effects appear to differ from those produced by conventional heating. Moressi (23) exposed mouse sarcoma-180 cells in suspension to microwave radiation and found no difference in mortality patterns between irradiated and nonirradiated cells. The ineffectiveness he noted may have been because he increased the temperature to that used by Pincus and Fischer employing only microwave radiation as a heat source.

### *Mutagenic and Chromosome Aberration Effect*

Among four types of nonionizing radiation, ultraviolet light is known to induce mutations and chromosome aberrations (4). Infrared radiation alone is ineffective in producing chromosome aberrations, but in combination with x irradiation increases the frequency of the induced aberrations (18, 32). By combining colcemid treatment and microwave radiation, Janes et al. increased the frequency of chromosome stickiness in bone marrow cells of microwave irradiated Chinese hamsters (17). Heller applied 27 MHz radiofrequency radiation to growing garlic root-tips and observed chromosome aberrations (13). Pirovano obtained a great variety of mutants and hybrids in various kinds of garden plants with electromagnetic treatment of seeds or pollen grains (30). The frequencies of the radiation used by Pirovano although not specified were probably in the microwave and radiofrequency range. These results indicate that microwave and radiofrequency radiations are mutagenic agents.

Although the types of chromosome aberrations recorded in this study were the same as those of the ionizing radiation induced aberrations, the frequency distribution of the microwave induced aberrations is different from that induced by ionizing radiation.

In our microwave radiation study, chromatid breaks were observed as late as 48 hours after irradiation, isochromatid breaks were predominant among the aberrations, and the peak aberration frequency was at 48 and 72 hours after irradiation. In x-ray irradiated cells, chromatid breaks were first observed about 6 hours after irradiation, and were predominant among the aberrations (3). The peak frequency of aberrations occurred at 12 and 24 hours after irradiation.

In this study chromosome aberrations were observed only in the cells that were exposed to microwave radiation at a distance of 10 cm from the oven (power density 5 W/cm$^2$) for more than 10 minutes but not longer than 20 minutes. Cultures that were exposed for longer than 20 minutes developed few or no mitotic cells. Therefore the exposure energy range of microwave radiation capable of inducing chromosome aberrations apparently is small. Disregarding the amount of energy the cells either absorbed or were exposed to, the average number of chromosome breaks per cell ranged from 0.06–0.10 for microwave radiation, 0.06–1.46 for ultraviolet radiation (4), and 0.06–3.00 for x-ray radiation (3). Microwave radiation in general appears to be less effective than either ultraviolet or x radiation in inducing chromosome aberrations.

## SUMMARY

Cultivated rat kangaroo choroid and bone marrow cells were irradiated with 2450 MHz microwaves at power densities of 0.2, 1.0, and 5.0 W/cm$^2$ to study microwave radiation effects on cell proliferation and chromosome aberrations. At power density of 0.2 W/cm$^2$, a 10-minute exposure increased cell proliferation, but a 30-minute exposure reduced cell proliferation. Cellular proliferation was reduced greatly at a power density of 1 W/cm$^2$ for exposures of 20 minutes or longer. Microwave radiation at a power density of 5 W/cm$^2$ severely reduced cell proliferation and at the same time induced chromosome aberrations.

The types of chromosome aberrations observed in the cells were the same as those induced by x-ray irradiation. However, the distribution of aberration types differed from that of x-ray irradiation. After irradiation, isochromatid breaks appeared first and were predominant over other types of aberrations. Mass chromosome destruction was observed in mitotic cells. The damaged chromosomes had the appearance of uncoiling, stickiness and dilation of chromosomal matrix.

The results also showed that microwave radiation disrupted RNA synthesis and reduced protein production and cell proliferation. The results of BUDR pretreatment and microwave irradiation indicated that microwave radiation acted directly on the chromosome matrix in causing chromosome aberrations.

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## DISCUSSION

*Dr. Michaelson*: What were your field measurements?

*Dr. Yao*: At a 50 cm distance, the measurement was 200 mW/cm$^2$.

*Dr. Michaelson*: Then I understood you correctly. Did you do any thermal control in these studies?

*Dr. Yao*: No.

*Dr. Michaelson*: I would like to read some excerpts. I mentioned yesterday how critical we have to be in evaluating studies or reports so I will just take a brief second. These are excerpts from the most recent report of the Federation of the American Society for Experimental Biology to the Army in the area of evaluating hazards from ionizing radiation in man. Important points are that "in evaluating studies on isolated cell systems it must be understood that although it is often possible to measure changes in molecules when they are not part of a living system, it is not always correct to extrapolate these findings to living situations where the molecules may be in a different chemical form and may be surrounded by other molecules with different sensitivities or protective capacities." Now, in reference to genetic effects in ionizing radiation studies, the results of chromosome studies should be viewed with the understanding that there is extreme difficulty in relying on this type of work since chromosome scoring techniques are elaborate and require considerable skill. The conclusion of some of the foremost cytogenetists such as Cinder, Evans, Brooks, Lindaman, and Amos is that cytogenetic studies in general are extremely difficult to review for meaningful conclusions. I will not go on any longer. In general, these studies are extremely complex and conclusions made from fragmentary studies are fraught with danger. In general such results as chromosome stickiness are interesting but unresolved phenomena. Such stickiness is reversible. Chromosome aberrations offer possibilities of early indications of radiation induced biological changes. Such effects on tissue cultures may reflect total response of a specific tissue but not genetic injury to the general epithelium where it is especially important. One should also be aware that there are several sources of uncertainty or error in estimating chromosome aberration frequencies and in using the estimate to evaluate such exposures. There are also many variables in tissue culture techniques. One has to consider the influence of heat, viruses, chemicals, etc., all of which are known to produce chromosome breaks and these must not be ignored. These are the conclusions of some of the most eminent cytogenetists in the country.

# EFFECTS OF MICROWAVE AND RADIO FREQUENCY ENERGY ON THE CENTRAL NERVOUS SYSTEM

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This symposium was organized for several reasons. One was to bring together active investigators in order to see where we stand in the state of the art. Another reason was to provide a tutorial situation for investigators who have interest in embarking upon experimentation in this area. For them, the organizers wished to provide an understanding of what has been done already, why certain lines have or have not been pursued, and the problems encountered or that can be expected. It is to meet these objectives that I shall address myself. Thus, I shall briefly sketch some of the history of this area of research, outline briefly the experimentation that I have carried out, and state strongly what I believe to be critical matters that an investigator must recognize.

The last substantial group of experiments in this area were carried out in the middle and late 1950's. The results of these experiments were brought together and detailed just before and after 1960; in the four annual conferences that were called Tri-Service Conferences. This afternoon's session is in a sense unique. There was no session on the nervous system in those conferences. Today, investigation of the neural effects of r. f. energy is recognized as a legitimate area of investigation. But existing with this recognition is also a good deal of confusion and misunderstanding. Such confusion and misunderstanding is characteristic in scientific areas in which there is a great deal of talk and very little data collection.

Why is there so much misunderstanding and confusion and so little data collection is this area? There are four sources that have contributed to the development of this situation. We should recognize them for what they are. Then we can move on to more useful pursuits such as meaningful experimentation.

First, when the Tri-Service research program was organized it was assumed that the only possible effect was the "heating" of tissue. Some people involved in that program quite confidently showed by means of equations that neural function could not be affected by r. f. energy. About the time of the last Tri-Service research conference, when I first became interested in this area, I can recall being shown on a chalk board the calculations that "proved" that nerves can not be affected by r. f. energy.

There was, however, one basic fault in this line of reasoning. The fault was the assumption that we have a good understanding of nervous system function. This assumption is wrong. Our understanding of how information is coded, transferred and stored in the nervous system is virtually nil. In fact, there is increasing evidence to indicate that even the existing hypotheses, such as the one that the electrical spikes recorded from nerves are the information carriers, are incorrect. Instead it appears that we must look at neural function from the standpoint of solid state physics. Looked at in this way, many possibilities for r. f. energy interactions with the mechanism of information transfer and storage in the nervous system are apparent. In this new context, factors almost totally ignored in the Tri-Service program, factors such as modulation, the deliberate use of low power densities, and the careful choice of specific carrier frequencies are clearly of importance.

Thus, through the acceptance of a false assumption, the only nervous system investigation in the Tri-Service program consisted of a small study in which the investigators were given an X band transmitter as an r. f. source. The logic in assigning a group of investigators responsibility for providing information on the effects of r. f. energy on the nervous system, and then giving them an X band transmitter, escapes me. Although these investigators worked quite diligently, one can not penetrate very deeply into the body with X band energy. In fact, the energy is largely deposited in the first few millimeters of skin. The best that could be done were marginal studies on stimulation of peripheral nerve endings.

The second source of misunderstanding can be traced to the controversy on thermal versus nonthermal effects. A very heated controversy developed between those who thought nonthermal effects could also occur. This controversy involved a good bit of emotion and investigators polarized into two opposing camps. Of course, those who held the thermal position and were dominant, considered any discussion of or experimentation with neural function as a part of the nonthermal camp and thus deserving of censure. The tragedy in this is that the thermal versus nonthermal controversy is one of semantics, not science. In general, the investigators were talking past each other. For example, one investigator obviously defined thermal in his mind as rise in core temperature. Another defined it in his mind as increase in molecular vibration. There never was a common definition of the words thermal and nonthermal.

The third factor that unfortunately contributed to the misunderstanding and confusion is a scientifically irrelevant one. There were jurisdictional battles among some groups as to who would control and be responsible for r. f. research. This resulted in positions being taken and energetically supported on the thermal versus nonthermal controversy, the possibility of nervous system effects, etc. The misinformation that this generated is phenomenal. For example, it was so bad that I finally felt compelled to include in papers that I had published in this area a statement such as "... Conclusions or inferences beyond this (stated in the foregoing sentence) are absolutely not warranted by the data." I had hopes that this would discourage to some extent the drawing of unwarranted conclusions, at least from my data, by people in the various camps who then neglected to indicate clearly whose conclusions they were.

A fourth source of this misunderstanding stems from the existence of a good bit of Russian work on r. f. energy effects on nervous system function. In general, this Russian work was rejected by American investigators for various good and bad reasons.

One reason was due to the differences in tradition in U.S. and U.S.S.R. biology. American investigators are oriented to looking for effects through a microscope. Investigators in the Soviet Union have a somewhat different tradition. They tend to look for effects in the modification of nervous system function. Since there was no one in the behavioral area substantially involved in the American program, there was no one who had the background to evaluate and interpret the significance of the Russian work. Instead, it tended to be dismissed as alien and uninterpretable.

Another factor involved in the rejection of the Russian work was the fact that many of the translations of the Russian work were simply atrocious. Many of these translations were completely misleading. For example, in one the word for hypothalamus was translated as cerebellum. This mistranslation in the context of the rest of the report made the experiment appear to be poorly done. One can easily understand the negative view of American investigators who evaluated the work through these translations. I personally found it necessary to have many of my own translations made of reprints that I received from Russian investigators. In this way, I checked on the accuracy of translations that were distributed by various translation groups.

An additional reason for the negative view of American investigators was the fact that the Russians often did not give information in their papers which we feel is necessary to evaluate the quality of the research. Russians working in other areas also do not give sufficient information. One sometimes gets the impression that many of the Russian investigators do not like to have their friends down the hall or in another institute know too much what they are currently doing.

Another reason was that some of the work was of poor quality. Thus, there were good and bad reasons for rejecting portions of the Russian work. In looking at this history, I think it becomes clearer why there is so much argument, confusion, and misunderstanding in this area of research.

There was the assumption that we had a complete understanding of nervous system function. This false assumption provided the underpinning for calculations that were glibly offered as proof that neural function could not be affected by r. f. energy. Thus, there was little research on nervous system function and little evaluation of factors such as modulation.

There was also the polarization of investigators into the thermal and nonthermal camps with the emotion and narrowing of views that this involved. There were the jurisdictional battles between certain groups for control over r. f. research. And there was also the substantial amount of Russian work on the nervous system that was not to our liking because it was alien to our tradition. They often omitted information that we regard as important in evaluating the quality of research. Many of our translations were misleading and some of the work was of poor quality.

With this recognition of the sources of confusion and misunderstanding, possibly we can now move forward in our ignorance of the function of the nervous system to develop an understanding of the effects and hazards of r. f. energy as a tool to help us obtain an understanding of nervous system function.

So much for general history. I shall now sketch the nature and results of the experimentation I have carried out in this area.

I have done a fair amount of research with this energy at carrier frequencies in the VLF, VHF, and UHF bands. This encompasses many of the frequencies used in radar, television, industrial processes, and includes some of the radio broadcast frequencies. The work has involved nervous system function, heart function, endocrine gland function, and mathematical modeling of effects. Much of the data is available in various journals. There is a substantial amount though that I have not had time to prepare for publication. The latter I shall emphasize.

My interest in this area began when I met a man whose work involved measuring the fields of new radars. He mentioned to me that certain radars induce the perception of sound. After a discussion which seemed to eliminate the obvious source of the sound, such as fillings in the teeth, I arranged to visit a radar site at which he could hear this sound. Such began my experimentation with r. f. energy.

Let me note here that I was not the first to publish a report on the perception of sound in a radar field. Credit should be given to a group of engineers at AIL who published a one page report on it about thirteen years before my first report. Unfortunately they did not pursue the matter. I learned from one of them later that when they brought the phenomenon to the attention of an expert on hearing, he told them that there was nothing to it; just teeth rattling. Should I ever become an expert in some area, I hope that I shall recognize the bounds of my own wisdom.

My work in this area began with the study of human perception of the r. f. induced sound. This human work has been fully reported and independently verified by several people who have adhered to the parameters that I have specified as necessary to induce the effect; parameters such as a specific band of carrier frequencies.

In Fig. 1, this band of frequencies is specified.

Early in the work, I explored the possibility of explaining the radar induced hearing effect as the electrophonic effect. The electrophonic effect involved putting the head between electrodes on which there is a high potential and thereby induce a sound through skin vibration. Knowledge of the phenomenon goes back to the time of Volta. More recently, Stevens, Flotorp and also Sommer and Von Gierke experimented with the electrophonic effect. I experimented with the electrophonic effect and also used radar energy to compare specific findings with the two effects to see if they were the same. This resulted in the finding that the radar effect could not be explained with the electrophonic model.

I therefore went on into animal experimentation in order to determine the locus and nature of the r. f.

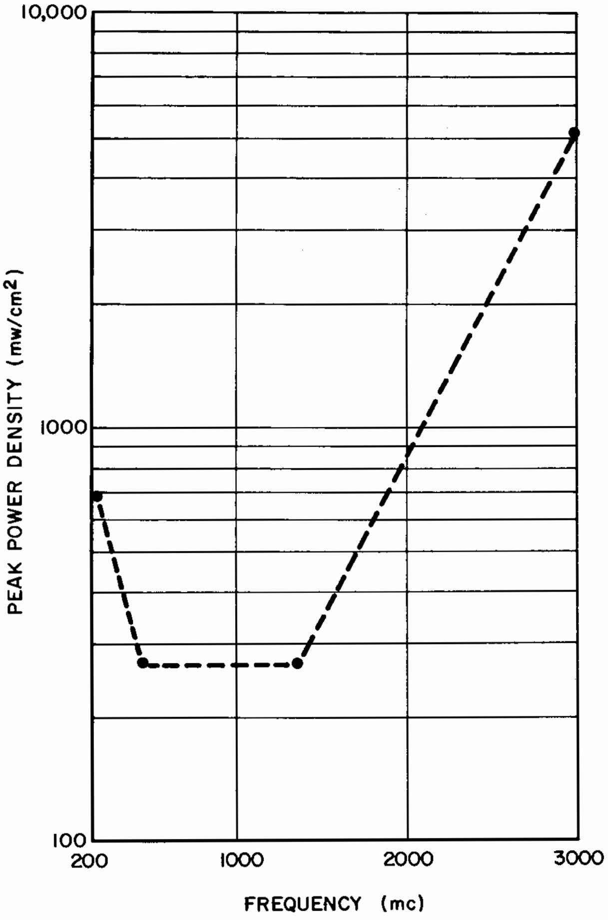

Figure 1. Thresholds for inducing the r. f. hearing effect in humans.

hearing effect. I searched for cochlear microphonics in guinea pigs and also in cats exposed to radar energy. We found that there were no cochlear microphonics in either species. Control test with acoustic energy of comparable waveform and loudness, including the alternation of acoustic and radar energy, indicated that a microphonic does not occur with the radar energy. The power densities we used were far above that needed to induce the effect in cats.

I carried the quest further by first conditioning cats to respond to radar energy cues and similar acoustic cues. I then destroyed the cochleas surgically in some cats and with neomycin in other cats. Unfortunately, the results of this study are not complete. I had borrowed the use of a transmitter whose characteristics were of particular interest to me and used it as the radar source. Just as I reached the final stage of the experiment, the transmitter was taken away on two days notice to be used in southeast Asia. We found though, in a crash effort, that the response to acoustic energy was lost. In some cats, the response to radar seemed to be there. We did a limited amount of cochlear histology and found the intended damage. No conclusions, however, should be drawn. Behavioral research with deafened cats is difficult at best. I wish to only point out that such work with radar can be done and that I shall complete it.

Concurrently with the foregoing work, we pursued another line to obtain suggestions as to the locus of the r. f. hearing-sensing mechanism. Using energy threshold levels obtained for the hearing effect in humans, we mathematically traced the r. f. energy through a mathematical model for forehead tissue layers. We felt that knowing where the signal strengths crossed in our mathematical model would enable us to make a reasonable judgment as to where to look in the animal for the sensing mechanism. In constructing our model, we picked all tissue electrical values in advance, used standard values for tissue thickness, and took into consideration only first reflections. Our calculations indicate that the first r. f. energy crossing is in the brain. It is emphasized that this should not be construed as proof. It is only a suggestion to guide research. As one of this afternoon's speakers can prove, the result of such calculations can at best be considered a research suggestion.

As an aside and incidental to the foregoing work, I noticed that headaches appeared to be induced at some frequencies at low power levels. A limited amount of exploration leads me to believe that the headache effect is probably real, but it requires verification. Thus, it is mentioned here only as a hypothesis for research.

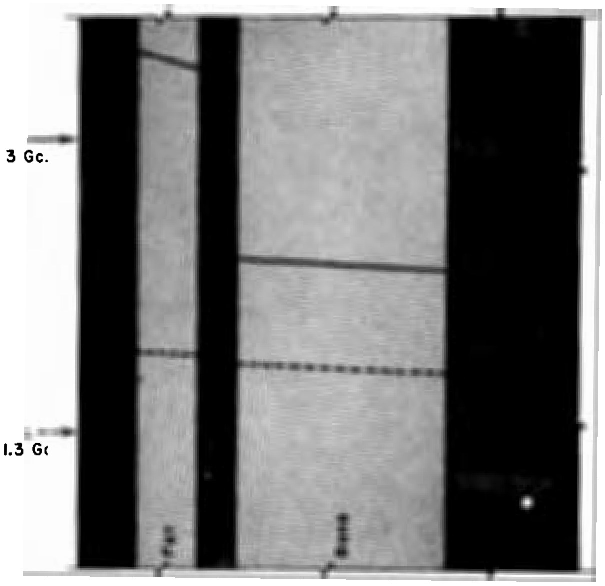

Figure 2. Calculated energy penetration through a head model at two carrier frequencies. The level at the entrance to the skin indicates the difference in threshold power density needed to induce the r. f. hearing effect.

I shall now leave the r. f. auditory effect and mention some other experimentation we have done. We have carried out experimentation with cats in which we established avoidance conditioning. We have also established r. f. thresholds for this in cats. I have also seen indications of avoidance behavior in monkeys though at relatively high power densities.

Since there were suggestions in some of the experiments that we might be modifying level of consciousness, we carried out limited experimentation with monkeys to determine if r. f. energy can modify level of consciousness. We found, at the frequency used, no drastic changes in level of consciousness as measured by a standard behavioral technique.

We also embarked upon a program to develop a recording electrode system that could be used in any r. f. field and would not itself introduce artifacts. We found that conventional electrode systems tend to give interesting but questionable results. This endeavor was successful and we have a patent pending on the electrode system.

With this electrode system, we were able to study brain activity in intact cats under r. f. stimulation.

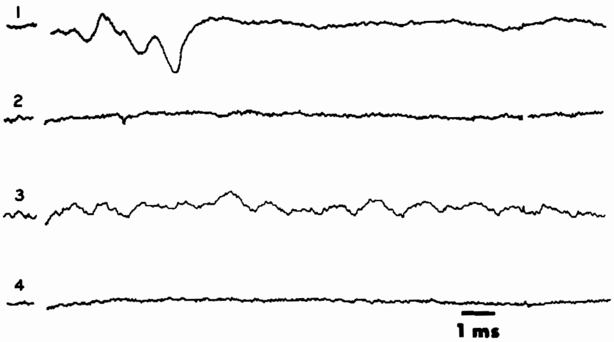

Figure 3. Traces 1 and 3 are typical evoked responses induced in live cats by r. f. energy. Traces 2 and 4 are from the cats within minutes of death but with r. f. energy illumination as when 1 and 3 were recorded. Traces 1 and 2 are from an electrode implanted in the hypothalamus and 3 and 4 from the reticular system. The break in the early part of the traces marks the occurrence of the r. f. pulse.

As may be seen in Figs. 3 and 4, evoked responses can be induced in the brain stem at average power densities of 30 mW/cm$^2$. Their characteristics in the reticular formation and hypothalmic areas are as one might expect from what we know about evoked responses in general. The details of technique and experimental controls are published.

With an electrode system and the evoked response as a dependent variable, we were able to do parametric studies. We found that the head must be exposed to r. f. energy for the effect to occur. It was observed that within the carrier frequency range used, there appeared to be a reduction in effect at the highest frequency used. Varying power density had a distinct effect. Changes in polarization of the energy did not seem to have much effect. Changing pulse repetition frequency does not seem to matter until the PRF is greater than 50 pps.

Leaving the evoked brain potential work, I will mention briefly several limited studies we have done. In limited experimentation with humans, at VLF, we have found that there is no auditory effect, even at very high field strengths. There is, however, stimulation of skin receptors. There is also an indication of the headache phenomenon again.

We have carried out exploratory work in brain chemistry under r. f. energy and have also looked at the effect of r. f. energy on isolated lobster ganglia. There is insufficient data, however, to discuss any effect.

So much for a mention of our several more recent exploratory experiments. Our work with the heart has been more extensive. I shall now briefly sketch the nature of our heart experimentation. Initially, we irradiated isolated frog hearts with pulse modulated r. f. energy. The pulses were synchronized with the electrocardiogram in an attempt to induce a positive feedback condition. We found that synchronizing the r. f. pulses with the *R* wave resulted in tachycardia and frequently arrhythmia and cessation of the heart. Synchronizing it with earlier portions of the ECG resulted in little effect on ECG.

We have extended this heart work along several lines. We have synchronized the r. f. energy with the later portions of the ECG. We find a tachycardia effect when we synchronize with the *T* wave but the effect is greater when we hit the heart at the *R* wave. Here, again, we see a distinction between the effect of electrical shock and the effect of r. f. energy. Studies with electrical shock show that the application of the stimulus at the rise of the *T* wave yields the greater effect. This is not the point of greatest r. f. energy.

We have also extended the heart work to include irradiating the animal with the heart intact and within the body. We find that tachycardia and arrhythmia still occur. The effect is not as great however. We are currently trying to determine if this is due to increased field distortion or one of the body's buffering systems.

We are also evaluating the nature of the change in the electrocardiogram. We observe shifts in the time relationships among various portions of the ECG, but have not had time to analyze the nature of the shifts.

I shall close by calling attention to several points that I believe to be of importance.

First, let us ignore the thermal versus nonthermal controversy. If it would be in my power, I would

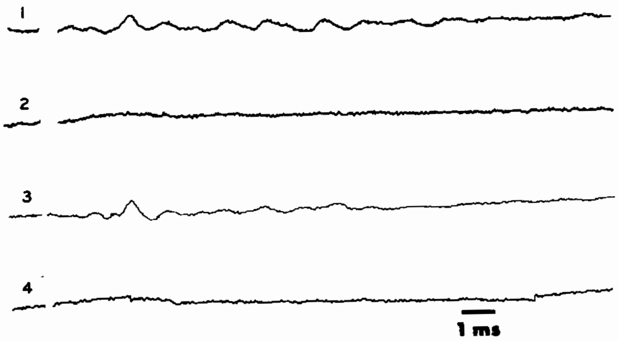

Figure 4. Traces 1 and 3 are typical evoked responses induced in live cats by r. f. energy. Traces 2 and 4 are from the same cats with echosorb shields interposed between the head and r. f. antenna to prevent the energy from reaching the head.

banish the words thermal and nonthermal from this area of research. We have had enough of semantic confusion. If one feels a real need to use the word thermal, then one has the obligation to make very clear how he is defining thermal. Then, when the inevitable argument starts, his opponent is obligated to provide a definition.

Second, we should recognize explicitly that we know very little about the function of the nervous system. We know even less about the possible interaction of r. f. energy with neural function. We should keep clearly in mind that we do not know how information is coded in the nervous system. We do not know how information is stored in the nervous system. Thus, we cannot conclude from calculations based upon some set of assumptions what effect r. f. energy will have on neural function. Nor can we draw conclusions on the function of systems such as the cardiovascular and endocrine which involve a measure of neural control. Hypotheses can and should be generated, but no conclusions drawn. These hypotheses must then be subjected to experimental test.

Third, parametric studies must be carried out and experimental controls must be recognized and used. Most of my experimental work has not been in the r. f. area. On the basis of my experiences, I have concluded that biological experiments with r. f. energy have an unusually great number of pitfalls. Many parametric studies are needed and extraordinary (for biology) experimental controls are needed.

Fourth, let us recognize, at least in working with the nervous system and heart, that r. f. energy is not "RF" energy and microwaves are not "MICROWAVES." One should not generalize conclusions based upon data at one frequency by referring to "microwave effects." We must define the specific frequency. For example, I have found that one does not obtain at 9 GHz the same effects that occur at 1 GHz. And there are other effects at 21 kHz.

Fifth, it should be explicitly recognized that there is not a category of r. f. effects and a category of r. f. hazards. One can only have biological effects of r. f. Whether or not these are a hazard is a matter of interpreting the influence of the effects in a particular set of circumstances.

Sixth, we must establish the minimum information on experimental method and technique that must be reported. Some of the most basic information, even in American reports, is lacking. I have experienced great frustration in writing the analytical reviews that I have done in this area because of this. For example, carrier frequency is often specified as simply X band or SHF. There is often no indication as to whether the energy was modulated or not. R. f. measurement technique is often not spelled out. It must be spelled out if one is to evaluate the report. Even with the best equipment and technique, the confidence limits for a measurement are wide; i.e., an order of magnitude.

This is compounded by investigators using dissimilar techniques. For example, one investigator measures the temperature of a glass of water while another investigator measures thermistor response as seen by a power meter. In theory, some comparisons can be made and conclusions drawn; in fact, such comparisons are strained and tenuous. We must establish standard measurement techniques and standardize the units in which they are reported.

The foregoing has been a limited history of the area, a brief sketch of my experimentation, and some points that I believe to be worthy of attention.

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# CLINICAL AND HYGIENIC ASPECTS OF EXPOSURE TO ELECTROMAGNETIC FIELDS

## (A Review of the Soviet and Eastern European Literature)[1]

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## INTRODUCTION

It has long been apparent that electromagnetic fields impose a health hazard, especially at field intensities greater than approximately 15 mW/cm$^2$, which cause thermal (heating) responses in the organism. Only quite recently it is suspected, from the Soviet and East European literature, that these fields might also elicit certain functional or so-called "specific" responses, especially in the nervous system, at field intensities less than 10–15 mW/cm$^2$, which do not cause heating.

Prior to 1964, no comprehensive effort had been attempted in this country to review the world (especially the Soviet and East European) literature on the general biological effects of microwaves. Soviet literature was in most cases scattered, quite difficult to locate, and consequently had never come to the attention of the U.S. scientific community. When in 1964, one of the first reviews on this subject was attempted by the writer, then affiliated with the Library of Congress, it was speculated by some authorities on the subject that an extremely low yield of literature would result from the attempt. It was therefore quite surprising that a search of the Soviet and Eastern European literature on the biological effects of microwaves revealed a large and virtually unexploited body of information which had never come to the attention of the U.S. scientific community. The first review (1) contained 132 references to Soviet and East European work on this subject. Subsequent reviews by the author (2–4) and a number of others (5–9) revealed that some of the most active research in the world was being conducted in the Soviet Union and some of the Eastern European countries.

It is the purpose of this paper to review Soviet and Eastern European studies of the effects of radiofrequency fields on the human organism. An attempt will be made to summarize the more noteworthy findings of some of the literally hundreds of published works devoted to this subject and to underscore the need for a more critical and systematic treatment of this subject. This review will concentrate nearly exclusively on human clinical studies and occupational hygiene surveys and will not consider the more theoretical or experimental aspects of the biological effects of microwaves.

## BACKGROUND

As early as 1933, certain Soviet scientists had already recognized that electromagnetic fields affected the human nervous system. In 1937, Turlygin (10) published one of the first comprehensive Soviet accounts of the effects of centimeter waves on the human central nervous system. He found that CNS excitability was increased by 100% of the control level when a crude spark oscillator in the vicinity of the head of a subject was switched on. In a lengthy review article, Livshits (11) cited no fewer than 28 Soviet publications on the general subject of clinical and biological microwave effects which had been published by the end of the 1930's.

During the 1940's and early 1950's, there was an understandable lull in research on this subject due to World War II. By the middle and late 1950's, there appeared a veritable deluge of Soviet literature dealing, in the main, with the clinical and hygienic aspects of microwave exposure which has continued unabated to this day. By the early 1960's, the Eastern European countries of Czechoslovakia and Poland had also become extremely active in the area of microwave exposure effects. In a cursory

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[1] The views expressed by the author do not necessarily represent those of the U.S. Navy.

search of the Soviet and Eastern European literature on this subject alone, a total of about 100 publications authored by 75 researchers was found and this figure is probably a conservative reflection of the available works which are estimated to be several hundred.

In an attempt to summarize the prolific Soviet and Eastern European work on clinical and hygienic aspects of exposure to microwaves, it became apparent that a number of human systems and functions had been documented to be affected by this factor (Table 1). By far the most frequently and repeatedly reported human responses to microwaves involve the central nervous system. These responses have been noted for a wide range of frequencies (~30–300,000 MHz) at both thermogenic ($>10$ mW/cm$^2$) and nonthermogenic (microwatts to milliwatts/cm$^2$) intensities.

An often disappointing facet of the Soviet and East European literature on the subject of clinical manifestations of microwave exposure is the lack of pertinent data on the circumstances of irradiation; frequency, effective area of irradiation, orientation of the body with respect to the source, waveform (continuous or pulsed, modulation factors) exposure schedule and duration, natural shielding factors, and a whole plethora of important environmental factors (heat, humidity, light, etc.) In addition, the physiological and psychological status of human subjects such as health, previous or concomitant medication, and mental status is also more often than not omitted. These variables, both individually and combined, affect the human response to microwave radiation. Despite these omissions, however, the reviewer cannot help but be impressed both by the consistency of the findings and the large size of Soviet and East European clinical and hygienic surveys which have involved literally thousands of people over the past 20 or more years.

TABLE 1

*Effects of electromagnetic radiation on the human organism*

I. Central Nervous System
II. Autonomic Nervous System
III. Neurohumoral Systems
IV. Endocrine Glands and Functions
V. Eye and Ocular Functions
VI. Blood and Hematopoietic Systems
VII. Miscellaneous Organs

## CLINICAL MANIFESTATIONS OF EXPOSURE TO RADIOFREQUENCY FIELDS

### *General Clinical Syndromes*

Many Soviet clinical workers have attempted to categorize the chronological stages of human responses to microwaves. Panov et al. (12) proposed three categories or stages of responses to microwaves (Table 2). These were listed as the asthenic syndrome, characterized by fatigue, depression, and a number of other changes. This first stage is not marked by severe episodes such as fainting or dramatic changes in pulse or blood pressure and the subject responds to outpatient treatment. The second category is called the "syndrome of autonomic and vascular dystonia". The essential feature of this stage is pulse lability (brady- and tachycardia), blood pressure lability (hypo- or hypertension), EKG changes, and general neurocirculatory asthenia. Severe episodes such as fainting spells may occur and the subject requires hospitalization of unspecified nature or duration. The third stage is referred to as the diencephalic syndrome in which visceral dysfunctions and crises are observed. Typical episodes during this stage are listed as "apathic ambulic" disorders, hypersomnia, hypokinesis, hypothalamo-pituitary-suprarenal weakness, and inhibition of sexual and digestive reflexes. Panov claims that these changes are not always reversible and that subjects require hospitalization. It should be noted that Panov did not specify the nature or duration of outpatient or hospital treatment, nor did he relate these symptoms to specific irradiation parameters.

### *General Subjective Complaints* (*Indirect Effects on the CNS*)

A large number of East European and especially Soviet clinical and hygienic workers (13–22) have consistently and repeatedly documented an astonishing number of subjective complaints which are usually referred to as evidence of the direct or indirect effect of microwaves on the central nervous system (Table 3). These responses have been reported for a wide range of wavelengths (30–300,000 MHz) and field intensities (microwatts to several milliwatts/cm$^2$). Unfortunately, it is often difficult to attach any significance to Soviet clinical findings in the absence of pertinent data on exposures and on patient backgrounds. Typical, for instance, was a survey conducted by Sadchikova (21) in which three groups of occupational personnel (technicians, assemblers, and maintenance workers around centi-

TABLE 2

*Soviet classification of general clinical syndromes of exposure to electromagnetic radiation EMF's*

A. The Asthenic Syndrome (reversible; outpatient treatment)
   1. fatigability and emotional changes
   2. acrocyanosis
   3. increased perspiration of extremities
   4. increased pilomotor reflex
   5. dermographism
   6. pulse lability
   7. blood pressure lability

B. Autonomic Cystonia (reversible; hospitalization)
   1. hyper- or hypotension
   2. bradycardia and tachycardia
   3. changes in EKG signs
   4. fainting spells

C. Diencephalic Syndrome (usually reversible; hospitalization)
   1. insomnia
   2. adynamia
   3. hypothalamo-pituitary-suprarenal inhibition
   4. inhibition of sexual function and digestive reflexes

meter wave generators) were exposed to: (1) periodic intense radiation (3–4 $mW/cm^2$); (2) moderate radiation (tenths of $mW/cm^2$); and (3) weak radiation (hundredths-tenths of $mW/cm^2$). As can be seen in Table 4, the group exposed to the weakest radiation was shown to display the highest incidence of complaints. This finding and lack of pertinent exposure data such as duration and affected body area make these data difficult to accept on face value. On the other hand, Edelwejn (14) has conducted interesting and comprehensive neurological examinations and interviews of Polish personnel exposed for up to six hours/day to microwave field intensities of 10 microwatts to several $milliwatts/cm^2$. He found that many of the subjective complaints listed in Table 3 (headaches, dizzy spells, fatigue, perspiration, etc.) depended upon the length of employment and degree of exposure. Only subjects exposed to high ($mW/cm^2$) intensities exhibited EEG changes. Edelwejn was of the opinion that there is a dramatic response to microwave exposure occurring during the first three years which are accompanied by neurotic symptoms. This three year period is followed by a phase of gradual adaptation. The reappearance of neurologic symptoms occurs after a long period (many years) of exposure to microwaves, even after adaptation has occurred.

Osipov (1965) (20) in a review of neurologic responses to microwave exposure concluded that most subjective symptoms were reversible and that pathological damage to neural structures was insignificant. Only rarely were microwaves found to cause hallucinations, syncope, adynamia and other manifestations of the so-called "diencephalic" syndrome.

Soviet workers have also documented subjective complaints identical to those in Table 3 as a result of exposure to electric and magnetic fields. Vyalov et al. (23) reported characteristic microwave symptoms such as headache, fatigue etc., in workers exposed to 150–1500 oersted magnetic fields. Asanova (24) reported analagous findings for workers exposed to 115–125 microampere fields around hydroelectric stations.

*Functional Changes in the CNS*

Many Soviet and Eastern European workers have attempted to identify specific CNS functional responses to microwave exposure. Most Soviet workers are of the opinion that the CNS is the most sensitive of all systems to the effects of microwaves, both at thermogenic and nonthermogenic field intensities. Based primarily upon experimental research, Presman (9) is of the opinion that the hypothalamus is the most sensitive CNS structure to microwave effects which would explain, in his view, the high incidence of blood and humoral changes noted in human subjects exposed to this factor.

Changes in human CNS function have been evaluated on the basis of EEG surveys, reflex tests, and general neurological examinations (Table 5). These changes are reported for a wide range of frequencies and field intensities (thermal and nonthermal). However, functional CNS responses appear to be de-

TABLE 3

*General subjective complaints resulting from exposure to electromagnetic radiation*

1. Pain in head and eyes
2. Lacrimation
3. Weakness, weariness and dizziness
4. Depression, antisocial tendencies, general irritability
5. Hypochondria, sense of fear, and general tension
6. Impairment of memory and general mental function
7. Adynamia and inability to make decisions
8. Inhibition of sex life (male)
9. Scalp sensations and loss of hair
10. Chest pain and heart palpitation
11. Dyspepsia, epigastric pain, and loss of appetite
12. Trembling of eyelids, tongue, and fingers
13. Asthma
14. Brittle fingernails
15. Sensitivity of mechanical stimulation and dermographism

TABLE 4

*Changes in the nervous system as a result of exposure to microwaves*

| | | Changes observed (in % of subjects studied) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Group | No. examined | Headache | Increased fatigue | Increased irritability | Sleepiness | Delayed dermorgraphism | Slowed orthostatic reflex | Wrist hyperdrosis | Thyroid hypertrophy |
| 1 | 184 | 12 | 20 | 8 | 2 | 16 | 19 | 6 | 15 |
| 2 | 129 | 39 | 31 | 12 | 14 | 7 | 21 | 37 | — |
| 3 | 78 | 36 | 31 | 15 | 19 | 14 | 11 | 26 | 52 |
| Control | 100 | 8 | 10 | 8 | 2 | — | — | 4 | 14 |

pendent upon wavelength; direct effects on the brain were reported by Gordon (1964) (25) and Presman (9) to intensify with increase in wavelength. However, when reactions are due to a combination of peripheral and direct stimulation, it is impossible to correlate response with wavelength.

A number of workers have reported changes in EEG patterns as a result of exposure to microwaves. Klimkova-Deutschova (26), a Czechoslovakian researcher, reported that both clinical and EEG findings suggested a predominance of an inhibition process. EEG's showed a predominance of sleep rhythms. In this connection, the interesting (if rather curious) work of Ivanov-Muromskiy (27), a Soviet expert on electrosleep and electroanesthesia deserves comment. His research on human subjects suggested that pulsed (10–1000 Hz) UHF fields of nonthermal intensity directed from bitemporal electrodes a few inches from the subject's head could induce inhibition similar to that produced by pulsed electrical currents (electrosleep). Unfortunately, this research was not described in detail by Ivanov-Muromskiy.

TABLE 5

*Functional CNS changes resulting from exposure to electromagnetic radiation*

1. Changes in EEG patterns
   a. "asthenic" signs
   b. predominance of inhibition process
   c. increased incidence of slow, high amplitude waves
   d. decreased incidence of alpha rhythms and waves
   e. predominance of "sleep" rhythms
2. Perceptual changes
   a. hallucinations (visual)
   b. decrease in ocular blind spot area
   c. shortening of optic chronaxie and reduction of rheobase
   d. auditory sensitivity changes
   e. decreased olfactory sensitivity
   f. increased olfactory activity
   g. parapsychologic phenomena
3. Alternating arousal and drowsiness
4. Stimulation of motor functions
5. Depression of mental functions
6. Involuntary motor reactions

Drogichina (13) reported that CNS damage is characterized by the "asthenic syndrome" which can be detected from EEG and neurological findings. Presman (9), in reviewing Soviet, Czechoslovakian, and Polish work, reports that the EEG's of subjects exposed to weak (nonthermal) microwave field intensities show an increased incidence of slow, high amplitude waves. In Poland, Edelwejn and Baranski (14) reported a decreased incidence of alpha rhythms and a decreased percentage of alpha waves in subjects exposed to "high" (mW/cm$^2$) intensities of microwave fields. All subjects examined in this study over-reacted to the administration of cardiozol, a respiratory and cardiac stimulant. In general, because of the rather primitive state-of-the-art of EEG analysis, these findings should be viewed with extreme caution.

Perceptual changes as a result of exposure to microwaves have also been frequently reported. Livshits (28) reported that "high intensity" microwaves had been found by Soviet workers to cause hallucinations. He also reported that high frequency, high intensity fields had been demonstrated to cause involuntary motor reactions in one healthy individual. Matuzov (29) noted visual perception changes after a 10 minute exposure to 10 cm microwaves of nonthermal (1.1 mW/cm$^2$) intensity. He found a considerable decrease in blind spot area,

TABLE 6

*Autonomic and cardiovascular effects of electromagnetic radiation*

1. Changes in cardiac function (EKG)
    a. decreased spike amplitude
    b. lengthened QRS interval
    c. slowed auricular and ventricular conductivity
2. Bradycardia and tachycardia
3. Hyper- and hypotension
4. Increased precapillary resistance
5. Increased vascular elasticity

shortening of optic chronaxie, and reduction of rheobase in two subjects. These effects were judged to be nonthermal (specific) and were found to be reversible. Sheyvekhman (30) noted changes in auditory sensitivity (5–10 dB) in response to 6 meter waves pulse modulated at 300, 1000, or 4000 Hz applied for five minutes to the heads of human subjects. He did not clarify whether sensitivity was increased or decreased. Lobanova and Gordon (31) noted a decrease in olfactory sensitivity after exposure to microwaves and suggested that this response might be a good index for identifying harmful microwave effects. These authors also found an increase in olfactory excitability (decreased threshold) after a single dose of caffeine. This was suggested as evidence of functional olfactory changes caused by microwaves.

In the realm of parapsychology, it is interesting to note that leading Soviet researchers who strongly believe in the nonthermal CNS effects of microwaves are involved in the electromagnetic (centimeter wave) theory of extrasensory perception (3). This work, initiated in 1966, is being conducted for a special Bioinformation Section of the Scientific and Technical Society of Radiotechnology in Moscow. The results of Soviet ESP research have thus far been interesting but statistically inconclusive.

Both the stimulatory and inhibitory effects of microwaves on CNS function have been frequently documented by Soviet workers. Subbota (32) reported alternating arousal and drowsiness in response to microwaves in working with dogs. As mentioned earlier, the Soviet electrosleep expert, Ivanov-Muromskiy (27) concluded from his studies of human subjects that pulsed UHF fields could be used as a form of contactless electrosleep which he calls "radiosleep". Depression of mental function, inability to concentrate, and general sluggishness is frequently documented by Soviet and Eastern European researchers as a subjective response to microwave exposure.

### *Autonomic and Cardiovascular Responses*

Reports of human autonomic and cardiovascular responses to microwaves are nearly as numerous as those documenting CNS responses to this factor (Table 6). Responses are noted for a wide range of frequencies at thermal and nonthermal field intensities and during acute and chronic exposure. Decreased EKG spike amplitudes have been noted by Drogichina (33) in subjects working around radiofrequency fields. Sadchikova (34) reported on various cardiovascular shifts in workers exposed to different field intensities (Table 7). Figar (15) and Smurova (35) have noted decreased coronary conductivity, sinusoidal arrythmia, brady- and tachycardia, and oscillating hypo- and hypertension. Monayenkova et al. (36) studied minute blood volume, peripheral resistance, average arterial pressure, and smooth muscle tonus using a mechanocardiograph. She found that a tendency toward hypertension, increased elasticity of myogenous vessels, increased precapillary resistance, sinus bradycardia, and changes in intracardiac conductivity were more often noted in exposed than in unexposed subjects. All of these changes were found to be reversible with one or two questionable exceptions.

There is some evidence that certain enzymes implicated in CNS function might be affected by exposure to microwaves (Table 8). Revuts'kyy et al. (37) found a change in the specific cholinesterase activity of erythrocytes in human whole blood with 13.56 and 23.75 MHz microwaves. The 13.56 MHz radiation was found to decrease blood histamine content while not altering cholinesterase activity. The 23.75 MHz radiation did not change blood histamine content but increased cholinesterase activity. Bartonicek et al. (38) surveyed the blood biochemistry of workers exposed to centimeter waves. Of a total of 27 blood sugar curves, 7 were flat, 7 were prediabetic, and four indicated slight glycosuria. The distribution of pyruvic and lactic acid and creatinine are shown in Table 9. Lactic acid was found to be decreased 2.5 times more than it was found to be increased. Roughly 75% of the subjects exposed to microwaves and examined by Bartonicek were reported to have prediabetic blood sugar curves. These metabolic shifts were attributed to autonomic dysregulation, possibly indicative to diencephalic lesions resulting from early exposure to centimeter

TABLE 7

*Cardiovascular changes in subjects exposed to electromagnetic radiation (Sadchikova, 1964)*

| | EMF parameters | Exposure/control ratio | | |
|---|---|---|---|---|
| Range | Field intensity | hypertonia | bradycardia | increase of QRS interval (up to 0.1 sec) |
| SHF | 1-several mW/cm$^2$ | 1.85 | 24.0 | 11.5 |
| | 1 mW/cm$^2$ | 2.0 | 16.0 | 12.5 |
| UHF | nonthermal | 1.2 | 8.0 | 21.0 |
| LF | tens to hundreds V/M | 9.21 | 12.0 | — |
| | hundreds to 1000 V/M | 1.2 | 5.0 | — |
| Percent incidence in controls | | 14% | 3% | 2% |

waves. Gel'fon and Sadchikova (39) noted increased blood globulins in 50% of a group exposed to microwaves which indicated a shift in the albuminglobulin coefficient. Haski (40) noted slight changes in the levels of blood sugar, cholesterol, and lipids of healthy subjects exposed to microwaves. However, there was a pronounced decrease in all three categories when diabetics were exposed.

### *Hematopoietic and Biochemical Responses*

Numerous human hematopoietic changes have been reported to result from exposure to microwave fields (Table 10). The severity of these changes range from minimal to significant. Sokolov (41) noted reticulocytosis in radar workers. Baranski (42) observed that a small drop in erythrocytes occurs in all people exposed to microwaves and that the phenomenon is related to the duration and severity of exposure. About 50% of the subjects examined by Baranski showed a moderate decrease in platelet count. Lysina (43) noted basophilic granularity of erythrocytes and was of the opinion that this index should be taken as an initial sign of microwave effects on the human organism. Presman et al. (44) found that the osmotic resistance of erythrocytes was negatively affected by microwaves. Smurova (22) and others found that the shape and volume of erythrocytes changes as a result of exposure to microwave fields. Prolonged exposure was occasionally noted to result in hemolytic processes. An increase in the RNA level of lymphocytes was also noted by Smurova in workers chronically exposed to microwaves; this finding corresponded to a concomitant increase in monocytes (young cells) which contain the greatest quantity RNA. Baranski (42) detected various leukocyte shifts in workers exposed for one year to microwaves. Normalization of this index was found to occur after prolonged exposure to this factor. He also found a tendency towards lymphocytosis with accompanying eosinophilia in subjects exposed for more than five years to low and moderate microwave intensities.

TABLE 8

*Neurohumoral responses to radiofrequency electromagnetic radiation*

1. Altered cholinesterase activity in human whole blood (erythrocytes)
2. Decrease in blood histamine content
3. Increase in blood proteins
4. Altered carbohydrate metabolism
5. Changes in blood sugar, cholesterol, and lipids (pronounced in diabetics)
6. Decreased hemoglobin

Soviet workers have also found biochemical changes to occur in other sites (8). A drop in RNA content was noted in the spleen, liver, and brain in animals chronically exposed to microwaves while DNA content was found to remain constant.

### *Ocular Responses*

Changes in human ocular function and eye pathology are widely documented and occur primarily

TABLE 9

*Distribution of pyruvic and lactic acid and creatinine excretions in workers exposed to microwaves*

| | Pyruvic acid | | Lactic acid | | Creatinine | |
|---|---|---|---|---|---|---|
| | number | % | number | % | number | % |
| No. of measurements | 40 | 100.0 | 35 | 100.0 | 34 | 100.0 |
| Normal | 28 | 70.0 | 14 | 40.0 | 14 | 41.2 |
| Increased | 4 | 10.0 | 6 | 17.2 | 6 | 17.6 |
| Lowered | 8 | 20.0 | 15 | 42.8 | 14 | 41.2 |
| Averages | 0.77 mg% | | 14 mg% | | 1.33 mg% | |
| Controls | 0.65 mg% | | 17 mg% | | 1.30 mg% | |
| Established standard | 0.5—1.0 | | 10—20 | | 1.2—1.9 | |

after acute or chronic exposure to thermogenic microwave intensities (Table 11). As mentioned earlier, one Soviet worker (28) has reported that exposure to intense microwave fields was noted to cause hallucinations. Matuzov (29) found the area of the blind spot to decrease after exposure to nonthermogenic (10 cm; 1.1 mW/cm$^2$) microwave field intensities. Other Soviet workers, as reported by Marha (8), have found that microwave radiation (a few mW/cm$^2$) can cause a decrease in sensitivity to color (blue) and difficulty in detecting white objects. Changes in intraocular pressure have also been noted by Soviet workers as have altered sensitivity to light stimuli during exposure to pulsed and nonpulsed fields. General ocular pain, eye strain and fatigue, eyelid tremor, and lacrimation are also common symptoms noted by Soviet workers.

Pathological changes in the eye (cataracts) occur primarily as a result of exposure to thermogenic (greater than 10 mW/cm$^2$) microwave intensities. Sadchikova (45) and other Soviet workers (6) have noted unilateral and bilateral cataracts to occur in subjects exposed to several mW/cm$^2$ field intensities. Presman (44) noted a drop in vitamin C content in the lens and anterior chamber fluid at nonthermogenic intensities. In the event of acute cataract development a decrease in ATP and pyrophosphatase activity of the lens was noted. In addition, it is suspected that damage to tissue respiration and oxidation mechanisms as a result of exposure to microwaves can lead to cataract formation.

There is some evidence that ocular responses to microwaves are frequency dependent. Pol (46) noted that 10 GHz fields caused anterior lens opacity while 2.45 GHz cause posterior opacity.

Belova (47) noted that in 370 microwave generator workers exposed to mW/cm$^2$, lacrimation, ocular fatigue, and frequent conjunctival irritation would occur at the end of each working day. Zydecki (48) suggested that all candidates for occupation around microwave sources receive comprehensive ophthalmological examinations. This suggests that certain ophthalomological profiles might be more vulnerable to microwave radiation than others.

TABLE 10

*Hematopoietic and biochemical responses to electromagnetic radiation*

1. Blood
    - a. reticulocytosis
    - b. basophilic granularity of erythrocytes
    - c. decrease in erythrocytes, platelets and hemoglobin
    - d. altered osmotic resistance of erythrocytes
    - e. neutrophilic leukocytosis
    - f. lymphocytosis, monocytosis, and eosinophilia
    - g. increased RNA in lymphocytes
2. Organs
    - a. Decreased RNA content in brain, liver, and spleen

### *Endocrine Responses*

Damage to sex glands and functions have frequently been documented to occur after chronic exposure to primarily thermal microwave fields (Table 12). Marha (8) in reviewing Soviet and East European findings noted decreased spermatogenesis, altered sex ratio of births, changes in menstruation, retarded fetal development, congential effects in newborn babies, decreased lactation in nursing mothers, and other related responses to occur as a result of exposure to thermal (i.e., greater than 10 mW/cm$^2$) microwave intensities. Microwaves were also implicated in an increase in the percentage of miscarriages in both humans and animals. Some of these findings reported by Marha are consistent with subjective complaints reported by Soviet researchers such as decreased sex activity, mentioned earlier. Specific genetic changes resulting from exposure to either thermal or nonthermal microwave fields have yet to be demonstrated.

TABLE 11

*Effects of electromagnetic radiation on the eye*

1. Perceptual and function changes
   a. hallucinations
   b. decrease in size of blind spot
   c. decreased sensitivity to color (blue)
   d. difficulty in detection of white objects
   e. decreased sensitivity to light stimuli in dark adapted eye
   f. change in intraocular pressure
   g. lacrimation, ocular fatigue, and ocular pain
   h. trembling of the eyelids
   i. altered tissue respiration and oxidation-reduction processes
2. Pathological changes
   a. lens coagulation (cataracts)
   b. decrease in vitamin C content of lens and vitreous humor
   c. decrease in ATP and pyrophosphinatase activity
   d. anterior and posterior lens opacity
   e. conjunctival irritation

Soviet sources have reported pituitary and other endocrine responses to microwave exposure. Kolesnik (49) suggested that pituitary-hypophyseal-adrenal changes were primarily due to CNS influences on the hypophysis after exposure to microwaves. Drogichina (33, 50), Sadchikova (21, 34), and Smirnova (51) have reported thyroid gland enlargement and increased iodine-131 uptake. These changes suggest an increase in thyroid stimulating hormone (6). Hasik (40) and Presman (44) noted increased activity of the adrenal cortex to occur after microwave exposure. Murashov (52) studied 20 subjects occupationally exposed to UHF fields. He noted a reduction in plasma corticosteroid content which was attributed to lowered adrenal, or possibly sex gland androgenic activity.

TABLE 12

*Endocrine responses to radiofrequency radiations*

1. Sex organs and ontogenesis
   a. thermal trauma (tissue damage) to male reproductive tissues
   b. decreased spermatogenesis (sterility)
   c. altered sex ratio of births (more girls)
   d. altered menstrual activity
   e. altered fetal development
   f. decreased lactation in nursing mothers
2. Endocrine glands
   a. altered pituitary and pituitary-hypophyseal function (CNS)
   b. hyperthyroidism
   c. thyroid enlargement
   d. increased iodine-131 uptake
   e. increased adrenal cortex activity
   f. decreased corticosteroids in blood
   g. decreased glucocorticoidal activity

### *Miscellaneous Responses*

Loshak (53) reported that various human responses, such as subjective complaints as a result of chronic microwave exposure, appeared to vary slightly with climate (Table 13). In general, responses to microwave fields were more pronounced in hot, dry climates. It was found that the electrical resistance of the skin of exposed workers was lower than in unexposed workers in a hot climate. Decreased resistance was attributed both to CNS stimulation or increased sympathetic tonus due to skin receptor reactions. These findings, while not dramatic, led Loshak to speculate that special hygienic considerations for workers exposed to microwaves in a hot climate should be exercised (improved ventilation etc.).

TABLE 13

*Miscellaneous effects on electromagnetic radiation*

1. Climatic effects
   a. responses to electromagnetic radiation more pronounced in hot climate
   b. decreased electrical resistance of skin in hot climate due to electromagnetic radiation
2. Internal Organs
   a. dyspepsia and epigastric pain
   b. decreased appetite
   c. liver enlargement

Orlva (54) and others have reported that workers exposed to microwaves complain of decreased appetite, dyspepsia, pain in the epigastric region, and exhibit enlargement of the liver. Marha (8) in reviewing Soviet and Czechoslovakian experimental work on animals reported that exposure to microwaves was noted to cause liver hemorrhaging, hepatic cell degeneration, and decreased filtration or renal tubules. Analogous findings for humans have not been documented.

## CONCLUSIONS

The large body of the Soviet and East European clinical and hygienic findings on human responses to microwave radiation reviewed in this paper suggest that a surprisingly wide variety of neurological and physiological reactions are to be expected during exposure to nonthermal (i.e., less than 10 mW/cm$^2$) field intensities within an extremely wide range of frequencies (approximately 30–300,000 MHz). These reactions, which are generally reversible, are often documented as a result of human exposure to field intensities as low as a few microwatts/cm$^2$. They are reported to be primarily effects upon the nervous system and reflect traditionally heavy Soviet emphasis on the central nervous system. Soviet and East European findings in this area are therefore in striking contrast to those of the West which have, in the main, documented non-CNS responses to thermal (i.e., greater than 10 mW/cm$^2$) intensities. Only in the realm of human endocrine, visual, and skin receptor responses to thermal microwave burdens is any real substantive agreement between Soviet and Western findings to be found.

The substantially lower Soviet and East European daily maximum permissible dose (MPD) value for human exposure to microwave radiation (0.01 mW/cm$^2$ vs 10 mW/cm$^2$ in the U.S.) appears to be based upon extensive findings of human subjective and other CNS-related responses to extremely low microwave field intensities and upon considerable CNS-oriented research on animals conducted in those countries. These findings also indicate that extensive dosimetric surveys around industrial and military sources of microwave radiation have been conducted in those countries (see, e.g., the report of Marha in this collection), although the extent and nature of Soviet work in this specific area has not been well documented. In the general context of differing U.S. and Soviet MPD's and MPC's, it is important to note that the Soviet union has traditionally been more conservative with regard to many industrial hazards than the U.S.

Although the majority of Soviet findings on human responses to low intensity microwave fields must be regarded with extreme caution because of the omission of exposure and other pertinent data, it is suggested that the surprising consistency of this large body of findings merits the critical attention of the U.S. scientific community. Of particular interest is the relatively recent Eastern European work in this area. Research conducted in these countries, although heavily influenced by the Soviet Union in the early stages, appears to be of high quality; reflects a good awareness of both Soviet and Western approaches to the problem of the biological effects of microwaves; and suggests a trend towards more independent approaches to this problem. The fact that East European countries such as Czechoslovakia and Poland have adopted essentially the same maximum daily permissible dose for human exposure to microwaves as the Soviet Union is of interest and should be investigated in more detail. The Czechoslovakian MPD for microwaves, while admittedly (by Marha) influenced by the Soviet MPD, was arrived at only after considerable hygienic and dosimetric survey work had been conducted in that country. Nonetheless, it is suggested that until additional research on this difficult problem has been conducted in this country, and a more critical analysis of the available Soviet and East European findings has been made, a judgment of the U.S. 10 mW/cm$^2$ MPD is presently rendered difficult, if not impossible.

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# THE NEURAL AND HORMONAL RESPONSE TO MICROWAVE STIMULATION OF PERIPHERAL NERVES

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## INTRODUCTION

The United States Congress and the Armed Services have taken steps to protect the public from the known harmful effects of microwave radiation. Because of the many reports here (1–5) and in the Soviet Union (6, 7) that nonthermal effects are seen at lower power densities, there are uncertainties in deciding on a safe level of exposure. However, it is our belief that some of the observations thought to be of nonthermal microwave origin, such as modification of behavior and of hormonal balance, are actually thermal effects produced in unusual ways. For example, heating the whole animal by microwave radiation produces results which differ from those obtained when more conventional means are used (8). Subcutaneous burns frequently occur because the power distribution of a microwave field is perturbed by the presence of an animal placed in the field. Standing waves may result and some regions of the animal will be heated more than others. Evidence of the burn is often not discovered for a week or two following irradiation when a patch of skin sloughs off revealing a healing area beneath (5, 8). Not all subcutaneous burns may make their presence known. Perhaps some burns heal without skin sloughing and some animals may be sacrificed before the burn is revealed. Physiological changes may be produced by a stress response to these subcutaneous burns.

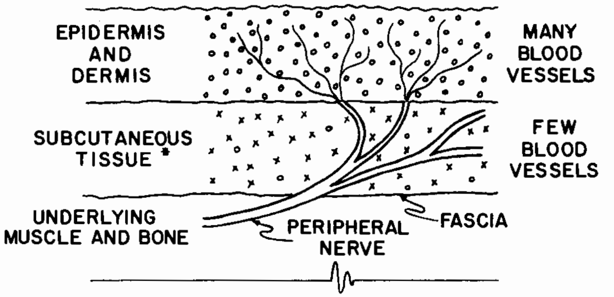
We have found that highly localized microwave induced heating can produce extensive changes in the physiology of an animal (2, 4, 9–11). With 3 cm, 10 cm, and 12.2 cm radiation in living subjects a temperature rise was produced within subdermal tissue which exceeded that produced in overlying epidermis. The well vascularized epidermis was able to dissipate the microwave induced heat, but the poorly vascularized subdermis was not able to do so as indicated schematically in Fig. 1. At temperatures below those required to produce burns, nociceptive responses were elicited. In decerebrated animals a nociceptive reflex includes the crossed extension reflex, cardiovascular reflexes and alterations in the action of the autonomic nervous system (12). We define a nociceptive response as the equivalent response that can be observed in anesthetized and unanesthetized animals. A nociceptive response can be produced with microwave irradiation by heating subcutaneous tissue to 45 °C. Since subcutaneous burns requiring higher temperatures are inadvertently produced by microwave radiation, it is obvious that a nociceptive response can be produced even when burns are not. Perhaps some of the observations made on experimental animals and taken to be evidence for a nonthermal central nervous system effect are actually the result of localized thermal stimulation.

## METHODS

The equipment used includes a hollow U-shaped cuff or thermode in which water at known temperature is circulated. An exposed peripheral nerve is placed in the thermode and the animal's respiration, blood pressure, pupillary diameter, cardiovascular system, and the like are observed as the temperature is raised at the thermode. A Sanborn Polygraph is used to follow these events. Temperature at the nerve is conveniently measured with a Yellow Spring Instrument Telethermometer and thermistors. A 12.2 cm Ratheon Microtherm apparatus and a surplus aircraft 3 cm radar were used in this study. The output at the 3 cm radar waveguide was about 200 mW at 1000 cps. The power density at the region subjected to radiation, about 6 inches away, was not determined except to note the length of time required to raise the temperature to 45 °C. Within subcutaneous tissue this temperature was reached within a few minutes. Within the epidermis, the temperature rose a few degrees and then equilibrated as the circulation carried away the heat. The animal was shielded with aluminum foil except for the area to be irradiated. This reduced the power available to the target but eliminated the possibility of stray radiation reaching other parts of the body.

## RESULTS

Areas well supplied with afferent cutaneous nerves, such as the lower limbs or face, of a decerebrated cat were irradiated. When the subcutaneous temperature reached 45°±2 °C, a powerful nociceptive reflex was produced. The blood pressure increased 50 to 60 mm Hg and the respirations became hyperpneic following a period of apnea. The crossed extension reflex was observed when the feet of the animal were irradiated. No changes were observed, however, when the subdermal region was injected with xylocaine, or if the peripheral nerve trunks serving these areas were sectioned. We believed that this response resulted solely from the temperature rise produced by absorption of microwave radiation and showed that an identical response occurred at the same temperature if the subcutaneous nerves were heated by other means such as infrared radiation, convective, or conductive heating, or if large nerve trunks were heated with a thermode or irradiated. The response was abolished when the temperature was allowed to fall below the temperature which produced it but was immediately re-elicited by raising the temperature to the critical level. In anesthetized animals, the nociceptive response was easily prolonged and the blood pressure elevation maintained for as long as one hour, but the cutaneous nerves were apparently not irreversibly harmed by the temperature required to produce and maintain the response (4). Other events were also observed. Pupils tightly constricted with Nembutal, used at anesthetic levels, dilated widely. Splenic contraction occurred in cats as did peripheral vasoconstriction (10).



*SUBCUTANEOUS REGION OF SKIN, LACKING RICH BLOOD SUPPLY OF EPIDERMIS, ALLOWS TEMPERATURE RISE TO OCCUR.

Figure 1. Schematic diagram of the skin indicating the poorly vascularized region where peripheral nerves pass from dermis to underlying muscle. A temperature rise in the subcutaneous tissue produced by 10 GHz and 2450 MHz microwave radiation elicits peripheral nerve stimulation at about 45 °C.

The possible elicitation of a nociceptive response during microwave irradiation of experimental animals may modify the results that will be obtained in a microwave experiment. We found that a cat placed in a box and heated with hot air will have its thermal equilibrium upset if a nociceptive response is superimposed on the already existing thermal stress. In dogs subjected to whole body irradiation, heat gain and loss equilibrates and body temperature stabilizes for a time. Then the irradiated animal fails to maintain thermal equilibrium and collapses. An animal heated by more conventional means can maintain temperature equilibrium for a longer period of time (8). We believe that a nociceptive response was superimposed on the hyperthermia; peripheral vasoconstriction occurred, precipitating the collapse of the animal.

Some behavioral and central nervous system effects that appear to be nonthermal microwave effects may be produced by thermal stimulation of peripheral nerves.

Our preliminary experiments indicate that cats are readily conditioned to avoid microwave radiation beamed to their head before any significant intracranial or subdermal temperature rise is observed (10). Cats were placed in a box which closed over their necks leaving the head outside. A thermistor was implanted under the skin of the forehead. The cats had been tranquilized with Librium and submitted docilely to the procedure. When 45 °C was reached in the subdermal region, the cat immediately struggled to withdraw into the box. Later, the animals which had previously experienced a nociceptive response would begin to struggle after the beginning of irradiation, well before an appreciable subdermal temperature rise was observed. We postulated that once a nociceptive response was experienced, the immediate warming of the surface of the skin by the microwave radiation during subsequent trials provided the clue for the impending unpleasant experience and the cat would begin to struggle. Perhaps microwave radiation experiments purporting to show low dose central nervous system effects should be examined with the possibility of inadvertent conditioning of the animal in mind.

The key to the thermally elicited nociceptive response is the thermally produced afferent peripheral nerve stimulation which occurs abruptly at 45°± 2 °C. This phenomenon has not been widely investigated. Prior to our investigation there were apparently no studies since one published by C. von Euler in 1947 (13). He reviewed the limited number of investigations which predated his study. It was his opinion that the nociceptive reflex (he mainly used decerebrated animals) produced by thermal stimulation (by means of a thermode) is the result of a specific thermal sensitivity of the thinly myelinated fibers of the A class delta group, and the unmyelinated fibers of the C class. He reported that the effect can be produced at any point along the axon. Large fiber activity is not elicited. It is our observation that the rise in subcutaneous temperature resulting from microwave irradiation of the skin is rapid and temperatures are reached which stimulate the C and delta fibers within nerve trunks lying within the subcutaneous region before the surface of the skin grows appreciably warm. The peripheral distribution of afferent cutaneous nerve fibers requires that for proper control of an experiment on behavior the regions to be irradiated must be carefully selected. If the back of the animal is irradiated as a control for irradiation of its head, the experiment is not properly controlled. If one wishes to eliminate the possibility of peripheral stimulation and the contribution of a nociceptive response, irradiation of the lower leg of an animal is preferred since many peripheral nerves are present in the lower limbs and face of the animal, but few are present in the back.

The adrenal medulla plays an important role in the nociceptive response. In dogs, Dibenzylene blocks the increase in blood pressure seen when the nociceptive response is elicited (2). In cats, adrenalectomy also blocks the blood pressure rise, but not pupillary dilatation (10) as shown in Fig. 2. Adrenal medullary secretion may also initiate adrenal cortical activity, or the latter may be independently elicited. The thyroid may also be stimulated as a factor involved in the response. In preliminary experiments, we have observed changes in the composition of the blood suggestive of the response to stress. Since stress is among those phenomena presumably characteristic of non-thermal microwave effects, we believe that it would be worth considering its origin as the result of a nociceptive response.

Hormonal release may be helpful to the unanesthetized animal in a fight or flight situation, but secretion of adrenalin may yield unanticipated effects when coupled with the anesthesia used in microwave experiments. Cardiac arrhythmias have been observed as a result of microwave irradiation of anesthetized animals and have been attributed to the nonthermal microwave effect. We have preliminarily investigated whether cardiac abnormalities may be inadvertently produced by the combination of certain anesthetics and the systemic release of adrenalin. Chloroform and similar anesthetics are well known for this effect.

Animals have been aroused from anesthesia by microwave irradiation of the head. Speculation on the possibility that microwave radiation may be used to increase alertness of servicemen during battle was communicated to us by members of the Armed Services. The fact that the Russians were also reported to be investigating the arousal effect of microwave irradiation lent some urgency to the request that we investigate this phenomena. We found that the analeptic effect of microwave radiation can be duplicated by irradiating regions other than the head. We irradiated the feet of cats, dogs, rats, and rabbits and found that we could arouse these animals from anesthesia by this means; rats and rabbits responded more easily than cats and dogs. When the animal's head was irradiated, arousal could be prevented by blocking the cutaneous nerves of the face with xylocaine, sectioning the trigeminal nerve, or scalping the animal. Our observation that pupillary dilatation occurs in the absence of the cat's adrenals also suggests reticular formation involvement in the nociceptive response. Figure 3 is a schematic diagram of the neural and hormonal interactions which may be occurring as a result of peripheral nerve stimula-

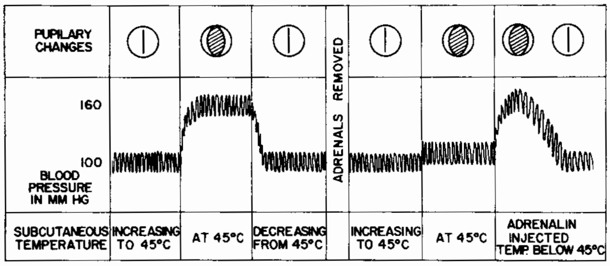


Figure 2. The effects of a 45 °C subcutaneous temperature on pupillary diameter and blood pressure in the Nembutal anesthetized cat. After adrenalectomy the blood pressure rise is abolished but pupillary changes continue to occur. Subsequent injection of adrenalin elicits pupillary dilation and a transitory blood pressure increase.

tion produced by thermode heating or heat from microwave radiation to 45 °C.

Species differences contribute to the response to microwave irradiation. The observation that in cats and dogs a blood pressure increase is observed and in rats and rabbits a blood pressure decrease is obtained as a result of a nociceptive response (10) is one example of species difference. We find that rats show other unusual behavior. When the head of a rat is irradiated with microwave, they convulse and often die even after irradiation ceases. This observation was once related to us as positive evidence for a nonthermal central nervous system effect of microwave irradiation. However, we subsequently produced an identical effect with thermode stimulation of the sciatic nerve and with microwave irradiation of the lower leg. When we tracheotomized the rat, it did not convulse. Rats, it appears, have a strong glottal reflex and will often asphyxiate themselves when a nociceptive response is produced.

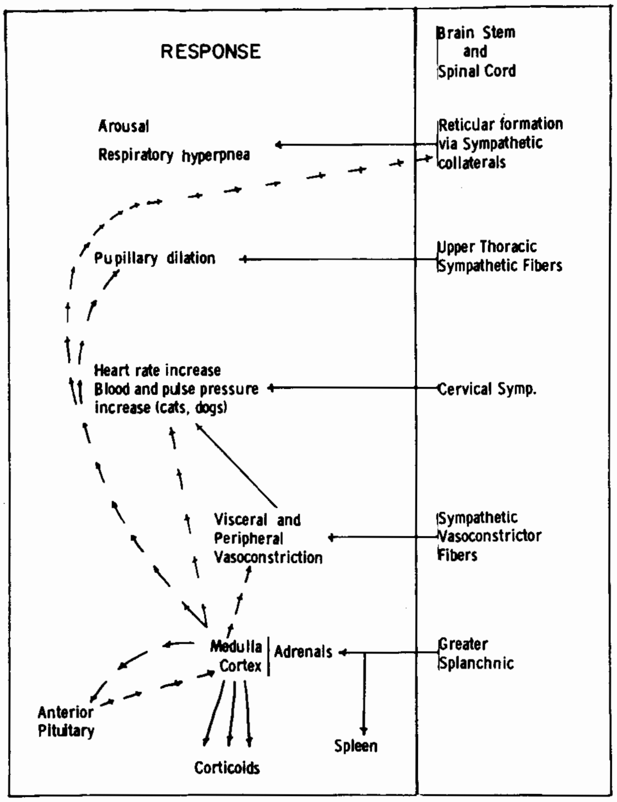


Figure 3. A schematic diagram of the neural and hormonal interactions which may be occurring as a result of peripheral nerve stimulation produced by thermode heating or heat from microwave irradiation to 45 °C.

In investigations of the response of various species of animals to the thermally induced nociceptive response, we may find other species peculiarities which have been viewed as convincing evidence for nonthermal microwave effects, but which are correctly interpreted as unanticipated effects resulting from a thermally produced nociceptive response. Perhaps our observations on the thermally produced microwave effect on the afferent peripheral nerves may help in the interpretation of some observations which might otherwise appear to be nonthermal central nervous system effects of microwave irradiation.

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# BEHAVIORAL EFFECTS OF LOW LEVEL MICROWAVE IRRADIATION IN THE CLOSED SPACE SITUATION[1]

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The investigations to be described in this paper had their conceptual precedent in Jaques D'Arsonval's laboratory before the turn of the century—in, specifically, his observations of mammals *behaving in* a fairly high frequency but nonionizing electromagnetic environment (cf. 1, 2). The passage of more than seventy years and the performance during more recent decades of numerous radiobiological studies have not, however, resulted in a coherent body of data on effects of "soft" (nonionizing) radiation. The field of behavioral radiology in particular—if we may capitalize on the pun—is distorted by conflicting data whose signals are buried in the noise of controversy. The basis of this state of affairs is complex. It is rooted to some extent in the limitations of methods and machines, but it also inheres in the difficulty of assimilating data from a domain of endeavor that necessarily embraces physics, chemistry, physiology, and behavior (and currently is affected by economics and politics as well!).

For the time being we shall resist the temptation to comment on contemporary, extrascientific implications of soft radiation and restrict discussion to philosophical and methodological issues of scientific relevance. Our interpretations and resulting strategy of experimental attack bear strongly on the interpretation of the data to be presented later, thus their inclusion at this juncture.

The issues are: the Doctrine of Emergence and the mischief that can occur when the Doctrine is unheeded; the advantages and disadvantages of "open-space" and "closed-space" irradiation techniques; problems and approaches regarding quantitative characterization of EM energy; and, finally, the advantages, disadvantages, and problems of empirically inter-relating field-density and calorimetric dosimetries.

## The Doctrine of Emergence

The unity of science is a noble goal, a faint hope, and a widely misunderstood concept. Physicists can be forgiven on grounds of disciplinary chauvinism for believing that the unity of science is to be realized by explicating everything—physically, chemically, physiologically, psychologically, sociologically, and cosmically—in terms of ultra particles. That

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biologists, psychologists and many other scientists find their thinking infected by the reductionistic fallacy is a pervasive if indefensible fact. Whatever his disciplinary persuasion and whether he chooses to face it or not the scientist is caught up in the implications of the phenomenon of emergence: *at any given level of analysis the combining of simple into more complex structures or relations entails the emergence of novelty*. Not causal uncertainty, but *epistemological* indeterminacy—to paraphrase J. S. Mill, the character of an organic whole may be stable and highly general, but is not predictable *a priori* from knowledge of its parts.

Consider this metaphor—the Brooklyn bridge—and the differing levels at which it can be functionally defined: for the physicist, it is a nexus of events involving ferrous atoms; for the structural engineer, an assembly of mechanical systems; for the psychologist, a vehicle for individuals who tell antediluvian jokes or commit suicide; and for the sociologist, a means whereby peoples communicate between disparate land surfaces. However, even if the physics of the bridge were perfectly determined and perfectly understood, Albert Einstein himself could not find in its ferrous atoms one jot of information necessarily predicting its mechanical, behavioral, or social functions. We would note, too, that the prime function of the bridge, its social utility, actually determines (in the Aristotelian sense of "final" causation) its mechanical and physical makeup. If the bridge didn't work, it would be replaced by one of differing design or materials.

The lesson of the metaphor is that a viable discipline of behavioral radiology will be crucial to the generating of uncontaminated biophysical and biological data. The lesson notwithstanding, some of the papers presented at this symposium will undoubtedly reflect the view that hypothetical or *in vitro* studies of molecular, tissue, or organ response to EM irradiation have *definitive* implications for human populations adventitiously exposed. This view frankly flies in the teeth of the emergence doctrine and is no more than dangerous question-begging. The living organism is a dynamic complex of interdependent mechanisms and what theoretically transpires in an idealized model of a membrane or is observed to occur in a slice of excised tissue is not a proof but a proviso requiring *in vivo* confirmation.

Even the *in vivo* experiment poses hazards. An animal that is physically immobilized to maintain it in a constant exposure geometry is also being artifactually subjected to an intense stressor. Physical restraint *per se* precipitates wholesale changes of endocrinal, gut, and other systemic functioning (see, e.g., 3, 4, 5) whose many possible interactions with irradiative effects cannot be unequivocally controlled—unless the endpoints of experimental interest derive from previously irradiated, unfettered animals. We therefore hold to the principle that the valid assessment of molecular, tissue, or organ response apropos irradiation of living, freely behaving animals will necessitate experimental study of living, freely behaving animals.

## "Open-" versus "Closed-" Space Irradiation

The open-space technique is the experimental arrangement in which an animal preparation or some other target is placed at a fixed point in free space with respect to a radiator of EM energy. If placed in the far field, i.e., at a sufficient distance to avoid the cyclical variation of energy density characterizing the near field, relatively large inputs of power and radiator apertures are required to produce uniform field densities and experimentally adequate energy levels at the target. These requirements plus the large laboratory spaces and accoutrements needed to render such spaces electrically anechoic add up to considerable and often forbidding cost. The usual experimental arrangement has been to irradiate the target in the near field where, because of the cyclical variations of energy density, loads must be precisely located and spatially fixed in order to preserve uniformity of incident energy.

When living preparations are immobilized and irradiated in fields near or far, there is not only the attendent physiological stressing via restraint already alluded to but another source of artifact: variation of incident energy as a function of the target surface area presented to the radiator. The mammal is essentially a cylindrical solid but is seen by incident EM energy at any given moment as one of a range of two-dimensional surfaces. When viewed in line with its longitudinal axis, the mammal presents a surface area much smaller than the area presented, say, by its broadside. Thus the differing two-dimensional surface geometries of a preparation—varying *Silhouette Surface Areas* (SSA's)—proportionally determine the amount of incident energy in a uniform field. In the adult albino rat, e.g., we have determined that the ratio of $SSA_{max}$ to $SSA_{min}$ exceeds three. To the extent that a preparation's exposure geometry is allowed to vary by an investigator, commensurate variability of energy absorption will occur. When this source of absorptive variability is considered along with variations incumbent with differing exposure distances (especially in the near field) and those incumbent with incident but reflected or otherwise nonabsorbed energy, one finds the making of an open-space, radiobiological dilemma: physical immobilization of living preparations introduces uncontrollable artifact, but institution of "free" behavior introduces wholesale variation of absorbed energy.

A possible path through the horns of the dilemma was paved more than 20 years ago when Dr. Percy Spencer of the Raytheon Corporation converted a microwave generator into the "radar" range—the electronic oven; this, the embodiment of the closed-space approach, has subsequently been developed for widespread industrial, commercial, and domestic applications. Less than a decade has passed, however, since the closed-space approach was theoretically championed as a tool for radiobiological research by Vogelman (6), and only a few empirical studies employing the tool have been published (7, 8, 9). The empirical studies cited all involved measurement of chronic behavioral response to irradiation at high energy levels and only King (10) has assessed acute effects of the lower level doses (circa 10 mW/cm²) of paramount interest to the participants of this symposium. The behavioral data to be presented later are largely based on King's work; we shall only be concerned now with her means of reducing energy levels and with a brief preview of the evidence she obtained that dose constancy can be achieved in unfettered animals in the closed-space situation.

Microwave ovens generally employ magnetrons with electrodynamic, as opposed to permanent, magnetic fields. By increasing dc current level through the field-generating windings, magnetic flux is increased. The increased flux, in turn, *lowers* r. f. power output. In the case of the Tappan R-3-L range used in our laboratories, increasing the field current from ~875 mA to ~1.75 A lowers available output power from ~1000 watts to less than a watt. The original field solenoid is still in use some 18 months after the modification and has not only been robust to the twofold increase of current but is not associated with saturation at the highest level of current indicated. It was necessary to replace the original dc power supply to the field with one providing higher, better stabilized currents; this was the only electrical modification required to convert the oven to a laboratory inductorium affording fairly stable (±5%) output at energy levels approximating 10 mW/cm².

Extensive pilot work with the Tappan range, after its oven had been fitted with a Plexiglas Skinner Box (operant conditioning chamber) revealed that any given albino rat working at a photo-operandum under a given power setting behaved in a highly predictable manner across repeated sessions of irradiation at 12.25 cm wavelengths. This behavioral stability occurred in spite of the animal's considerable freedom to move about within the inductorium (see Fig. 1) and frequent changes of body geometry with respect to the opening of the waveguide. The observation of behavioral stability comported with subsequent observations of comparable temperature rises occurring both in phantom water loads and in anesthetized animals possessing common gram weights; both the phantom and living preparations had been moved about to provide differing geometries and locations with respect to the waveguide opening.

Figure 1. Front view of a Tappan R-3-L microwave oven as modified into a combined closed-space inductorium, operant-conditioning chamber. A precision liquid (sugar-water) pumping apparatus is mounted on the oven door to the reader's left. Within the oven when the door is closed is a photo-operandum (lick detector) at which an experimental animal works to obtain sugar-water payoffs. The fans at the top of the oven circulate cooled air within the operant chamber.

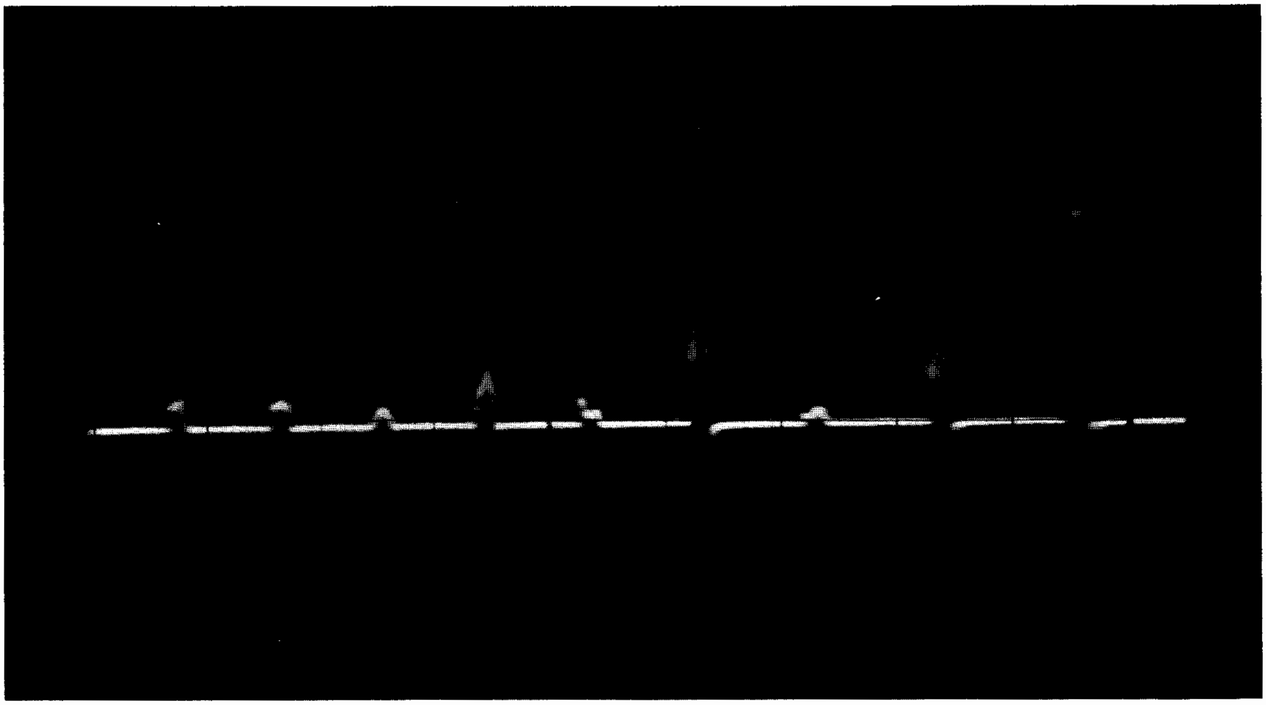

Figure 2. Demodulated signal from probe located in microwave oven as displayed by cathode ray oscilloscope. The time interval between adjacent peaks (which reflect halfwave 60 Hz ac anode voltage) is ~16.7 msec; variations of amplitude are produced by a metallic "chopper" fan that rotates between waveguide opening and lower chamber.

The behavioral and calorimetric evidence then, points not only to fairly constant dosing but fairly constant absorption of 12.25 cm microwaves in the Tappan apparatus. We offer the following speculation regarding the basis for this constancy. Between the waveguide opening and the Plexiglas enclosure forming the operant chamber is a four-bladed, metallic "chopper" fan that rotates at 3 Hz. The chopper is part of the original equipment design and serves to diffuse the EM energy emitted from the waveguide. When the chopper is not in operation, there are noticeable "hot-spots" as evidenced by varying thermal increments in constant-volume phantom loads placed at various loci within the chamber. Too, r. f. probes placed at various points through the small, radiopaque holes in the oven door (whereby visualization of the oven's interior is realized) result in oscilloscopic displays of different amplitudes of demodulated voltage peaks. When the chopper is in operation, the display with the probe at any of several locations is one of continuously varying peak amplitudes—but there is no noticeable difference in range of maxima to minima from locus to locus of probing. Figure 2 is a photograph of the demodulated signal picked off by a probe near the center of the oven; the moment-by-moment variation of amplitude is readily apparent—it is varying at 12 Hz because each of the chopper's four blades sweeps past the waveguide opening three times a second—as is the clipped, half-wave sinusoidal character of the (60 Hz) current flowing to the anode of the magnetron.

The observed dose-and-response stability may also lie in the closed-space arrangement *per se*. Energy emitted from the waveguide into the metallically walled oven has three known avenues of dissipation: back reflection to the magnetron, penetration of the walls, and absorption by the load. Since the 12.25 cm microwaves incident to the metallic walls of the enclosed chamber have a much higher probability of reflecting back than penetrating through, the load likely does what the ideal open-space load can not—it *absorbs reflected* energy. What proportion reflects to the magnetron and what is eventually absorbed by the load have not been determined as we have not concerned ourselves with measurement of forward and back-reflected powers.[2] Whatever the physical bases of uniform thermal translation in

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[2] We measured the difference directly via simple calorimetry; see p. 159.

closed-space, the electrolyte load is an observably patent sink of EM energy.

In comparing the two methodologies we should mention a currently unqualified question with respect to assessment of irradiation hazards, i.e., the generality of closed-space data with respect to adventitiously exposed human beings. The control tower operator, e.g., who is regularly swept by a radar beam appears akin at first blush to the preparation in the open-space experiment. So, too, does the housewife whose electronic oven may be leaking r. f. energy into her heat-labile eyes. The likely differences here—and ones with important implications for the establishment of "safe" levels of irradiation—are the limited (180°) body-surface areas directly exposed to, and the greater coherence of, EM energy radiated in open-space. Under conditions of equivalent energy absorption, the diffuse, polyangular illumination falling upon a closed-space-preparation simply in being less concentrated would be less likely to result in lethality or tissue injury. However, because the open-space preparation may reflect or be invisible to a considerable percentage of impinging EM energy (13), effective doses in the closed-space situation where more available energy is absorbed may not underestimate those occurring in open-space.

Whether great or small the differences in character of illumination of the two techniques do not *a priori* limit the generality of the closed-space approach. In the first place, upon closer scrutiny one finds that the control tower operator and the housewife are straw men—to identify either with the experimental open-space preparation begs the question. He *is* moving around in his tower and is therefore over time diffusing illumination of his body surface—and she *is not* strapped to a chair and forced to stare at a loaded waveguide. Second, and more important, what differences exist are empirically resolvable via, e.g., research where animals' behavioral or systemic responses to irradiation are titrated across alternating open- and closed-space experiments. Indeed, we believe that the greatest scientific yield in the way of information needed to establish valid exposure standards will be harvested from co-validating research designs. Even the practitioners of the open-space art are troubled by its inaccurate, error-susceptible dosing measures (cf. 1, 6, 12, 13), and since the closed-space principle promises dose-determinable experimentation, integrated research employing both methodologies seems strongly indicated.

## Soft Irradiation: Problems of Dose, Fate, and Dosimetry

Although the fate of anything ingested, injected, or otherwise absorbed is logically distinct from its quantitative characterization in terms of dose, the two concepts are easily confused. In the case of soft irradiation[3], accordingly, the question of *how much* energy is available or absorbed should be distinguished from the question of mechanism(s) of absorption. We shall deal but briefly with the latter question as we see it as a set of problems empirically unresolved but only resolvable empirically—and highly dependent on priorly gaining concensual meaning and reproducible measurement of dose.

### *Fate of Absorbed Microwaves*

Hard radiation by $\beta$, x-ray, deuteron, and $\alpha$ particles results in varying proportions of reversible and irreversible cellular change. The probability of a lethal change occurring is dependent on quantum energy; $\beta$ bombardment, which is associated with the lowest range of quantum energies of the particles mentioned, produces relatively minuscule irreversible effects (14, 15). Since the quantum energy of a 10 cm microwave is at least a million times less than that of low energy $\beta$ particles, we are at a loss to *specify* nonthermal sources of irreversible cellular or systemic damage. Many nonthermal effects are mentioned in the current literature and such fates as demodulation, molecular resonance, pearl-chain formation, and reorientation of polar molecules are suggested (13, 16); similarly, K. H. Illinger in this volume mentions segmental rotation, protein tunneling, ring deformation in hydrogen-bonded molecules and vibration of the lattice structure of water. Some of these absorptive mechanisms conceptually overlap the acceleration of molecular rotation ("vibration") believed to be the nexus of microwave-induced heating; none of them necessarily implicates irreversible damage; few could account for more than a tiny fraction of absorbed energy; and all of them are presently lacking the critical operational specification whereby occurrence or nonoccurrence *independent of thermal effects* is subjectable to experimental verification.

This is not to say that primary nonthermal effects

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[3] "Soft" irradiation is defined by some investigators as low quantum energy, particulate bombardment; e.g., by $\beta$ particles; we use the term more inclusively to denote *any nonionizing irradiation* whether particulate or undulatory in conception.

do not occur; or if occurring, that they would not affect the irradiated preparation. If there were, e.g., wholesale reorientation of water molecules in neural membranes, gross changes would likely be seen in an animal's behavior. One would be dealing here, however, not with lethal molecular or cellular deformation, but with *information*; thermodynamics theory tells us that the number of bits of information potentially inhering in a few milliwatts of absorbed energy is enormous (17). By way of simple analogy, a radio broadcast may involve thousands of watts of radiated power, but the bit of information signalling presence or absence of the r. f. carrier is decipherable at microvolt levels via a simple crystal detector.

But how is one to go about the tasks of experimentally discriminating primary from secondary thermal effects? and each of these from possible nonthermal, deformational or informational consequences? We view these tasks as possible, but only after the community of radiobiological investigators can, 1) agree on means of conceiving and operationally measuring their major independent variables, quantity available and quantity absorbed of EM energy; and 2) begin to generate reproducible methodologies and confirmable data. Our task was to begin at the beginning, and at the beginning is the dose.

## *On Estimating Available and Absorbed Energy*

Open-space exposure methods involving both hard and soft radiation are historically identified with field-density dosimetry. The preparation is treated as a two-dimensional surface and the energy illuminating it is likewise couched in planar terms, W/cm$^2$. Vogelman (6) and Hirsch (12) among others have cited the difficulties of accurately determining the energy actually illuminating an open-space preparation as opposed to the field strength measured by an r. f. probe. Particularly in the near field is this difficulty compounded; the preparation is three dimensional, and in order to measure field strength at its median plane (its hypothetical depthless surface) it must be removed during measurement. Removal, however, may and likely does change antenna loading characteristics thereby resulting in changes of the energy distribution; too, insinuation of the probe and its associated paraphernalia into the field can change the energy distribution. Even without these problems, the achievement of uniform and determinate energy densities would still leave unanswered the amount of energy absorbed by the preparation. As mentioned in earlier paragraphs, the preparation may change its exposure geometry and it may partly reflect or be transparent to impinging energy.

The vagaries of field-strength dosimetry added up in our reckoning to an unacceptable state of affairs, a quantitatively "dirty" independent variable. Since we were interested in achieving an accurate index of *absorbed dose* and since "... radiation calorimetry seems to be in the process of becoming the absolute standard of measurement for absorbed dose ..." (18, p. 369), we turned to simple water calorimetry as our dosing measure.

Vogelman (6) suggested in his theoretical discussion of closed-space irradiation that back-reflected and forward power measurements be taken, the difference being the measure of absorbed power. Through simple calorimetry involving phantom (water) loads we elected to measure this difference directly. In practice, small plastic containers approximating the cylindrical geometry of the preparation are filled with distilled water, volumes being established on the basis of gram weights of our rat preparations. The plastic containers are selected to provide low heat loss and for a dielectrical constant of unity. A phantom load (container plus electrolyte) is placed into the microwave oven and irradiated for a given amount of time. Temperature immediately before and after exposure is read from a thermometer. The measure of available wattage (which is also the estimate of power absorbed by an animal preparation) is gained via the formula:

$$W = \frac{T\Delta V}{kt} \qquad (1)$$

where:

$W$ = watts
$V$ = volume of phantom water load in milliliters or net grams
$T\Delta$ = temperature increment in degrees Celcius
$k$ = Joule's conversion constant = 0.239
$t$ = time of exposure in seconds.

Our prime dosimetry measure is expressed in terms of a preparation's mass, i.e., the weight of the animal in grams is divided into the measured wattage. For example, an animal weighing 400 grams and exposed to 2 watts of available power per unit time is said to be dosed at 5 mW/gm. Combining this rationale with Formula (1) yields:

$$\mathrm{W/gm} = \frac{T\Delta V}{ktm} \qquad (2)$$

where:

$m$ = preparation's weight in grams.

The low levels of EM energy typically programmed in our experiments never result in more than a few milliwatts per gram; thus an absorbed energy dose is expressed as mW/gm, or even μW/gm. Our recourse to a unit-mass convention is based upon its intuitive appeal and its ease of calculation. It should be stressed, however, that the convention carries no implication of uniform distribution of absorbed energy in an animal preparation—no more than does an intramuscular or intravenous injection of a drug as couched in terms of mg/kg imply uniform systemic diffusion of the innoculum. The mW/gm dose-index, as is true of the mg/kg, is simply a statistical convenience that has proved methodologically and operationally meaningful.

A unit-mass dosimetry, as embodied in Formula (2), would seemingly be simplified by observing temperature increments directly in the animal preparation. There are several reasons why we chose to measure thermalization in phantom loads: 1) distilled water was found to exhibit the same temperature rises under given input power settings as did 1% saline and Ringer's solutions of equivalent volumes—and these rises were close to those observed in equivalent gram weights of cat kidney and liver tissues and of deeply anesthetized rats (we expected to find some differences because of variation in specific gravities and heats and, indeed, such differences might be obscured in the probable ~10% error of reading spirit thermometer scales); 2) our primary experimental preparation, the male albino rat, has an elaborate, arterial-venous heat-shunting mechanism proximal to its large bowel and anus that necessitates very deep insertion of rectal thermometers in order to obtain unconfounded core temperatures; chronic placement of a thermistor by surgical means or deep insertion of a thermometer was contraindicated by our wish to study initially the unfettered animal; 3) even if there were means of reading temperatures "on line" without interfering with an intact preparation's behavior, its ability to dissipate heat would lead to an underestimation of thermalized energy; and 4) the distilled water phantom provides a physically salient and universally accessible calibration medium.

Before moving to the problem of inter-relating the new, unit-mass dosing convention to traditional unit-surface dosing, we wish to comment upon our past and current use of simple spirit thermometry, and what we think should be used to enhance accuracy of temperature measurement. As is so often the case in a laboratory, a tool is used because "it is there, is not too expensive, and within limits, gets the job done." So it was with our use of Trident, expanded-scale alcohol thermometers. In subsequent studies, because the major wrinkles of water calorimetry have been ironed out, and because the feasibility of undertaking precision measurements is now indicated, we shall be using the expensive but highly precise quartz thermometer. Whatever concesssion to inaccuracy of dosing is indicated with respect to our completed work should be contrasted with the relatively much greater error inherent in open-space, field-strength dosimetry practices; i.e., we think we have obtained estimates of absorbed energy that fall within 10% of actual values—the factors impeding specification of absorbed energy in the open-space preparation likely cumulate to a total error-of-measurement greater by several multiples.

### *Inter-relating Unit-surface and Unit-mass Dosimetries*

Even if it is granted that a unit-mass dosimetry has merits surpassing those of the unit-surface measure, a problem arises because the latter suffuses the thinking and the literature of radiobiology. How is one to make quantitatively meaningful comparisons of data based on differing conventions? A conceptual bridge is needed to provide translation and can be formed from two assumptions and a set of empirical measurements. The first assumption stipulates an ideal case of open-space irradiation: *all* of the energy of a uniform field incident to a preparation is absorbed. The second assumption is that an animal presents its maximum surface (maximal silhouette surface area or $\mathrm{SSA_{max}}$) to the incident energy. Given these assumptions, the energy absorbed is the product of field density and $\mathrm{SSA_{max}}$. For example, a rat with an $\mathrm{SSA_{max}}$ of 100 $\mathrm{cm^2}$ exposed to a 10 mW/$\mathrm{cm^2}$ field would be absorbing one watt per unit of time. This rat would absorb what the preparation in the closed-space situation is assumed to absorb when one watt of energy is available as calorimetrically determined with a phantom load.

With the precaution that a maximum limiting case has been developed, we can recast Formula (2) to provide an estimate of a unit-surface dose from unit-mass values and $SSA_{max}$ data:

$$W/cm^2 = \frac{T\Delta V}{kt SSA_{max}}. \quad (3)$$

Empirical measurement of surface areas of experimental preparations constitutes the final step in bridging the two dosimetry conventions. We began the final step by examining photographs of rats. Exposures providing a diversity of postural attitudes revealed that the horizontally positioned animal viewed directly from above (or below) presents its $SSA_{max}$. This overhead view is easily recorded by a still camera mounted over a runway. In practice, a rat is allowed to run along a runway, which is painted black and is inscribed along both axes with white lines whose resulting squares are constant surface area units. An exposed negative is then enlarged upon high quality, constant thickness photographic-print paper. Each animal's silhouette is then carefully cut-out with scissors and weighed on an analytical balance. Squares of known surface area from the periphery of the print are also weighed, the relative weights of the two cut-outs then being projected to an estimate of $SSA_{max}$.

This "photometric" procedure has been carried out on dozens of rats ranging in weight from ~15 to 700 grams. A sizeable correlation was found between an animal's $SSA_{max}$ and its weight in grams at time of photographic exposure. A scatter plot was made (see Fig. 3) which shows $X$–$Y$ data for a) six experimental (open circles) and seven control (filled circles) rats yielding the data presented later in this paper; at time of exposure the experimental animals were food deprived to 85% of control weights; controls, fed *ad lib.*; b) six *ad lib.* fed, infant animals ranging in weight from 15 to 95 grams; and c) 24 *ad lib.* fed rats of heterogenous weight that were obtained from Simonsen of Minnesota in a common shipment—and were intentionally so ordered to provide the range of weights that would encompass those typical of the species in most laboratory work: between 100 and 450 grams. All animals with weights between 14 and 425 grams are denoted by filled squares.

A regression analysis was performed on the $SSA_{max}$ and weight data of the 24 specially ordered animals; the resulting product-moment correlation is 0.96 which, when transformed to the coefficient of determination, $r^2$, and multiplied by 100 allows us to say that knowledge of gram weight of adult male rats (within the weight range noted) "predicts" $SSA_{max}$ with an efficiency of 92%. As can be seen in the regression plot, the largest discrepancy between predicted and actual values occurs in the case of a 353 gram animal whose measured $SSA_{max}$ is ~10 cm² below its predicted value of 119 cm², an error of less than 10%.

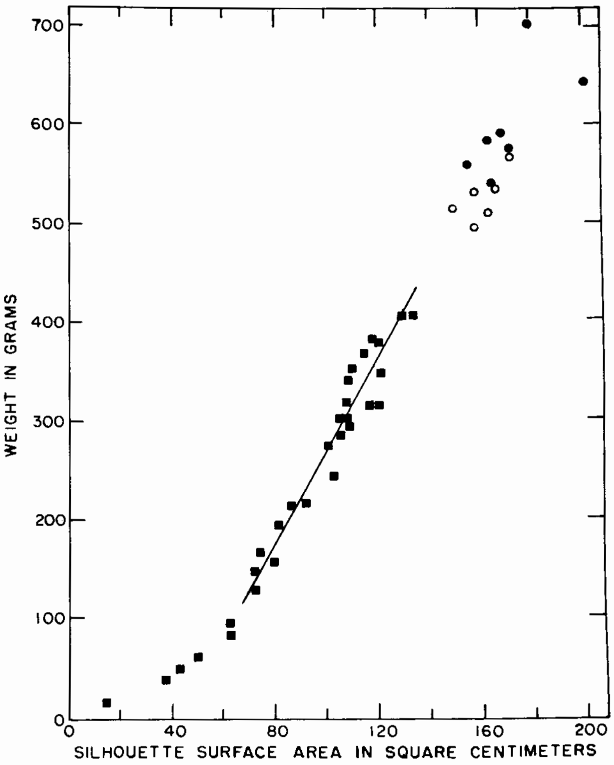


Figure 3. Scatter-plot based upon an animal's weight in grams and maximal silhouette surface area, i.e., the maximum two-dimensional surface that would be "seen" by an open-space radiator of EM energy. Legends are explained in text.

Since the values of the regression equation are known [i.e., $X_{SSA_{max}} = Y_{gms}(0.21) + 44.92$] it is not always necessary to determine empirically the $SSA_{max}$ of an experimental rat preparation in utilizing Formula (4); rather, the readily obtainable weight function as expressed by the regression equation can be substituted:

$$W/cm^2 = \frac{T\Delta V}{kt[m(0.21)+44.92]}. \quad (4)$$

For a less precise but quickly estimated projection of m/Wcm² from mW/gm, the latter may be multiplied by three—roughly the average ratio of the *adult* rat's gram weight to its $SSA_{max}$. Both Formula

(4) and the rule-of-thumb hold for adult females except when they are gravid. Near the time of parturition there is especially great variability of SSA's, probably because of variable numbers and volumes of fetuses. When studying the gravid female (in, e.g., teratogenic and other fetal irradiation experiments) we would recommend empirical measurement of $SSA_{max}$ data via the "photometric" method described earlier.

Other species obviously differ from the rat in their body geometries; the empirical mapping of weight-SSA relations will shortly be undertaken by us in several strains of mice, guinea pigs of the Hartley Strain, and the rabbit. It is hoped that the same close fits will be found between weight and SSA data, as the latter are more difficult and time consuming to obtain.

We conclude this section with the formula for the "quick-estimate" of unit-surface dosing of the mature, albino *rattus Norvegicus* from the unit-mass values presented in this paper:

$$\sim W/cm^2 = 3(W/gm). \qquad (5)$$

## ACUTE BEHAVIORAL RESPONSE TO MICROWAVE IRRADIATION

### Prefatory Comment

The data presented in this section arose from the first known attempts to study a freely behaving mammal in a relatively dose-determinate, low-level microwave environment. In keeping with the precursory nature of the experiments the questions that were posed are simple and fundamental:

1. Is reflexive behavior altered?
2. Is instrumental behavior altered?
3. Is there alteration of an animal's ability to discriminate conventional sensory stimuli?
4. Can the animal discriminate presence of closed-space microwave energy?
5. Are the levels of microwave energy employed associated with observable temperature elevations in the irradiated animal? and
6. Are brain materials, as determined by post-mortem histological analysis, discernibly affected by the irradiation received during behavioral studies?

Our strategy was to combine individual-subject and small-sample experimental designs in the hope of shedding light on possible individual differences and on generality of effects in the rat preparation. Across sessions of a given phase each animal usually served as its own control; during any given session the animals were often partitioned into control and experimental conditions whose reversal during a subsequent session provided for: counterbalancing of treatments; inter-subject comparisons; and intra-subject control of experimental effects. Since we are addressing a multidisciplinary audience, we shall resort primarily to "common" language in describing experimental designs and data—and qualify in all instances technical psychological terms when used.

The basic methodology employed was the *free-operant* conditioning technique. The technique is generally used to study variables that acutely affect previously well-established habits—as opposed to *controlled-operant* techniques such as mazes that are used directly to measure acquisition of habits. As our experimental questions primarily focus upon acute behavioral effects of microwave irradiation, it was necessary first to pretrain our subjects in and bring them to highly stable performance of an operant task. Detailed information on the methodology and instrumentation underlying the task as adapted for microwave irradiation is presented elsewhere (cf. 10, 20) and shall only be given brief description in this paper.

Inclusive of the pretraining, the studies involved a total of 124 daily measures on each of the six animals. With exceptions to be noted later, each animal's daily session was 60 minutes in length. The several experiments involved can be assorted into six major phases ordered across time (see Table 1).

Our discussion of findings will follow the chronology of the experimental sessions except where subsequently obtained data suggested retrospective analysis.

### Methods and Materials

A Tappan R-3-L electronic oven was electrically modified to provide low output power (<6 watts) by increasing flux of the electrodynamic field of the oven's QK 707 magnetron. Levels of dc current exciting the field were varied by a rheostat to produce a desired r. f. output as calorimetrically indexed with phantom water loads. The nominal r. f. frequency of the QK 707 magnetron is 2450 MHz; as the anode is excited by 60 Hz ac voltage from a line-driven step-up transformer, the magnetron acts as its own plate-voltage rectifier. Less than 180° of the available anode current flows at low power outputs, however, as a result of biasing action by the high flux density of the electrodynamic field. The resulting 60 Hz, less-than-half-wave sinuosoidal modulation of the r. f. output is compounded with a mechanical source of 12 Hz modulation—from a rotating metallic chopper whose four blades pass between the waveguide opening and lower radiation chamber at 3 Hz.

The primary behavioral endpoint of the study was the rat's tongue-licking response (see, e.g., 19, 20, 21); to measure the endpoint, a photo-operandum (lick detector), a liquid feeder, and a testing chamber were fabricated from dielectrical materials, the resulting operant conditioning ensemble then being installed in the microwave oven. An animal's first task was to learn to lick at a tiny area on the lower surface of a smooth, tapered Pyrex nozzle projecting through the door of the oven. Once an animal learned the task of licking for a drop of sugar water pumped through the nozzle by an investigator—and it is a quickly mastered response—interruptions of a light beam by the tongue movement were electronically detected and used to provide automatic sugar-water payoffs. Solid-state sensing, recording, and control modules could be adjusted to provide various ratios of payoff to performance. In most of the experiments an animal had to lick 40 times in order to receive a single drop of sugar solution which, when the animal was properly positioned to break the light beam by its tongue, was directly posited in its mouth. The arrangement is much akin to an animal drinking liquid from a conventional water delivery tube except that liquid is only provided every nth lick. In technical parlance such providing of intermittent payoff is referred to as a *fixed-ratio schedule of reinforcement*; when an animal is paid off regularly every 40th operant response, the contingency is termed a *FR-40 schedule*. The sugar solution (10% wt/wt dextrose in distilled water with 0.001% sodium benzoate wt/vol to retard spoilage) was paid out in single, discrete 30 microliter droplets through the small orifice of the Pyrex nozzle.

The source of illumination for the photo-operandum, the photo-resistor for detecting interruptions of the light beam, and the pump for dispensing sugar water were all mounted externally on the oven door of the Tappan range. The photo-beam was conducted through one of an array of small radiopaque holes (that make up the standard "window" in the door of the Tappan oven) via a semi-loop of Sterite photo-conductive tubing; another semi-loop of Sterite tubing returned the beam through another hole to the exterior of the oven and to contact with the photo-resistor; within the oven the Sterite tubes stopped short under either side of the Pyrex nozzle, the resulting aperture physically and photically defining the locus of lick-detection. The droplet of sugar water, when reinforcement was programmed, was pumped through a third hole in the oven door; the pumping apparatus was so constructed that a static column of liquid was never present in that portion of the nozzle situated within the microwave oven.

TABLE 1

*Sequence of experimental phases and sessions*

| Phase | Ordinal number of daily sessions | General purpose |
|---|---|---|
| I | 1 thru 65 | Pretraining of operant tasks; Debugging of operant apparatus |
| II | 66 thru 92 | Debugging of microwave apparatus; Tests for effects of intermittent irradiation upon reflexive and operant behaviors |
| III | 93 thru 99 | Pairing of microwaves and tonal cues to test for behavioral disruption |
| IV | 100 thru 119 | Microwaves tested for sensory stimulus properties |
| V | 120 thru 124 | Temperature measurements in animals before and after intermittent microwave irradiation |
| VI | — | Post-mortum analyses of brain materials |

### Calorimetry and Dosing Levels

The phantom water loads and Trident No. 43918 expanded scale thermometers used to index thermalized energy were always brought to the atmospheric isotherm of the radiation chamber before commencement of calibration; the phantom load containing a pipette-measured volume of distilled water was then irradiated for an electronically timed interval and observed for temperature increment. Available wattage was obtained by Formula (1). Calibrations were made both at the beginning and the end of all sessions in which irradiation was programmed. During irradiation of experimental animals a constant influx of fresh, cooled air was provided in the operant conditioning chamber; the ambient chamber temperature ranged between 22 and 26 °C during most sessions, but on occasion rose higher—the effects of such rises to be commented upon later. The fan systems providing circulation of cooled air were always shut down during calibration checks to prevent heat-loss from the phantom load to the surroundings.

The parameters of power employed in the studies can be characterized three ways: 1) peak instantaneous—not determined and probably only determinable via computer tracked spectral analyses; 2) local average—the calorimetrically indexed, available power at time of irradiation; and 3) global average, the net power available during an experimental session (a meaningful value since irradiation was never continuously programmed during any experimental session). Global average powers were selected to overlap the equivalent (theoretically perfectly absorbed) unit-surface dose of 10 $mW/cm^2$; i.e., mW/gm values approximating 2.5, 5, 10, and 15 $mW/cm^2$. Local average power per experimental session never exceeded the equivalent of 30 $mW/cm^2$.

### Animal Subjects

Twenty male albino rats (Sprague-Dawley descendants of *rattus Norvegicus*) were purchased from Simonsen of Minnesota in a common shipment. All animals were experimentally naive and 18 weeks old at commencement of studies requiring 21 weeks to complete. An experimental group of six animals was randomly selected; a second randomly selected group of seven rats was never irradiated or behaviorally conditioned but was fed *ad libitum* to provide a floating anchor for food-depriving the young and still growing experimental animals to 85% of median control weight. Two animals, "runts," were discarded. The remaining group of five animals was similarly fed to 85% of body weight but was neither irradiated nor conditioned; the animals of this group were to provide control over deprivation effects, if any, that might appear in post-mortem histological analyses of experimental animals. The purpose of the food-deprivation regimen was to assure motivation for operant habits predicated upon sugar-water payoffs; while there is no indication that the deprivation regimen employed impairs the otherwise healthy rat—indeed, longevity and freedom from disease are associated in this species as they are in human beings with mildly restricted food intake—control was sought over possible interactions, histologically registered, between irradiation and deprivation. All animals were fed Purina Rat Chow, the experiment animals one to two hours after a daily session, in their home cages where a supply of drinking water was always available.

The rat was selected as the experimental animal for a combination of reasons: first, its elegant, well recorded ability to perform operant tasks; second, its economy of acquisition and maintenance; third and primarily so, for its ideal physical makeup with respect to absorption of 12.25 cm microwaves. The potato does very well in the way of diffusely absorbing and thermalizing EM energy in the Tappan range which suggests that the Raytheon Engineers pioneering the closed-space cooking concept had this ubiquitous vegetable in mind when selecting r. f. parameters; similarly, we had the potato in mind when selecting an animal of like volume, mass, and geometry. One should bear in mind, however, during the paragraphs to follow, that the potato gets the benefit of 1000 watts of available power; our rats, less than 1% of this amount.

### Experiments and Results

*Phase I: Operant Pretraining*

Each of the six experimental animals worked during daily sessions in which the operant licking response was first conditioned and brought from low demand FR-10 to more demanding FR-50 and finally to a slightly less demanding FR-40 schedule. Simultaneously, the FR schedules were made complex by adding an extinction component to the reinforcing component. The two components alternated throughout a session, but only during the reinforcing component was sugar-water payoff available. Three of the six animals were cued by a 525 Hz tone that was present when reinforcement was available; the other three animals were cued by the tone being present during the extinction component; i.e., "tone-off" to these animals signified availability of payoff. The aim here was to make a randomly ordered 1, 2, or 3 minute tone presentation (or removal) a discriminative stimulus for reinforcement. During each 60 minute session and for all animals there was an equivalent number of 1, 2, and 3 minute tone and no-tone presentations cumulating to 30 total minutes of "tone-on" and 30 total minutes of "tone-off," but the temporal ordering of intervals was randomized. A clearer picture of this complex schedule and the cumulative record conveying the end-result of an animal's performance on it may be found in Fig. 4.

As one animal (Rat No. 12) worked at the photo-operandum during a 60 minute FR-40 control session, each of its detected lick responses was converted to a discrete horizontal (upward) tracing on a chart by a pen mounted on a stepper. Since the chart on a cumulative record moves continuously (to the reader's left) at a precisely clocked rate, activation of the stepper via regularly recurring tongue-licks resulted in the diagonal tracings seen in Fig. 4. Each time the animal was paid off a hatch mark appears in the record. When the animal wasn't working at the photo-operandum, the tracing was horizontal. The stepping pen of the cumulative recorder automatically reset (returned to the lower excursion limit) after each 500 licking responses had been executed. The lowest tracing in Fig. 4 also derived from the chart of the cumulative record and reflects the binary state of an event marking pen.

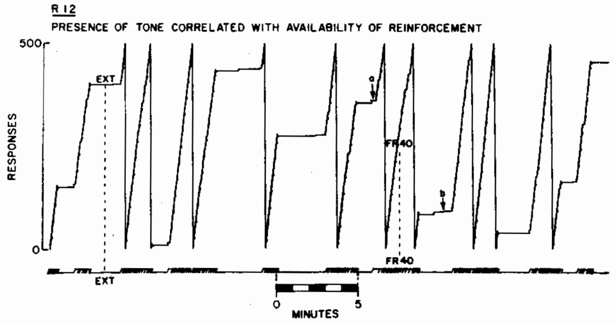


Figure 4. A cumulative record from a control (sham irradiation) session reflecting the performance on a complex operant schedule by animal subject number 12. The temporal lengths and ordering of reinforced and extinction components are illustrated—and fully explained in text.

In its upward position, the event trace is signalling that a 525 Hz tone was being presented and sugar-water payoffs were available; too, the momentary downward deflection of the trace signals when a payoff was given. When the event trace is continuously deflected downward, the tone signal wasn't being presented and the animal was in an extinction (no-payoff) component. Close scrutiny of the chart in Figure 4 reveals that Rat No. 12 was responding to the tone cue in a highly efficient manner, working nearly constantly when the tone was present, and ceasing to work when the tone cue was removed. Exceptions are to be seen at "a" (a brief pause when payoff was available) and "b" (a few licks occurring during an extinction component).

The rationale for making absence as well as presence of a tone a discriminative cue was to counterbalance for possible asymmetry (interactions) between standard sensory cues and microwave irradiation during subsequent experiments based on the complex schedule. In all, a total of 65 daily sessions was run by each animal during this pretraining phase. Ordinarily, many fewer sessions would have been required to institute efficient responding to the complex schedule; however, all of the equipment involving the lick-detection and liquid payoff apparatus was newly designed and built for the microwave situation and, as with most maiden ventures, there was frequent breakdown and functional failure. As a result, much time was spent repairing and recrafting—and retraining animals who were often inadvertently extinguished when programmed payoffs failed to materialize. Generally, sessions during pretraining lasted 60 minutes for each animal, but had to be aborted on many occasions when equipment failure occurred. By the 65th and final session of pretraining technical problems with the operant apparatus had been overcome and all six animals were responding stably and efficiently to the complex FR-40 schedule.

### *Phase II-A: Reflexive Behavior Under Microwave Illumination*

A rat's tongue-lick is a phasic reflex, a burst of 6 to 10 or more licking movements being triggered by a drop of water to the tongue. As the burst component involves a simple reflex circuit with a highly stable rate parameter (21, 22), we wished to see whether irradiation at levels high enough to be mildly thermalizing would increase the reflex rate. Such an increase would be predicted, e.g., by Fischer

(23) who theorizes that body temperature (metabolic rate) is the nexus of and inversely conditions biological time—any iterative biological event such as a phasic reflex should be sped up so long as systemic tolerance of heat is not exceeded.

During several 60 minute sessions when irradiation at various levels was alternately presented and terminated at five minute durations, we attempted to record licking rates in bursts triggered by sugar-water payoffs. Limitations of recording apparatus—digital tape-printers designed to track events of much lower recurrence rate—prevented us from achieving more than a glimpse of a possible functional relationship. The number of licks per unit time in payoff-triggered bursts was found to increase and then fall off as doses of global average power increased from 0 to 4.7 mW/gm. If this suggested curvilinear relation had been observed in a methodologically patent experiment we would have made much of it; all we can point to now is a statistically unreliable finding deserving further investigation.

### *Phase II-B: Operant Changes Under Microwave Illumination*

There was no difficulty in recording absolute numbers of operant or reflexive licking responses via simple digital counters and the cumulative recorder. Thus, after learning that the reflexive-rate datum couldn't be contained, we devoted our attention to the issue of primary interest—the effects of intermittent irradiation upon global levels of operant responding. A schema illustrating the manner of presenting sham- or actual-irradiation during the 37 sessions of Phase II is shown in Fig. 5. All but one session was 60 minutes in length and each of the six animals worked on the FR-40 complex schedule; three animals, as before, were cued for availability of payoff by the 525 Hz tone; the other three, by absence of the tone. Irradiation was alternately turned on and off at five minute intervals throughout each session. As can be seen in Fig. 5, the tone cues were perfectly correlated with reinforcing and extinction components while irradiation was effectively randomly presented. During sham-irradiation control sessions voltage to the anode of the magnetron was uncoupled but all other circuits controlling timing and switching functions continued to operate as during irradiation sessions. Within irradiation sessions, r. f. power was also terminated for the five minute intervals by uncoupling of anode voltage.

From session 66 to session 82 a total of six irradiation experiments was conducted; these, primarily to evaluate the reflexive endpoint referred to earlier. During the six sessions considerable variability (±25%) in output power was observed—and was found to result from r. f. energy leaking from the door of the Tappan oven. In mounting the heavy feeding and lick-detection apparatus on the door, we had decompensated the springs usually holding the door in an r.f.-tight position. Conventional window-sash locks placed on either side of the door restored an effective seal and thereafter power levels did not fluctuate within our ability to read power calibrating thermometers.

Sessions 83 through 85 involved sham-irradiation and serendipitously revealed, when airconditioning failed during the 85th session, that the operant measure is highly sensitive to increases of ambient temperature. The ambient temperature in the operant chamber reached 28 °C and every animal stopped working within 5 to 25 minutes; session 85 was terminated for each animal after 30 minutes. During the remainder of the phase each animal worked three control and five irradiation sessions under global average dosing levels pegged at ~1.5, ~3.1, and ~4.6 mW/gm, the lowest dose being presented during two sessions. The global average powers programmed during these sessions (0.8, 1.59, and 2.35 watts, respectively) were constant for all six animals which, in possessing slight variations of weight, received commensurately varying doses of power per unit gram. In no instance did the actual calculated dose vary from the stated mW/gm dose by more than 4%.

When the animals' average total responses per

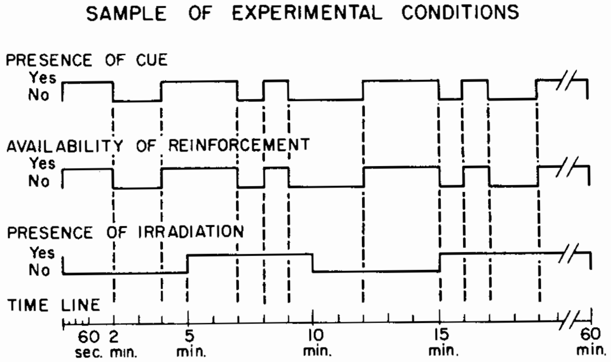


Figure 5. A schema illustrating the temporal relationship between schedule components and alternating presentation and removal of irradiation. The effective randomization of schedule components with respect to irradiation characterized most phases of the experiments reported in the text.

session, as drawn from reinforced but not extinction components, were compared across control and irradiation conditions, mean level of responding was found to decrease as dosing power increased. The averaged data are presented in Fig. 6. An analysis of variance was performed on control data and those deriving from the low level of irradiation, revealing that the difference in means was statistically negligible ($F = 3.07$, at 1, 4 *df.*, $p > 0.10$). The analysis also partitioned the data into the two cueing conditions (tone correlated with reinforcement versus tone correlated with extinction); the means associated with the two cueing conditions were very close. Our acceptance of the comparability of the two methods of cueing was not changed because of the low probability of difference found ($p \simeq 0.50$).

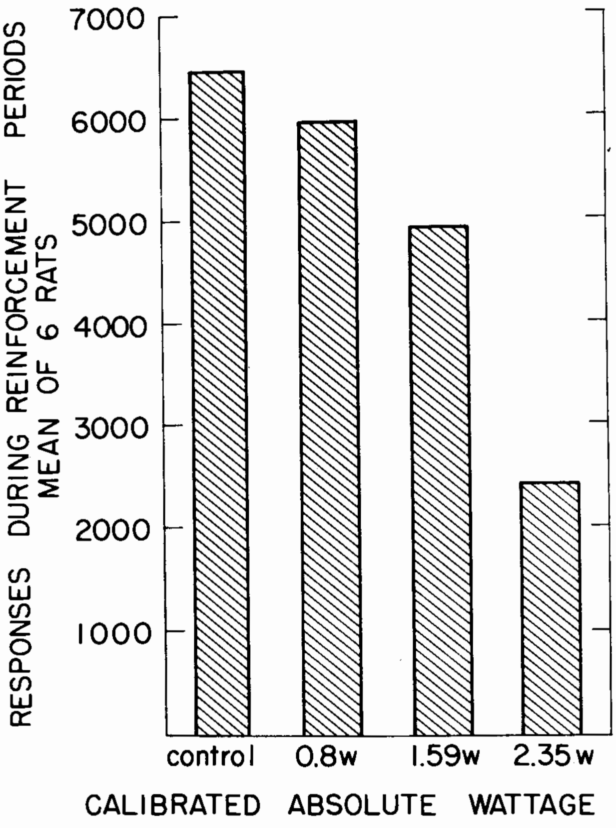


Figure 6. Total number of responses during experimental and control sessions averaged for six animals across four irradiation conditions. Each of the animals was dosed (within 4%) at 0, 1.5, 3.1, and 4.6 mW/gm, respectively. Irradiation during experimental sessions was alternately presented and removed at 5 minute intervals throughout the 60 minute sessions.

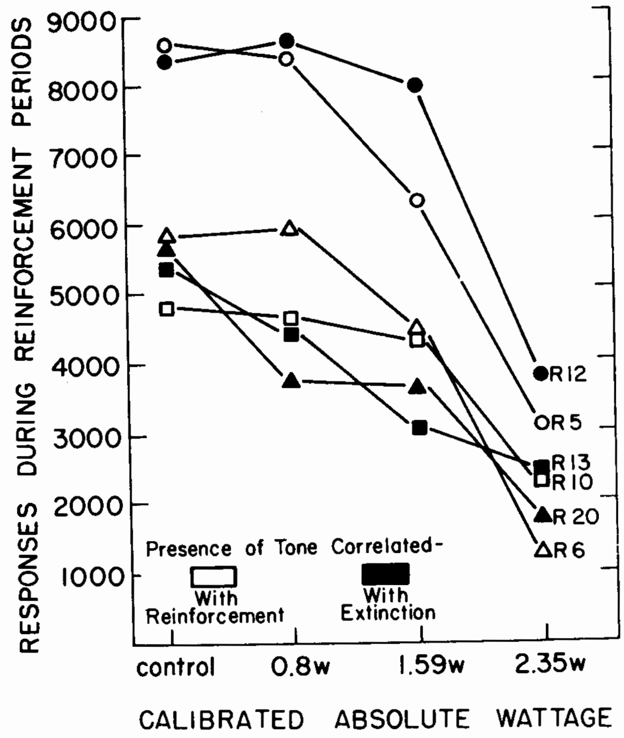


Figure 7. Individual total responses across four irradiation conditions (originally shown in averaged form in Fig. 6) for each of the six animals.

Statistical tests were unnecessary when comparing control data with those associated with either the intermediate or high power dose; there was a uniform decline at the intermediate dose and no overlapping of data at the high dose indicating strong depression of responding by the higher doses of irradiation. Visual observation of the animals while each responded under the intermediate dose—as well as scrutiny of individual cumulative records—confirmed that the lowered levels of responding did not arise from lower local rates of licking but from the animals' complete cessation of responding at times, particularly near the end of a session. We had noted earlier and on several subsequent occasions that all the animals exhibited cessation of responding when uncontrollably high ambient temperatures occurred. It is possible that warming of the animals by microwaves was causing them to stop working. Since each animal had exhibited a consistent set of work-stopping latencies to high ambient temperatures (although there was considerable variation among all six), we compared each animal's latencies under high ambient temperatures with those observed during higher microwave dosing. Curiously enough, the correlation over animals was close to zero. If the intermediate and higher power doses were warming the animal, why should such warming differ from

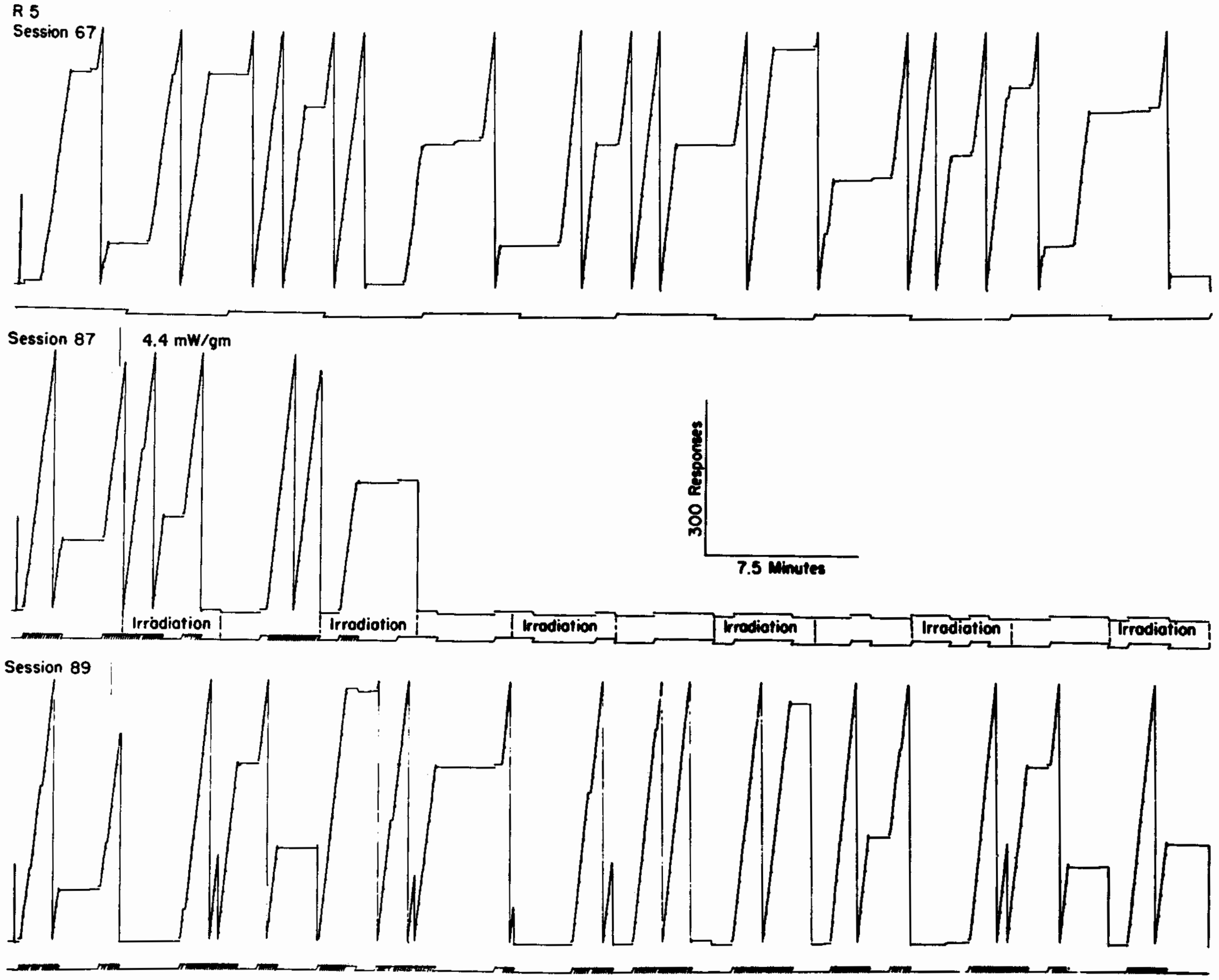


Figure 8a

conventional heating so far as a stable behavioral indicator is concerned? We do not know the answer, but are inclined to believe that the more diffuse heating associated with microwave irradiation may invoke a different thermoregulatory response from that evoked by normal heating.

In addressing the large response decrement observed under the highest power dosing, we must state that the gross behavioral picture was dramatic and unequivocal: each of the six animals began working during its session with efficiency and dispatch, and continued working for 8 to 26 minutes into its particular session; then responding abruptly stopped. Sooner or later each animal fell away from its postural station at the photo-operandum, slipped to the floor of the operant chamber thereafter making feebler and feebler movements in what appeared as attempts to regain its station, and finally assumed a fully prone and immobile posture. In every experiment, we permitted the session to run its 60 minute limit—to determine whether recovery from some form of acute effect would take place. With the exception of one animal, no signs of intrasession recovery were observed, even during subsequent 5 minute intervals when irradiation was intermittently turned off. At completion of its session each animal was removed from the chamber, visually examined, and gently palpated. A characteristic noted at this time in each animal was an extreme flaccidity of both skeletal and gut muscle. All animals appeared as if injected with a curariform drug.

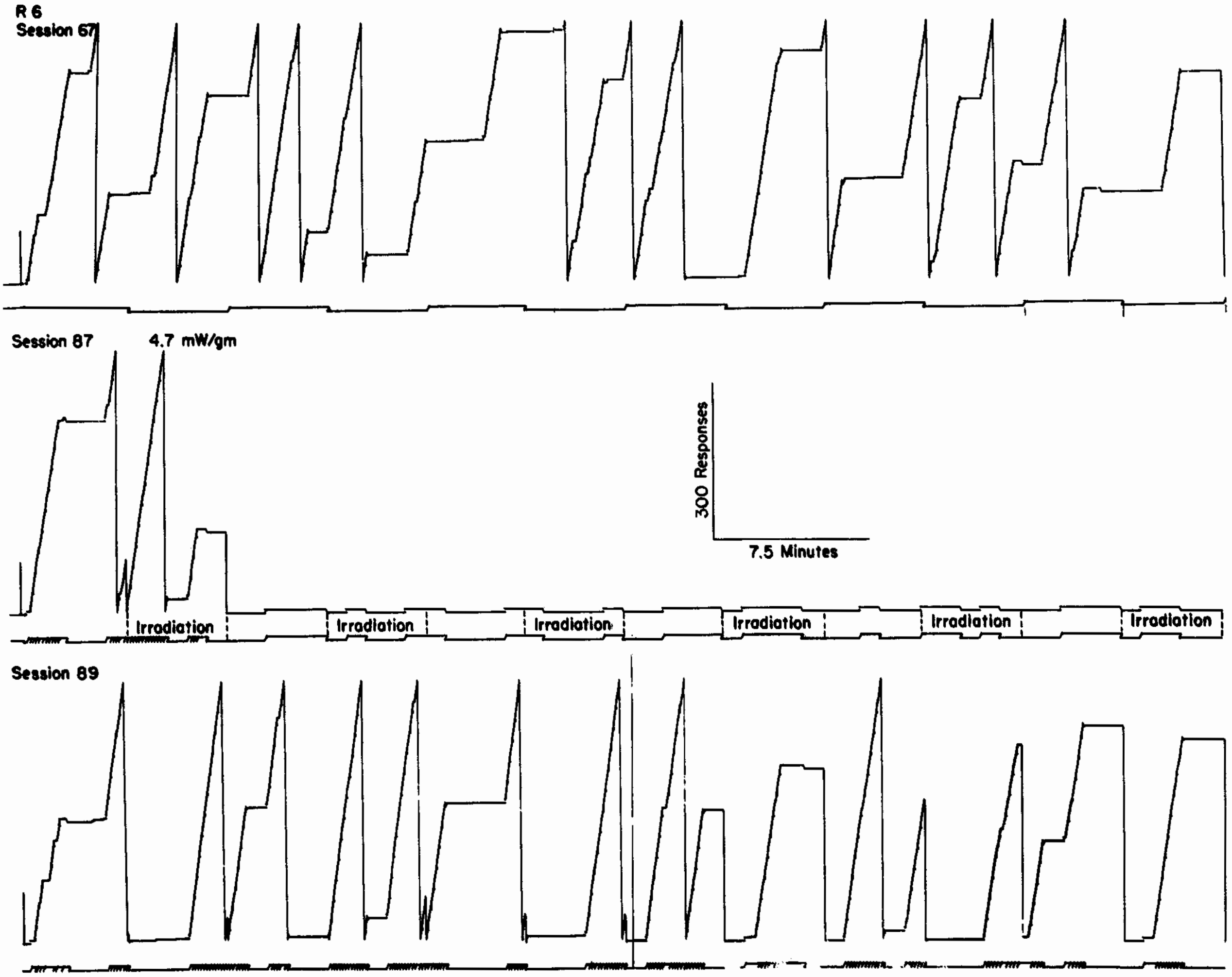


Figure 8b

We do not know the cause of this apparent flaccid paralysis, but whatever its physical basis no psychic scars were evident thereafter. Within 5 to 10 minutes after removal from the chamber each animal recovered and displayed no signs of irritability or hostility. Similarly, next day when a session involving the low power dosing was conducted, not a single animal exhibited the aggressive behaviors or attempts to escape one sees in a rat upon return to an operant chamber in which it has been acutely insulted by electrical footshock, an airblast—or intense radiant heat.

Figure 6 presented averaged data on global responding; to provide information more revealing of individual performances, a graphical plot of each animal's response totals (again exclusive of responses made during extinction components) is presented in Fig. 7. Large individual differences in control levels of responding are seen as are the doubtful declines of responding under the low level (0.8 W$\simeq$1.5 mW/gm) dose. The declines under 1.59 W ($\sim$3.1 mW/gm) and 2.35 W ($\sim$4.6 mW/gm) are readily apparent.

Since differing body weights of two rats of identical age would suggest differing thicknesses of fatty tissue (and since a thicker layer of fat would augur poorer dissipation of excess heat) it is instructive to compare animals R-5 and R-12. Animals R-5 and R-12 were the heaviest (534 grams) and the lightest (500 grams) of the six animals at time of high power dosing; note, nonetheless, the similarity of their response decrements and clear differentiation from the other four rats. The two were the most refractory

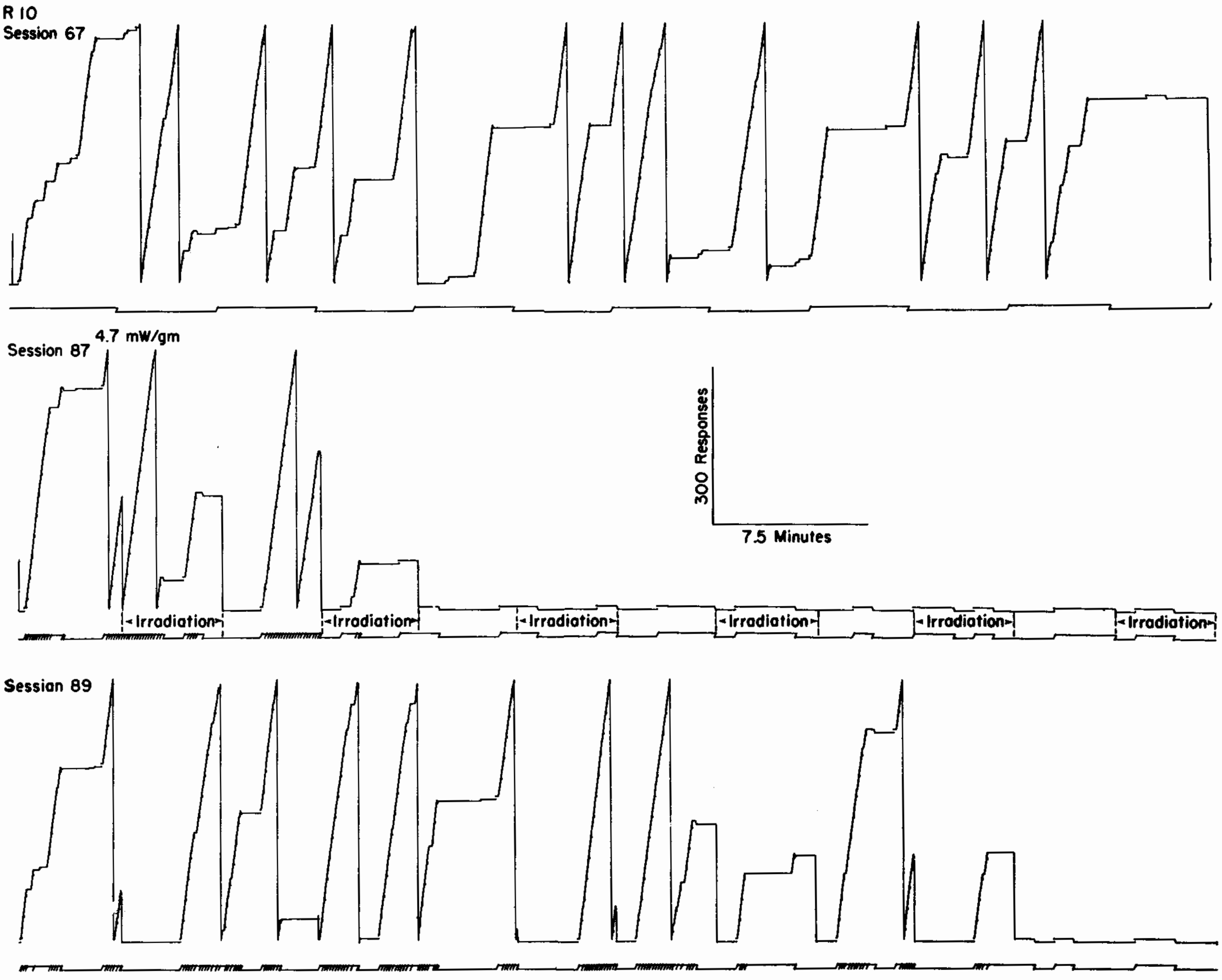


Figure 8c

to presumably thermalizing irradiation. In contrast, Rat-12 was behaviorally the most refractory to high ambient temperatures; R-5, the most labile. These observations as well as the abrupt character with which responding ceased during high level irradiation can clearly be seen in the animals' cumulative records. Figures 8a through 8f are photographs of cumulative records obtained during an earlier (pre-irradiation) and a later (post-irradiation) control session (numbers 67 and 89), and of the records obtained during session 87 when the high power dosing was intermittently presented. Comparing the records of other animals with those of animal R-12 (see Fig. 8d) reveals, first, that R-12 exhibited the greatest persistence of all animals in responding during high level irradiation; second, that it was the only animal that recommenced responding after a fairly lengthy pause; and third, that its responding during the early control session (number 67) was least persistent of the six animals. During session 67 ambient chamber temperature fell to 20 °C (at which temperature the other animals worked continuously when payoffs were available); R-12's behaviorally indexed sensitivity to cooling is exemplified by its spotty performance.

The inferences we would draw from these findings are: 1) the rat is not only a transitional homeotherm, but one with marked individual variation; some of our animals, e.g., behaved as if more nearly poikilothermic than homeothermic in their response to high ambient temperature; and 2) there are different (e.g., vascular-neurophysiological) mechanisms in-

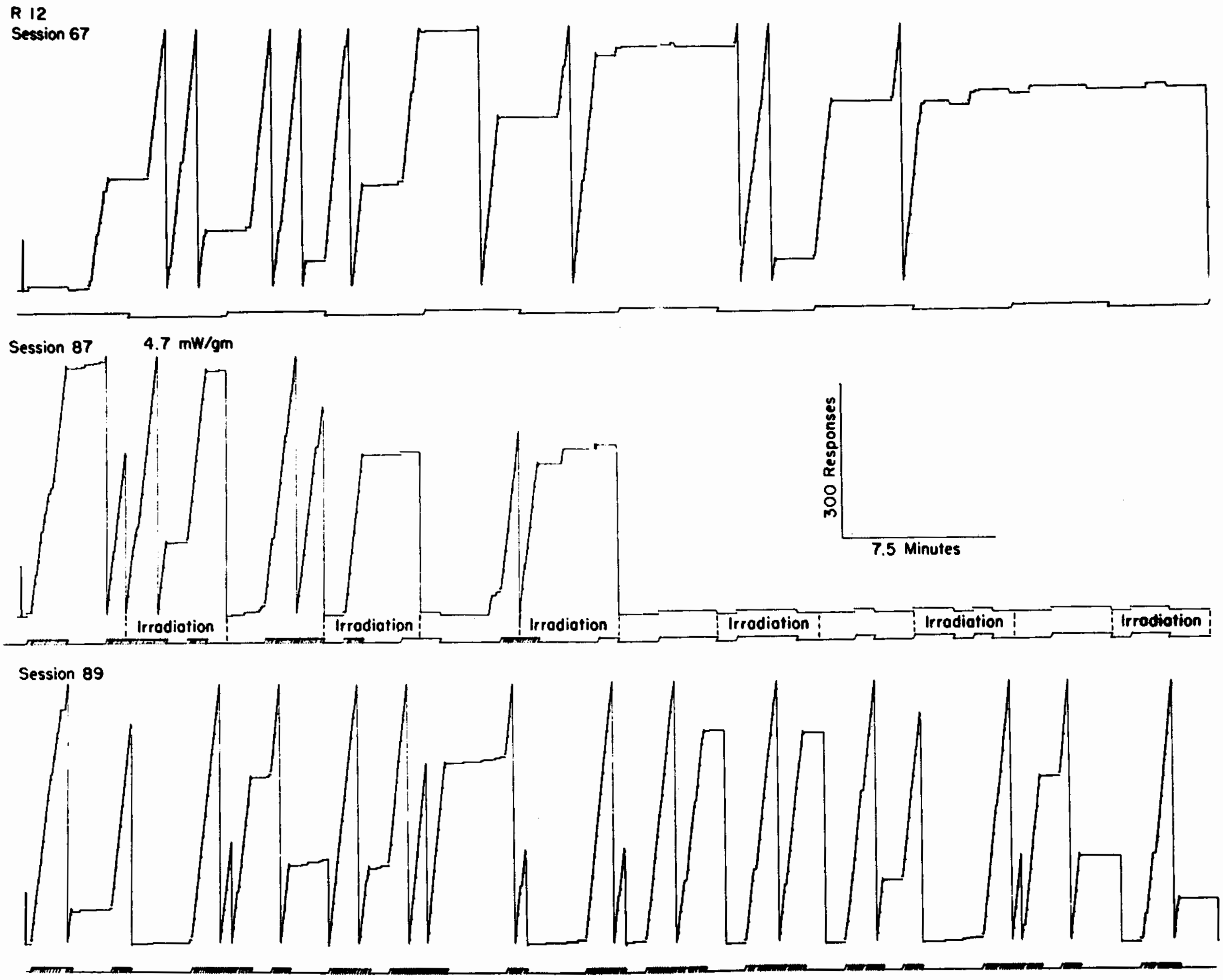


Figure 8d

volved in this species's response to superficial ("normal") and diffuse (microwave) heating. Just what the latter might be in view of the absence of exogenously produced diffuse heating in the evolutionary history of this—or any other—species is a mystery, but may be related to that endogenously triggered and ubiquitous phenomenon of diffuse warming known as *fever.*

### *Phase III: Pairing of Sensory Cues and Microwaves*

During sessions 95, 96, and 99 control experiments were conducted with the six animals evenly split into the two cueing groups, as before. During sessions 97 and 98, microwave irradiation was programmed at ~1.5 mW/gm, but instead of being randomly presented with respect to tone cues and availability of reinforcement, its presentations were perfectly correlated. For three animals, microwave irradiation accompanied "tone-on" during reinforced components of a FR-40 schedule; and for the other three animals, "tone-on" during extinction components. An analysis of variance was performed on the data (total responses per session during reinforced components) that controlled for the two cueing conditions, and tested for differences between control and irradiation means. The consolidated mean number of responses in the absence of irradiation was 5492, and when irradiation was paired with tone cues, 3731. The difference was moderate—during irradiation level of responding dropped 32%—but highly reliable ($F=26.7$ at 1, 4 *df.*, $p<0.01$).

Why low level microwaves accompanying tone cues would lower levels of operant responding is not clear; there were few lengthy cessations of responding

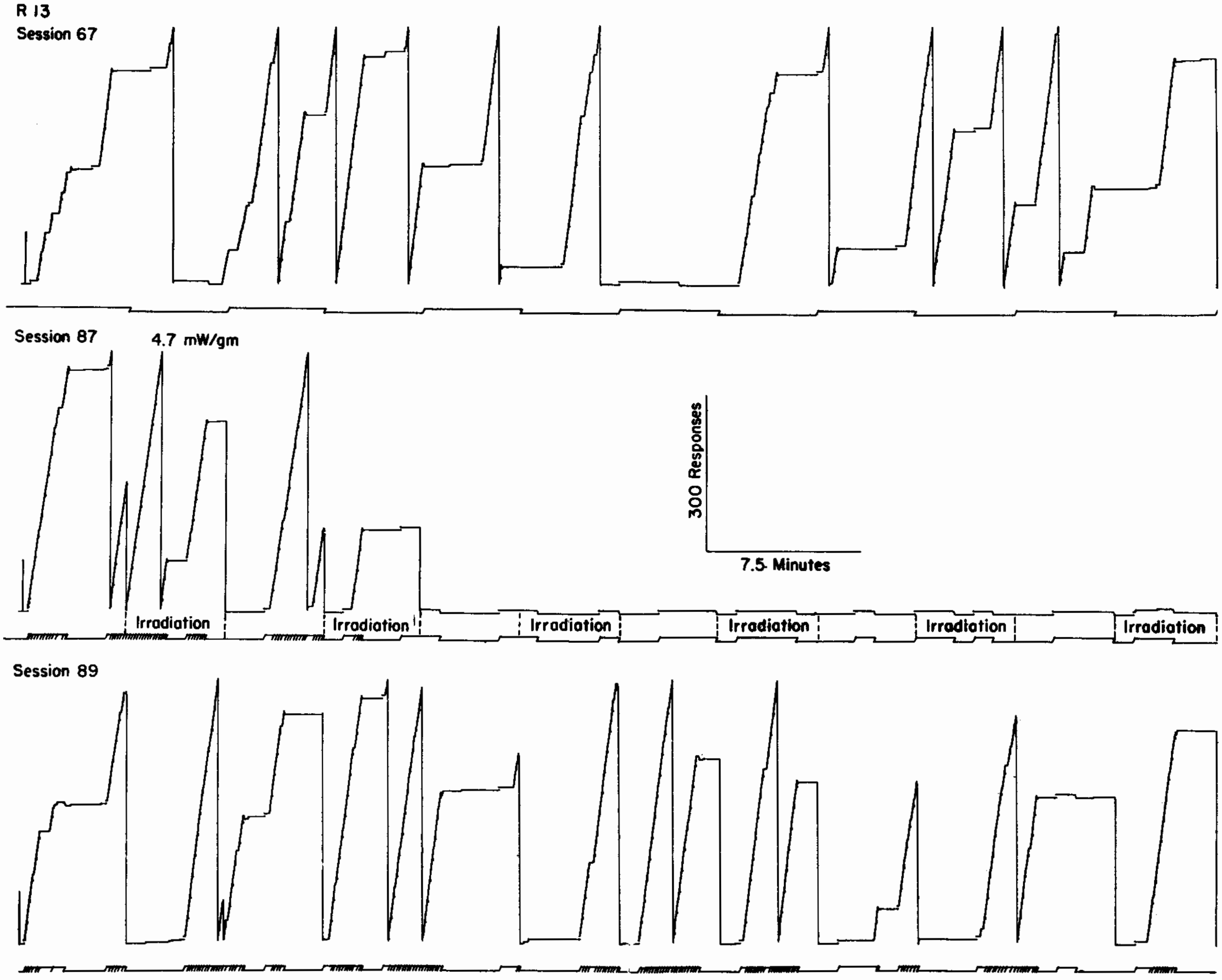


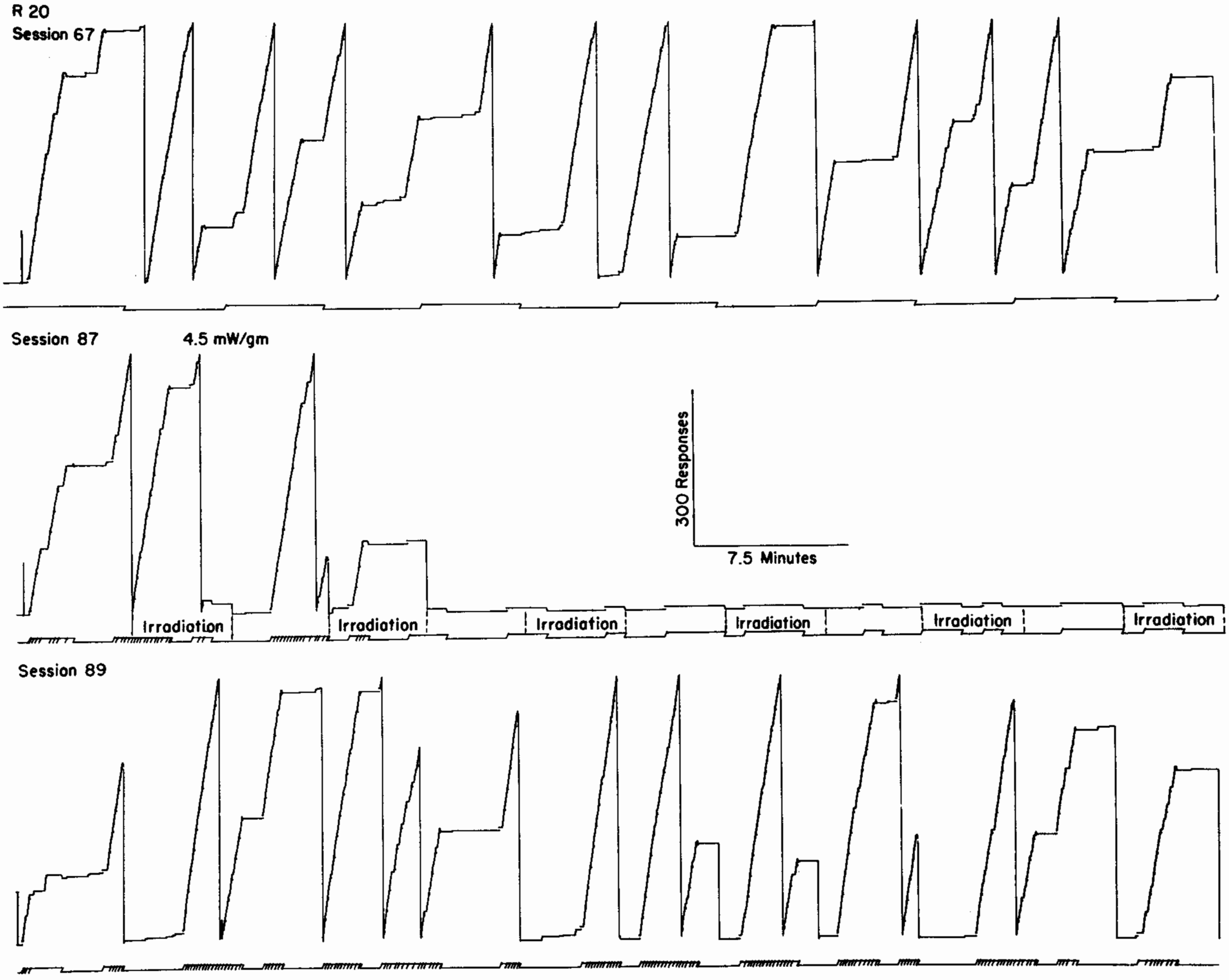
Figure 8e

as occurred in previous experiments under higher irradiation levels, but more frequent short pauses when the animals momentarily left the photo-operandum. One could speculate that sensory blocking was occurring in light of reports by Grinbarg (24) and Lobanova and Gordon (25) that microwave illumination reduces sensitivity to pain and otherwise increases sensory thresholds. Perhaps at the low level of power employed there is, as it were, a mild "clouding of the sensorium," that possibly culminates in a full blown anesthesia at higher levels. Such a possibility is fully consonant with the apparent flaccid paralysis seen earlier in all animals under ~4.6 mW/gm local power doses.

Casting doubt on the sensory-blocking notion was the observation that intermediate and high power levels of irradiation during Phase II were associated with no gross evidence of sensory impairment so long as animals were capable of performing. It seems safer, then, to conclude that the moderate if statistically reliable response decrement observed in the paired-case represents a performance disruption from, possibly, a sensorily *distracting* influence. If low level microwaves are such a distracting influence, they might possess sensory cueing properties in their own right. This question was empirically addressed in Phase IV.

### *Phase IV: Microwaves Presented as a Possible Sensory Cue*

A series of experiments was conducted during sessions 100 through 119 in which power doses of



Figures 8a through f. Cumulative records produced by each of six animals during an early, pre-irradiation session (number 67), an experimental session (number 87) under ~4.6 mW/gm dosing; and a subsequent control session (number 89) under sham irradiation. Details are given in text.

0.4 W (~800 $\mu$W/gm) and 0.8 W (~1.6 mW/gm) were tested for cueing efficacy. The aim was to substitute irradiation for the priorly well discriminated tone cue. To control for the attempted transfer, all animals during one set of sessions were observed responding on FR-20 complex schedules to presence (or absence) of a houselight (illumination through radiopaque holes in the oven's overhead provided by a standard 100 W incandescent lamp excited by 52 rms ac V providing a maximum of 1365 phots within the operant chamber).

All six animals mastered the transfer from tone ("on" or "off") to house-light ("on" or "off") cues in two to three sessions. None of them responded much above baseline values to ~800 $\mu$W/gm or ~1.6 mW/gm irradiation even after 13 sessions of training. Figure 9 presents data for each of the six animals; the measure of responding, the *discrimination ratio*, is an efficiency index in which an animal's total responses per session during reinforced components are divided by its responses during extinction components. Figure 9 also presents reversal data, i.e., discrimination ratios calculated from data of late sessions in the phase when the cueing rule was "switched" halfway through the session for each animal. The animal that had learned during control sessions, e.g., to discriminate "house-light on" as the cue for reinforcement, now found the house-light "off" during reinforced components. So, too, during irradiation sessions for each animal with respect to

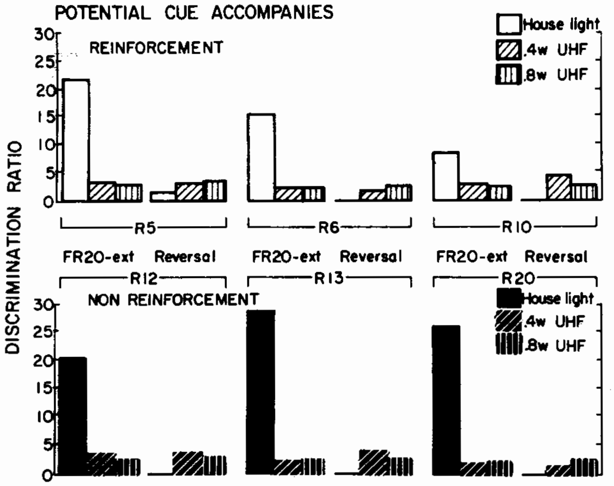


Figure 9. An index of discriminative efficiency, the discrimination ratio, was calculated for each of six animals under control (luminous-flux) cueing and attempted cueing by microwaves at 0.4 and 0.8 watts of available power. Doses per subject (within 4%) were 800 $\mu$W/gm and 1.6 mW/gm. The ratios reflect discriminative efficiency both during original training and under cue-reversal conditions.

the attempted microwave cueing; if microwaves had been presented during reinforced components, they were shifted to extinction components.

Normally, the reversal of a well discriminated cue strongly interferes with the efficiency of an animal's performance in a complex schedule. This interference is readily seen in the data of each animal responding to house-light cues in Fig. 9. Animal R-5, e.g., yielded a discrimination ratio of 22 before reversal; and 2, after reversal of its house-light cue. The ratios changed little under attempted microwave cueing either before or after reversal as is evident from the consistently low ratios observed under both levels of irradiation.

The reader may wonder why the discrimination ratios under attempted microwave cueing, while small in magnitude, were always greater than unity. These small above chance elevations likely derive from intrinsic cueing by the sugar-water payoff; animals *without* cueing will keep probing at an operandum in a lower demand complex schedule and once in a reinforced component, the occurrence of a payoff effectively signals that more payoffs are available. There is little evidence, therefore, that the microwaves functioned as a sensory cue. However, especially in view of the reliable performance disruption observed during Phase III under equivalent power dosing of the animals, we would not argue from our negative evidence that cueing under differing experimental circumstances is not likely to occur. It has been found, e.g., that sizeable doses of x irradiation have no discernible cueing properties in complex schedules but that in other paradigms combining operant and Pavlovian techniques (where nociceptive events, not payoffs, are predicted by a cue) that sensory detection of x rays does take place. We accordingly defer the question of sensory cueing by closed-space microwaves to future experimental test.

Before discussing Phase V experiments, we would like to present some data from a retrospective analysis suggested by the outcomes of Phases III and IV. Phase III data indicated that "something was going on" when conventional sensory cueing and microwave irradiation were paired; Phase IV data indicated that this "something" nonetheless lacks the saliency of a luminous flux (house-light) cue. We began to wonder upon completion of Phase IV whether the *efficiency* of the animal's tonal discriminations during the second phase of studies was impaired—i.e., efficiency would not necessarily change with the absolute lowering of response levels observed as power levels increased. Figure 10 presents some unexpected findings. When discrimination ratios were calculated for the six animals and

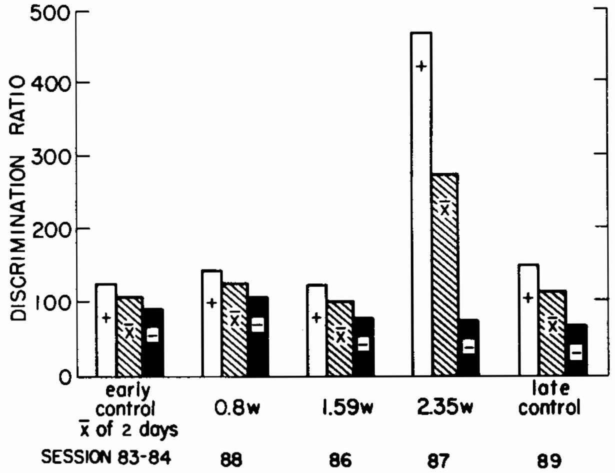


Figure 10. Discrimination ratios reflecting efficiency of responding to a positive ("tone-on") or a negative ("tone-off") tone-cue under four conditions of intermittent sham- or microwave-irradiation (doses within 4% were 0, 1.5, 3.1, and 4.6 mW/gm). The ratios shown for each condition are based on the average of the three animals assigned to each of the two cueing conditions.

plotted across the four radiation conditions, it was found that efficiency of making "tone-on" or "tone-off" discriminations was not impaired, even at the highest power dosing; indeed, the three animals for whom "tone-on" signalled availability of reinforcement, showed a dramatic and highly reliable ($p<0.01$) increase in discriminative efficiency.

If all the animals had shown the same sizeable enhancement of discriminative efficiency at the high power level, we would likely be touting microwaves as a tonic for a low I.Q.! The finding harkens, once again, to Roland Fischer (23) and the notion that exogenous (thermal) acceleration of metabolic rate may likewise accelerate cerebral processing and efficiency. Because of the observed interaction—because "tone-off" cueing of reinforced components was not associated with changes of discriminative efficiency—the notion of cerebral quickening seems unlikely; we are completely in the dark, therefore, as to possible mechanisms controlling the observed enhancement effect. In spite of the high reliability of the finding we would like to replicate the effect again, particularly in animals with more advanced CNS development, and thereafter attempt to discover controlling mechanisms.

### *Phase V: Thermal Measurement*

On many occasions during previous phases of the study we came close to breaking our early vow not to take deep rectal temperature readings in our irradiated animals until behavioral studies were concluded. Only the fear of breaking a thermometer *per anum profundis*, and thereby losing an animal, kept the thermometers in their cases. In sessions 120 and 121 the animals were returned to work on the FR-40 schedule as programmed during Phase II. During sessions 122 and 123 work on the same schedules continued, but before and after each session deep rectal temperatures were read and radiation was programmed at 2.26 W of global average power.

The rectal temperature readings are presented in Fig. 11 as read immediately before and after 60 minute sessions at 0, and 2.26 W (~4.25 mW/gm) power doses. Since some animals' temperature readings went "off the scale" during session 123 another and final session was run the following day in which 3 animals underwent 19 minutes intermittent irradiation at the higher level and 3 animals at 0.8 W (~1.5 mW/gm). The 19 minute session lengths were empirically determined by the first animal to start the session—it became prone and immobile after 19 minutes into the experiment. As seen in Fig. 11, there was a tendency for both sham irradiated animals and animals in the 0.8 W group to exhibit increased temperature rises; neither increase, however, is reliable ($ps>0.10$). Under the 19 and 60 minute high-level irradiation conditions, there was obvious incrementing of temperatures.

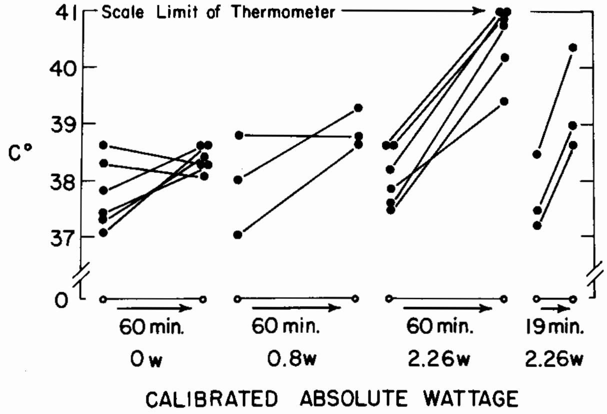


Figure 11. Celcius temperatures (deep rectal) in animals before and after sham- and intermittent-irradiation at doses approximating 0, 1.5, and 4.25 mW/gm. Note individual variability in basal temperatures.

The temperature data confirmed to us what our animals' behaviors had suggested throughout the studies—that there are marked differences both in individual temperature variation and in response to thermalizing irradiation.

### *Phase VI: Histological Analyses*

After conclusion of session 124, the animals were killed with an overdose of Pentothal and their brains removed and fixed in formalin for histological processing. So, too, for the food-deprived and non-food-deprived control animals maintained in the colonies since inception of the studies. The brains were then bottled, coded, and shipped "in the blind" to Dr. K. R. Brizzee of the Delta Regional Primate Center for extensive histopathological analyses. We have learned from Dr. Brizzee that no observable differences indicative of adverse effects have been observed in any of the brain materials. The negative histological findings therefore square with our gross and operant behavioral observations: frequent, intermittent exposure of animals over long intervals of time to mildly thermalizing irradiation is not survived by any discernible presentment of chronic adverse effects in the endpoints studied.

## Discussion and Summary

As interpretive comment was made in the course of presenting findings, this discussion in its first portion will focus upon a brief summary of methods, measures, and primary data. In later paragraphs we shall speak to some applications and limitations of the closed-space approach to the study of non-ionizing radiation. We shall conclude by commenting on a contemporary issue of potentially great import—the distinction between the scientific problem of evaluating microwave hazards, and the hazards of politics entering into scientific evaluation of problems.

### *Summary of Findings*

Six sexually mature male albino rats were exposed in a closed-space inductorium—specially fitted with a radio-transparent operant conditioning chamber—to ~2450 MHz EM energy doubly modulated at 60 and 12 Hz. Low levels of input power were achieved in the domestic "radar range" serving as the closed-space microwave generator by increasing flux in the electrodynamic field of a magnetron. Levels of available (and presumably absorbed) power were calorimetrically determined via irradiation of phantom loads of distilled water. While the primary dose was couched in terms of a new unit-mass convention, W/gm, analytical studies (involving measurement of the spatial geometry of freely behaving animals) yielded a means of equating the new dosing measure to the traditional unit-surface dose. In the maximal limiting case, the relation between doses for the mature, nongravid rat was found roughly to approximate $mW/cm^2 = 3$ (mW/gm). Reflexive and operant behavioral measures based upon the tongue-licking response to 30 µl sugar-water reinforcers were taken while unfettered animals worked individually at a photo-operandum. Sham irradiation or intermittent irradiation (always with a net 50% duty-cycle) was automatically programmed during 60 minute experimental sessions at global average power-levels approximating 2.5, 5.0, 10, or 15 $mW/cm^2$. In view of the duty-cycle employed, no animal was exposed to irradiation whose (theoretically perfectly absorbed) unit-surface dose during actual exposure exceeded 30 $mW/cm^2$.

The major findings were:

1. Rate of recurrence of an iterative (phasic) tongue-licking reflex was found to increase and then fall off as dose increased from 0 to 4.7 mW/gm. Limitations of instrumentation providing rate-detection led to inaccurate measurement of rates, an overcomeable but not yet overcome methodological problem that limits the validity of the curvilinear relation to an hypothesis requiring further experimental test.
2. Global levels of operant responding monotonically fell, and highly reliably so, as available power increased in dose from 0 to 4.7 mW/gm.
3. When microwave illumination at ~1.5 mW/gm was presented conjointly at 1–3 minute intervals with a priorly well discriminated 525 Hz tone signal, global levels of operant responding decreased reliably to 68% of control levels.
4. An attempt was made to substitute microwave irradiation at ~800 µW/gm and ~1.6 mW/gm for tone signals in a discrimination task. While all six animals quickly transferred to a control, luminous-flux discrimination, none of them even after protracted training exhibited any evidence of using the microwaves as a sensory cue.
5. At the high level of power dosing (~4.6 mW/gm) there invariably occurred a behavioral state suggestive of a curariform flaccid paralysis. The "limp-and-not-moving" animal recovered within 5–10 minutes after removal from the experimental chamber and thereafter exhibited no behavioral signs indicative of stressing.
6. When each of the six animals' *discriminative efficiency* (as opposed to global levels of operant responding) was assessed as a function of 0, ~1.6, ~3.2, and ~4.6 mW/gm doses, no impairment whatsoever was observed. At the higher dosing levels responding during an experimental session might have ceased, but before cessation the animals' ability to discriminate presence or absence of the 525 Hz tone cue did not degrade. Indeed, three of the animals (for whom presence of the tone—as opposed to its absence—was the discriminative cue) displayed a sizeable and highly reliable rise of efficiency at the highest dose.
7. Near completion of behavioral studies the animals were observed for rectal temperatures—a measure that had been deferred because the extreme depth of thermometer insertion required to obtain

unconfounded core temperatures in the rat presupposed possible stress and physical insult. Readings from rectal thermometers were taken immediately before and after 0, ~1.5, and ~4.25 mW/gm doses. The 0 and ~1.5 mW/gm doses were associated with small but statistically unreliable rises in average temperature after 60 minutes of intermittently presented irradiation. The ~4.4 mW/gm dose reliably increased temperatures after 19 minutes of intermittent irradiation—and after 60 minutes two of the animals exhibited increases that "went off the scale" of the conventional rectal thermometer. The temperature data confirmed an impression growing from earlier behavioral observations that the rat is not only highly variable in its individual thermoregulatory capability, but responds differentially to "normal" and microwave heating.

8. At completion of behavioral studies CNS materials of irradiated and control animals were subjected "in the blind" to histological analyses. No discernible evidence of adverse effects was observed.

### *Applications and Limitations of Closed-space Irradiation*

There are at least two broad areas of inquiry to which we think the closed-space principle is particularly applicable: febrile phenomena and *in vivo* biological thermodynamics. Successful application would first require overcoming of several limitations we have encountered in our instruments; we shall speak to these limitations before commenting on application as they also condition the generality of the findings just summarized.

Because of dependence upon the magnetron as a source of r. f. energy, the commercial electronic oven has a fixed wavelength and relatively restricted modulatory capability. Our data were all to issue from a set of parameters that was controllable only in terms of average power level. We have no way of knowing whether the complex (60 and 12 Hz) modulatory signature was a source of variance in its own right, or if not, whether 1 cm or 100 cm wavelengths, say, would produce the same effects as our ~12 cm carrier. The antidote to this uncertainty may lie in klystron oscillators capable of sinuosoidal and high peak-power, low average-power modulations as well as continuous wave operation. Such an oscillator, if tuneable over a relatively wide spectrum of carrier wavelengths and effectively matched to a closed-space inductorium, could provide a basis for experimentally parcelling-out modulation- and frequency-specific effects, if any.

A second problem attaches to the control of ambient temperature. We found the operant behavior of our experimental animals, even during control experiments without irradiation, highly sensitive to changes in ambient temperature. While the sensitivity proved utile, it also underscored the need for close control over ambient temperature and, possibly, humidity.

A third limitation alluded to earlier is the absence of knowledge about the character of instantaneous peak energies in the closed-space inductorium. As in any near field, there are undoubtedly present the intrinsic cyclical variations of energy density; how the mechanical chopper changes the character of these variations, and what kind of energy peaks, standing waves, or r. f. eddies are present should be examined both physically and experimentally. For example, r. f. probing of the closed-space inductorium, aided by signal-averaging and -characterizing computer systems, would yield a picture of instantaneous energy distributions. Too, examination of common endpoints of a given experimental preparation in alternating open- and closed-space experiments (employing the same formal parameters of radiation) would be useful in establishing empirical equivalence.

Once controllable electrical and environmental parameters were achieved, we believe the closed-space approach would have far-reaching significance for studying biological thermodynamics and the broad pathogenic significance (if any) of febrile states. Speaking to the former first: there is a plenitude of questions that attaches to the *intact* organism undergoing diffuse thermalization. Is there change in rates of neuronal conduction? of muscular contraction? of simple and complex reaction times involving various CNS circuits? Further, if biological time, as Roland Fischer theorizes, is conditioned by general metabolic rate and if absorption of microwave energy accelerates the rate, can not biological time and its correlates of aging, growth, and growing old be experimentally manipulated in the laboratory?

That nearly universal accompaniment of disease, fever, is little better understood than it was during Hippocrates' time. It is not known whether febrile states generally play a positive, negative, or indifferent role in, say, infectious diseases; our knowledge is so limited we yet can not say with certainty whether germs cause fever, or fever causes germs. If it turns out to be that microwave irradiation at a particular set of parameters produces little more than an imitation of the endogenous thermalization associated with disease, one would have access to a powerful tool for investigating the immunological and pathogenic significance of fever.

### *Microwave Hazards*

We mentioned earlier the difficulties of investigating and interpreting possible hazards of microwave irradiation—not the least of which difficulties is the trans-disciplinary concern for a form of energy in our environment that currently excites the interests of politicians as well as physicists and biologists. "Politician" is not a dirty word in our lexicon; it denotes someone potentially noble, necessarily practical, but sometimes misled by those upon whom he relies for information. The reference here is to those of us in the "academic-scientific complex" who may be overly provincial in defending theoretical or economic interests. Such provincialism is potentiated when times are tight—and right now is one of those times. Constricting federal budgets tend first to suppress those lower priority objectives we fuzzily call "pure" research with "low probability" long-range payoff. Less likely to be affected are projects or programs possessing a strong scare quotient. To state it bluntly: the marketplace of research is currently bullish on fear and bearish on benefit.

This symposium would never have been convened had not a critical mass of scares and fears exploded into a congressional appropriation and the formation of a new bureau to protect us from possible evils in the radiomagnetic "out-there." We, too, are afraid of the evils that may be "out-there," but are equally concerned lest apprehensions be so great and focus so narrow that possible benefits are overlooked and neglected.

Ours is the thesis that too little has been achieved in the way of hard data on hazards of low-level microwave irradiation to warrant a scientific base for establishing exposure standards. In our admittedly highly limited studies we discovered no chronic ill effects behaviorally or neurohistologically to derive from fairly long-term intermittent exposures approximating 2.5 to 15 mW/cm$^2$; although some striking acute effects were observed, none of them was or is incompatible with the supposition that thermalization was the only consequence of irradiation. Because of the morphological and phylogenetic chasm separating the rat from the human being, there is little basis for generalizing the data beyond this rhetorical point: has anyone, anywhere, published confirmed or confirmable evidence that lethal or tissue-injuring effects of nonthermal origin occurred in any mammal to any low-level microwave exposure?

Provisional standards of microwave exposure must of course be established because of the unknown long-term genetic effects that may accrue from this ever more prevalent energy form in man's environment. In the meantime, the day when adequate scientific data are available to vouchsafe standards should be hastened; our hope is that strong moral and economic support will be given to research whose focus is broad enough to illumine the good as well as the ill in the radiomagnetic "out-there."

## RESPONSES TO QUESTIONS

*Dr. Sher:* Raised issue with the terminology "flaccid paralysis" and "clouding of the sensorium."

*Dr. Justesen:* Doctor Sher's question really gets at a problem that occurs when scientists of differing training and background try to communicate. When we first observed what we privately call the "zonk" effect, it seemed simplest just to say that the animals acted as if they were asleep. This brought the wrath of neurophysiologists down upon us who wanted to see our EEG records—which of course we didn't have; to these specialists the notion of sleep has rather exact electrophysiological referents and our behavioral ". . . as if they were asleep," didn't register at all. Next we took a more descriptive tack: one, the animal was palpably very flaccid and two, it wasn't moving; ergo "flaccid paralysis." But maybe Doctor Sher is right—if I interpret his question correctly—the label does have sort of a sinister ring to it. Why don't we settle for a common language statement such as: the animals were limp and not moving? Doctor Sher also took a bit of umbrage at my use of the statement, "perhaps these animals had a clouding of the sensorium." What was meant here was the possibility, during the interval of intermittent irradiation before the animal zonked, of lessening awareness, lowered sensory acuity, call it what you will; it was noted, of course, that tests of the animals' discriminative efficiency—ability to respond and withhold responding in consequence of appropriate cueing—showed no decline and, in half the animals, a definite potentiation. Finally, I must say I am very much in agreement with Doctor Sher's statement that the zonked animals may be akin to students cooped up in a hot classroom. The implication is that heating of the rats by the microwaves might have made them sleepy—no! not sleepy, "limp and not moving."

*Dr. Frey:* Posed question as to whether additional research on sensory detection has been conducted.

*Dr. Justesen:* Early during these sessions Dr. Frey responded, and with justification I think, to the charge that a difficulty of duplicating Soviet behavioral research inheres in the insensitivity of their Pavlovian conditioning techniques. I can kill two birds with one stone—support Doctor Frey's assertion of the sensitivity of Pavlovian conditioning and respond to his question of our ongoing research—with the following reply. Doctor Nancy King and her assistant Rex Clarke have been employing a hybrid technique in our Kansas City laboratories that combines operant and Pavlovian conditioning. Pioneered by William Estes and B. F. Skinner, the technique involves training an animal in an operant task and then superimposing a stimulus such as a tone that terminates in a noxious electrical footshock. In a very short time the animal begins to suppress operant responding when the tone or some other sensory cue is presented—but continues working otherwise. Dr. King and Mr. Clarke found that low-level microwaves—1 minute presentations at 600 $\mu$W/gm to 6.4 mW/gm doses definitely possess cueing properties. The efficiency of this Pavlovian conditioned suppression isn't nearly so great as to, say, tone cueing, but the suppression is highly reliable with considerable resistance to extinction. Why the rat will use microwaves as a cue that predicts brief noxious stimulation, but not as a cue that predicts availability of a sugar-water payoff, is hard to understand. There is, however, one possible parallel in the behavioral literature of attempted cueing with hard radiation. Presentation of x rays at fairly intense doses didn't work in the payoff situation, but did work with the suppression technique. It was eventually found that ozone produced by the x rays was the effective (olfactory) cue. Whether the microwave cueing produces its effects peripherally or directly through the nervous system or whatever is something we'll have to discover. We hope, incidentally, to use the evoked potential technique by which Dr. Frey has studied response to open-space irradiation to determine whether there are electrocortical events associated with the suppression endpoint.

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# BEHAVIORAL EFFECTS OF LOW INTENSITY UHF RADIATION[1]

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Investigations of ultra high frequency (UHF) effects have focused on somatic effects, the chief interest being in assessing body tissue damage resulting from relatively short-term exposure to radio fields of high power and high frequency levels. There have been relatively few long-term studies of behavioral effects at low power and low frequency levels. Investigations of the latter sort are needed since 1) little information is available concerning subtle behavioral changes which occur as a result of exposure to low intensity fields; 2) duration has been suggested as a critical variable in UHF effects (1); 3) experiments dealing with the physiological effects of UHF radiation indicate that the central nervous system is more sensitive to UHF energy at low power densities (2) and at low frequencies (3) than to high level UHF fields; 4) a relatively small percentage of the population is exposed to high level UHF fields, whereas exposure to low intensity fields is not uncommon.

In light of the need for behavioral investigations using low levels of long-term UHF radiation, the author has carried out a series of replicated experiments. The specific aims of these experiments were 1) to determine possible UHF effects on several forms of behavior, 2) to explore behavioral effects for varying durations of exposure, and 3) to investigate the extent to which various power level and frequency parameters produce differential behavioral effects. The results obtained from these experiments show that exposure to low levels of UHF radiation does produce behavioral changes in albino rats. Furthermore, there are indications that these behavioral changes may be related to the parameters of duration, power level, and frequency.

## BEHAVIORAL EFFECTS

### Activity, Emotionality, Seizure Latency

Twenty 30-day-old naive male Sprague-Dawley rats were used as subjects (Ss) in the initial experiment designed to determine possible behavioral effects of UHF radiation (4). Experimental Ss were exposed to low intensity (50,000 microvolts; estimated at 0.76 mW/cm$^2$), low frequency (300 to 920 MHz presented in successive ascending and descending sweeps) UHF radio waves for 47 consecutive days. Although the experimental animals were exposed to UHF waves at all times other than the times when behavioral tests were being made, the control animals were never exposed to the UHF waves. Experimental and control Ss were compared on the following variables: activity, emotionality, weight, water consumption, electroconvulsive shock (ECS) susceptibility, and audiogenic seizures.

A General Radio amplitude-regulation power supply (1263A) and a General Radio oscillator (1209B) were used. A discone antenna, resonant on the frequencies being used, directed the waves to the experimental Ss in their lucite living cages. The antenna was placed so that no S could be more than 24 in. nor less than 12 in. from the antenna at any time. A similar discone antenna was placed in the center of the control group living cages but was not connected to a source of r. f. energy.

Experimental and control groups lived in separate, identical compartments ($7\frac{3}{4} \times 7\frac{3}{4} \times 5\frac{3}{4}$ ft.), each compartment being completely lined with bronze screening. In addition, the living cages of each group were enclosed in a small bronze cage ($5 \times 5 \times 3$ ft.). In the experimental group compartment, all bronze shielding was grounded through 6 ft. rods driven into earth ground. The purpose of the shielding in the experimental compartment was to contain the r. f.

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energy within the experimental compartment, while the shielding in the control group compartment served chiefly as a control; i.e., to maintain identical environmental conditions in experimental and control compartments. Field strength readings were made daily with a Simpson field strength meter.

### *Behavioral Tests*

For 40 consecutive days, activity level measurements were made in photocell cages for 30 min. a day. As an indicant of emotional behavior, Ss were observed in an open-field box for 3 min. a day for 24 consecutive days. Measures of emotionality included the number of boluses and the number of squares traversed relative to a 100 W light bulb which was hanging 30 in. above the center of the box. At the end of the first 40 days, half of the UHF group and half of the control group were tested for resistance to audiogenic seizures (3 min. daily exposures to 140 dB), while the other half of the UHF group and the other half of the control group were tested for latency of ECS (measures of duration of tonic and clonic phases of the convulsion subsequent to stimulation of 60 mA for 0.5 sec.). These measures of ECS and audiogenic seizures were made from days 41–47. Measures of weight were taken every three days while measures of water consumption were made every five days.

### *Results*

All data meeting the assumptions for a parametric test of significance were analyzed by either $F$ tests (Factorial Design with repeated measures on one variable) or $t$ tests. The Mann-Whitney $U$ test was used for data appropriate for a nonparametric test of significance. In order to reject the null hypothesis, the 0.05 level of significance was required.

Analysis of the activity data revealed a significant interaction between UHF and days of radiation ($F=4.19$, $df=39/702$, $p<0.01$). Simple effects analyses indicated that the UHF and non-UHF groups differed significantly on 18 of the 40 days, the UHF-treated Ss showing a brief initial increase (days 4, 5, 7, 9, 15) and then a subsequent consistent decrease in activity as the days of radiation progressed (beginning on day 21, but particularly prevalent from days 30–40). Analysis of emotionality data indicated no significant differences in the number of boluses ($U=3$, $p=0.20$). However, analysis of the more sensitive emotionality measure, squares traversed relative to a bright light, indicated that the UHF rats avoided the bright light more than did the non-UHF rats ($F=4.78$, $df=1/18$, $p<0.05$). Significant interactions were found for both the tonic ($F=1285$, $df=6/48$, $p<0.01$) and clonic phases ($F=3.57$, $df=6/48$, $p<0.01$) of the ECS convulsion. UHF and non-UHF groups did not differ in weight ($F=1.27$, $df=1/18$, $p>0.25$), water consumption ($F=0.23$, $df=1/18$, $p>0.25$), or audiogenic seizures ($U=3$, $p=0.056$).

### *Discussion*

It is evident that stimulation by low intensity, low frequency UHF radio waves does have effects on behavior. Specifically, UHF radiation has an influence on activity, emotionality, and latency of ECS. Upon inspection of activity through the days, it is apparent that some time is required for the UHF to have a consistent effect on behavior. At day 30, the two treatment groups separate and remain separated, the UHF group being consistently less active than the control group. The data also point to a reversal of effects in that UHF radiation resulted in an initial increase and a subsequent consistent decrease in activity level as the days of radiation progressed.

Not only were the UHF-treated rats more emotional than the nontreated rats, but also showed a longer latency of ECS. The clonic phase of the convulsion is of greatest interest in that during this phase the experimental group showed a gradual increase in the time of the clonic phase, while the control group showed a decrease; i.e., the control group exhibited the pattern of shorter latency of convulsions as the administration of shock increased. This pattern, which is usually found in ECS experiments, is not applicable to UHF animals.

## Learning and Stress

The learning and stress experiment, as well as subsequently reported experiments, involved the use of the same type of apparatus, general procedures, and basic environmental conditions as reported in the previous study. Two exceptions include the use of different power meters and the rearrangement of the Ss' living cages so that they were not more than 25½ in. nor less than 15½ in. from the antenna.

In order to determine a possible relationship between UHF and the variables of learning and stress, 15 experimental Ss were exposed to low intensity waves (0.43 mW–0.15 mW as measured at the front and back of the living cages respectively; Hewlett-Packard 431-A) at a low frequency range (300–900 MHz, ascending and descending sweeps) for 80 consecutive days. Fifteen control Ss were not so exposed to the UHF radiation. All Ss were naive 21-day-old male Sprague-Dawley rats. Experimental and control Ss were compared in terms of body weight (measured every third day from day 1 to day 80), time and errors in a 16-choice water maze (measured every second day from day 30 to day 80), and adrenal weight (measured on day 81).

### *Results and Discussion*

Statistical analysis indicated that the experimental and control Ss did not differ in terms of body weight ($F=0.24$, $df=1/28$, $p>0.25$).

### *Learning in the Water Maze*

Although the number of errors made by the UHF group exceeded those made by the control group (Mean Rank $E=10.70$; Mean Rank $C=9.22$), this difference was not statistically significant ($U=38$, $p>0.05$). Only in day 48 did the experimental group make significantly more errors than the control group ($U=24.5$, $p<0.05$). In terms of time scores, experimental Ss required significantly more time to swim the maze than did the control Ss on days 3 through 7 and on day 12. In addition, it is evident that learning, as indicated by decrease in time required to swim the maze, occurred for both groups since the days effect was significant ($F=1.92$, $df=25/700$, $p<0.01$). Therefore, according to one of the criteria of learning, time, it may be concluded that UHF-treated rats are poorer learners than non-treated ones. However, since the greater time required to swim may merely reflect the hypoactivity associated with radiated Ss, it is recommended that other measures of learning should also be applied.

### *Stress as Measured by Adrenal Weight*

The adrenal weight to body weight ratio measurement on Ss showed that the UHF Ss had significantly smaller adrenal glands as compared to non-UHF Ss ($t=2.12$, $p<0.05$). Although a stress differential exists between groups, it may not be concluded that the UHF Ss were more stressed than the control Ss unless it is assumed that swimming in a maze is a low degree of stress; i.e., since an interaction exists between degrees of stress and weight of adrenal glands, it is possible that lighter adrenals may be associated with low degrees of stress while heavier adrenals may be associated with high degrees of stress. Therefore, an experiment is planned in which UHF and non-UHF Ss will be compared on adrenal weights after they have been subjected to several degrees of stress.

## FREQUENCY PARAMETERS

Since the frequency range of the previously reported experiments was relatively broad (300–920 MHz), an experiment was designed to investigate frequency parameters within this broad frequency range. Specifically, the task of this research was to determine the relationship, if any, between frequency of low intensity UHF radiation (0.43 mW–0.15 mW) and activity level (5).

Thirty-six 28-day-old naive male Wistar rats were used as Ss in two experiments. In Experiment 1, a low frequency range (320–450 MHz, ascending and descending sweeps) was used, while a higher frequency range (770–900 MHz, ascending and descending sweeps) was used in Experiment 2. The same power levels were maintained for both experiments.

### *Results*

Analyses revealed that the UHF-treated Ss were significantly less active than control Ss in both Experiment 1 ($F=7.56$, $df=1/16$, $p<0.05$ difference between means$=19.5$) and Experiment 2 ($F=4.85$, $df=1/16$, $p<0.05$, difference between means$=12.2$). The treatment variance components for each experiment indicate that the variance due to UHF treatments is approximately 2.5 times greater in Experiment 1 (164.86) than in Experiment 2 (59.39). The interaction between UHF and days was nonsignificant in both experiments (Experiment 1: $F=1.22$, $df=20/320$, $p>0.10$; Experiment 2: $F=1.28$, $df=20/320$, $p>0.10$).

### *Discussion*

Not only do the results of this investigation substantiate the relationship between low intensity, low frequency UHF and behavioral changes in the form of decreased activity, but they also point to the importance of the frequency parameter. Although both high and low frequency ranges produce a decrease in activity, the lower frequencies at a given power level are more effective in producing activity changes.

These data confirm previous findings by the author in that the major effect of low levels of UHF radiation on activity is one of hypoactivity. However, these data do not show an early short-term period of hyperactivity as was previously found. This discrepancy may be due to the change in power levels in the present investigation relative to the previous experiment which used activity as a dependent variable.

## POWER AND DURATION PARAMETERS

At the present time the author is carrying out a series of experiments designed to determine any UHF induced behavioral changes associated with various power levels and durations of exposure.

For the first experiment in this series, the maximum power level used was 0.50 mW/cm$^2$ (monitored by Narda B86B3) while the frequency levels used were 300–920 MHz presented in ascending and descending sweeps. Experimental Ss were irradiated for 40 consecutive days. Ss included thirty 21-day-old naive male Sprague-Dawley rats.

Behavioral measurements were made on the following: 1) activity (20 min. measures made on alternate days from days 4–30), 2) emotionality (3 min. measures of squares traversed in the open-field box made on alternate days from days 1–30), 3) learning (time and error measures made for one trial a day for days 31–40), and 4) stress (adrenal weight/body weight ratio measures on day 41).

### *Results*

Analysis of the activity data showed that except for the first day of measurement (4th day of irradiation) and the ninth day of measurement (20th day of radiation), the UHF-treated animals had a lower activity level than the non-UHF animals. However, none of the activity differences proved to be statistically significant at the specified 0.05 level of significance (Range of $U$ values = 52–108).

In terms of emotionality measures, two significant differences were found between experimental and control groups. UHF rats traversed significantly fewer total number of squares on the 23rd day of radiation ($U = 62$, $p < 0.05$) and on the 27th day of radiation ($U = 58$, $p < 0.05$). These two differences may not be interpreted as differences in emotionality, however, since the indicant of emotionality in the open-field box is not the total number of squares traversed, but the number of squares traversed relative to the bright light. Therefore, these two differences probably reflect differences in general activity level.

No significant differences were found in learning or stress measures. The UHF and non-UHF groups did not differ significantly in terms of learning as measured by the number of errors made in the water maze (Range of $U$ values = 53–89) nor in terms of learning as measured by time required to swim the maze ($F = 0.001$, $df = 2/25$, $p > 0.25$). UHF and non-UHF Ss did not differ significantly in the adrenal weight/body weight ratio ($F = 0.012$, $df = 1/24$, $p > 0.25$), although this ratio was numerically smaller for the UHF animals.

### *Discussion*

At the power level of 0.50 mW/cm$^2$, there is an indication of a hypoactive response, but no indications of an effect in terms of emotionality, learning, or stress. However, the direction of trends for all the measures was in the direction found at other power levels. Two general conclusions seem feasible: 1) Except for activity, UHF radiation at this power level does not affect the behavior of rats, at least in terms of the behaviors sampled in this experiment; 2) Although this power level does not affect these behaviors for 40 days of exposure, there might be some effect if the number of days of exposure were to be increased since duration of exposure appears to be a critical variable.

At the present time the author is carrying out an experiment designed to provide data which may aid in choosing between the two alternative conclusions; i.e., an experiment utilizing the same power level as the previously reported experiment (0.50 mW/cm$^2$), but extended in duration (130 days).

## SUMMARY

1. At some low intensity power levels, rats exposed to continuous ascending and descending sweeps of frequencies from 300–920 MHz showed the following behavioral changes as compared to control Ss: (a) consistent, long-term hypoactivity which may be

preceded by a short-term period of hyperactivity, (b) greater emotionality, (c) longer latency of recovery from electroconvulsive shock, (d) longer time to learn to swim a water maze, and (e) a differential stress reaction as determined by weight of adrenal glands.

2. Within the band of frequencies investigated (320–900 MHz), frequencies toward the low end of this band (320–450 MHz) have a greater effect in producing hypoactivity than those at the higher end (770–900 MHz).

3. At the low power level of 0.50 mW/cm$^2$ applied for 40 days, UHF appears to be related to hypoactivity, but has essentially no significant effect on emotionality, learning, or stress.

4. Results suggest that some time is required for UHF to have a consistent effect on behavior.

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# BIRD FEATHERS AS SENSORY DETECTORS OF MICROWAVE FIELDS

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## INTRODUCTION

Microwaves have been demonstrated to produce specific biological effects (see, e.g., Refs. 1 to 6) that could be exploited to help solve the increasingly serious bird hazard problem in aviation (7, 8). For example, chickens subjected to pulsed microwave radiation at an intensity of 50 mW/cm$^2$ have shown specific escape reactions; namely, immobilization, initiation of collapse (flanking), and the initiation of flight (4, 5). Pigeons and seagulls react similarly with the exception that seagulls tend to initiate flight.

It has also been demonstrated that radiation of a feeding area has a strong deterrent effect (3, 6) on birds approaching the area to feed.

Birds in flight take avoiding action (9) when they are confronted with a microwave field. The compulsiveness of this action depends on the field intensity and such environmental factors as temperature, humidity and wind velocity.

These findings have prompted a closer look at the physiological correlates in an attempt to identify the control hierarchy and sensory systems involved. Once these are established it will be possible to arrive at a microwave field design that will produce a particular avoidance reaction for the least expenditure of power.

Electrophysiological studies have revealed that all areas of a bird show changes in biopotentials when the bird is subjected to pulsed microwave radiation (10, 11, 12). Whether these changes are due to the influence of the electromagnetic field, local changes in the skin or physical changes in the behavior of the animal so that feedback of the motor activity is modified, has yet to be determined.

Interaction with the neuromuscular system has been demonstrated in electromyographical studies of the muscles (11) responsible for extending the limbs outward as observed in a collapsing bird. Following the onset of radiation an imbalance of muscular activity occurs that is demonstrated by an increase in the activity in the contralateral muscles almost to complete paralysis. The asymmetry of this reaction points to the involvement of the central nervous system but, again, the nature of the mechanism has yet to be determined.

A question arises as to the possibility of physiological mechanisms associated with the feathers that would be activated by a microwave field. The reaction of chickens whose tail feathers only were subjected to microwave radiation was explored together with the effects of radiation on defeathered birds.

## RADIATION OF TAIL FEATHERS—LEGHORN HENS

A Leghorn hen was placed in the test cage and absorbent material (Eccosorb) was arranged around and over the cage in such a way that only the tail feathers of the bird were exposed to the microwave field. The field intensity measured at the tail was 50 mW/cm$^2$ (average power) at a frequency of 9.29 GHz pulsed at 416 pps with a pulse width of 2.35 $\mu$sec. When the radiation was switched on the bird immediately ceased what had been a moderately inquisitive exploration of the cage. After a period of approximately 10–20 seconds the bird showed mounting signs of distress vented in the form of vocalization, defecation and the initiation of flight. Repeated periods of exposure produced the distress reaction in a shorter time. Tests on members of the same species produced the same result and in each case when the field was switched off the bird responded by fluffing its body feathers and actively preening. The feathers alone appear to be responsible for this reaction.

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## EXPERIMENTS ON DEFEATHERED CHICKENS

Radiation tests were conducted on chickens with feathers plucked and with feathers cut in order to gain further insight as to the associated sensory mechanisms.

Three Leghorn hens were plucked under anaesthesia. Upon recovery from the anesthetic these birds were radiated with pulsed microwaves as previously described. Exposure to microwave radiation was given for two minutes every day for the following 23 days. Little or no reaction was observed in the birds, except for an initial startled reaction, until the 12th day when the characteristic flanking reaction reappeared. It was noted at this time that feathers had started to regrow and were about ½ inch in length.

A similar experiment conducted on Leghorns that had had their feathers cut off close to the skin revealed apparent indifference to the microwave field up to 30 days following defeathering. During this period there was no appreciable change in the feather structure, i.e., no new growth appeared. Control birds showed the normal escape reactions.

From these experiments it is evident that feathers serve in a sensory role but to ascertain the exact nature of the coupling that occurs between a feather and an electromagnetic field further tests are required.

## MICROWAVE ABSORPTION CHARACTERISTICS

A simple qualitative test was performed to determine the opacity of feathers to microwaves. A neon discharge lamp was placed in the microwave beam and ignited by raising the field intensity above the striking threshold. The field was then reduced to the point at which the neon discharge was on the threshold of extinction. Interposing any absorptive material between the microwave radiator and the neon lamp resulted in an immediate diminution or extinction of the discharge.

Feathers were inserted in layers corresponding to their arrangement on the bird but no change in the neon discharge was observed. Various groups and layers of feathers were then inserted but in all cases there was no noticeable change in the neon discharge—an indication that no sensible absorption of microwave energy occurred.

This negative finding must be considered in relation to the possible mechanisms responsible for the avoidance reaction observed. The following are suggested:

1. Direct electrical excitation of sensory receptors in the skin by direct coupling between the feathers and the microwave field;
2. Mechanical excitation of sensory receptors by induced vibration in the feathers; and
3. A combination of 1 and 2.

Since feather tissue has dielectric properties, feathers may be expected to act as dielectric antennas. Mechanical excitation of a feather would be produced by piezoelectric conversion of electrical energy. One can imagine that the physiological picture must be very complex when the large number of feathers and their integrative functions in flight control and temperature regulation are considered.

## PIEZOELECTRIC PROPERTIES

An experiment conducted to determine the mechanical response of feather tissue to electrical stress (13, 14) indicated that under specific conditions of electrical stress the quill section of a chicken feather responds with multiple resonance peaks in the 0.1 to 10 kHz region. Only rotational modes of vibration were detected in the quill but it is reasonable to consider that an intact feather subjected to radiation would respond with complex resonance modes. Although the amplitude of vibration would be very small, the compound effect of a large number of feathers may evoke a strong escape reaction.

## DISCUSSION

These experiments demonstrate that feathers play an important sensory role in enabling a bird to detect a microwave field. The physical properties of quill tissue and particularly the piezoelectric characteristics point to a multiple physiological role and suggest sensory modalities that have been overlooked in the past.

The different experimental approaches and results described in this paper present a common denominator, namely, the stress that a microwave field creates in a bird. Interaction of some kind is always observed which leads to the premise that electromagnetic fields are of paramount importance in biological systems.

### *Acknowledgment*

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# MAXIMUM ADMISSIBLE VALUES OF HF AND UHF ELECTROMAGNETIC RADIATION AT WORK PLACES IN CZECHOSLOVAKIA

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There is no doubt that radio waves may have unfavorable effects upon man under certain conditions. This fact is of greatest significance in heavily industrialized countries where electromagnetic waves are being used to a continuously increasing extent. They are not only being applied for information transmission (radio, television, radar) but especially in industry, as a source of heat energy. Thus a continuously greater number of workers, as well as the normal population, is being exposed to the effects of electromagnetic fields of different intensity, character, and frequency.

For this reason a Department of High Frequency was established in Czechoslovakia in 1960 at the Institute of Industrial Hygiene and Occupational Diseases in Prague. This Department has, since that time, concerned itself solely with the problems of electromagnetic waves of the nonionizing spectrum in relation to man and the possibility of man being unfavorably affected.

During these ten years the initial effect was devoted to hygiene problems in connection with maximum admissible values of electromagnetic fields and later to basic research to clarify the mechanism of biological effects of electromagnetic waves. In this report I shall—due to lack of time—attempt to discuss merely the hygienic part of the work of our Department and perhaps there will be an opportunity at some other time to further discuss the problems we are currently investigating.

First of all I will consider the way we approached the determination of maximum admissible values of electromagnetic fields.

At first we elaborated some methods for measuring the intensity of the field in the HF band and power density in the UHF band. Thereupon we visited factories, broadcasting stations, television and radar centers, and spoke with the people there and performed individual measurements. We visited approximately 200 work places with diverse applications of electromagnetic waves. Furthermore we also carried out some simple biological experimentation in animals in order to verify the findings from the plant surveys.

It appears that the effects of the HF field upon the organism are reversible to a considerable extent and the effects of repeated irradiation are cumulative. We may say that in the course of time the organism becomes more perceptive of the effects of the field. The biological activity depends directly upon the field intensity; not only the average power but the peak power as well. A pulsed output generator is therefore biologically more effective than a continuous wave generator of equal average output of the same frequency. Results obtained to date tend to indicate that poly-frequency radiation is biologically more effective and therefore more hazardous. The enhancement of biological effects of the HF field by the conjunctive action of other physical or chemical factors must not be ruled out. This is of special significance in industrial situations where such factors may occur in the environment of the worker which may add to the detrimental effects of exposure to electromagnetic radiation. Electromagnetic waves at certain intensities may cause primarily neurologic complaints. Typical symptoms are pains in the head and eyes and fatigue connected with overall weakness, dizziness, and vertigo when standing for a longer period. Sleep at night is restive and superficial, there is sleepiness during the day. Exposed individuals are subject to changing moods, they often become irritated to the point of becoming intolerable. Hypochondric reactions are manifested along with feelings of fear. Sometimes those affected feel nervous tension or, on the contrary, mental depression connected with inhibition of intellectual functions, mainly decreased memory. The afflicted workers complain of a feeling of strain in the skin of the head and forehead; their hair falls out; they complain of pains in the muscles and in the heart region connected with irregular heart beating and breathlessness. Not infrequently there are complaints in the sphere of sexual life with respect to potency as well as libido. Slight quivering of eye lids, tongue, and fingers, increased sensitivity of extremities and dermographism is also observed. Exposure to higher intensity fields for a longer period leads to significantly decreased blood pressure sometimes resulting in collapse. At the same time we observed considerable individual differences in the sensitivity of the organism to this factor.

With respect to the effect of the HF field upon sex it was found that although no special changes in the female organism were detected, women in general are more sensitive to this factor than men. The symptoms of damage are disturbances of menstruation with the cycle irregularly prolonged by as much as eight days. An increased incidence of miscarriage is also suggested. Young people appear to be more sensitive than old people.

From the point of protecting people against possible damaging effects of electromagnetic fields, naturally the threshold biologic effects of the field intensity are of importance. In respect of the heat effect it is agreed that heating of the organism occurs at power densities of 10–15 mW/cm$^2$ in animals as well as man. This level for thermal effects is in agreement with theoretical calculations.

For other types of effect other field intensities pertain. Thus for example for cataract induction an intensity of 10 mW/cm$^2$ is required; changes in the sensitivity of the auditory apparatus occur even at 1 mW/cm$^2$ but the feeling of pain in the skin only at 0.6 W/cm$^2$.

For microwave frequencies biological effects may be induced at power densities as low as 0.1 mW/cm$^2$. At lower frequencies histopathological changes may result from field strengths 100 V/m or greater. The latter values were used in Czechoslovakia and in the U.S.S.R. as a basis for the maximum admissible field intensity. Considering the large differences observed in the sensitivity of different people an additional safety factor of 10 was applied to arrive at the value 10 $\mu$W/cm$^2$ in the microwave band and 10 V/m in the lower frequency band.

It must also be born in mind that many biological processes may be even more sensitive than those previously considered. Thus it is known, for example, from reports in the literature, that the velocity of cell division with *Vicius fabus* is accelerated at field intensities of $10^{-4}$ V/m at frequencies of approximately 30 MHz and the velocity decreases at values above 0.1 V/m.

Field intensity alone is, however, not a sufficiently good measure of the threshold of effectiveness. This threshold undoubtedly depends also upon the time factor. The organism has a certain ability to protect itself against adverse external stresses. The extent of the protective effect may be expressed by the equation

$$K_n = f(N_n \cdot t_n). \tag{1}$$

This formula states that the ability of an organism to withstand a certain stress is proportional to the quantitative value of this factor $N_n$, which in this case is the intensity of the field or power density, and to the period of effect $t_n$. If the value of the function on the right side of Equation (1) is smaller than the respective measure $K_n$, an adverse effect upon the organism will not occur. The question therefore remains: What is the value of measure $K$ for electromagnetic waves in man and what is the form of the function $f$?

For chemical hazards, heat stress, and damage from ionizing radiation this function is known to be given by the product of the variables. Admitting this analogy it is therefore possible to write for the effect of radiowaves in the UHF band

$$K_{\mathrm{UHF}} = N' \cdot t' \tag{2}$$

and in the HF band

$$K_{\mathrm{HF}} = E' \cdot t'. \tag{3}$$

The primed quantities are the maximum values satisfying the equality of both expressions and therefore of $K_{\mathrm{HF}}$ and $K_{\mathrm{UHF}}$ are the maximum admissible irradiations in the given band.

The product of the actual field intensity and the exposure period is then called the irradiation $O$. For microwaves, for example,

$$O_{\mathrm{UHF}} = N \cdot t. \tag{4}$$

It is obvious that in practice care must be taken that the irradiation does not exceed the maximum admissible values and therefore

$$O \leq K. \tag{5}$$

Values of maximum admissible irradiation $K$ for both frequency bands were stipulated on the basis of the present knowledge of biological effects with due consideration to the fact that they can only cover a certain average sensitivity of the organism at

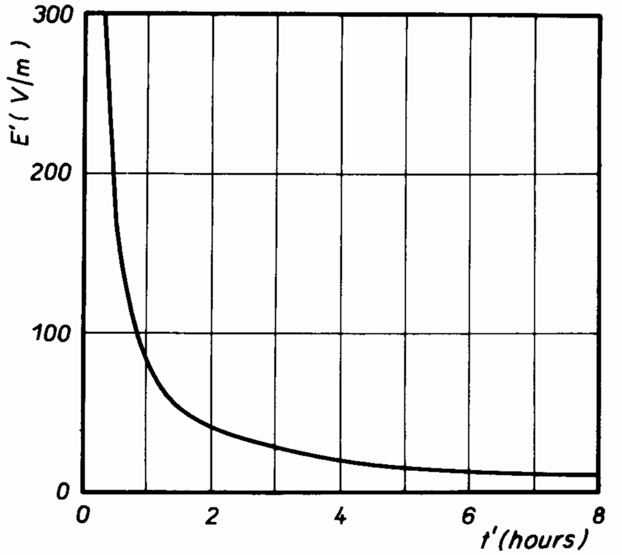

Figure 1. Maximum permissible field intensity in the HF (30–300 MHz) band for various times of irradiation during the work day.

average partial parameters of the field. For this reason a safety factor was included as well.

The maximum admissible irradiation was specified in Czechoslovakia not only for workers subjected to this hazard but also for the rest of the population.

Permit me now to give you a survey of the values of irradiation currently in effect in Czechoslovakia at present and I should like to remind you at the same time that irradiation is given by the product of field intensity in V/m or power density in $\mu W/cm^2$ and the time of exposure in hours.

1. As hygienically tolerable for workers in the vicinity of HF and UHF generators, who are subject to medical examinations, the values are such that the irradiation does not exceed the following mean day shift values as calculated from the irradiation of the worker during one work week:

a. in the HF band from 30 kHz to 30 MHz a value of 400. This corresponds for an 8 hour work day to a mean field intensity of up to 50 V/m. It must be stated here that the V/m unit is used as the most suitable although the measurement is carried out in the near field;

b. in the HF band from 30–300 MHz a value of 80, corresponding during an 8 hour work day to a mean field intensity of up to 10 V/m;

c. for continuous wave generators in the UHF band a value of 200, this corresponding for an 8 hour work day to a mean power density 25 $\mu W/cm^2$;

2. The values considered as hygienically tolerable for other workers and the entire population are such that the radiation in the surroundings of the individual does not exceed the following mean daily values calculated from the irradiation during one calendar week:

a. in the HF band from 30 kHz to 30 MHz a value of 120, this corresponding for 24 hours of exposure to a mean field intensity of up to 5 V/m;

b. in the HF band from 30 to 300 MHz a value of 24; for a 24 hour per day exposure this corresponds to a mean field intensity of 1 V/m;

c. for continuous wave generators with outputs in the UHF band a value of 60 which for a 24 hour per day exposure corresponds to a mean power density 2.5 $\mu W/cm^2$;

d. for pulsed output generators in the UHF band a value of 24; this corresponding for a 24 hour per day exposure, to a mean power density of 1 $\mu W/cm^2$.

In practice it is of advantage to draw a diagram of maximal values of field intensity as a function of exposure time as shown in Fig. 1 for the 30–300 MHz band. The period the worker is permitted to stay in a given field is evident from this figure. Figure 2 demonstrates the maximum length of stay in the field of given power density in the microwave band for pulsed fields (solid line) as well as for continuous wave fields (broken line).

In order to estimate the hygienic tolerance under given working conditions the regulation also specifies a uniform method of measurement including the recommended apparatus.

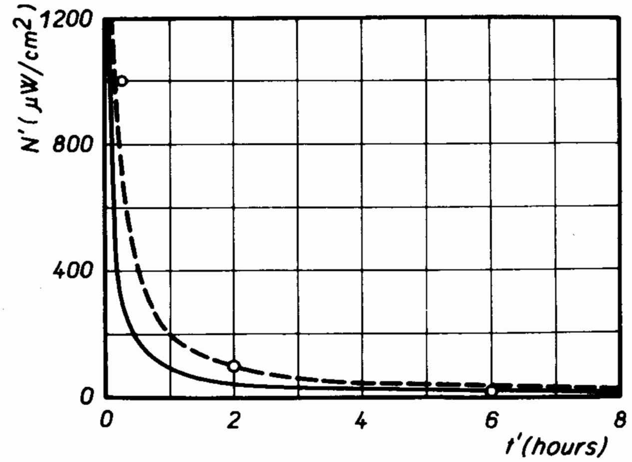

Figure 2. Maximum permissible power density in the UHF band (>300 MHz) for various times of irradiation during a work day. The dotted line refers to CW operation and the solid line is for pulsed operation. The circles on the CW graph indicate the maximum permissible values in effect in the U.S.S.R.

All equipment currently produced in Czechoslovakia which has HF and UHF generators as components must comply with these regulations or their production or sale is not permitted. We know from many years of experience that it is possible by technical and organizational means to achieve the tolerance values we have specified.

I would also like to indicate that our regulations state that work with HF and UHF is not permitted for pregnant women in those cases when the individual daily values of irradiation are being exceeded even if the mean maximum admissible shift values are being maintained. Furthermore work is prohibited for women and in certain circumstances also for adolescents when the mean maximum admissible shift values are being exceeded at the work location.

I should like to stress in conclusion that the mentioned maximum admissible values of irradiation valid in Czechoslovakia were decided so as to prevent not only damage to the organism, but to prevent unpleasant subjective feelings as well.

*Editor's Note*—Although no bibliographic material was submitted by Dr. Marha, a thorough survey of the biological effects of microwave radiation is presented in the book written by Dr. Marha et al. originally published in Prague in 1968 and available in English translation: K. Marha, J. Musil, and H. Tuha, *Electromagnetic Fields and the Life Environment,* San Francisco Press, 255 12th St., San Francisco, California, 94103, (1970).

## DISCUSSION

*Dr. Illinger:* I would like to ask Dr. Tanner why he would expect the piezoelectric effects would persist in the modulated high frequency signals? Is this frequency modulation or amplitude modulation? Presumably the former.

*Dr. Tanner:* Yes, all our signals were modulated. May I put the question to you? Why should it not persist?

*Dr. Illinger:* I don't know.

*Dr. Tanner:* The animal detects whatever it is, you see.

*Dr. Illinger:* Well, a very simplified view of looking at this is that there is a piezoelectric effect which is in part, of course, mechanical and one may detect its frequency at low frequency of about 10 kHz. Now if the system is being irradiated at a high frequency, say 8 GHz and at the same time the radiation is frequency modulated, this is quite a different thing from an electrical field that is varying at low frequency. I would have said naively that the piezoelectric effect doesn't have any high frequency component. There is some evidence for this. Piezoelectric materials mostly, as far as I know, are reasonably low frequency in their dispersion. I may be completely wrong in this.

*Dr. Tanner:* This is a mystery to us, you must realize. Although this work is continuing, we still haven't by any means come to a satisfactory answer.

*Dr. Illinger:* I am very hazy about this because I know very little biology but it is my understanding that in some species of birds the liquid crystals that one sees painted on the feathers of things like pigeons, these irridescent things which are complicated aromatic molecules play an important biological function; the nature of which I don't know. There has been some work on the orientation of these liquid crystals at microwave frequencies. I wonder whether that is not another possible mechanism of interaction with something that is central to the biology of birds.

*Dr. Tanner:* Yes. But the question that I pose is why do we not detect any absorption?

*Mr. Nelson:* I'd like to inquire whether you check the adequacy of your shielding by putting the birds in this shielded enclosure and remove the tail feathers or clip them? Was this done at all?

*Dr. Tanner:* Yes, we have in fact plucked the birds and run a whole series of tests on plucked birds.

*Mr. Nelson:* And failed to get a response?

*Dr. Tanner:* Yes. This is something very characteristic of the feathers. We have plucked about ten birds under anesthesia and tried this.

*Dr. Zaret:* I would like to address two questions to Dr. Marha. One is the question of monitoring the field. Is there anything done to measure and monitor the radiation fields where workers are actually working?

*Dr. Marha:* Yes, we have a hygienic control program for the 110 microwave or r. f. facilities. At 10 or 11 of these there is equipment for measurement of electromagnetic fields. At the other installations the equipment is surveyed once a year and controlled if changes are detected.

*Dr. Zaret:* The other question relates to the fact that these standards have been in existence for many years and yet the literature keeps showing the central nervous system symptoms being reported in the people that work in these environments where the safe level should be such that they shouldn't have the symptoms. How are they getting exposed?

*Dr. Marha:* Yes, but what I said occurred 8 to 10 years ago. Since then there has been no trouble.

*Dr. Frey:* Let me mention that this is specific to Czechoslovakia and it does not include the Soviet Union.

*Dr. Zaret:* Several years ago I had the opportunity to talk to someone in the radio frequency field from the Soviet Union and he came from the Radioelectric Institute in Moscow. He told me that they didn't measure fields in their laboratories but each man knew what he was permitted to be exposed to. They relied on the individuals avoiding the field rather than measuring them.

*Mr. Martinelli:* In regard to the chicken feathers I note that at the short wavelength involved it is quite possible that waves which literally travel up the feather itself can be induced. These are quite similar to ordinary cylinder-rod waves which can be induced in glass rods and indeed when the chicken feather is sticking out it could well have a wave going up intercepting the hind quarters of the chicken. I think this could be checked by simply tying with twine plucked feathers to the existing tail feathers and seeing to it that only the plucked feathers are illuminated and probably you will have the same response.

*Dr. Tanner:* Thank you very much. We rather suspect it is something like that.

*Dr. MacAfee:* We also raised chickens, we also plucked them, and we ate them. But in the meantime we measured whether or not the feathers passed microwaves and we got the same result that Dr. Tanner got. Now at that power level, at that distance, we suspected that we were introducing a nociceptive response to these animals. The chicken feather being a very good insulator and keeping the heat that might be rising on the skin of the chicken from escaping, the skin temperature may be rising very rapidly to this magical number of 45 degrees, or whatever it might be in the chicken. You get the nociceptive response and the animal collapses. This is just a suggestion.

*Dr. Tanner:* Could this occur in five seconds?

*Dr. McAfee:* I would say so since you have an excellent thermal blanket.

*Dr. Sher:* I have a comment for Dr. Justensen and a question for Dr. Marha. Less the terms arouse undue anxiety, flaccid-paralysis which sounds nasty, and clouding of sensorium, happens to me in a private conference room whenever the door is closed and the temperature rises. The clinical significance of microwave effects must be kept in mind. If all or most conventional ovens in the U.S. were today replaced with the available microwave ovens with their attendant possible problems of leakage, I suspect that the clinical effects for the general population would be favorable. The number of accidents associated with the use of the conventional ovens is very significant. My wife burns herself regularly and it is certainly not unusual for ovens, gas operated and electrically operated, to generate very clinically significant problems such as the house catching on fire or other untoward results of cooking.

*Dr. Frey:* May I ask a question? Why don't you get a microwave oven?

*Dr. Sher:* I would love to have one, but they are a little expensive. Regarding the figure of 10 mW/cm$^2$ and the papers which we have heard, I have to say that if a person or an animal is exposed to 10 mW/cm$^2$ a sufficiently sensitive experimental technique must detect some change. Whether this is a change in the partition of biochemical components or a change in galvanic skin response or a change in the quivering of the large toe, a sufficiently sensitive experiment must detect a change. We know that there is energy going into the animal's body and it is reasonable therefore to expect a change. Now getting more toward the question to Dr. Marha; considering how many people have been exposed to microwave radiation and considering how few injuries we have to contend with; considering how useful microwave radiation is, most of our long distance communication today is by microwave radiation, radar serves obvious functions. Furthermore, the hazard of microwave radiation must be viewed in the context of the hazard due to other forms of more conventional energy such as sonic, mechanical, chemical. We are subject to many possible insults from our environment. How can it be justified to limit microwave radiation to such intensities that the smallest possible effect is precluded and furthermore a factor of safety of ten is included?

*Dr. Marha:* This is a difficult question to answer. You see, our standard, as I said in my paper, is not only to prevent damage but to avoid discomfort in people. I would like to ask if a physiologist in the U.S.A. can measure headaches? No. And if I have a headache at work, it makes my work uncomfortable. Why 10 $\mu$W/cm$^2$? I said that this standard was set in the Soviet Union and we have the same standard but with slight modifications. We have a time factor and 10 $\mu$W/cm$^2$ applied to irradiation for an entire working day. We have surveyed our microwave and r. f. facilities and before we set our standards we found two cases of cataracts, even though we have relatively few people engaged in this type of work. Since the standards have been set and enforced we have had no cases. It is possible that the standard is too conservative but we feel that the use of the time factor makes it quite reasonable. We make our power density measurements at the height of the head and the testes and the minimum distance of measurement from the source is 20 to 25 cm. This is how we apply our standard.

*Dr. Justesen:* Dr. Sher's question really gets at a problem that occurs when scientists of differing training and background try to communicate. When we first observed what we privately call the "zonk" effect, it seemed simplest just to say that the animals acted as if they were asleep. This brought the wrath of neurophysiologists down upon us who wanted to see our EEG records—which of course we didn't have; to these specialists the notion of sleep has rather exact electrophysiological referents and our behavioral "... as if they were asleep," didn't register at all. Next we took a more descriptive tack: one, the animal was palpably very flaccid and two, it wasn't moving; ergo "flaccid paralysis." But maybe Dr. Sher is right—if I interpret his question correctly—the label does have sort of a sinister ring to it. Why don't we settle for a common language statement such as: the animals were limp and not moving? Dr. Sher also took a bit of umbrage at my use of the statement, "perhaps these animals had a clouding of the sensorium." What was meant here was the possibility, during the interval of intermittent irradiation before the animal zonked, of lessening awareness, lowered sensory acuity, call it what you will. It was noted, of course, that tests of the animals' discriminative efficiency—ability to respond and withold responding in consequence of appropriate cueing—showed no decline and, in half the animals, a definite potentiation. Finally, I must say I am very much in agreement with Dr. Sher's statement that the zonked animals may be akin to students cooped up in a hot classroom. The implication is that heating of the rats by the microwaves might have made them sleepy—no, not sleepy, "limp and not moving."

*Dr. Frey:* Have you conducted additional research on sensory detection?

*Dr. Justesen:* Early during these sessions Dr. Frey responded, and with justification I think, to the charge that a difficulty of duplicating Soviet behavioral research is the insensitivity of their Pavlovian conditioning techniques, I can kill two birds with one stone—support Dr. Frey's assertion of sensitivity of Pavlovian conditioning and respond to his question of our ongoing research—with the following reply. Dr. Nancy King and her assistant Rex Clarke have been employing a hybrid technique in our Kansas City laboratories that combines operant and Pavlovian conditioning. Pioneered by William Estes and B. F. Skinner, the technique involves training an animal in an operant task and then superimposing a stimulus such as a tone that terminates in a noxious electrical footshock. In a very short time the animal begins to suppress operant responding when the tone or some other sensory cue is presented—but continues working otherwise. Dr. King and Mr. Clarke found that low-level microwaves—1 minute presentations at 600 $\mu$W/gm to 6.3 mW/gm doses definitely possess cueing properties. The efficiency of suppression isn't nearly so great as to say, tone cueing, but is highly reliable with considerable resistance to extinction. Why the rat will use microwaves as a cue that predicts brief noxious stimulation, but not as a cue that predicts availability of a sugar-water payoff, is hard to understand. There is, however, one possible parallel in the behavioral literature of attempted cueing with hard radiation. Presentation of x-rays at fairly intense doses didn't work in the payoff situation, but did work with the suppression technique. It was eventually found that ozone produced by the x-rays was the effective (olfactory) cue. Whether the microwave cueing produces its effects peripherally or directly through the nervous system or whatever is something we'll have to discover. We hope, incidentally, to use the evoked potential technique by which Dr. Frey has studied response to open-space irradiation to determine whether there are electrocortical events associated with the suppression endpoint.

*Mr. Dan O'Connell:* I have a question for Dr. Marha on the interpretation of the Czech and Russian standards. In understanding any standard for microwave measurement work we must also understand the test conditions and the instrumentation. In drafting the American standard we specify near field measurements taken 5 cm from the radiating surface of a microwave oven. The level at that point is $X$ mW/cm$^2$. How are the Czech and Russian standards defined for CW allowable radiation?

*Dr. Marha:* In Russia, there are procedures and instrumentation but I do not have details on either. In Czechoslovakia we measure 25 cm from the surface of the source as compared to the 5 cm measurement in the United States.

*Dr. Heller:* I would like to make a comment on your statement. I want to report a large series of one case. We had a colleague who was a parasitologist. All of our r. f. work was done in a doubly shielded copper room so naturally we normally left the door open and within a building that had a 100 foot length, whenever we would turn it on he would put both hands on his head and say "Oh God, they're turning on the damn r. f. again." We really thought this was psychological; we checked him out and so far as we could determine this was real. The power levels must have been trivial. I don't know whether this was ESP even though I report the datum I really still don't believe it but there was quite a correlation between an acute and intense headache and the time that the r. f. was turned on.

*Dr. Frey:* On this headache phenomena, I am convinced that it is a real effect. To study the nature of headaches and quantify this is a little bit difficult. I have, in doing some exploratory work and trying various and sundry things, doing some subtle questioning of people who are in r. f. field and such and trying to use all possible controls that I could and to avoid suggestions and such, I have come to the conclusion that there is something happening there. . . that there is a headache type of phenomena. I can see ways and means experimentally to explore this. I have not done so with humans because I think there is an ethical question here; I have seen too much. I very carefully avoid exposure myself and I have for quite some time now. I do not feel that I can take people into these fields and expose them in all honesty and indicate to them that they are going into something safe. I can see possible ways of exploring this with animals but that is another story.

*Dr. Fred Harris:* I would like to direct a question to Dr. McAfee. Was any attempt made to monitor impulse traffic in small fibers either in peripheral nerve or in central spinal pathways which might have been set up by the heating of subcutaneous layers?

*Dr. McAfee:* Yes. As the temperature rises there is an increase in the small fiber neural electrogram. In other words, if you raise the temperature by any means the little spikes on small fibers increase in number. There is no initiation of action potential from the larger nerves. In other words, you don't see the big spike potentials from the myelinated fibers. There is a very peculiar thing however. If you look at the small fibers electroneurogram at the 45 degree level, when you get the nociceptive response you would expect to see a sudden increase in this activity. It is not seen by those who have reported this particular measurement and so we really don't know why this occurs at this temperature and why it can't be seen in the electroneurogram.

*Dr. Carpenter:* Several speakers during the Symposium have mentioned power levels and some have specified measurements without the subject animal in the field. Particularly the chicken for example; the measurement of the level at the chicken's back if the chicken's back was there. In other cases it was not specified. I think we ought to keep in mind the fact that if you measure power density in a free-field you can get a nice figure. Put an animal in the field and it isn't the same field anymore; you might have an entirely diferent power density. Dr. McAfee mentioned the cases of Michaelson's and our work in which subcutaneous burns were produced. This is the case where the animal is exposed in a field and some days later the side of its face sloughs off revealing a sterile burn that has already begun to heal. One of my graduate students did some measurements at 10 GHz in an anechoic room using a scatter technique with the scattering reflector of infinitesimally small dimensions in relation to the wave length and using a "magic T." It was possible to plot the field and find a rather uniform field in the empty room. Now if we put a rabbit in the field and measured, we found it was not a uniform field at all but it turned out that there was a very hot spot right over the rabbit's zygoma. This is the place where the skin usually gets burnt. I think if this had been done by Drs. Michaelson and Howland they would have probably found some hot spots in their experiments. Now a piece of lucite can do quite a job to a field. It can reflect, refract, and change the conditions of the experiment.

If you use a plastic cage you may not have the field at all and if you're going to measure it the only measurement that has some validity is if the measurement is made with the animal in the cage and you measure the field inside the cage. This is not easy but if you're going to report measurements I think you have to take into consideration that a measurement in the free field is not the same thing as a measurement with the subject that you are experimenting upon present in the field.

*Dr. Frey:* Thank you very much. You have brought up a subject that I hope to bring up during some of our discussions on measurements. This is a very difficult problem. You should also add to your comment that simply putting a dipole in the field to measure it with the animal in or out in itself changes the field. I myself work in an r. f. anechoic enclosure and the technique that I use is to measure the power density in the field at the place where the animal would be rather than with the animal in the field. The reason for this is, as you point out, the animal in the field disturbs the field. What I am primarily concerned with is reproducibility of results so that anyone anywhere who sets up an anechoic chamber comparable to ours and uses the same measuring set up, puts it in a free field no matter what his animal size or looks or what have you, at least to that point they have a comparable measurement and at least to that point a comparable reliability. This, however, needs further discussion as it is a rather difficult problem.

*Dr. Carpenter:* It certainly is because of the fact that animals, even rabbits, vary in shape. There are times when we wish we could get a standard rabbit with the same shaped head, because a long nose rabbit and a short nose rabbit can change the field differently.

*Dr. Frey:* Exactly, and because of this I tend to do it without the animal in the field. At least to that point anybody replicating something that I do is with me. After that, well, we then worry about the shape of the head of the cat or what have we.

*Dr. Zaret:* I have a question for Dr. Marha about the two cases of cataracts. There has only been one case reported from Russia, one by Shimkhovich and Shiliaev. They had reported power density levels comparable to the ones we have seen in this country. Namely, as I recall 350 mW/cm$^2$ power densities repeated several times. Do you know whether the exposures were comparable in the Czechoslovakian cases?

*Dr. Marha:* I don't know if it was described in literature since they occurred many years ago. The cases were examined by our ophthalmologist in Prague but I will try to determine the levels and provide you with this information. In the first case we don't know the power density since it occurred 7 or 8 years ago. In the second case we know that the duration of exposure was fifteen years and the worker was employed in a scientific laboratory, and he worked with devices such as magnetrons. The worker looked into a waveguide with rather high power density.

*Dr. Zaret:* This is typical of about 25 percent of the cases that we have seen. They look through the end window, adjust the grid and are exposed to about a watt per cm$^2$ in this region. The first case, in order to add it to the accumulated number of cases, I would appreciate it if at some future date, you would look into it.

*Dr. Michaelson:* Since the question of burns has come up and since they are my animals that have been discussed, I think in order to avoid confusion that we should state that it is interesting that these burns, the typical third degree burn of which we have sections, occur only over selected areas of the body, mainly the rib cage. This occurred in probably 10 percent of the cases in animals that were exposed to 2.8 GHz and also this indicated some selective heating and maybe some standing wave formation beneath the skin in the area of the burn.

*Dr. Shapiro:* This is for Dr. Marha. It would be very helpful, if you could report on any one experiment where at a level of say 100 $\mu$W/cm$^2$ you have a definite effect that was observed, either the headache effect or any one of these effects that you have mentioned at any level that is close to the level that you have set as a threshold. Is there any such set of data that you could tell us about?

*Dr. Frey:* As a point of clarification, are you looking specifically for a human study?

*Dr. Shapiro:* Yes, I would prefer a human study.

*Dr. Marha:* The experiments at these levels were not performed by us. We have people who work in microwave or r. f. environments of 1 to 10 mW/cm$^2$ or more for short periods of time due to the use of our time factor.

*Dr. Shapiro:* Do I understand then that your hazard level is based on the assumption that all of the effects are cumulative? As I understand it you have evidence of workers who were exposed at 1 or

10 mW/cm$^2$ for 15 minutes at a time and they had some bad effects such as headaches.

*Dr. Marha:* The headaches were produced in fields of 100–150 mW/cm$^2$.

*Dr. Shapiro:* You don't have headaches below 150 mW/cm$^2$?

*Dr. Marha:* Below 150 mW/cm$^2$ perhaps but not below 100 mW/cm$^2$.

*Dr. Shapiro:* I am trying to understand how you arrive at this number of 10 $\mu$W/cm$^2$ for an 8 hour shift for a week. That is you are getting this product that you had on your slide of a power density multiplied by a time.

*Dr. Marha:* This value is obtained as an average exposure rate over the total work week and in the case of short exposures the power density may be suitably adjusted upward.

*Dr. Shapiro:* I think I understand that you are saying that if a person got 10 $\mu$W/8 hours a day for 5 days a week that that is the same exposure as if he had for example, 10 mW/1 minute for 100 minutes.

*Dr. Marha:* I cannot calculate that so quickly at this moment.

*Dr. Shapiro:* Yes, but that is the general idea.

*Dr. Zaret:* Did you want to specify any upper limits? Could this be also 1 watt for 10 seconds, for example, or is there an upper limit where you cut off? You see, in this country, we have an upper boundary. You are not supposed to pass this boundary. Or under some conditions, with a time average. Do you have a boundary?

*Dr. Marha:* We have considered this but since at present we do not have equipment capable of producing enough power to produce damage in these short exposures, we have not set an upper limit. Perhaps when this becomes necessary we will do so.

*Dr. Zaret:* I hate to take up so much time but your 10 $\mu$W/cm$^2$ may turn out to be quite similar to what we find here with our milliwatt per cm$^2$ boundary.

*Dr. Frey:* Dr. Korbel, you mentioned, as I recall, that your exposure is within a Faraday cage. Is your Faraday cage a resonating cavity or what is your field pattern within this?

*Dr. Korbel:* You are interested in knowing the field pattern within the Faraday cage?

*Dr. Frey:* r. f. energy within a Faraday cage could lead to some interesting field patterns. Do you have any data as to the field patterns?

*Dr. Korbel:* I myself did not make measurements. I must admit that I am completely dependent on my engineer. I do have patterns plotted for the various power levels that I used. I don't have them with me but if you will write to me and tell me exactly what you want and I will send them to you.

*Dr. Frey:* Do you recall how smooth the fields were? Whether you have hot spots or not?

*Dr. Korbel:* The fields were relatively homogeneous.

*Dr. Frey:* Your frequencies were on the order of 400 MHz to 900 MHz?

*Dr. Korbel:* 300 to 920 MHz.

*Dr. Frey:* And what was the size of the Faraday cage?

*Dr. Korbel:* It was 7′9″×7′9″×5′9″. Incidentally, my measurements were made inside the plastic cage sans the organism.

*Dr. Frey:* By the way, you mentioned using a Hewlett-Packard power meter. Was it a 430 or something akin to this?

*Dr. Korbel:* I don't remember the number.

*Dr. Frey:* Do you know what was attached to the power meter? Such as a thermistor mount?

*Dr. Korbel:* In terms of the probe? Yes.

*Dr. Beyer:* Dr. Marha, you alluded to medical examinations for people who are in microwave fields. Do your routine medical examinations also include routine slit lamp examinations of the eye and sperm analysis?

*Dr. Marha:* (Dr. Susskind answering for Dr. Marha): Yes, Dr. Marha says they make an internal examination and on the eye as well as a biochemical examination.

*Dr. Beyer:* By biochemical, you mean the blood, various enzymes. Does it include a sperm analysis or a motility study of the sperm in the male?

*Dr. Susskind:* This is only the case where the patient complains that this is one of his difficulties.

*Dr. Marha:* In our biochemical studies of the blood the only effect we have detected is alterations in gamma globulin.

*Mr. Prucha:* Dr. Marha, I am belaboring a point I fear, but it is an important one for my notes. The question is with regard to your weekly dosage limit and as I interpret the point that we had some difficulty with arithmetic on, you are making the point that the 10 $\mu$W/cm$^2$ dosage limit applies for 8 hours a day 7 days a week which would give you 560 $\mu$W hours per week. Is that a proper number?

*Dr. Frey:* The answer was yes.

# QUANTIFYING HAZARDOUS MICROWAVE FIELDS: ANALYSIS[1]

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## INADEQUACY OF ACCEPTED CONCEPTS AND STANDARDS

For a linearly-polarized monochromatic infinite plane wave in a linear homogeneous isotropic medium, the magnitudes of the electric field, magnetic field, energy density,[2] and energy flow[2] (power density) are all readily measured and each of these magnitudes may be computed from any of the others without approximation, given the properties of the medium. Hence, any one of these magnitudes constitutes a valid index of such a field and, in fact, completely specifies the field apart from phase and the directions of propagation and polarization. Further, for such a wave in a lossless medium, only the phase varies with position or time. However, no such computation can be made for an arbitrary field. Rather, the ratios of these magnitudes can vary widely with the detailed nature of the field, i.e., depending upon detailed information seldom available in field monitoring or even in biological exposure experiments. For example, a standing wave formed from two of the preceding plane waves of equal amplitude and the same linear polarization but opposite direction has zero time-average energy flow (power density), yet the amplitudes of both the electric and magnetic fields are double those of the original waves at specific locations. Further, at distances from a source less than a small number of wavelengths (reactive zone), the time-average power flow may be zero, yet the electric and magnetic fields may be arbitrarily large.

The preceding complications are of little or no importance in the far field, i.e., for the usual practical sources, at distances from the source large compared to $a^2/\lambda$ where $\lambda$ is the wavelength and $a$ is the greatest distance between points in the source, considering reflectors to be a part of the source. However, hazards and electromagnetic interference[3] (EMI) arising from microwave and lower frequencies tend to be important in the near rather than far field and a large fraction of biological exposure experiments are carried out under near field conditions to achieve high power levels.

"Measurements" of near fields based upon far field concepts must be regarded as simplistic and are at best semi-quantitative, often not even qualitatively correct. For example, in certain regions, the field arising from a microwave oven in a stainless steel kitchen may increase significantly with increasing distance from the oven. Even for a high gain antenna carefully designed to give a uniform field, the energy density may vary by a factor of two in a region of nominal constancy outside the reactive zone. The near electric field amplitude of such a horn-lens antenna 100 wavelengths on an edge is shown in Fig. 1; the horizontal dependence is nominally that of a square wave and all the structure shown is real, not noise. Due to the wavelengths involved, analogies between microwaves and optics, x-ray behavior, or gamma-ray behavior are commonly invalid and normally not as good as those with sound waves, since standing waves, resonances, and echoes occur with both microwaves and sound. Although workers in the field base their hazard measurements upon energy flow and commercial

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[1] Contribution of the National Bureau of Standards not subject to copyright. This work was partially supported by the Bureau of Radiological Health, U.S. Public Health Service.

[2] Strictly speaking, the familiar expressions for both energy density and energy flow (in terms of the electric and magnetic fields) can neither be proved nor disproved (3). However, the expressions for energy absorption have strong foundations and "direct" measurements of energy density and energy flow are usually really measurements of energy absorption. Because the hazard discussed here is indeed related to the hypothetical energy density, we will use the expression energy density without qualification.

[3] Analytical considerations of electromagnetic interference parallel those of radiation hazards to a considerable extent. Thus, most of this paper also applies to EMI.

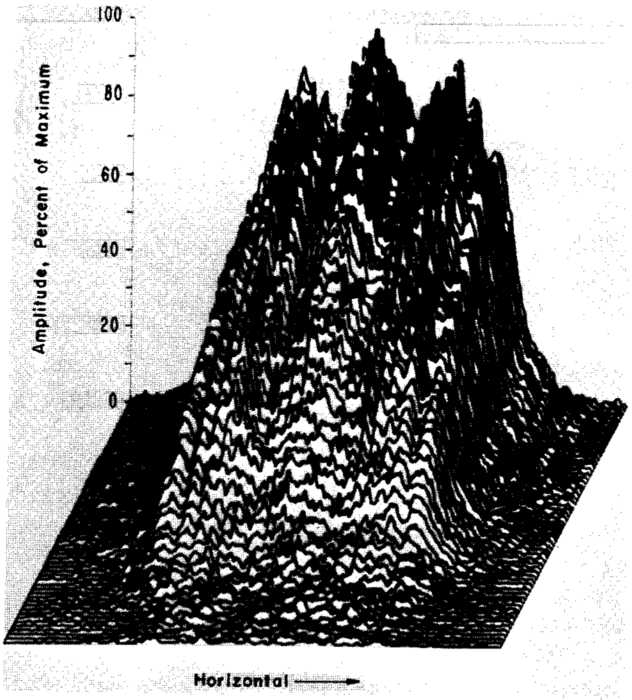

Figure 1. Amplitude variation near a horn-lens antenna.

probes have energy flow scales, some of these probes respond primarily or partially to energy density *per se*.

## EXPOSURE OF MEASUREMENTS IN WAVEGUIDE AND COAXIAL LINES

Perhaps the simplest nonfar field situation applicable for exposure experiments with tissues or small animals is inside rectangular waveguide or coaxial line. Here the walls and inner conductor may be a copper mesh, fine compared to a wavelength. For waveguides, the largest inside dimension should be well between one-half and one wavelength so that one and only one mode will propagate. For lower frequencies, rectangular coaxial line such as that used in a Stark cell and shown in Fig. 2 may be used; here the longest dimension should be significantly less than half a wavelength to prevent the propagation of more than one mode. If the tissue and its surrounding culture medium constitute a transverse slab which completely fills the cross-section of the guide or coaxial line and has a uniform complex dielectric constant, the field inside the sample may be readily computed from the dielectric constant and the input power. The field varies with the position in the cross-section and, if the slab is not thin compared to a wavelength, often with the longitudinal position as well. However, the longitudinal variation may be minimized by filling the guide with a medium having essentially the same complex dielectric constant and magnetic susceptibility as the slab, minimizing reflections. (In this case, the dimensions of the guide should be related to the wavelength in the medium and the medium should extend far enough on both sides of the tissue slab to insure a pure mode.) Further, attention may be confined to a region of uniform field. In the case of the Stark cell, high fields may be generated where the septum approaches the outside wall; to avoid contamination of the sample being studied by decomposition products from regions of high field, the septum should not be close to the wall and/or the portion of the sample being studied should be separated from the portion in the high field by a thin impervious dielectric. For a whole animal (invariably of irregular shape and varying dielectric constant), the situation is more complicated in any near field; however, in principle, reflection effects could also be minimized by immersion in a medium with a similar dielectric constant provided that gaps were

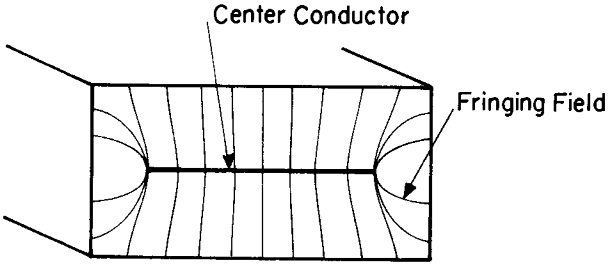

Figure 2a. Cross section of a Stark cell.

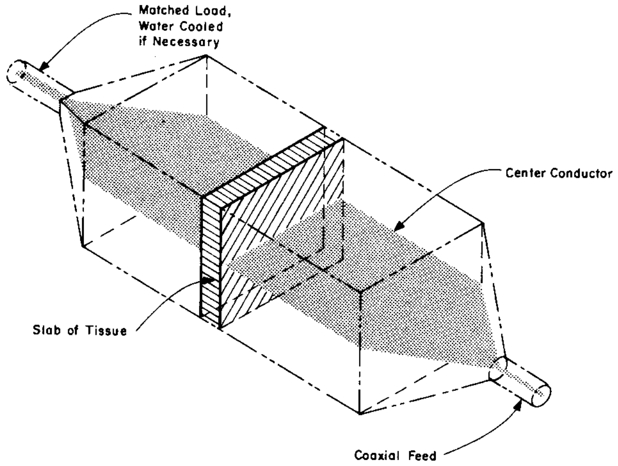

Figure 2b. General plan of a Stark cell.

small compared to a wavelength, that the medium did not cause too great an attenuation, and that thermal effects, respiration, etc. were properly handled.

## ENERGY DENSITY AS A MEASURE OF HAZARD

Since a field with initially zero energy flow (power density) may be responsible for arbitrarily great hazard to a subject later placed in it or arbitrarily great EMI to an electronic device placed in it, power density is not a suitable index of either hazard or EMI caused by a near field. Preferably the index should be closely related to the hazard and be easy to measure. Electrical energy density is proposed for the index. Since biological materials are essentially nonmagnetic, they interact with an electromagnetic field primarily only because of their dipole moments (more strictly, the dipole transition moments), absorbing energy quanta at a rate proportional (for a linear medium) to the electrical energy density in the tissue. Although the quanta are much too small to cause the breaking of a chemical bond, a molecule which has absorbed one or more quanta has an activation energy which may well cause the molecule to be significantly more reactive in a general sense, say for exchange reactions involving the breaking "bonds" between compounds in the protoplasm and loosely held water. If desired, this may be considered to be extremely localized heating. Thus, electrical energy density should be a reasonable hazard index for both thermal and nonthermal effects including resonant absorption by specific molecules.

It is expected that the hazard to each portion of the body will be associated with its own "constant" of proportionality and that this "constant" will vary with frequency, perhaps sharply. There may well be other effects associated, e.g., with polarization of the field or nonlinearity of the tissue (say in pulsed fields). However, such effects can be studied as deviations from those predicted from energy density measurements assuming a linear isotropic medium.

For EMI in a near field, energy flow has the same disadvantages and energy density has many of the same advantages as for hazards.

## MEASUREMENT OF ENERGY DENSITY

The preceding energy density discussion is based upon the energy density within the given tissue, not upon that of the field into which the animal or person might enter. In principle, probes might be implanted in an animal or either the animal or person might be simulated in terms of the complex dielectric constant and magnetic susceptibility as a function of position. Since these procedures would be inconvenient for monitoring, the relation between the energy density inside an animal or person to that inside the probe must be considered (including perturbation of the field by the probe, person, or animal) and used in probe design. General principles will be discussed first, then illustrated with an exact treatment of a possible probe.

In principle, a probe should simulate the body or a given electronic instrument in its extraction of electrical energy from the field. Since the body makes only a slight perturbation in a field of hard x rays or gamma rays, so should a probe used to measure them, i.e., the probe should be analogous to a high resistance voltmeter rather than a shorting ammeter which gives a reading strongly dependent upon the internal impedance of the source. In contrast, from the shortwave radio region through the ultraviolet, the body absorbs almost all the incident energy apart from that which it reflects. The penetration depth[4] increases steadily from 3000 GHz to 3 MHz with a depth of 10 cm for 30 MHz and 52 cm for 3 MHz. Hence, a probe designed for this important frequency range should also absorb most of the nonreflected energy and probably have a low reflectivity as well. (However, in some circumstances, say in continuous monitoring of a radar beam, it is impractical to use a probe which absorbs large quantities of energy.)

A related phenomenon concerns the magnetic field associated with the electric field. In absorption of a quantum of radiation, both magnetic and electric energy are involved. Further, both the initial electric and magnetic fields and the fields remaining after absorption are related by Maxwell's equations so that absorption of all the electric energy requires absorption of all the magnetic energy. For an infinite plane wave in a vacuum, the magnetic and electric energies are equal. However, the ratio of the energies may vary widely in a near field, say from the predominately magnetic field near an electromagnet to the predominantly electric field between plates of a large capacitor. Thus, a probe which properly stimulates the body gives readings partially de-

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[4] Skin depth as defined in electromagnetics.

pendent upon the magnetic field, although the probability of quantum absorption is essentially independent of the magnetic field. For EMI measurements, a probe which reacts directly to the magnetic field may be desirable and is discussed in the succeeding section on probe design.

Any device which measures a single complex voltage or its magnitude may be regarded as a device which measures a single constituent of a field, i.e., the coefficient of a single basis function from the infinite series of basis functions used to represent the field. Thus, an ideal dipole measures the coefficient of one of the three electric dipole constituents of the field and completely neglects all magnetic multipoles and all but one of the electric multipole constituents of the field, regardless of their strengths. This limitation does not apply (in a practical sense) to a dipole in a linearly polarized plane wave only because the probe has a fixed calibration factor (which may be accurately computed); however, even in an infinite plane wave, a dipole oriented to give maximum amplitude can give an error of a factor of two in the energy density, depending upon whether the field is linearly or circularly polarized. A probe based upon losses (say, resulting in heating or pressure rise) does not have these limitations and so is suitable for direct measurement of total electric energy density; such a probe measures the energy density and adds all components without cancellation, all of the contributions being positive. For any electric (or magnetic) dipolar field, a probe which sums the squares of the absolute values of the voltages from three identical perpendicular dipoles can give an accurate result independent of probe orientation. Note that even an infinitesimal probe need not measure the field at a point, e.g., a quadrupolar probe; thus, a tiny dipole and a tiny quadrupole measure unrelated quantities.

A probe comparable in size to a wavelength will show resonances much the same as a half-wave dipole, i.e., the calibration constant will be a rather strong function of frequency, less so if the medium is lossy.

For convenience, a probe should not require orientation nor discriminate on the basis of direction of the incoming waves. It should be noted that no voltage probe has these properties, but that an energy density probe with spherical symmetry does. A general theory of such a probe is given in the next section including a procedure for *a priori* computation of its calibration "constant," i.e., the ratio of the energy density of the field prior to the introduction of the probe to the energy density in the probe. No calibration constant can be computed for any probe without some knowledge or assumptions concerning the spatial dependence of the field, but an energy density probe with spherical symmetry requires a minimum of knowledge—much less than is required for a voltage probe.

For pulse power, the analysis is significantly more complicated. The present analysis has been modified to include pulse effects but will not be reported here.

## DETAILED DESIGN OF A POSSIBLE PROBE

Since previous studies have involved assumptions and approximations inappropriate for near fields, a detailed study is carefully carried out for a mathematically-manageable probe. The study reveals complications which can arise and illustrates some of the general statements of the preceding portions of this paper.

Consider a medium which is linear, isotropic, piecewise homogeneous, source-free, and subject to Ohm's law. For every homogeneous region, every solution of Maxwell's equations is solenoidal and is a solution of the vector Helmholtz equation. For a single frequency and a medium which has spherical symmetry, the complex electric field **E** and magnetic field **H** are conveniently expressed as a linear combination of Hansen's **m** and **n** functions (4). (The time-dependent factor $\exp(-i\omega t)$, where $\omega$ is the angular frequency, is assumed but suppressed.) Every such function is a solution of Maxwell's equations (5) and the set of functions is presumably complete (6) for the problem at hand. (The **L** and **l** functions are not solutions of Maxwell's equations.)

Let $\mu$ and $\epsilon$ be the complex permeability and permittivity and $k=\omega(\mu\epsilon)^{1/2}$ be the propagation constant. As shown in Fig. 3, consider a probe with instrumentation from radius $R=0$ to $a$, a shield $S$ from $R=a$ to $b$, a lossy material $L$ from $R=b$ to $c$, and a dielectric $D$ used for thermal insulation from $R=c$ to $d$, immersed in a medium $A$, say air. If no internal instrumentation is used, $a$ and $b$ would be zero. Both the media and the propagation constants are indicated by the upper case Latin letters as shown in the diagram. The corresponding lower case Greek letters are used in the permeabilities. For an electrical probe, the permeabilities will ordinarily be essentially that of free space.

In the expression for the electric field, let $M_{emnb}$

and $N_{smnb}$ be the coefficients of the ratios of $\mathbf{m}_{smnb}$ and $\mathbf{n}_{smnb}$, respectively, to the square root of $[n(n+1)(1+f)2\pi(n+m)!]/[(2n+1)(n-m)!]$, where $f$ is unity for $m=0$ but otherwise zero (7). The subscript $s$ is used to denote the symmetry, either even ($e$) or odd($o$). The subscript $b$ indicates the kind of the spherical Bessel function, either the first ($j$) or second ($y$) kind. (The $y$'s are not needed for the central region of the probe ($R=0$ to the first discontinuity) nor for the field in the absence of the probe.) The corresponding coefficients for $i\omega\mu\mathbf{H}/k$ are $N_{smnb}$ and $M_{smnb}$, respectively (note reversal) (5).

Given the coefficients in any one region of the probe or the region outside the probe, the coefficients of the other regions can be obtained with the aid of boundary conditions.[5] Because of symmetry, coefficients with different $s$, $m$, or $n$ are independent, as are the $M$ and $N$ coefficients. Thus, for given $s$, $m$, and $n$, the four $M$ (or four $N$) coefficients corresponding to the two kinds of Bessel functions on the two sides of a boundary are related by two equations. Suppressing the $s$, $m$, and $n$ subscripts and adding a subscript to indicate the medium, the following equations are obtained

$$(N_{jA}j_A+N_{yA}y_A)A/\alpha=(N_{jD}j_D+N_{yD}y_D)D/\delta \quad (1)$$

$$(N_{jA}\partial_{jA}+N_{yA}\partial_{yA})/A=(N_{jD}\partial_{jD}+N_{yD}\partial_{yD})/D \quad (2)$$

$$M_{jA}j_A+M_{yA}y_A=M_{jD}j_D+M_{yD}y_D \quad (3)$$

$$(M_{jA}\partial_{jA}+M_{yA}\partial_{yA})/\alpha=(M_{jD}\partial_{jD}+M_{yD}\partial_{yD})/\delta \quad (4)$$

for the $A$-$D$ interface, where

$$j_A=j_n(AR), \quad y_A=y_n(AR),$$

and

$$\partial_{yD}=\partial/\partial R\{Rj_n(DR)\},$$

all here evaluated for $R=d$.

The coefficients of the field in the presence of the probe may be related to those for the field in the absence of the probe ("unperturbed field") by an integral equation, assuming that the perturbation of the field does not affect the distribution of the sources.[6] Because of orthogonalities, the equation separates into a number of equations, each involving only $M$ or $N$ coefficients and a single set of $s$, $m$, and $n$ values. Thus, a knowledge of the coefficients in any part of the probe, surrounding space, or in the unperturbed field permits determination of all the other coefficients, given the properties of the probe; further, determination of the coefficients splits into separate problems as indicated.

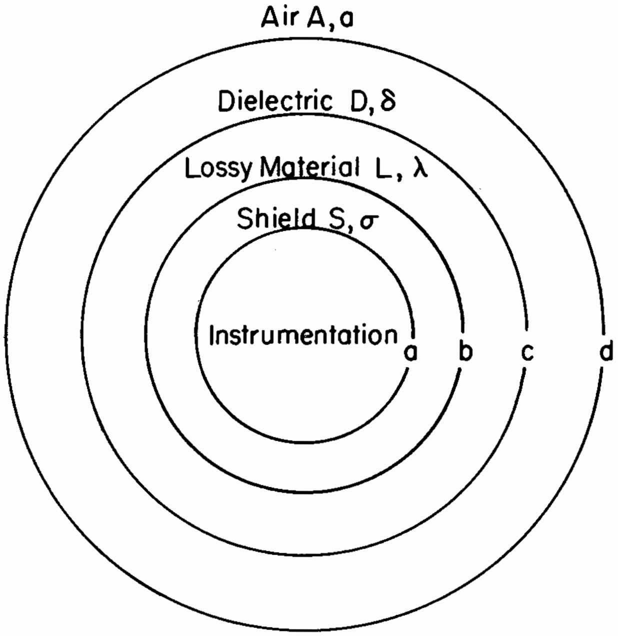

Figure 3. Cross section of a spherical energy-density probe.

The time-average energy density is given by $\mathbf{E}\cdot\bar{\mathbf{E}}\ \mathrm{Re}\ \epsilon+\mathbf{H}\cdot\bar{\mathbf{H}}\ \mathrm{Re}\ \mu/4$, where the overline indicates that the complex conjugate is to be taken and the symbols $\mathbf{E}$ and $\mathbf{H}$ represent peak values. The integral of the time-average energy density over the polar and azimuthal angles $\theta$ and $\phi$ is simplified by the fact that the orthonormalities between the $\mathbf{m}$'s and $\mathbf{n}$'s given by Stratton (7) also apply for the Hermitian dot products (including those for solutions involving different kinds of Bessel functions) if each square of a Bessel function in Stratton's expressions is replaced by the product of the first Bessel function by the complex conjugate of the second, both of the given order. For any medium, the integral of the time-average electric energy density over $\theta$ and $\phi$ is given by

$$\frac{\mathrm{Re}\ \epsilon}{4}\sum_{s,m,n}\Big[|M_{smnj}j_n+M_{smny}y_n|^2 + \frac{n+1}{2n+1}|N_{smnj}j_{n-1}+N_{smny}y_{n-1}|^2 + \frac{n}{2n+1}|N_{smnj}j_{n+1}+N_{smny}y_{n+1}|^2\Big] \quad (6)$$

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[5] See Ref. (3) pp. 483–484, (1a), (5), (10).

[6] For a similar case, see Morse and Feshbach, *Methods of Theoretical Physics* (McGraw-Hill Book Co., New York, N.Y., 1953) pp. 1897, 1875.

and the integral of the time-average magnetic energy density is given by the expression obtained by interchanging the symbols $M$ and $N$ and replacing Re $\epsilon$ by $\beta$. Here $\beta=|k/\omega\mu|^2$ Re $\mu=|\epsilon/\mu|$ Re $\mu$; hence, for real $\mu$, $\beta=|\epsilon|$. The Bessel functions of course have the argument $kR$. The losses in a medium are given by an expression identical to that for the energy except the Re $\epsilon$ is replaced by $2\sigma$ and Re $\mu$ is replaced by $2\chi$, where $\sigma$ is the electrical conductivity and $\chi$ is the analogous magnetic quantity, both for the given frequency. Thus, Re $\epsilon$ and $\beta$ are associated with the electrical and magnetic density, while $\sigma$ and $\chi$ are associated with the electrical and magnetic losses respectively. The possibility of a magnetic probe will be discussed later.

Neither the unperturbed field nor, in the absence of internal instrumentation, the field in $L$ involves $y$ functions. Therefore, the time-average angular integrals of energy density in the unperturbed field and the loss in $L$ depend only upon the sums

$$\sum_{s,m} |M_{smnj}|^2 \quad \text{and} \quad \sum_{s,m} |N_{smnj}|^2,$$

not the individual coefficients. Further, the relations between the coefficients for the unperturbed field and those for $L$ are independent of both $s$ and $m$, so that specification of the sums for the unperturbed field determines the sums for $L$. Thus, neglecting losses in other regions, the calibration constant of the probe is independent of any changes in the unperturbed field which do not change the sums. A wide range applicability of the calibration "constant" is, of course, important for any probe, whether the calibration is computed or measured; such a range seems to be characteristic of the proposed probe.

It is, of course, convenient to be able to use and calibrate a probe in a plane wave and also to be able to specify the class of fields for which the calibration constant is applicable. For a plane wave travelling in the $z$ direction with its electric vector in the $x$ direction, the $M_{olnj}$ are proportional to $i^n\{[(2n+1)(n+1)!]/[n(n+1)(n-1)!]\}^{1/2}$, the $N_{elnj}$ proportional to $-i$ times these quantities, and all the other coefficients zero (8). Assuming that

$$\sum_{s,m} |M_{smnj}|^2 = \sum_{s,m} |N_{smnj}|^2,$$

for each $n$ requires that the electric and magnetic energies of the unperturbed field be equal if Re $\epsilon=\beta$. Assuming in addition the sums to be zero for $n=0$ but proportional to $[(2n+1)(n+1)!]/[n(n+1)(n-1)!]$ for other $n$ permits one to compute a calibration constant (given the propagation constants and susceptibilities), valid for a large class of fields, including plane waves as a special case. (The calibration constant can, of course, also be obtained by direct measurement.) As will be discussed later, these assumptions may be relaxed to a degree for a small probe with low dielectric constants.

Ordinarily the lossy material of the probe would have a complex permittivity and essentially a real permeability and so provide a measure of the electric field.

It would be desirable to obtain an independent measure of the magnetic field, and this would be possible if a suitable material could be found, i.e., one which is linear and isotropic with complex permeability but fairly small dielectric loss tangent. Such materials do exist for small fields (low on the hysteresis curve), but only exploratory work could determine whether a practical probe could be developed. The preceding analysis would apply for both kinds of probes, and provide information concerning the relative magnitudes of $M$ and $N$ sums.

For a probe small compared to each of the $1/|k|$'s, the Bessel functions may be approximated by $j_n(z)\cong z^n/(2n+1)!!$ and $y_n\cong-(2n-1)!!/z^{n+1}$, where $(2n+1)!!$ is the product of the odd integers up to and including $2n+1$. Hence, for the lower microwave frequencies and below, the preceding expressions are significantly simplified. Further, because practical fields have a limited amount of fine structure, at least the higher $M$ and $N$ coefficients tend to decrease with increasing $n$, much like those for a plane wave. As a result, only the lower terms need be used for a probe tiny compared to both the scale of the field structure and a wavelength. (The wavelength condition is not required for x or $\gamma$ rays, where the wavelength is small compared to the dimensions of the probe, introducing averaging effects).

## SUMMARY AND CONCLUSIONS

The existing standards for microwave radiation hazards are based upon far-field concepts which may have little or even no validity in near fields. However, hazards occur largely in near fields, and even many dosimetry experiments are carried out in near fields. Because of the great complexity possible in a near field, a probe should, in principle, simulate the individual who might be subject to the possible hazard; however, such a probe is not feasible. Electric energy density provides a reasonable index of a large class of microwave radiation hazards and is simpler to measure in a near field than is energy flow. Analytical aspects of near field measurements are discussed in general, and design of a possible probe described in detail. So that near-field dosimetry experiments are meaningful and reproducible, great care must be used in field measurements and describing conditions which determine the field in the subject.

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# QUANTIFYING HAZARDOUS ELECTROMAGNETIC MICROWAVE FIELDS: PRACTICAL CONSIDERATIONS[1]

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## INTRODUCTION

A companion paper by P. F. Wacker is concerned primarily with analysis and with the problem of realizing an accurate probe for quantifying hazardous electromagnetic (EM) fields under very general conditions. In contrast, this paper is concerned mainly with the problem of making easy, reasonably accurate survey measurements of hazardous EM fields. For general survey use, instruments should be rugged, easy-to-use, and should be capable of fast response as well as having long-term averaging capabilities. These, and other considerations to be discussed, place restrictions on practical instrument designs for general survey use.

It is very difficult to quantify, even with reasonable accuracy, the biological hazards associated with EM fields. Even in the simple case of a plane-wave field with uniform power density, the energy absorption by biological material is quite complicated (1). At the present time, only the hazards related to uniform plane waves in free space (i.e., far from the source and any scattering objects) have received extensive study; and the standards, terminology, and most of the measuring instrumentation pertain only to this simple case. Apparently, this is why "power density" (i.e., the time-averaged magnitude of the Poynting vector)[2] is the presently used quantity for stating EM hazard levels, despite the serious objections to this practice raised in Wacker's paper. Since the usefulness of power density to quantify EM hazards is questionable except for uniform plane-wave fields and since some of the most important EM hazards involve very complicated field configurations (for instance, fields near powerful radio stations or near leaking cracks in microwave ovens), it is important to establish a more rational measure.

Many complicated issues are involved in selecting a suitable parameter for quantifying the hazards associated with EM fields. The discussion here will be qualitative and is intended merely as a sketchy introduction to the complications considered. It is hoped that the discussion will clarify the basic issues.

## COMPLEXITIES OF ELECTROMAGNETIC FIELDS

### *Discussion*

Undoubtedly, another reason that the use of power density has become established is that it presents a simple conceptual picture of the interaction of the field with matter. Unfortunately, this conceptual picture is often very inaccurate. EM fields with frequencies below about 10 GHz do not bear much analogy with optical radiation or ionizing radiation. However, they do bear some analogy with audible sonic fields because of the comparable wavelengths involved. The wavelength of a plane-wave 1000 MHz EM field is about one foot, and the wavelength of a plane-wave 1000 Hz sonic field is also about one foot. Of course, plane-wave EM radiation involves transverse rather than longitudinal vibrations so that the polarization is an important additional complication of EM radiation, but otherwise there are useful analogies between microwaves and audio waves. Some of these analogies will be used below in discussing the complexities that will commonly be encountered when surveying for EM field hazards.

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[1] This work was partially supported by the Bureau of Radiological Health.

[2] Poynting's interpretation of the energy density and power flow in electromagnetic fields is subject to philosophical difficulties. See Footnote 1 of Wacker's paper. Also, see D. S. Jones, *The Theory of Electromagnetism*, (MacMillan, N.Y., N.Y., 1964) pp. 51–53. These considerations are beyond the scope of this paper, and they will not involve us in any concrete errors.

### *Elliptical Polarization*

In general, the tip of the electric vector (or of the magnetic vector) will trace an ellipse if the vector is plotted as a function of time. Except for the rotational sense, the polarization of the field can be specified by the axial ratio of the ellipse. Radar, telemetry and communications systems normally use antennas with either linear or circular far-field polarization, which are special cases of elliptical polarization; but at points near the transmitters of these systems, the polarization can be arbitrary. Very often, the polarization of the field will not be known when making hazard surveys. Furthermore, the polarization of the field may change radically from point to point within the field. For instance, if a microwave oven has a leak from a horizontal crack and also a leak from a vertical crack, the polarization of the resulting field will vary in a very complicated way in the region around the oven. (It should be mentioned that polarization is usually only defined with respect to plane-wave propagation. However, it is possible to define polarization for arbitrary waves (2), and it is this general situation that is of interest for hazard surveys.)

### *Multipath Interference*

Propagation of fields of the same frequency to a given region of space will cause interference patterns ("standing waves"). This is a familiar phenomenon with sound waves, and the spacing between positions of constructive and destructive interference for audible sound waves will be roughly equal to those for microwave multipath interference because of the comparable wavelengths involved. Usually, the term "multipath interference" refers to the situation where there is interference between direct propagation from a source and reflected or scattered fields from objects illuminated by the source. However, if there are two or more different sources operating at the same frequency, the resulting interference is essentially the same. This latter situation would occur, for instance, if there were two leakage cracks on opposite sides of a microwave oven. Then, the space in front of the oven could be expected to display a complicated interference pattern.

### *Reactive Near-Field Components*

Within distances of roughly one wavelength of some sources (for instance, inefficient radiators), there can sometimes exist strong EM field components that do not have a time-averaged power flow (though they will have instantaneous power flows). That is, the total field in these regions can be divided into a radiation component and reactive components (see almost any text on electromagnetic theory); and the time-average of the Poynting vector for the reactive fields components is identically zero. The radiation field represents a flow of energy away from the source, but the reactive field has no corresponding energy loss. The energy associated with reactive field pulses back and forth between the source and the surrounding space during the period of the oscillation, similar to the energy flow between capacitances and inductances in electrical circuits. (This situation is analagous to the operation of an unbaffled speaker cone. At low audo frequencies, i.e., for wavelengths larger than the dimensions of the cone, a speaker cone operating in free-air is an inefficient radiator because the air propelled by the cone merely rushes around to the reverse side of the cone. This produces relatively little sound radiation to points far from the cone even through the instantaneous air flow around the cone can be very great.)

### *Interactions Between the Source and Nearby Objects*

A measuring instrument, subject, etc. placed near to a source can establish multiple propagation back-and-forth between the object and the source. This interaction can involve both scattering from the external surfaces of the source and also coupling with the internal regions of the source. In one sense, this can be considered as a complicated case of multipath interference, but it should be remembered that the coupling with the internal regions of the source can substantially (even greatly) change the total amount of energy withdrawn from the source. This interaction can be exceedingly complicated and is determined not only by the electrical composition of the source, the object of interest, and other nearby objects but also by the sizes, shapes, positions, and orientations involved.

### *Complicated Time Variation of the Configuration and Intensity of the Field*

We are not concerned here with the periodic variation of the field vectors at the radio frequency. Rather, we are concerned with the longer term variation in the configuration of the field and in the amplitudes of the electric and magnetic vectors.

Consider, for instance, a microwave oven that has two widely-separated leakage cracks. Since the microwave sources in many ovens are operated from unfiltered power supplies, the field created by the leakage from these cracks may go on and off at twice the power-line frequency. Further, since most ovens have "mode" stirrers (metal vanes that rotate, typically, every few seconds to "stir" the field configuration inside the oven), the phase and amplitude of the field just outside each crack may change radically every few seconds, independently of the other crack. The resulting time variation in the multipath field outside the oven can be extremely complicated. (It is pertinent to note that a leakage crack in an oven may leak only for a fraction of a cycle of the mode stirrer. Therefore, it is possible for the peak-to-average power ratio to be quite high for microwave oven leakage.)

## APPROACHES TO QUANTIFYING EM HAZARDS

### *The Dosimetry Approach*

In surveying for hazardous EM fields, one wishes to determine as accurately as possible the potential biological dose (i.e., the temperature rise) or the exposure (i.e., the induced currents or the EM field established) that would result at points of interest inside a subject if introduced into the field. In general, because of the complications mentioned in the previous section, it is not practical to accurately predict the biological dose or exposure from knowledge of the parameters of the unperturbed field (i.e., the field before the biological material is introduced). This means that accurate dosimetry for EM field hazards must be done with phantoms that simulate not only the electrical characteristics of the body but also the size and, to a lesser degree, the shape of the body. Probably a head-sized sphere or ovoid would suffice for a phantom in most situations of interest. At points inside the phantom, the thermal dose could be measured by the temperature rise or the exposure measured by the currents or the EM field established. The usefulness of this type of instrument is limited because the size and weight of the phantom would seriously hamper general survey measurements of potentially hazardous EM fields. Therefore, even though the dosimetry approach is most accurate, it is felt that it will probably not be used much outside the laboratory.

### *The Field Parameter Approach*

This approach assumes that the biological effects, or at least the possible effects, resulting from the EM field can be adequately predicted from knowledge of one or more parameters that describe the field. Because the biological effects are so difficult to predict, this approach will always involve a conservative standard for the maximum allowable level of the field parameter used to quantify the potential hazard. Though this approach is somewhat arbitrary, it is felt that it is the most practical approach to the problem of making general survey measurements of EM hazards. Some discussion about the choice of a suitable field parameter and the general characteristics of suitable instrumentation will be given later.

### *The Arbitrary Approach*

This approach would use an instrument that would respond to the EM field but would not, in general, yield an accurate measurement of either the dose that could be expected from the field or one of the parameters of the unperturbed field. For instance, suppose that the instrument is based on the temperature rise in a small piece of material that simulates only the electrical characteristics of biological material. Since a small piece of material cannot adequately mimic the energy absorption of, say, a human head, this instrument could not be expected to yield an accurate measurement of the dose resulting from complicated EM fields. Further, unless the piece of absorbing material is quite small, the instrument will strongly effect the field near, say, a radiating crack; and thus a measurement of the unperturbed field would be practically impossible. (If the piece of absorbing material is quite small, it could provide an accurate measurement of some parameter of the unperturbed field, but then the instrument would satisfy the more stringent approach outlined in the preceding section.)

The arbitrary approach is considered to be the least satisfactory of the three approaches outlined. However, until very recently, it is the approach that was in practice due to a lack of better instrumentation. That is, until recently, instruments suitable only for uniform plane-wave fields (and in some cases only linearly polarized fields) were used to measure leakage from ovens at points close to the leaking cracks. Very little quantitative meaning can be assigned to such measurements, though they are probably adequate to establish rough estimates of the hazards involved.

## CHOOSING A SUITABLE FIELD PARAMETER FOR QUANTIFYING HAZARDOUS EM FIELDS

### *Parameters for Describing Uniform Plane-Wave Fields.*

For a uniform plane-wave field traveling in free space, very simple relationships exist between the magnitude $E$ of the electric vector (i.e., the electric field strength), the magnitude $H$ of the magnetic vector (i.e., the magnetic field strength), the time-average $S$ of the energy flow (i.e., the power density), the time-average $U_E$ of the electric field energy density function (i.e., the electric energy density), the time-average $U_H$ of the magnetic field energy density function (i.e., the magnetic energy density), and the time-average $U$ of the electromagnetic field energy density function (i.e., the total energy density). Using root-mean-square values, these simple relationships are as follows:

$$\frac{E}{H}=Z_0 \quad \text{(the intrinsic impedance of vacuum)} \tag{1}$$

$$Z_0=\left(\frac{\mu_0}{\epsilon_0}\right)^{1/2} \tag{2}$$

$$S=\frac{E^2}{Z_0}=Z_0H^2 \tag{3}$$

$$U=\tfrac{1}{2}(\epsilon_0E^2+\mu_0H^2)\equiv U_E+U_H \tag{4}$$

$$\frac{U_E}{U_H}=1. \tag{5}$$

For such fields, the energy density can be considered as propagating through the field point with the speed of light, $c$. That is,

$$S=cU. \tag{6}$$

For comparison, if the simple field being considered here has a power density of 10 mW/cm$^2$, the total energy density is $\frac{1}{3}$ pJ/cm$^3$ (picojoules per cm$^3$), and the electric field strength is 1.94 V/cm.

Because of the simplicity of relations (1) through (6), the "intensity" of this very simple type of EM field can be adequately described by any one of the parameters defined above. However, not all of these parameters are adequate for describing the "intensity" of complicated EM fields. Further, in choosing a suitable parameter for characterizing the "intensity" of complicated fields with respect to biological hazards, one must consider the manner in which biological material interacts with EM fields.

### *The Interaction of Biological Material with Electromagnetic Fields*

It will be assumed here that there are no significant "nonthermal" biological effects due to the magnetic component of the field. Then, since biological material does not normally contain more than minute amounts of lossy magnetic substances, there is no significant direct interaction of the magnetic field within biological material. It is emphasized, however, that energy associated with the magnetic field will be indirectly absorbed in the biological material. That is, if the electric field penetration into the material is "damped" because of dielectric losses, energy associated with the magnetic vector will be absorbed also. This consideration could be important when interference fields exist or when reactive field components exist since the penetration of the electric field could be considerably greater than one would expect based on "plane-wave" absorption concepts.

### *Choosing Suitable Field Parameters*

As indicated in the last section, both the thermal and the nonthermal biological effects are caused by the internal electric field. The problem is to determine the most suitable parameter or set of parameters for relating unperturbed fields to the maximum possible internal electric fields resulting when a subject is placed at any possible position and with any possible orientation in the unperturbed fields. Because the resulting internal fields are generally extremely difficult to relate to the unperturbed fields, this problem can not be resolved without introducing simplifications, some of them rather arbitrary. Since it would go beyond the scope of this paper to adequately justify the following statement, it will be merely asserted that: the potential hazards of unperturbed electromagnetic fields are, in general, most closely associated with the electric components of the fields except (a) near the magnetic field maxima in multipath fields and (b) for some reactive near-fields. For the exceptions, the magnetic components of the fields may be equally or more important than the electric components.

The "suitability" of a field parameter for quantifying hazardous EM fields is dependent both on the relevancy of the parameter to the potential hazard and on the ease of measuring the parameter. Except for very simple fields, power density is least suitable because (a) the power density of some very strong fields can be small, and (b) power density is a relatively difficult parameter to measure. The difficulties involved in measuring power density[3] follow from the fact that the power density is given by the time average of $|\mathbf{E}\times\mathbf{H}|$. Certainly, in complicated fields, it is much easier to measure $E$ and $H$, which are scalars, than it is to measure the time-average of $|\mathbf{E}\times\mathbf{H}|$. The electric and magnetic energy densities are also relatively easy to determine since the simple relations (4) also hold for complicated fields. That is, the electric or magnetic energy density can easily be calculated from $E$ or $H$; and instruments that respond to $E$ or $H$ can easily be engineered to display $U_E$ or $U_H$. As shown in Wacker's paper, it is even feasible to measure the total energy density with a single sensor. Except, perhaps, for nonthermal biological effects, it is felt that $U$, $U_E$, and $U_H$ are the most suitable parameters for quantifying the potential hazards because: (a) the thermal heating is proportional to $U$, $U_E$, and $U_H$; and (b) it is convenient to have the same units for stating the "intensities" of the total field, the electric field, and the magnetic field. The remaining discussion will be simplified by assuming that the EM field will be quantified in terms of energy density, though it is felt that $E$ and/or $H$ would also be satisfactory.

At frequencies above about 1 GHz, that is for wavelengths shorter than about one foot, a measurement of the electric energy density alone is probably adequate. In part, this simplification is possible because reactive fields are seldom stronger than radiation fields at distances greater than about one quarter wavelength from the source. Also, for wavelengths shorter than about one foot and longer than about one inch, it is usually easy to probe the interference patterns caused by multipath propagation and thus locate the electric field maxima. The $U_E$ for each maximum should be a reasonably good indication of the potential hazard in the immediate region of the maximum. Magnetic field maxima will exist between adjacent electric field maxima, but it is very unlikely that these magnetic field maxima will represent a larger hazard than the electric field maxima.

For wavelengths longer than about one foot, the magnetic energy density becomes increasingly important. At the present time, hazardous electromagnetic fields below about 1 GHz are not nearly as common as those at higher frequencies[4] so that the measurement of total energy density or of magnetic energy density is perhaps not a crucial issue. However, there are important needs for such measurements (for instance, around powerful radars that operate well below 1 GHz).

## INSTRUMENTS FOR QUANTIFYING HAZARDOUS ELECTROMAGNETIC FIELDS

### *General Characteristics*

From the preceding discussions, it is felt that an ideal instrument for survey measurements of electromagnetic hazards should have the following characteristics:

1. the instrument should measure in terms of energy density (or, alternatively, $E$ and/or $H$);
2. the sensor of the field probe should be much smaller than the shortest wavelength of the fields to be measured;
3. the probe should not cause significant scattering of the field;
4. the probe should be independent of its angular orientation in the field (i.e., independent of both the polarization of the field and the directions of the vectors of the field);
5. the instrument should be capable of reading either peak or average power for complicated waveforms;
6. the instrument should have a dynamic range of at least 20 dB without having to change probes;

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[3] For some of the difficulties involved in measuring power density, see Moore School Report 63-13, *Study of power density measurement techniques*, University of Pennsylvania, Moore School of Electrical Engineering, Jan. 31, 1963 or Moore School Report No. 63-23, *Feasibility studies of Poynting vector measurements*, University of Pennsylvania, Moore School of Engineering, July 31, 1963.

[4] In large part, this situation is due to the existence of large numbers of microwave ovens.

7. the instrument should be direct reading, that is, it should not need a calibration chart, nulling, or frequent rezeroing.

In addition to the above characteristics, the instrument should, of course, be stable, rugged, lightweight, battery operated, etc.

*Realization*

It is not apparent that instruments can be realized that have characteristics even approximating those outlined in the last section. Recently, commercial instruments have become available[5] that provide some of these characteristics, but it would appear that there is no available instrument that approximates an ideal instrument as defined here. However, these new instruments are vast improvements over previously available instrumentation, and they are considered to be very useful despite their limitations.

There are a number of possibilities for realizing probes that will approximate the "ideal" instrument (for instance, see the references outlined in Footnote 3). In fact, there are a number of efforts in progress to develop improved or lower cost instruments for measuring hazardous EM fields. It is felt likely that more-or-less ideal instrumentation, at least for measuring $U_E$ or $E$, can be realized.

*Dosimetry*

It is worth emphasizing that the problem of measuring the electric field strength $E$ or the electric energy density $U_E$ in complicated fields is essentially the same problem as measuring the internal electric field within a phantom. Therefore, if it is possible to realize an electric field measuring instrument having the characteristics previously outlined (having a very small field sensor in particular) it should be fairly easy to incorporate this probe into a phantom to accurately measure the exposure (i.e., the dose rate) in very complicated fields. The realization of such a dosimeter is very important since much work needs to be done to determine the potential hazards of complicated fields and how these hazards relate to the parameters of the unperturbed fields.[6]

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[5] See the paper by P. W. Crapuchettes in this volume.

[6] As of January, 1970, a prototype instrument approximating the ideal as defined in this paper has been developed by the National Bureau of Standards, Boulder, Colorado. This instrument is limited to measuring $U_E$ (or $E$), but otherwise it appears from preliminary tests to meet the essential characteristics outlined in this section.

# MICROWAVE LEAKAGE INSTRUMENTATION

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The very first biological effect induced by microwave energy of which I am aware is that which occurred in the Research Laboratory of General Electric. Early in World War II they received a model of a device called a strapped magnetron which promised great things in the new technique called radar. One of the tests to which it was put was that of cooking a ham in a microwave beam being radiated from a simple antenna.

This is quite typical of the events which followed in the next decade or so. Microwave energy was deliberately radiated for military purposes in increasing amounts. With this increase in hazard to military personnel there came an increasing awareness of the biological effects induced by microwave energy. Instruments were developed which did and do correctly measure the energy content of radiating systems whose volume is very large compared to the volume of the instrument introduced to measure the field.

Naturally, within the last decade or so, the rate of increase of connected capacity in microwave power has spiraled upward and now applications not related to the military have appeared. Plastic and foam are being cured, food production lines depend on conveyorized microwave cooking, microwave cooking is appearing in a limited way in the home, many restaurants and even the military are using microwave cooking to speed the preparation of food and to decrease kitchen waste by more efficient preparation.

Those involved in the design of such equipment naturally made use of those instruments available for the measurement of leakage hazard. When the Microwave Oven Range Standards Committee of the Association of Home Appliance Manufacturers had its first meeting in April 1967, the universal experience of ambiguities of measurement using the instruments became known. Thus, it was recognized that proper evaluation of leakage near microwave ovens would likely be the principal roadblock to completion of their assigned task.

The work undertaken by and for this committee is the subject of this paper. One might ask why a tube manufacturer became involved in determination of microwave leakage. One facet of the answer relates to our long experience in microwave quantitative measurements and our almost unique capacity to provide microwave power in any part of the spectrum from 190 MHz to 13,000 MHz at levels from 0 to 500 watts average. Though skilled in microwaves, our skills do not necessarily run to radiation systems so that the methods used in instrument evaluation, while seeming to us to be technically sound, do not necessarily conform to National Bureau of Standards practices. Our interest was that of expediting the development of satisfactory instruments by several instrument manufacturers by assisting them in recognition of the nature of the problems they faced.

The proliferating uses of microwave energy in nonradiating systems have introduced new elements into the subject of hazard evaluation. In the earlier radiating systems, the presence of something as large as a man in the field was not so great a perturbation as to result in any major redistribution of the fields. The operator of a conveyorized microwave oven is not limited in his access to areas remote from the source of leakage. He may, in fact, find himself periodically checking the brownness of potato chips or the tenderness of chicken and to do so he must be in close proximity to the source. The chef in a restaurant will pass directly by his microwave oven many times each day. The child in the kitchen may peer intently as his hamburger is cooking with his eyes 2 inches from the oven door. It is this need to measure leakage very close to its source which makes the early radiation sensors unsuitable for leakage measurements. Unfortunately, it introduces some technical difficulties which render

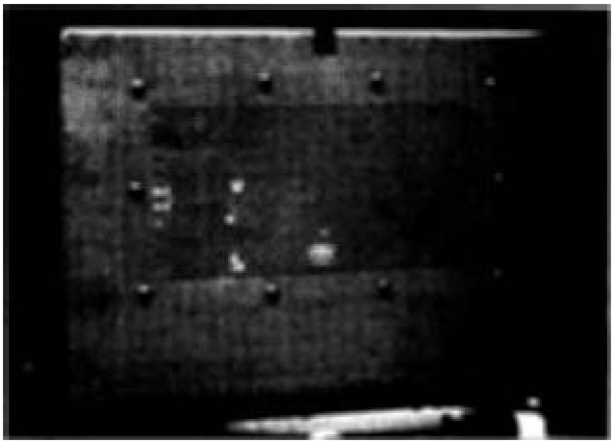
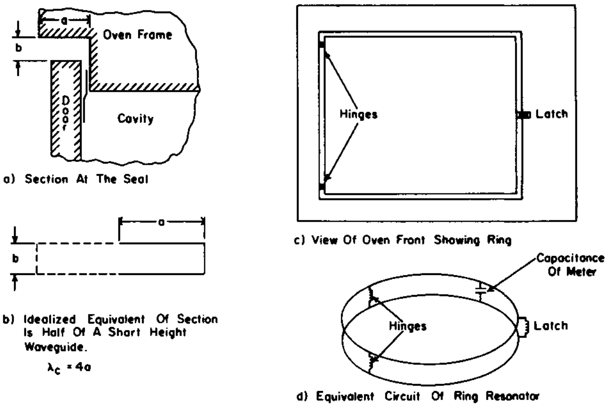


Figure 1. Notched seal plate.



a) Section At The Seal

b) Idealized Equivalent Of Section Is Half Of A Short Height Waveguide.

c) View Of Oven Front Showing Ring

d) Equivalent Circuit Of Ring Resonator

Figure 3. Description of ring.

simple instrumentation across the whole microwave spectrum very unlikely and may make necessary the fragmentation of leakage standards into bands according to instrumentation availability.

The sources of leakage from "nonradiating" microwave devices can be broadly classified as either dipoles or slots. The dipole is either something introduced through the cavity door or wall by the user or may be a loosened screw which couples energy out of the cavity through its loosely fitting threads. The radiating patterns of such dipoles are well known to consist of two terms: a radiating term whose power density varies as the square of the distance from the antenna and a near field or reactive term which is very large close to the source and which falls off so rapidly as to contribute less than 1 db error at distances greater than one-half wavelength from the source.

When the source is a short slit the field components are in fact complimentary to those of the dipole. As the slit increases in length beyond a wavelength, the distribution of the leakage energy progressively changes.

If the long slit is folded upon itself as it is in the case of a leaky access port in a conveyorized oven or the door of a microwave oven, the slit is now transformed into a nonuniform array whose radiation characteristics are even more difficult to predict. The reactive term continues to be important at distances from the source of one-half wavelength or less. The vector summation of fields from the several parts of the door may result in an undulating pattern which persists out to a distance about equal to the major dimension of the opening.

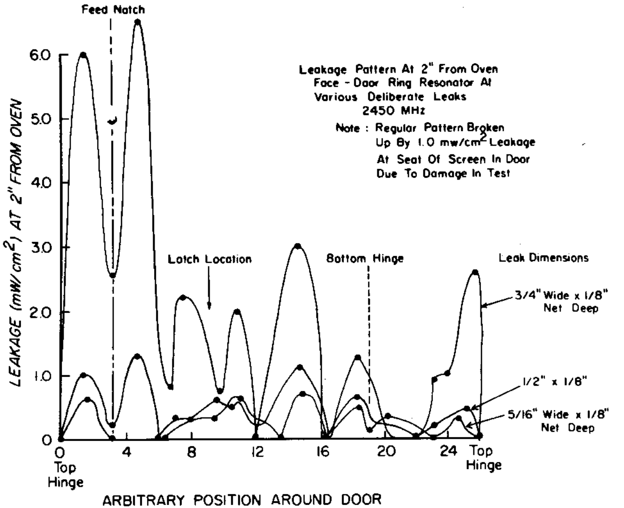


Figure 2. Field around door with notched seal plate.

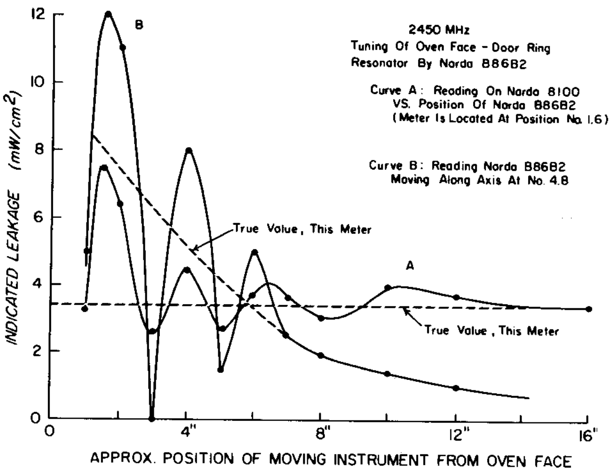


Figure 4. Narda B86B2 vs door.

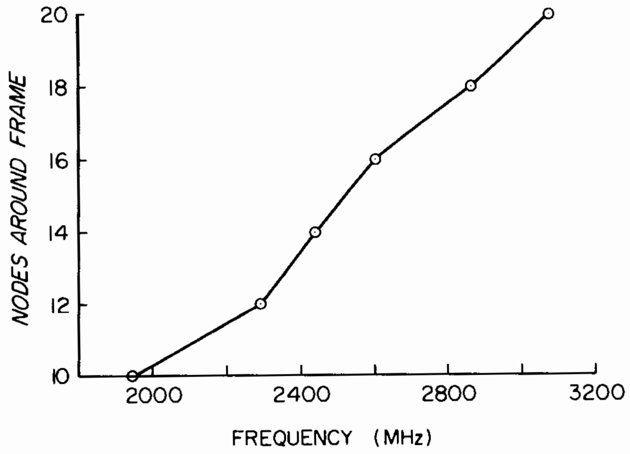


Figure 5. Node *N* vs frequency.

To demonstrate the validity of some of these concepts, I deliberately made a notch in the seal plate of a contacting-type microwave oven door, as shown in Fig. 1. In Fig. 2 the field around the perimeter as measured with the Narda 8100 is shown at different values of the width of the notch in the door. Thus, though there was only a single leak source, the whole door-oven frame region was involved in the leakage. In Fig. 3 a physical picture of the phenomena is developed. The door and oven frame are seen to act as opposite sides of a semi-waveguide ring resonator. It is tuned and adjusted in coupling coefficient by the placement of the latches and hinges or other nearby bodies including the test instruments. The significance of nearby metallic bodies is shown in Fig. 4, in which the readings of the field on a Narda 8100 fixed in position 2 inches from the oven at one of the peaks in the field pattern is shown to vary as the Narda B86B2 is progressively moved toward the oven surface. Also shown are the readings of the Narda B86B2, which at one point is reflecting the principal part of the energy illuminating it back into the slot.

Since the IMPI meeting at Edmonton where I presented other curves describing the effect due to other instruments which will appear in the next Journal of Microwave Power (Volume 4, No. 3), I have made a further effort to quantify these experiments. In spite of the fixed location of the leak in the notched oven door, the field pattern around the perimeter did not remain fixed for a series of door operations.

To provide a fixed source, a ring was made up whose dimensions were similar to those of an oven door and frame region. Figure 5 shows how the number of nodes around the door varies with frequency. Measurements with the Narda B86B2 indicated that the principal effect of its presence was that of varying the coupling from the generator rather than that of tuning the resonance of the loop. Figure 6 shows how the field facing the ring varies with distance as a Narda 8100 was moved directly outward from one of the elements of the ring. Very near the source, the fields are varying almost according to square law. Farther away the contributions of the other elements begin to add in phase and the field values actually increase for a while. It is significant to note that this effect begins at a distance approximately equal to the minimum dimension of the loop and that the maximum value so recorded will generally be much less than the value measured at 2 inches from the source.

Considering again the matter of the presence of the meter influencing the actual value of the leakage field around the door away from the immediate vicinity of the instrument, theoretical considerations and the experimental evidence both indicate that the effect is a function of the impedance and size of the instrument. Antennas are frequently described in terms of their effective aperture, which is the area which is calculated by dividing the power received out of the antenna by the strength of the field. However, in Fig. 7 two antennas are shown whose effective aperture is essentially the same as determined according to this definition, yet their effect on the field outside the ring is different by a factor of three. The large ground plane (4×4

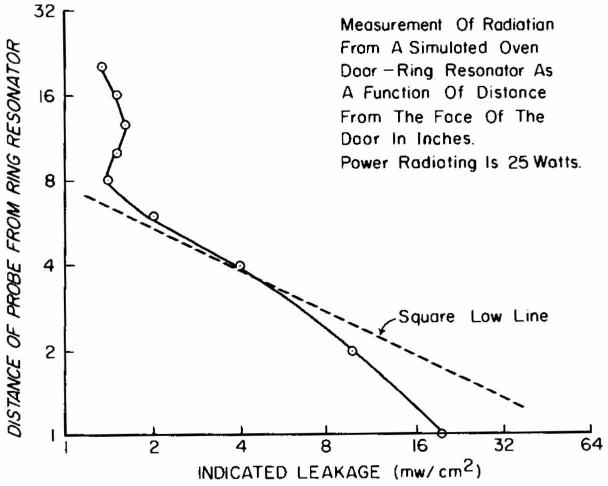


Figure 6. *P* vs *d* for ring.

inches) very seriously perturbs the field near the door. How can we quantify this effect so as to include it in a specification?

The AHAM committee has proposed a method as shown in Fig. 8 which has been found to correlate quite well with the evidence of the effect of the presence of the meter in the vicinity of the ring.

The measurements have been made in the vicinity of a small monopole radiator and 2-×2-foot ground plane as shown in Fig. 9. This provides the opportunity to compare instrument calibration with the known field pattern of such a source (we found a maximum error of 4%) and permitted observers and other sources of reflection to make necessary adjustments without causing errors due to reflections. This results from the reduction in relative strength of any echoes by operation of the square law relation with distance. This system has been used to check the calibration of the various instruments evaluated, by comparison of the measured radiated power with the value obtained by integrating the observed field over the surface of a hemisphere. This also permitted measurement of square law conformity and the influence on calibration of holding the instrument by hand.

Before reporting on the measurements of various instruments, there is one more instrument parameter which merits discussion. That is sensor impedance. If the sensor impedance is quite high as in a properly designed Golay cell, very little of the energy incident upon it will be absorbed or reflected. When such a cell is moved close to the source it will be found to depart quite considerably from the square law relationship because, at its high impedance, it will disproportionately couple to the near field.

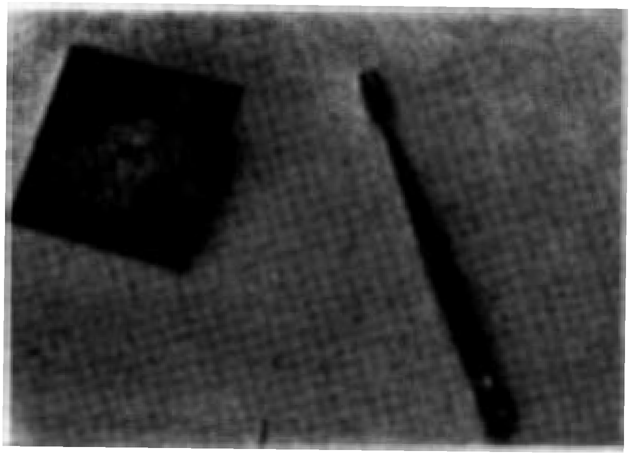
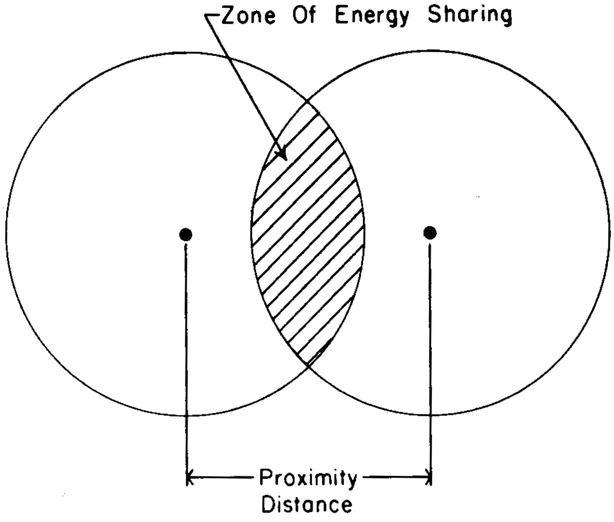


Figure 7. Two dipoles.



TWO IDENTICAL INSTRUMENTS ARE USED. ONE IS PLACED IN A UNIFORM FAR FIELD OF A DENSITY SUCH AS TO PRODUCE AT LEAST 50% INSTRUMENT DEFLECTION. THE SECOND INSTRUMENT IS THEN BROUGHT INTO PROXIMITY OF THE FIRST UNTIL THE INDICATION OF THE FIRST HAS CHANGED BY ±20%. THE DISTANCE BETWEEN CENTERS OF THE TWO PICK-UPS IS THUS MEASURED IN FOUR QUADRANTS (SIDE, TOP, OPPOSITE SIDE, BOTTOM). THE LARGEST VALUE SO DETERMINED IS DEFINED AS THE PROXIMITY DISTANCE.

Figure 8. Proximity effect distance.

Thus, measurements 2 inches from the source of a leak in a microwave system will need correction. The correction coefficient required is a function of the geometry of the leak which makes this a very unsatisfactory instrument for any but the most sophisticated user who is able to evaluate source parameters and make suitable estimates of their frequency dependent effects. Dipole type instruments on the other hand tend to have an impedance lower than the free space impedance and thus will more or less overlook the field strength contributed by the high source impedance near field term. Since the dielectric constant of tissue is quite high at microwave frequencies, tissue will treat the reactive terms in essentially the same way, reflecting the wave rather than absorbing power from it.

In the far field, field strength can be measured in either *E*, *H*, or W/cm$^2$ units because of their fixed inter-relationships. In the near field the vector *E* field as measured by a high impedance Golay cell will not relate to actual energy or *E* field absorbed in tissue due to the reflective effect of tissue on

Figure 9. The radiator and Ramcor 1200.

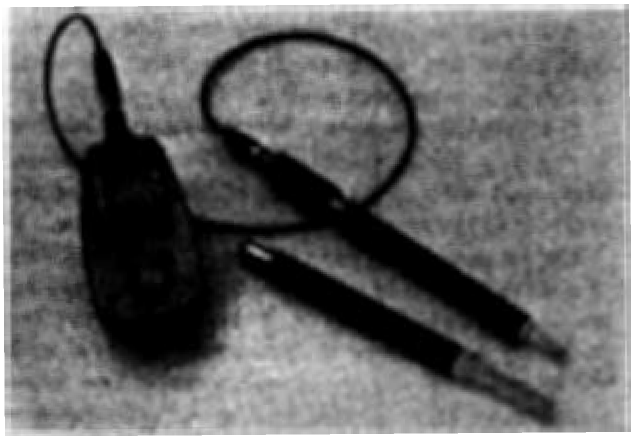


Figure 10. Ramcor 1270.

the near field term. Thus, measurements made with a low impedance instrument calibrated in mW/cm$^2$ will be valid for measurement of hazard in all parts of the field.

The instrument shown in Fig. 9 on the ground plane of the antenna having a rectangular horn is the Ramcor Model 1200. It has been used extensively for some time in far field measurements. The sensor is a thermistor bead receiving energy from the microwave horn. In the field near a microwave oven it is found to significantly change the level of the field leaking from the door if the instrument is within 5 inches of the door. It is clearly unsuited for measurements made at 2 inches from the source as it may cause errors of measurements of up to 300%.

Ramcor has participated in the development of new units for use in near fields. The Ramcor Model 1270, shown in Fig. 10, includes some considerable improvement in zero set of the instrument, has a linear scale in mW/cm$^2$ and is available in ranges 0–2 mW/cm$^2$, 0–20 mW/cm$^2$, and 0–200 mW/cm$^2$ with suitable accessories, and the sensor time constant itself is directly 1 second. Separate dipoles are required for 915 and 2450 MHz. The dipoles follow square law to within 2 inches of the source and have a proximity effect distance of less than 2 inches. The instrument is very susceptible to cable effects in which the cable seriously perturbs the field and to hand held effects in which the readings of the instrument vary 100% when hand held or supported in a polyethylene foam slab in the same field. On the basis of this report, Mr. Solomon recently sent me for evaluation a special engineering model probe in which the hand-held effect was reduced to 20%. The cable effect has not yet been changed but hopefully could be improved by using a smaller cable and coating the cable with absorbent material. This instrument, modified in accordance with the recent engineering model and better cable as suggested above, can be used with confidence in the measurement of leakage from microwave equipment.

Figure 11 shows the two Narda instruments. The large circular unit is the Narda B86B2 which uses 2 pairs of quadrature oriented beads to provide wide frequency response, with the instrument polarized so that it directly faces the source. It has been useful in far field measurements less than 10 or 12 inches from the most simple of radiators. The Narda 8100 is also shown in the figure. Crossed thin film dipoles and thermistor beads have been used to provide a plane-polarized sensor of small size. Since the antenna is so small, attempts to amplify thermistor output of 915 MHz ran into problems with microwave coupling into the amplifier which was significant even though the meter was located in a field 10 db lower than the field being measured. Thus, the spacer which holds the unit at 2 inches from the surface of the oven has been modified at 915 MHz by some dipole extenders which appear as crossed dark lines on the back of the 915 MHz spacer. Three separate probes are available, each of which has dual range as follows:

| | |
|---|---|
| the blue probe | 0–0.2, 2 mW/cm$^2$ with time constant of 5 msec; |
| the white probe | 0–2, 20 mW/cm$^2$ with time constant of 0.5 sec; |
| the red probe | 0–20, 200 mW/cm$^2$ with time constant of 0.5 sec. |

All the probes have a 5 db overload capability.

This unit follows square law well within 2 inches and has a proximity effect distance less than 2 inches. The hand effect variation is less than a few percent if the probe is held by the grip provided. The human engineering aspect of the unit is on a par with its technical achievement and its designer, Mr. Ed. Aslin, who will be honored tonight in Chicago at the IR-100 Awards banquet as the originator of one of the 100 outstanding designs of the last year. Figure 12 shows the ease and consistence of zero set on successive turn-ons. In the ranges covered by the white and red probes, spanning 0–2 and 0–200 mW/cm², this unit is completely acceptable for use in all near or far fields. In the final design there are no cable effects or case leakage.

Figure 11. Narda B86B2 and 8100.

The blue probe having inadequate time constant will burn out in oven testing because of the 10:1 peak-to-average effect of the stirrer. The manner of holding the probe is a significant factor in the success of this design in this respect.

Figure 13 shows the Wayne-Kerr RAD 200 instrument, an engineering model of which was made available for evaluation. It was found to be a very promising instrument but suffers from large proximity effect distance and hand effects. It is the lowest cost of the promising instruments tested but is still beyond the price range needed for service use.

Also shown in the figure is the pocket dosimeter of CIT, which was found completely unsuitable because of its many-lobed pattern, cable effects, etc.

The gas-filled probe instrument of Phillips, marketed by International Crystal, was found to be subject to very rapid deterioration which resulted in lack of indication in fields of 100 mW/cm² when the unit had earlier given indication at 2 mW/cm². Having such an instrument around could result in serious injury to a concerned person. It cannot be recommended for any purpose, according to our tests.

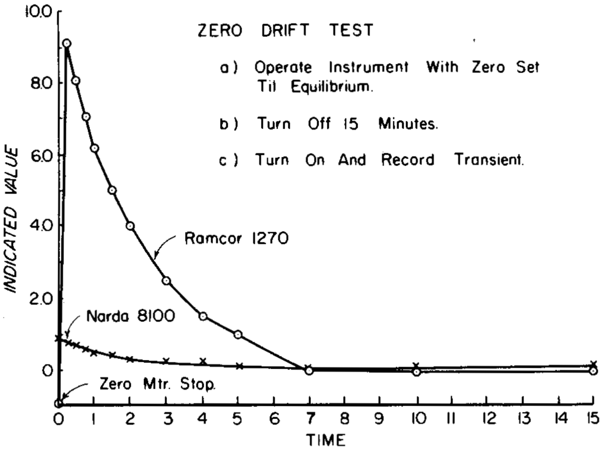


Figure 12. Zero set.

Rank Precision Industries, Ltd. has developed an instrument which was not evaluated. It is a plane polarized unit whose proximity distance is estimated at 3 to 4 inches from design data made available. It is designed for separation of the sensor from the

Figure 13. Wayne-Kerr RAD 200.

indicator by cable connection and in that mode of use would be free from hand held effects. Even when used as a hand held unit it is not likely that the hand effect will be too severe due to the relatively remote position of the hand from the sensor.

The paper by Professor Woods of the University of Surrey which he presented at the Bio-effects Conference in London at the turn of the year describes a unit which will be marketed by Wayne-Kerr. It is a Golay cell and clearly is subject to the comments made earlier about the need for sophistication on the part of the user. The price of the instrument tends to make it more of a conversational item than a test instrument also. But of all the instruments it is the only one which in a far field is truly broad band and totally nonpolarized.

The desirable characteristics of the Narda 8100 and the potentials of the Ramcor 1270, limited in frequency response as they are, make it seem desirable that the rather limited spectrum coverage which they provide should be recognized by restriction of the scope of the proposed standard to that part of the spectrum for which suitable instruments are available. In this same manner, in establishing the new standard it must be remembered that the instruments available are only applicable, without severe burn-out risk due to stirrer operation, in the range 0–2 mW/cm$^2$.

# MICROWAVE HAZARD CONTROL IN DESIGN

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## ABSTRACT

Domestic and industrial microwave heating is considered in terms of the U.S. and Russian safety standards. Typical leakage problems are discussed in relation to the leakage trapping and interlock methods available to the designer. It is suggested that some microwave doors now in use are unsafe after a period of time. It is specifically proposed that mesh viewing screens be used as little as possible, and, where essential, should be covered by clear plastic or glass. All hazard measurements should be made when systems are operating (loaded) as well as empty. Periodic follow-up inspections are essential in industry. Severe fires can occur in microwave heating equipment which distort metal wave traps and damage protective circuitry. A better design philosophy would ensure that all microwave heating equipment met the Russian safety standard, the adoption of which is proposed for this continent, in view of the uncertainty as to the consequences of some of the recently reported biological effects.

## INTRODUCTION

In this continent, the maximum permissible exposure to nonionizing radiation ($10$–$10^5$ MHz) has been set at 10 mW/cm$^2$ for long exposures and, in the case of short exposures, to 1 mWhr/cm$^2$ for each six minute period. Thus the MPE is the same for industrial r. f. systems as it is for equipment at the three microwave industrial scientific and medical (ISM) bands, $915 \pm 25$ MHz, $2450 \pm 50$ MHz and $5800 \pm 75$ MHz. Sweden, in 1961, adopted a lower level, 1 mW/cm$^2$, for general public, prolonged exposure, at all nonionizing frequencies and the work of Mumford (1) suggests that, on thermal considerations alone, this is necessary in many cases. Certain organizations in the U.S. and elsewhere had, prior to this work, lowered the maximum permissible exposure level (MPE) to 1 mW/cm$^2$, at least over parts of the relevant frequency spectrum. The standards throughout the free world are based solely on thermal considerations and developed as the need arose. An excellent review has been given by Michaelson (2), and Püschner (3) illustrates the changing exposure limits for organizations in the U.S. during the years 1953–1960. There were three orders of magnitude difference between the Bell System (0.1 mW/cm$^2$) and the USAF and USN (100 mW/cm$^2$) between 1953 and 1957 (3). No distinction has ever been made on this continent between continuous and pulse waves. The Russian literature on biological effects at low average power levels, indicates that effects that have been called nonthermal were ignored at the time the Russians introduced their current standard, in 1965, of 1 mW/cm$^2$ for periods up to 20 minutes, 0.1 mW/cm$^2$ for periods up to 2 hours in a day and no more than 0.01 mW/cm$^2$ for daily exposure. Poland introduced a similar level earlier, in 1961, and various eastern countries have adopted this MPE guide, with minor variations, some allowing longer periods for pulsed waves, others working on a weekly basis. All the Russian countries have, however, used basically the levels stated for frequencies above 300 MHz. At lower frequencies, the U.S.S.R., in 1965, specified a maximum field strength exposure at 20 V/m for the range 0.1–30 MHz and 5 V/m for the range 30–300 MHz. The reason for the three orders of magnitude difference currently existing between the Russian and U.S. MPE standards in the critical range 300 to 3000 MHz is not hard to find. Experiments and human effects are vaguely reported in the Russian literature. Very few unemotional reviews of the Russian work exist in the English language literature, a notable and important exception being Frey's review in 1965 (4). The subject has since been catalogued (1968) in terms of known parameters and in great detail (5). Biological effects, *per se*, are not necessarily hazards (some advantages to exposure occur, one case being diathermy) but it became apparent last year, from the newly published work of Frey (6, 7, 8), that some of the effects on the heart and CNS could be significant and, at least, were serious justification for a far more detailed look at and attempt to replicate the Russian experiments. A relatively inaccessible report (9) assisted the auditory perception studies of Frey (10, 11) and indicated that the penetration of electromagnetic energy, in a narrow band around 1000 MHz, was in fact sufficient to cause at least some of the effects reported earlier in Russia for pulsed waves under conditions where the average power involved is thermally insignificant.

In view of the recent work of Frey (6, 7) designers of all microwave equipment should become very cautious. In fact, there is more than enough doubt now for us to adopt the Russian exposure limits until the effects are sufficiently well understood that we can reasonably establish hazard levels, particularly where long exposure times are likely to occur.

If all the data currently available are analyzed in terms of pulse and continuous wave forms (peak and average power) at the different frequencies, it appears that hazard prevention with microwave heating equipment will be less of a problem than that faced by the microwave communications industry. If some design changes are needed in heating equipment, both for industrial and domestic equipment, those changes will reduce other known hazards, for example, fire. If we were now to introduce an MPE guide of 1 mW/cm$^2$, as measured on a reliable and repeatable instrument (12) at 5 cm from a surface, for all equipment, ban the use of certain doors and screens, use the warning notices that have been recommended, and add the stipulation that, in industry, normal, continuous working tasks be kept the required few feet away from equipment, we would be on the safe side of our biological knowledge for the cost of some barriers, and solid reliable oven doors. The work of Suroviec (13) has shown a little of what happens in practice to small microwave ovens; the financial support for some more work of this design evaluation type is as necessary as is the support of biological research into effects.

## SOURCES OF LEAKAGE AND ITS PREVENTION

A typical 2 kW magnetron at 2450 MHz radiates 50 watts from its cathode. A surprising number are still operated in laboratories without protective shielding. Even if a 20-gauge perforated, nonmagnetic, metal shield is used, measurement checks are needed to ensure that the leakage level is even thermally safe (10 mW/cm$^2$). Distance, or another cover, adds the remaining protection. Tubes are still delivered without the recommended warning labels attached. The existence of the hazard warning sign on microwave tubes and power supplies should be a law, not just a recommendation to manufacturers.

Perforated stainless steel panels in microwave oven doors may, in themselves give rise to only a low leakage level; the actual field strength, for example, that the eye of a curious child is exposed to, is unknown, and in practice indeterminant; a pencil point pushed through the screen can and has caused a major discharge in the oven. Fires can be very easily started in this way with certain foods in a microwave oven. A clear glass or plastic covering seems essential if a perforated metal viewing screen is to be used. Solid metal doors make far more sense; they should slide or hinge open horizontally. Side hinging is unsatisfactory (13).

In our work on the performance of batch microwave ovens, we looked for a door design that (a) had the double interlock principle, whereby touching the catch opened the microwave circuit, causing the door to open mechanically thereby breaking the power line circuit, and (b) had no measurable

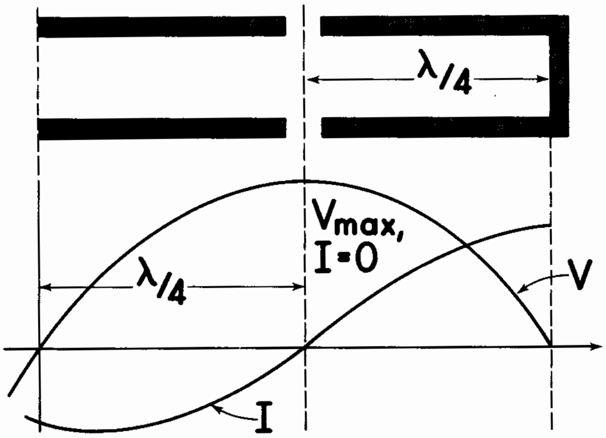

Figure 1. The quarter wave trap, illustrating the principle of a nonleaking discontinuity.

leakage with any reasonably acceptable power meter under both load and no load condition. We found several units which approached these criteria; the best, a 2 kW restaurant model made by Philips in Europe, has the required interlock protection—the microwave power circuit opens before the door catch is lifted. After six years of use and three further years of misuse in our laboratory, this oven has only a local leakage, recorded at 1 mW/cm², around and adjacent to the catch, roughly a semicircle of 5 cm radius. There is no measurable leakage from the large and admittedly heavy door frame. The door seal is a metal to metal facing (no hollow "wave trap" is used—Fig. 1). Further, if the hinge-spring mechanism holding the door (and operating the power line breaker) were any stronger, it would be a finger hazard. A thin wet cloth in the door causes the leakage to exceed 1 mW/cm² at the surface (as recorded, but not an accurate figure, because of the need to measure in the near field); beyond this thickness of insertion, the door catch will not shut and the oven microwave circuit is not activated. There are no signs of arcing on the door (a common and escalating fault), which opens to a horizontal position. All surfaces are easily cleaned. Thus, good design has, we believe, been achieved; there appears to be no serious aging problem with the solid door in general. Elaborate wave-traps, which often involve fiber material and are the delight of the microwave engineer, are put in their correct perspective by this particular oven. In high power industrial systems, doors of the solid type have a great advantage. If dielectric or wire screen material is used as a part of a wave-trap and seal, microwave ovens should not be sold beyond recall.

The case for strong doors and warning labels on domestic microwave cooking equipment is obvious: the moving truck, the ambitious TV repairman, the repair-it-yourself husband, the accidental fire warping thin metal work.

Domestic equipment is not likely to operate for many minutes in a day; 1 mW/cm² is probably acceptable in the long term as a domestic MPE standard at 2450 MHz. The Russian standard allows this exposure level for 20 minutes. However, if this level is specified as measurable at a given distance from a door (for example, 5 cm) the leakage (in terms of a child's eye) could be above the thermally hazardous level on the door surface, allowing for perturbation and coupling effects. Errors and difficulties in using even the best (and very expensive) instruments, factors which, fortunately, Crapuchettes (12) has investigated in detail, are of grave concern. Proximity hazards can only be overcome with well designed doors. A few feet away from an oven, the leakage will be down to the 10 μW/cm² level and one has to assume that this is acceptable.

If the need for biological research is obvious, equally obvious to the designer is the need for better measuring devices, particularly in view of the increasing oven sales. It is not realistic for the local service agency or the research laboratory to have to keep recalibrating power meters. We have three meters and the calibration equipment in the laboratory has to be used every few weeks.

If all the doors and ports on industrial microwave equipment were designed to have leakage levels at or below 1 mW/cm², as measured 5 cm away from the door, there is no difficulty in meeting the Russian standard, at least in spirit, if railings are placed around the equipment. For it has to be up to individuals not to over-expose themselves when exposure time factors are involved. Consider a long processing tunnel at 915 MHz. It has two end ports and (possibly) a series of doors. Assuming the doors and ports are spaced two feet or so apart, with no leakage exceeding 1 mW/cm² at a 5 cm distance, the power density is reduced to an average 10 μW/cm² level in a few feet, the exact distance depending on the surroundings. A simple fence or rail would surround the equipment so normal long time exposures to people outside the rail are below 10 μW/cm². Operators periodically have to inspect the equipment and do so for short periods of time, knowing the time restriction. The conveyor, probably running at a high speed, needs protective barriers in any case, which are now placed so as to meet leakage requirements.

Very high power processing equipment may need some elaborate wave-trap techniques. Mode filters and absorbers have been designed and used; some of them have sufficient bandwidth to contend with tube frequency variations. Designs have been described by Püschner (3). In the case of waveguide applicators, the material slot in the broadside wall, Fig. 2, does not perturb the normal wall currents and there is very little leakage in the absence of a material. With a heavy dielectric load, the power spreads into the material and strong surface waves are present outside the wave-

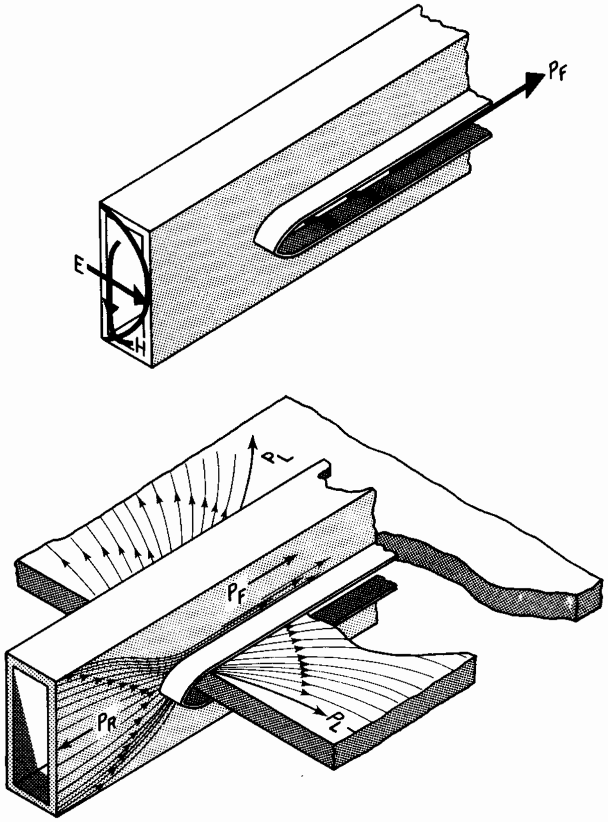

Figure 2. Slotted waveguide applicator (a) field components, (b) power distribution heavily loaded, e.g., drying application.

guide. Lip designs are not able to contend with a material's changing dielectric parameters and considerable leakage can occur even if the design is a good one. An enclosing "oven" is needed, that oven having wave-trap systems of its own. The greater the leakage, the larger the oven, or the more absorbent material that is required. The same principle applies to cavity applicators. Some designs are easier to shield than others, e.g. microwave fluid bed systems offer favorable advantages in terms of building design. Plastic water pipes, for example, become dielectric waveguides and can cause ports, which are, when empty waveguides beyond cut-off, to propagate. It is, therefore, essential that all systems be measured for leakage in use, and measurements be taken at regular intervals.

The Russian standard, which represents a cautious set of exposure limits, due to the probable and not well-understood biological effects (5), can be met for industrial microwave systems without any great extra cost. The potential hazards that may be associated with pulsed transmissions over a long period of time from communications equipment is another matter, and from a design viewpoint, far more difficult to control.

## RECOMMENDATIONS

The need for better, cheaper and reliable low power measuring equipment is paramount. Very few repair organizations are going to pay from $500–$800 for a densitometer and check the calibration every month. For that is required now if many of the better instruments are used in the field. The educational problem of ensuring that the instruments are used correctly cannot be ignored; polarization and proximity effects must be understood by the users; the correct frequency position must be selected. Microwave heating equipment should clearly state the operating frequency on a front panel. In field checks on operating equipment, a number of measurements have to be made; leakage changes with load and originates from irregular sources. Where leakage is locally above 1 mW/cm$^2$ several measurements should be made to verify the reading by square law distance-radiation calculations. Readings with a field strength meter (for levels below 0.2 mW/cm$^2$) may always be needed. However, with available power meters, it is even now possible to predict the 10 $\mu$W/cm$^2$ contour reasonably accurately.

Warning signs and the consistent use of the same potential hazard symbol should be made compulsory. A protection guide book should be provided with all industrial microwave equipment and an annual inspection should be mandatory.

An immense and coordinated effort has been placed on research into biological effects. Support for the work described by Frey, Vogelhut, Tanner, Illinger and others at this Symposium is essential. The systematic analysis of these biological effects will do more than establish hazards; it may well find positive effects,[1] and add to the use of electromagnetic energy along the lines suggested by Maskalenko (14), or Heller and Teixeira-Pinto (15). Studies on the emission of electromagnetic energy from the human body, started by Frey (16), are of immense importance. Possibly the human body emits microwave radiation. Perhaps some of the

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[1] "Microwave beam booms egg output," states a headline in the Financial Post of October 11, 1969, p. 43 (added).

higher mammals could be programmed to operate machines using pulsed wave forms at 1 GHz. And what a tool for warfare! The point is that we have to do the research first and use the results afterwards. There is now far too great a justification of some of the effects for us to ignore them and stay in our entrenched positions, saying that the Russians (and some of our well known physiologists and biologists) are poor experimenters; that our original dielectric models of the human body must be right and must explain everything. The existence of polywater, for example, was only confirmed this year. There may be some very basic facts we do not yet know; while polywater was discovered some time in this decade, its dielectric properties are not yet known. There may be others. A group of influential biologists, engineers and medical specialists have dismissed too much for too long. It is not all science fiction.

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# RADIO FREQUENCY RADIATION HAZARDS TO PERSONNEL AT FREQUENCIES BELOW 30 MHz

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## INTRODUCTION

The intensity of radio frequency environments in Naval vessels has increased over the years, not only as a result of the installation of higher power radars operating at microwave frequencies, but also due to the increase in source power and the improvement in the radiation efficiency of the MF/HF communication systems being fitted.

With regard to radiation from microwave sources, the regions in which the power density exceeds 10 mW/cm$^2$ are deemed hazardous to health. These regions are fairly well defined and readily measured and, in many cases, located remotely from working spaces.

However, by their very nature, the MF/HF transmitting antennae produce intense radiation in local working spaces and this radiation has a complex form which does not allow unsafe regions to be defined in terms of power density. Investigations have been carried out, therefore, into the nature and magnitude of the r. f. fields near typical shipboard antennae and into the r. f. absorption characteristics of simulated body tissue under such conditions. An outline of these investigations is given in the following, along with a brief description of experiments which were aimed at determining a realistic safety criterion to be used for delineating unsafe areas.

## R. F. RADIATION HAZARDS

Present regulations governing the safety of personnel in r. f. environments are based on the criterion that the maximum rise in temperature the human body will tolerate is 1 °C. Such a rise in temperature requires the absorption by the body of about 100 watts of power. This would be provided by an r. f. field having a power density of 10 mW/cm$^2$ incident, uniformly over half the surface of an average adult body—assuming total absorption. Thus, 10 mW/cm$^2$ is taken to be the upper permissible limit of radiation power density for continuous daily exposure (1). Such a limit can be applied to delineate unsafe areas, provided the power density of the r. f. field can be measured.

It is only possible to make such measurements where plane-wave (far-field) conditions exist, i.e., where the electric ($E$) and magnetic ($H$) components of the field are in time phase and space quadrature. Under these conditions, the field impedance is given by the ratio $E/H$ and is a pure resistance of 377 ohms. A measurement of either $E$ or $H$ will suffice to determine the power density. Such conditions predominate at a distance greater than a wavelength from the source. At closer distances the so-called near-field conditions prevail; the induction components of the field becoming more prominent than the radiation components as distance decreases.

## THE NATURE OF THE NEAR-FIELD ENVIRONMENT

Under near-field conditions, the time phase between $E$ and $H$ and the value of field impedance ($E/H$) are influenced by the induction components of the field. It is the measurement of time phase which is a major problem in determining power density. Figure 1 shows the theoretical variation in amplitude and phase of the field components and the ratio of near-field to far-field impedance ($\eta'/\eta$) with distance from a quarter-wave resonant monopole in which the instantaneous value of current is given by $I = I_m \sin\omega t$. The induction-field components ($Ez \sin\beta r \sin\omega t$, $H\phi \sin\beta r \sin\omega t$) are seen to predominate at close distances.

Figure 2 is a theoretical plot of the variation of field impedance with frequency and distance for a monopole of the same height as a typical shipboard "whip" antenna. In the frequency band of interest, i.e., below 30 MHz, near-field conditions exist out to distances of more than 10 meters from the antenna. Thus, potentially hazardous shipboard environments are of this complex nature.

## A SAFETY CRITERION FOR FREQUENCIES BELOW 30 MHz

Since it was impossible to measure the power density of the shipboard near-field environments some other form of safety criterion was called for which would enable unsafe areas to be delineated.

A study of the electrical properties of human tissues shows that they resemble lossy dielectrics and that any heating due to r. f. radiation would be a function of the electric component of the field. It was decided therefore to specify a maximum permissible electric-field strength for continuous exposure. As a first step, the limit was set at 200 volts/meter, which is approximately the value of the electric field in a far-field environment of 10 mW/cm² power density. This criterion was considered to be very safe and subject to relaxation following further investigations in the meantime into the behavior of human tissues at the frequencies concerned.

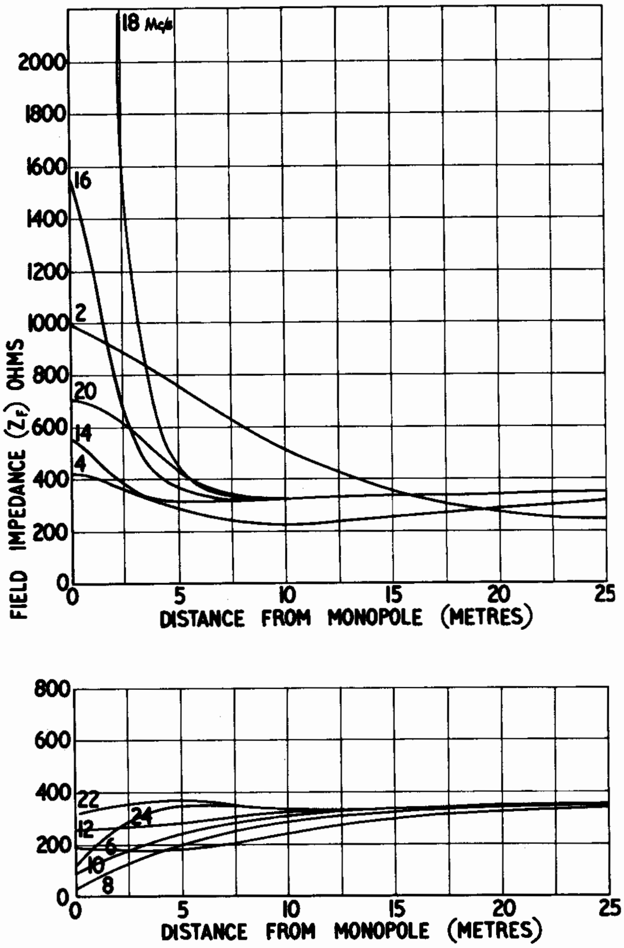

Figure 1. Variation of field impedance with frequency for ideal 35-ft. monopole.

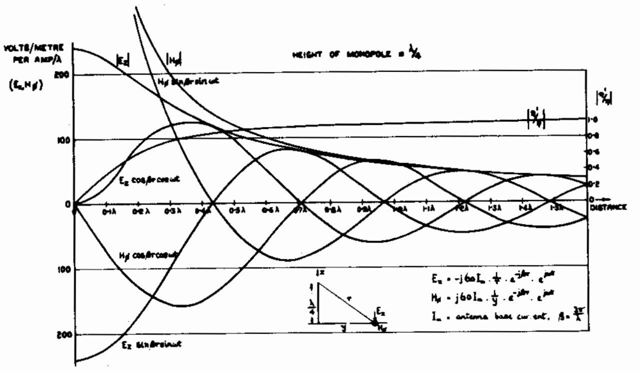

Figure 2. Variation of field components with distance from quarter-wave resonant monopole.

## BEHAVIOR OF HUMAN TISSUE TO R. F. RADIATION

Investigations were made into the thermal response of human tissue subjected to r. f. radiation in the MF/HF bands by making three simple theoretical analyses and by performing two kinds of experiments.

In determining the maximum permissible value of electric-field strength it was not possible to use the basic criterion quoted above (i.e., maximum tolerable rise in temperature of 1 °C) since the models considered in the analyses do not possess the same temperature regulating mechanisms as the human body. Instead, an acceptable rate of rise of temperature was taken as the criterion, and heat losses were assumed to be zero.

It is considered that 1 °C/hour is a conservative estimate of the rate of rise of temperature of the body during the transient period between the incidence of radiation and the stabilization of temperature at 1 °C above normal. The theoretical analyses were made only on homogeneous dielectrics which simulate human tissue and not on multiple layers of dissimilar tissues. The effect of multiple layers was not expected to be important at the frequencies concerned since the wavelengths in the

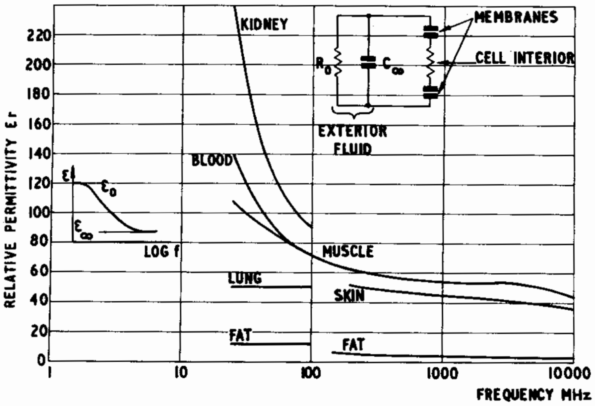

Figure 3. Variation with frequency of relative permittivity of human tissues.

media are much greater than the dimensions of the body.

The analyses made were for:

(a) a plane wave incident normally on a semi-infinite layer of dielectric;
(b) a plane wave incident on a sphere of dielectric;
(c) a capacitor field applied to a slab of dielectric.

The experiments carried out were to determine the rate of rise of temperature of simulated tissue contained in:

(a) a glass cell subjected to a capacitor field;
(b) a phantom when subjected to the near-field environment of a whip aerial.

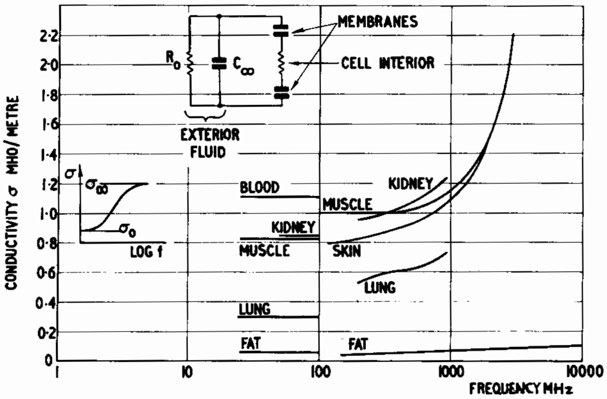

Figure 4. Variation with frequency of conductivity of human tissues.

## PLANE-WAVE ANALYSIS FOR SEMI-INFINITE LAYER OF DIELECTRIC

Consider a plane wave of r. f. radiation incident normally on a semi-infinite layer of dielectric which simulates human tissue. The effect of the dielectric on the amplitudes and phases of the electric and magnetic components of the field within the dielectric will depend on its electrical properties, namely, permittivity ($\epsilon$), conductivity ($\sigma$), and permeability ($\mu$). The variations of $\epsilon$ and $\sigma$ with frequency for various human tissues are shown in Figs. 3 and 4, which are based on the results of various investigations (see, e.g., (2) and (3)). Also shown is the equivalent circuit for a single cell of tissue and the theoretical variation of the electrical property with frequency. The permeability of human tissue is taken to be the same as that of free space.

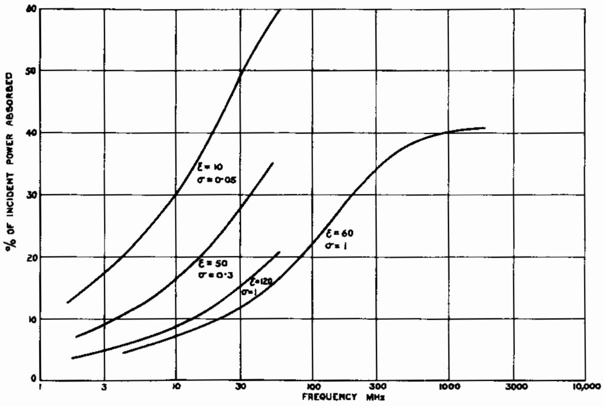

Figure 5. Variation with frequency of percentage of power absorbed in semi-infinite layer of lossy dielectric.

Figure 5 shows the variation with frequency of the percentage of incident energy which is absorbed by a semi-infinite layer of dielectric. It indicates that there is appreciably less absorption at frequencies below 30 MHz than at microwave frequencies (>300 MHz). The percentage absorption is higher in fatty tissue than in muscle. Figure 6 shows the variation with frequency of the electric-field strength required to produce a rate of rise of temperature of 1° C/hour within the skin depth of the layer. Appendix I describes the method of deriving Figs. 5 and 6A.

## PLANE-WAVE ANALYSIS FOR A SPHERE OF DIELECTRIC

Some appreciation of the effect of the shape of the dielectric may be obtained by considering a plane wave incident on a sphere of dielectric. The simplest case to consider is one in which the diameter of the sphere is very small compared with the wavelength of radiation, since only the first-order electric oscillations need be considered (4). This case is pertinent since the dimensions of the human body are small in relation to the wavelength for frequencies below 30 MHz. Figure 7 shows the variation with frequency of the radiation absorption cross section of the sphere (i.e., ratio of absorbed power to power incident on the shadow cross section of the sphere). Figure 6 shows the variation with frequency of the electric-field strength required to produce a rate of rise of temperature of 1° C/hour in the dielectric. The derivation of Figs. 6B and 7 is given in Appendix II.

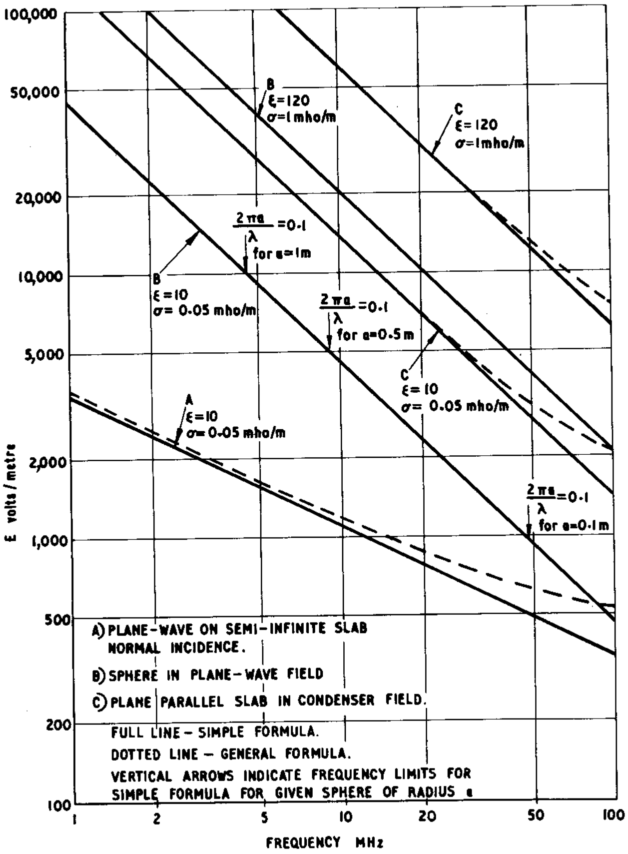

Figure 6. Variation with frequency of electric-field strength to produce rate of rise of temperature of 1 °C/hr, in: (a) The skin depth of semi-infinite layer of lossy dielectric in plane-wave field. (b) Sphere of lossy dielectric in plane-wave field. (c) Slab of lossy dielectric in capacitor field.

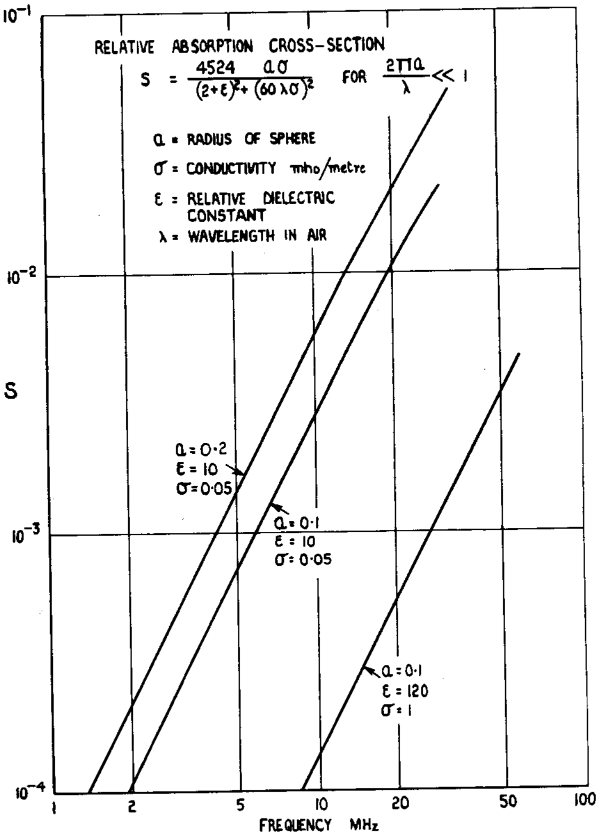

Figure 7. Variation with frequency of the radiation absorption cross section of a sphere of lossy dielectric.

## CAPACITOR FIELD ANALYSIS FOR A LAYER OF DIELECTRIC

This analysis applies to heat dissipation in a lossy capacitor. Consider a layer of dielectric placed between, but spaced from the plates of a capacitor. The equivalent circuit is one in which two capacitors are connected in series, one having a lossy dielectric simulating body tissue, the other having air as the dielectric. Figure 6 shows the variation with frequency of the electric-field strength required to produce a rate of rise of temperature of 1° C/hour in the dielectric. This assumes that the edge dimensions of the plates and dielectric layer are large compared with the plate spacing and thickness of the layer. Appendix III gives the derivation of Fig. 6C.

## EXPERIMENTAL WORK

The relationship between the three cases considered is shown in Fig. 6. This suggests that to perform experiments to confirm theory where practicable, (i.e., for the sphere under plane-wave conditions and the layer in the capacitor field) a field strength in the order of 1000 V/m is required. This was impossible to obtain under plane-wave conditions at the frequencies concerned. However, the required capacitor field could be set up in the laboratory (5).

Near-field conditions at this intensity could also be set up using a "whip" aerial and a further experiment was performed to see whether or not any heating could be measured in a phantom under these conditions. A field-strength plot of the electric-field intensity near a 35-ft.-whip antenna energized by a 1000 W source is shown in Fig. 8.

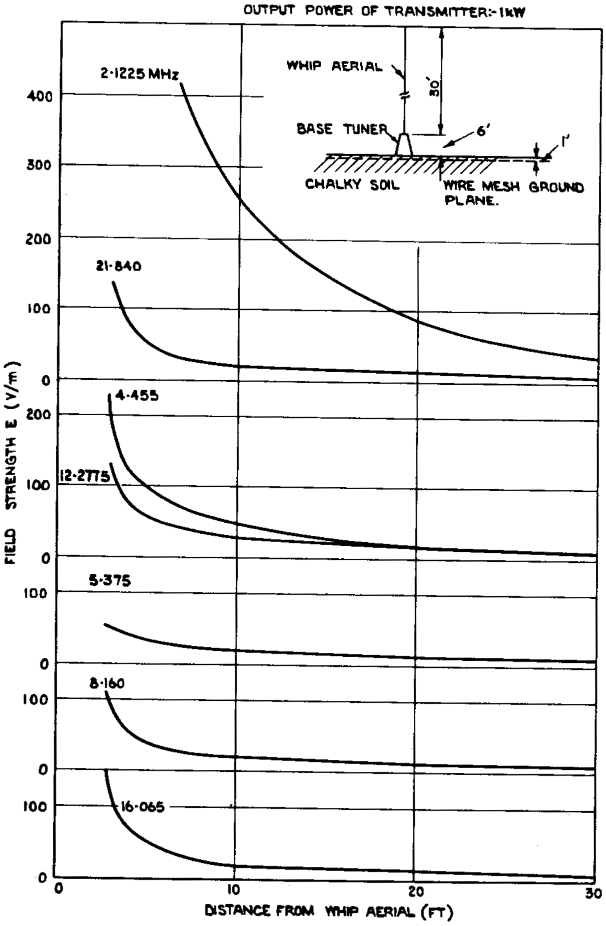

Figure 8. Plots for various frequencies of the electric-field strength from a 35-ft. whip antenna.

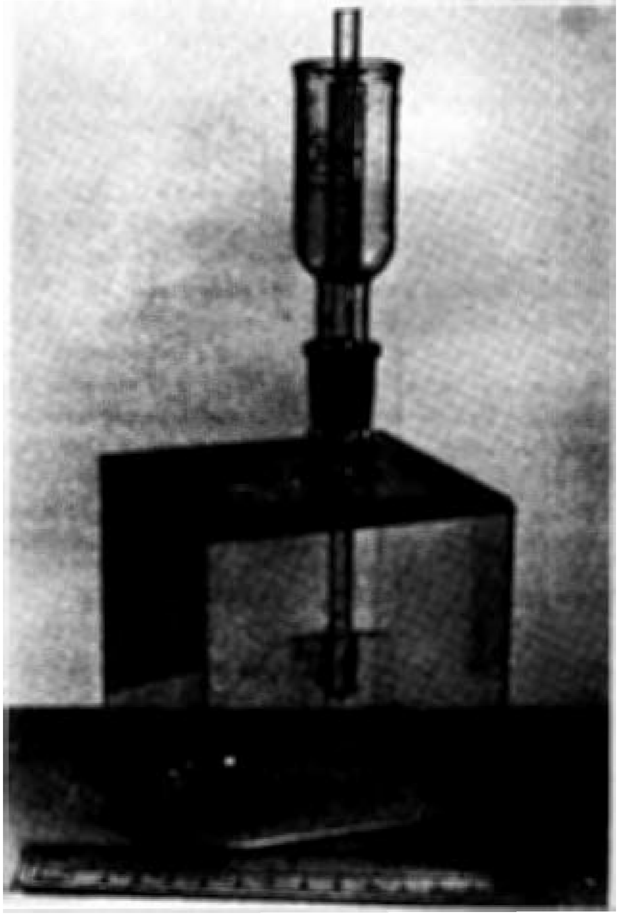

Figure 9. The glass test cell.

*(a) Capacitor Field*

Figure 9 shows the cell, a 10-cm hollow glass cube in which a liquid simulating human tissue was placed. Stirring was effected by a Quickfit stirrer mounted on the lid using the plastic paddle shown. The temperature of the liquid was measured by a thermometer inserted through the hole shown in the lid. The thermometer was a mercury-in-glass type which was N.P.L. traceable and graduated 14–25 °C by 0.01 °C. Preliminary experiments had been carried out in very intense capacitor fields to ensure that the thermometer was not susceptible to r. f. Figure 10 shows the capacitor field set up in a thermal enclosure made up of expanded polystyrene. Parts of the copper plates forming the capacitor are visible, protruding from a block of expanded polystyrene which was hollowed out to take the cell. The plates are identical, having dimensions 20 cm by 30 cm. Thus, the ratio of plate area to cross-sectional area of the cell is 6:1. The plates are water cooled, their temperature being maintained within ±0.01 °C, the water being passed through copper pipes connecting the plates to the r. f. source. Radio-frequency power was supplied to the plates from a wide-band amplifier driven by an oscillator, an arrangement which provided a sinusoidal waveform of high purity. The voltage across the plates was measured by an oscilloscope with Y-plates connected directly to the capacitor plates. Time-base and normal Y shift were removed, and an external accurately measured d.c. potential was applied to return a peak of the r. f. signal to the zero (null) position.

A number of test liquids of different permittivities and conductivities were measured. In each case, the apparatus was allowed to reach thermal equilibrium before a run in which temperature was recorded at 5-minute intervals for 90 minutes, during the middle 30 of which r. f. was applied to the plates. Test runs were made for various frequencies and plate voltages. From the results and Equation (3) in Appendix III, the field strength $E$ in the equivalent air-gaps between the plates and cell was calculated for a rate of rise of temperature of 1 °C/hour. Figures 11 and 12 show the experimental results against predicted values for the field strength required to produce 1 °C/hour temperature rise in a $N/200$ KCl solution ($\epsilon \cong 81$, $\sigma = 6.8 \times 10^{-2}$ mho/m), and in a KCl–Dioxan–water mixture ($\epsilon \cong 10$, $\sigma = 2.7 \times 10^{-2}$ mho/m). The salt solution has an energy absorption peak in the HF band at about 15 MHz and the mixture is representative of fatty tissue.

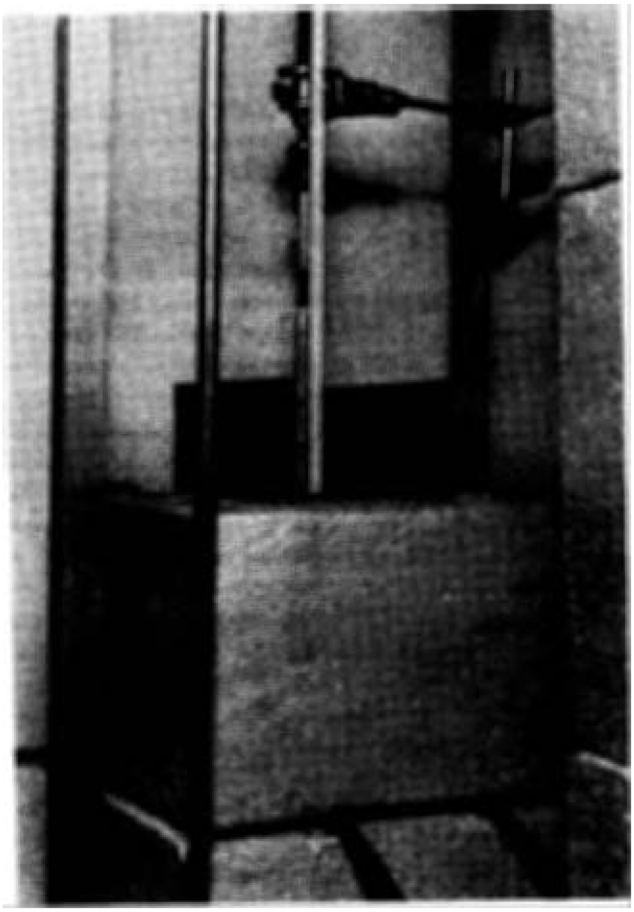

Figure 10. Capacitor field set-up and test cell in thermal enclosure.

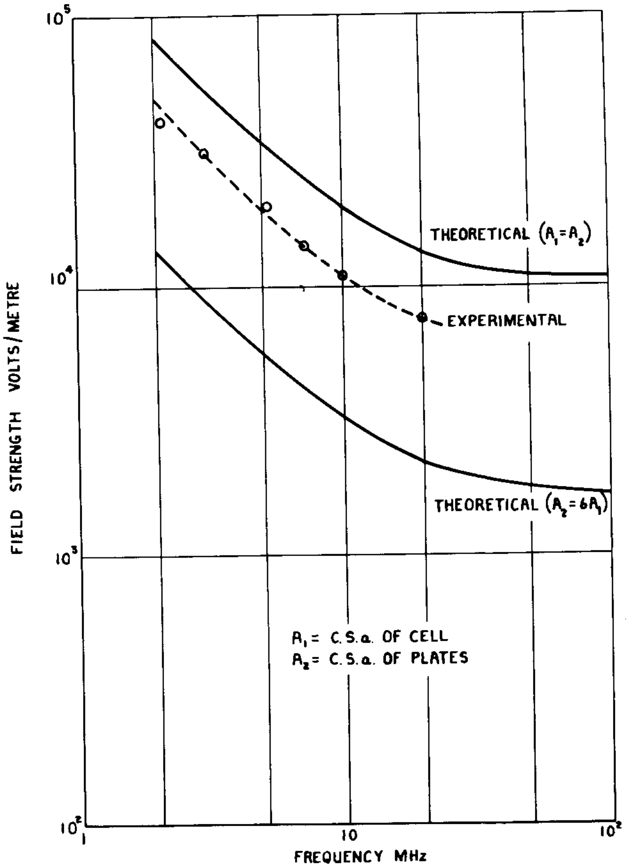

Figure 11. Electric-field strength required to produce 1 °C/hr. in $N/200$ KCl solution.

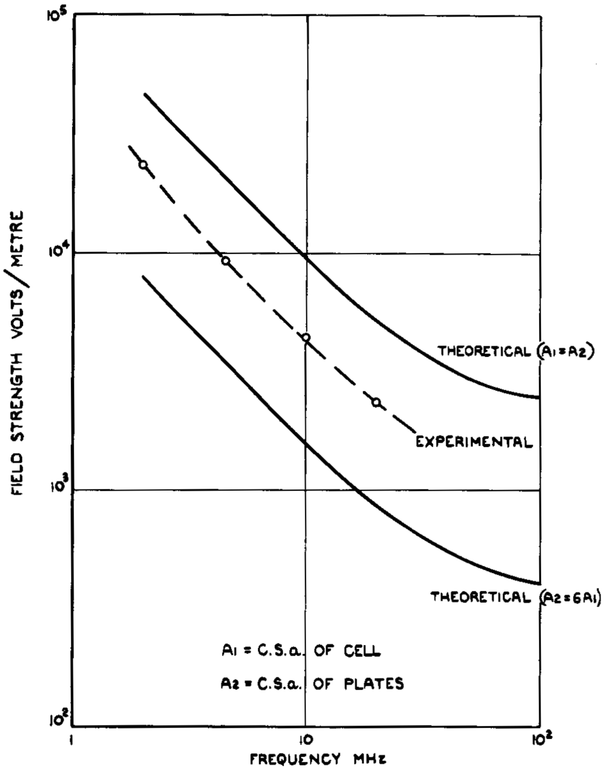

Figure 12. Electric-field strength required to produce 1 °C/hr. in KCl/Dioxan mixture.

### (*b*) *Tests in Near-Field of Whip Aerial*

Figure 13 shows the phantom used. This was the head of a polystyrene dummy man and was filled with the $N/200$ KCl solution. It is shown in its thermal enclosure, which consists of an inner compartment made by hollowing out a 1-ft. cube of polystyrene and an outer cubical container of polystyrene of 4-in. wall thickness and outer dimensions of 2 ft. The thermal stability of this enclosure mounted in the open against a "whip" aerial is indicated by a typical temperature–time plot shown in Fig. 14. The temperature of the liquid inside the phantom was measured using the monitor shown in Fig. 15. This consists of a miniaturized Wien bridge oscillator driving an earpiece. The temperature-sensing element is a bead thermistor connected in one arm of the bridge so that, as its resistance changes with the temperature of the liquid, the frequency of the sound output from the earpiece varies. The sound is piped down a plastic tube to a similar earpiece, the output of which is amplified to operate a counter and printer. The use of the acoustic link and miniature components reduces field perturbation to a minimum and enables adequate screening of the monitor against r. f. pickup. The monitor was calibrated against the mercury-in-glass thermometer used for the capacitor tests. The change of frequency per degree centigrade at the test temperature was 30 Hz. By measuring frequency to 0.1 Hz, a minimum discrimination in temperature change of 0.01 °C was possible. Temperature was recorded at 1-minute intervals over an 8-hour period, r. f. being applied for 1 hour during this period. Tests were made at

TABLE 1

| Frequency MHz | Field strength V/m | Max. temperature excursion, °C | |
|---|---|---|---|
| | | Over 1 hr. radiation period | Over 3 hr. |
| 2.1255 | 900 | −0.12 | −0.21 |
| 4.4550 | 250 | +0.01 | +0.13 |
| 5.8750 | 75 | −0.01 | −0.04 |
| 8.1600 | 180 | −0.03 | −0.04 |
| 12.2775 | 200 | −0.06 | −0.18 |
| 16.0650 | 120 | +0.01 | +0.04 |
| 21.8400 | 170 | +0.04 | +0.12 |

Figure 13. Phantom used in near-field tests.

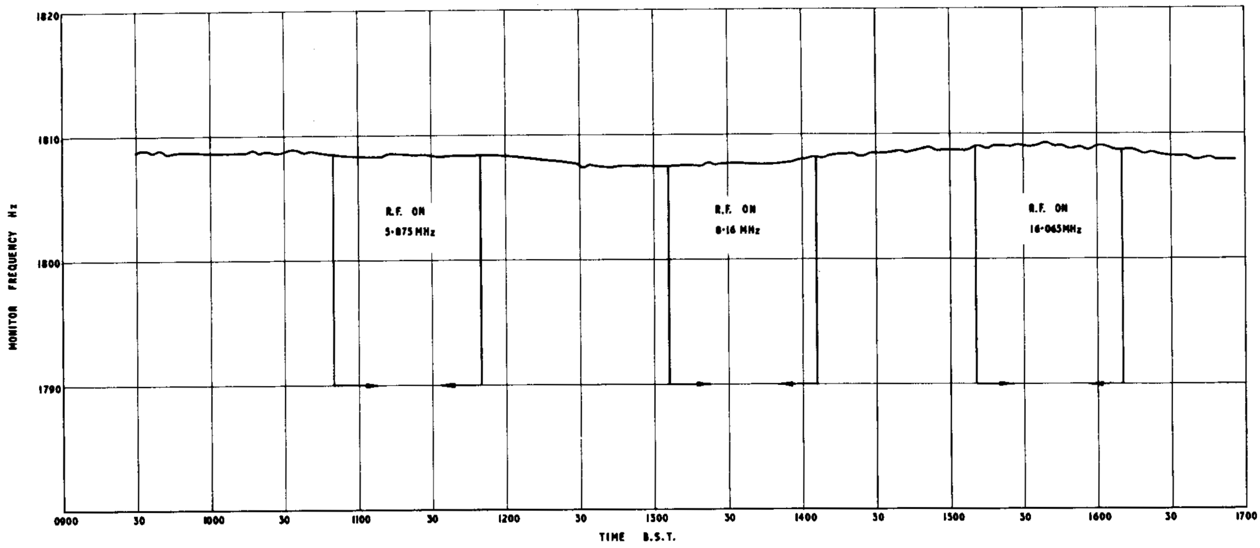

Figure 14. Typical temperature–time plot for phantom in near field of whip aerial.

various frequencies and field strengths in the vicinity of the phantom were recorded. Results are shown in Table 1. Figure 14 shows that the response, if any, is lost in the small ambient changes. For this test, the temperature monitor was located in the upper part of the phantom and the liquid was not agitated.

*(c) Test at S-Band Frequencies*

To prove the apparatus used in the previous test, the phantom in the enclosure was set up in the beam of a waveguide horn fed from a pulsed radar source working at a frequency of 3 GHz. Figure 16 shows the result of a 15-minute exposure to a field of 40 mW/cm$^2$ power density. This indicates a rate of rise of temperature of about 2 °C/hour. As in test (b) above, the liquid was not agitated.

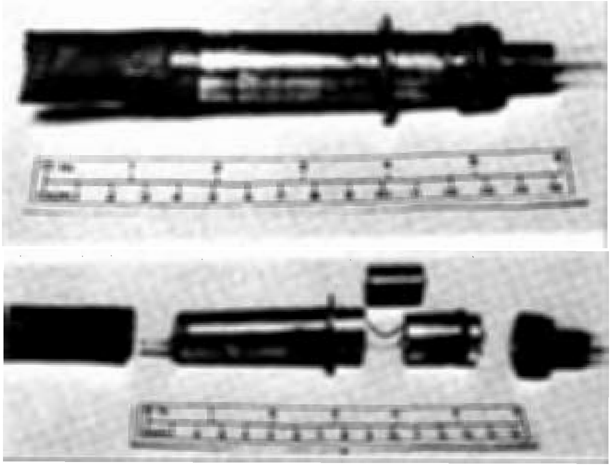

Figure 15. Temperature monitor for phantom tests.

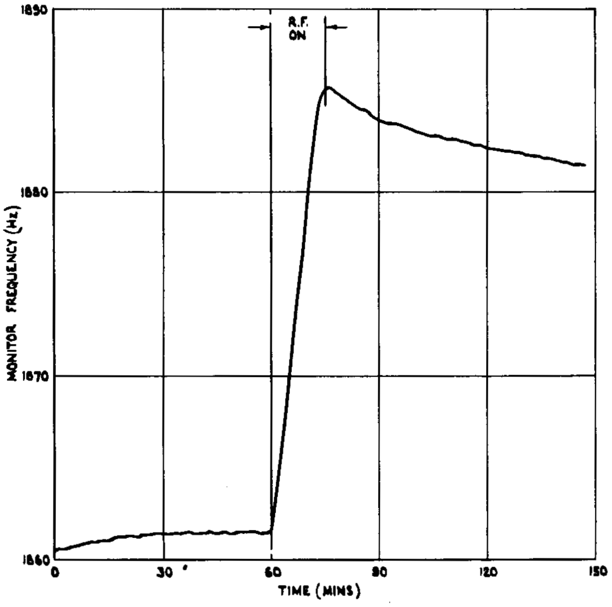

Figure 16. Temperature–time plot for phantom in S-band field.

## CONCLUSION

The capacitor-field tests show that the electric-field strength ($E$) required for a rate of rise of temperature of 1 °C/hour varies with frequency in accordance with theory, and, normalized for equal areas of plate and dielectric cross section, has a minimum value of 3900 V/m at 30 MHz, which is three times the value predicted by simple theory. The discrepancy is attributable to the low ratio of plate dimensions to plate spacing.

The field strength required for 1 °C/hour decreases as the plate area exceeds the cross-sectional area of the dielectric. This would have practical significance in the rather unlikely case where the human body was exposed to the field between plates the area of which exceeds the parallel cross-sectional area of the body.

However, the near-field tests against the "whip" aerial indicate that the rate of rise in temperature of the test liquid is less than 0.1 °C/hour even for $E=900$ V/m, so that for 1 °C/hour a field strength greater than 2840 V/m would be required.

The analyses and experiments indicate that a maximum permissible electric field strength of 1000 V/m for continuous exposure is a reasonable safety criterion for delineating unsafe environments in the MH/HF bands.

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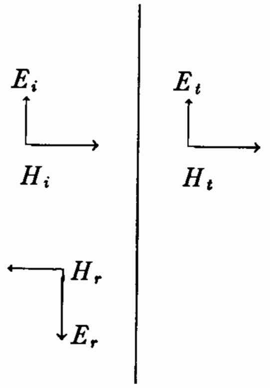
## APPENDIX I
## PLANE-WAVE ON SEMI-INFINITE LAYER OF DIELECTRIC

| *Air* | *Lossy Dielectric* |
|---|---|
| Permittivity, $\epsilon_0$ | $\epsilon' = \epsilon_r - j60\lambda\sigma = N^2$ |
| Permeability, $\mu_0$ | $\mu = \mu_0$ |
| Conductivity, $\sigma_0$ | $\sigma$ |
| Attn. const., $\alpha_0 = 0$ | $\alpha = \beta_0[1/2(\lvert N^2 \rvert - \epsilon_r)]^{1/2}$ |
| Phase const., $\beta_0 = \omega\sqrt{\mu_0\epsilon_0}$ | $\beta = \beta_0[1/2(\lvert N^2 \rvert + \epsilon_r)]^{1/2}$ |



Reflection coefficient:

$$R_v = \frac{E_r}{E_i} = \frac{1-N}{1+N}$$

At the interface:

$$H_i - H_r = H_t$$

$$E_i + E_r = E_t$$

$$\frac{E_i}{E_t} = \frac{1+N}{2} \quad \text{and} \quad \frac{H_i}{H_t} = \frac{1+N}{2N}$$

Fraction of power absorbed from incident wave = Re $\{E_t H_t^* / E_i H_i\}$

Intrinsic impedance of dielectric, $Z = Z_0/N$

Applying the above relationships for a dielectric $\epsilon_r = 60$, $\sigma = 1$ mho/m

| Frequency, MHz | 5 | 10 | 50 |
|---|---|---|---|
| Z ohms | $4.5 + j4.5$ | $6.4 + j6.2$ | $15.1 + j12.8$ |
| $E_i/E_t$ | $21.7 - j21.2$ | $15.8 - j14.8$ | $7.8 - j6.2$ |
| $H_i/H_t$ | $0.51 + j0.01$ | $0.51 + j0.01$ | $0.52 + j0.01$ |
| $E_tH_t^*/E_iH_i$ | $0.01 + j0.05$ | $0.07 + j0.06$ | $0.15 + j0.12$ |

## APPENDIX II
## PLANE-WAVE ON DIELECTRIC SPHERE

Amplitude of first-order electric oscillations in sphere is given by

$$b_1^r = -j^{2/3}\left[\frac{N^2-1}{N^2+1}\right]\alpha^3,$$

where

$N = (\epsilon_r - j60\lambda\sigma)^{1/2} =$ refractive index;

$\alpha = \beta a$;

$a =$ radius of sphere;

$$\therefore\ \mathrm{Re}\{b_1^r\} = -\frac{120\lambda\sigma\alpha^3}{(\epsilon_r+2)^2+(60\lambda\sigma)^2}.$$

The power absorbed by a sphere is given by

$$W_a = 2\pi\frac{E^2}{\beta^2 Z_0}\left\{\sum_n^{\infty} -(2n+1)\times\left[\mathrm{Re}(a_n^r+b_n^r)+|a_n^r|^2+|b_n^r|^2\right]\right\},$$

where $a_n^r =$ amplitude of magnetic oscillation.

For $n=1$,

$$W_a = \frac{12\pi\sigma a^3E^2}{(\epsilon+2)^2+(60\lambda\sigma)^2}\ \text{watts}\ |b_1^r|^2 \ll b_1^r \qquad (1)$$

$$S = \frac{\text{power absorbed}}{\text{power incident on shadow cross section}}$$

$$= \frac{W_a}{P_D\pi a^2},$$

where $P_D =$ power density of incident field $= E^2/Z_0$.

$$\therefore\ S = \frac{4524a\sigma}{(\epsilon+2)^2+(60\lambda\sigma)^2}\quad \text{for } \beta a \ll 1$$

Heat produced in sphere for a rise in temperature of 1 °C/hr

$$= \left(\frac{4\pi a^3}{3}\right)4.2\times10^6/3600\ \text{watts.} \qquad (2)$$

This assumes specific heat and specific gravity are both unity.

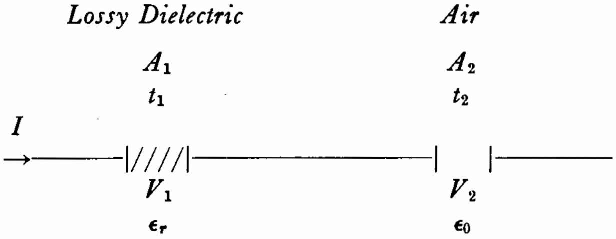
Equating (1) and (2)

$$E = 11.38[(\epsilon+2)^2+(60\lambda\sigma)^2]^{1/2}/\sqrt{\sigma}\ \text{volts/meter.}$$

For frequencies where $(\epsilon+2)^2 \ll (60\lambda\sigma)^2$,

$$E = 2.05\times10^{11}\sqrt{\sigma}/f\ \text{volts/meter.}$$

## APPENDIX III
## DIELECTRIC IN CAPACITOR FIELD



$$V_1 = I\frac{t_1}{j\omega\epsilon_0(\epsilon_r - j60\lambda\sigma)A_1}$$

$$= \frac{It_1(60\lambda\sigma - j\epsilon_r)}{\omega\epsilon_0A_1[\epsilon_r^2+(60\lambda\sigma)^2]}$$

$$V_2 = \frac{It_2}{j\omega\epsilon_0A_2}$$

$W_a =$ power dissipated in lossy dielectric $= \mathrm{Re}\{IV^*\}$

$$= V_2^2\frac{t_1}{t_2^2}\times\frac{A_2^2}{A_1}\times\frac{\sigma}{\epsilon_r^2+(60\lambda\sigma)^2}\ \text{watts.} \qquad (1)$$

For a temperature rise of 1 ° C/hr, assuming specific gravity and specific heat to be unity, heat produced

$$=A_1t_1\times 4.2\times 10^6/3600 \text{ watts.} \tag{2}$$

From (1) and (2),

$$E_2=\frac{V_2}{t_2}=34.2\times\frac{A_1}{A_2}\left(\frac{\epsilon_r{}^2+(60\lambda\sigma)^2}{\sigma}\right)^{1/2}$$

Related to applied voltage $V$

$$E_2=\frac{VA_1[\epsilon_r{}^2+(60\lambda\sigma)^2]}{\{[t_2A_1(\epsilon_r{}^2+(60\lambda\sigma)^2)+t_1A_2\epsilon_r]^2+(t_1A_2 60\lambda\sigma)^2\}^{1/2}}. \tag{3}$$

For frequencies where $\epsilon_r{}^2\ll(60\lambda\sigma)^2$,

$$E_2=6.16\frac{A_1}{A_2}\times 10^{11}\sqrt{\sigma}/f \text{ volts/meter.}$$

Power absorbed in depth $(1/\alpha)$,

$$W=\left(1-\frac{1}{e^2}\right)W_a$$

$$=\left(1-\frac{1}{e^2}\right)\mathrm{Re}\{E_tH_t{}^*\}$$

$$=\frac{4E_i{}^2}{Z_0}\left(\frac{|N|\cos[\frac{1}{2}\tan^{-1}(60\lambda\sigma/\epsilon r)]}{|N^2|+2|N|\cos[\frac{1}{2}\tan^{-1}(60\lambda\sigma/\epsilon_r)]+1}\right).$$

For dielectrics in which $\epsilon_r\ll\lambda\sigma$,

$$W=\frac{E_i{}^2}{Z_0}\left(\frac{2\sqrt{2}}{\sqrt{2}+(60\lambda\sigma)^{1/2}}\right).$$

Heat produced in the skin depth

$$=\left[\frac{1}{2\pi}\left(\frac{\lambda}{20\sigma}\right)^{1/2}\right]4.2\times 10^6/3600.$$

Hence, $E_i=201\sqrt{\lambda}=3.48\times 10^6/\sqrt{f}$ volts/meter.

# PANEL DISCUSSION I: MICROWAVE MEASUREMENTS METHODS AND STANDARDS FOR BIOLOGICAL RESEARCH AND HAZARDS SURVEYS

*Moderator:* DR. SOL ROSENTHAL

*Polytechnic Institute of Brooklyn, Brooklyn, New York*

*Dr. Rosenthal:* This is a panel discussion on the Microwave Measurements Methods and Standards for Biological Research and Hazards Surveys. I would like to introduce the panel members to you now and tell you of their relevance to this panel. My own interest relates to the fact that I do some work in the area of the biological effects of microwaves and I am also associated with the C-95 Committee of the United States Standards Institute which is concerned with r. f. radiation standards for hazard evaluation. Another member of the panel is Allan Frey from Randomline. Dr. Frey's interests are in the area of biophysics and he has a long background of research in this area. He will be talking about r. f. measurements in biological research.

Frank Lemaster represents the Air Force and he is very much concerned with the radiation hazard prevention program of the Air Force.

Ronald Bowman, who you heard just a short time ago, is with the National Bureau of Standards and his specialty is standards and measurement practices in electromagentic fields which is, of course, very pertinent.

Henry Rechen is with the United States Public Health Service. He is Associate Director of the Division of Electronic Products and is concerned with the drafting of standards for electronic products and that is quite an important aspect at present.

Dr. John Osepchuck is with Raytheon Corporation but he is also a member of AHAM. Dr. Osepchuck is a microwave engineer and is particularly concerned with some of the applications of microwave power, particularly the microwave oven and I am sure he will have a good deal to say about it.

The last panelist is Dr. Sol Michaelson from the University of Rochester who you all know quite well. He is going to talk about vital indices of response to microwave exposure.

Before turning the floor over to the panelists I would like to say a few words in connection with some of the aspects of the C-95 program and work in general in biological effects. Incidently, for a microwave engineer, it is really a pleasure to get involved with the biological area.

There are a number of points I would like to raise, some of which are a result of what we have heard at the meetings. Hopefully someone in the audience or a panel member will be able to comment on some of these. We do have most of those concerned with such problems here at this meeting and this is the important point of the meeting that all of the people involved are here. I think it is a great opportunity for all of us and hopefully some direction as to the future activities will result from these discussions. The first item is in connection with present standards. At the present time all we really have is a number and a time element and very little else. We need additional information to provide a better standard. For example, the present standard applies to the frequency band 10 MHz to 100 GHz. It covers the entire range and we think we certainly should find out if there is any frequency specificity for the biological effects. There is also the problem of environmental specification. Again, it is indicated in the standard that appropriate reduction of the standard will depend upon the environmental conditions. William Mumford had a proposal with respect to this but we do have to do additional work in trying to use this information as a part of the actual standard. In order to find out anything about it additional work will have to be done.

We are concerned about low level effects. Again there is very little information available except for the Russian work. Possibly we have to do a good deal of work ourselves. Also it might not be a bad idea to replicate some of the Russian work to see how valid it is. To the best of my knowledge there is at present no coordinated and organized program of research that provides this type of information. For example, the information for the present standard comes from material that was developed in the early 60's and very little has been added since then. In fact a good deal of information at this meeting is actually work that was done a fair amount of time ago. The question still remains and controversy exists at this meeting and this is a very healthy thing, but I would like to settle some of it with additional research.

Item 2. In order to carry on such a program it is necessary to provide standard techniques, standard methodology for r. f. measurements in connection with biological studies so that we can repeat results, compare results, and possibly add to results so they are more meaningful. We also have to decide what type of biological measurements will give us meaningful data. Since we will be using animals, we will have to find out how to extrapolate to the human situation and then to the establishment of a hazard level.

In connection with measurements, for example in terms of survey instruments, we have discussed the difficulties involved in the near field measurements. We hear that there are instruments being developed which will not perturb the field let's say, for example, near an oven door. It will not perturb the field but when you bring the biological entity next to it which could be the eye of a child or a woman looking near the leakage port, a different field exists because such objects may perturb the field. It is rather difficult to know exactly what to do about this. Someone once suggested that the probe actually be an eye, if it were an eye you were considering. This is apparently not too practical. It is similar to the problem in research about free-field measurements. I think it is a matter of using the information that we can obtain and then applying it properly. This calls for a good deal of collaboration between both the biologists and the engineers.

We have to consider taking into account the different population segments and work situations. Should we have one standard for all or should we differentiate? And finally another problem that is of some concern to me, particularly in respect to the C-95 committee, but also in research efforts, is the duplication of effort. In connection with standards, there are a number of groups that are interested. For example, the Army, the Navy, and the Air Force as well as the Department of Health, Education, and Welfare and USASI (C-95), and industry; AHAM for example. The Biomedical Engineering Society has also expressed an interest and has committees associated with this problem. There is a good deal of interchange of information. But many times it is more by accident than by design, that the interchange of information takes place; despite the fact that the same people are involved over and over again. To some extent there is also a great amount of duplication and wasted time. This brings up the idea of a clearing-house for information. There should be an agency of this kind. Again information does get around but it is more by accident then by design. I understand that Dr. Heller intends to set up such a structure. Whether he does it or not somebody ought to. We should be able to be aware of what is going on in the field and what to expect. A Symposium such as this is a very fine and long awaited beginning and the Public Health Service and Virginia Commonwealth University should be commended. It is really a tremendous step forward and it is something that is really needed. One other point and then we will get to our panelists. It begins to appear that the period of voluntary standards, such as those of C-95, is over and we are approaching a period of mandatory standards. Now with mandatory standards it is more important that we obtain good information and good measuring systems and techniques, and research programs, and put to rest some of the mythology in favor of methodology.

I would now like to call upon the first panelist, Dr. Michaelson, and as I pointed out before he is going to be talking about vital indices of response to microwave exposure.

*Dr. Michaelson:* I think I have a more difficult job than the engineers or the physical scientists. It's bad enough to talk about problems in the physical sciences but in the biological sciences I'm sure it is worse. I think it is appropriate to discuss some of the indices that should be considered in measurements of responses to microwave exposure. Although a considerable amount of work has been done to characterize and elucidate the interactions of microwave energy with biological systems, these have been more or less of a qualitative nature.

Little quantitative information is available at present and as far as I can see no more quantitative information has come out of this Symposium than we had in 1961 at the end of the Tri-Service Conferences. Now what has happened is that the studies to date have resulted in confusion concerning the type and extent of microwave "injury," "responses," and "expense."

It is essential to realize that there is no universally accepted specific biological indicator of exposure to microwaves and there is no reason that a single biological test would be a satisfactory indicator of exposure to microwaves. I might say that the concepts and techniques developed in studies on the biological effects of ionizing radiation, although I hate to confuse the two or to even interject ionizing radiation into a microwave symposium, and also the large advances that have been made in bio-engineering can within reasonable limits be applied to all electromagnetic radiation and with these assets in mind we can develop criteria for hazard assessment. Proper investigation of the biological effects of microwaves requires an understanding and appreciation of biophysical principles and comparative bio-medicine. I'm sure we won't find both of these in one individual. Such study requires the selection of bio-medical parameters which should consider basic physiological functions such as work capacity, identification of specific and nonspecific reactions, and the differentiation of adaptational or compensatory changes from pathological manifestations. I can define these terms if anyone wants me to.

The most valuable parameters available at present are those which under normal conditions show self regulatory properties such as body temperature, lower endocrine, central nervous system, and cardiovascular responses. Here again suggestions from studies of ionizing radiation can be applied to the analysis of the effects of microwave exposure. The biological indicators of microwave response should express themselves in a reasonably short time. The technique of measuring should not require elaborate equipment. Microwave induced biological changes should have a high probability of occurring. The range of experimental values for the parameter selected should be well defined and should have a very poor range of variability. Ideally the range of normal values for the individual in question rather than the range for the group should be the reference value when evaluating the post exposure data. Behavioral studies should be done to assess a degree of function decrement of possible neurological dangers that may be observed.

Certain questions are pertinent to selection of parameters for such investigations. When the central issue has to do with an effect on the human animal: What are we trying to determine? Does the exposure to microwaves result in biologically measurable effects? Are these effects harmful? Are they likely, for example, to be more serious than taking a new job in a very hot boiler room? Or trying to get a good sun tan at the beach? What kind of effects are they? Are they acute and reversible such as first degree burns? We could go on and on. What concepts and criteria should be used in selecting problems to study when the major concern is man? What systems would one likely expect to show changes from microwave exposure? Of these systems which ones are likely to show well defined and relatively narrow ranges of variability in the exposed animals so that relatively small changes will be recognizable as a result of microwave exposure? What approaches are appropriate?

Actually as far as I am concerned any approach that provides reliable answers is acceptable. Usually those changes that reflect a degree of alteration from a balanced state in response to a measured stimulus, will alternatively return to a steady state. Heating and cooling rates of animals exposed to specific microwave frequencies and field densities are most reliable indicators, but these are not the only ones. One must consider the physiological, anatomical correlations between or among animal species that would bolster rather than weaken one's confidence when extrapolating from animal data to man. No single animal species can represent an ideal model. No experimental method is universally suited for all foreseeable uses. It is essential therefore that a comparative approach be used in selecting animals most appropriate for laboratory investigations of microwave effects. Such a comparative approach requires identification of similarities and contrasts in microwave absorption and thermal regulatory capabilities in various animal species if extrapolation to man is to have validity. Extrapolating the results of microwave experiments from various species of animals to man has been done frequently without consideration of the differences in mass and size of the animal or the inherent differences in thermal regulation or other physiological functions. Experiments performed on rodents cannot be used to predict effects on humans unless the difference in body mass and thermal regulation are taken into account. Also, the very last question of isogeneity versus heterogeneity as we have in man has to be considered. It is essential in designing experiments that the experimental subject be maintained in a relatively "normal" life situation, and that restraints, tranquilizers, or anesthesia be avoided whenever possible consistent with the principles of humane treatment of animals. Consideration should be given to the use of large animals. Generally large animals may be kept under a wider range of conditions than smaller laboratory species. The advantage of using a larger animal is the ability to obtain more and larger samples from one animal and a single large animal can be studied in more detail over a longer period of time. The importance of body mass is also of some consequence. Another important consideration is the work with larger species of animals in addition to rodents to extend our base and provide a firmer basis of extrapolation of certain findings to man. Because so many metabolic correlations of body mass such as rate of oxygen consumption, pulse rate, neural and endocrine function, etc., are directly concerned in temperature regulation this is central to the whole problem of microwave effects.

In general there is little doubt that a biomedical study of several species is required to provide the most reliable extrapolation to man. Ideally one should use taxonomically unrelated species to bring out generalizations with the realization, however, that simply to study multiple species alone will not advance understanding. The main contribution of a comparative approach is not to record the same phenomenon in as many different animals as possible but rather to select intelligently some that will reveal meaningful comparisons. From a spectrum of species, basic information on microwave effects can be recorded which in turn can be used to elucidate mechanisms of action. Study of the animal model should be complimented whenever possible by retrospective and prospective studies on man himself. In conclusion I might say that the central issue for the biologist and for people concerned with hazard assessment and standard development is the development and proper use of adequate instrumentation for dosimetry. Without proper dosimetry anything that I have said or anything that has transpired at this meeting is only academic.

*Dr. Rosenthal:* The next panelist will be Dr. John Osepchuck and he will be talking about measurement problems in connection with microwave ovens.

*Dr. Osepchuck:* I am from the microwave tube community basically, and therefore, I am one of the thousands of living subjects who, for many years, has been exposed to microwave irradiation. I can't report that I have any traumatic memories of either pleasure or displeasure. However, very recently while sailing in a fog in Buzzard Bay, I recorded extreme pleasure when I realized, as a horn blowing tanker appeared 200 yards off the port bow, that it was carrying an operating radar. I won't be as enthusiastic about microwave exposure as Dr. Percy Spencer, inventor of the magnetron, was when he told the following story when people inquired of the possible dangers of microwave exposure around the plant. He said, in his Yankee fashion, "I think there is nothing to it. I have observed people for many years. They come in in the morning dragging and after 8 hours of exposure, they get so charged up that when the bell rings at 5 o'clock they charge out of here." So maybe opinions are changing.

There is certainly a need for perspective and I appreciate very much the material by Dr. Wacker and Dr. Bowman this morning since it brought out many of the considerations that have to be taken into account if one really wants to be rigorous. As a matter of fact we might as well recognize that in using the term microwave radiation we in general use it very loosely here, and in practice many times we prefer to use the term leakage from an oven. That is a more exact term—at least it doesn't imply that we are measuring a radiating field. Certainly the type of rigor that one wants to apply to analysis and design has to be different for the cases of detailed scientific research connected with biological experiments and design work toward the development of a day to day practical indicator of the possibility of a hazard.

Now many things have been said about the nature of microwave oven leakage. I would like to briefly review at least one aspect of it's basic nature. Mr. Paul Crapuchettes gave a very good description of the existence of slot modes. It might be helpful to many of us if we realize that the microwave oven door seal problem is very similar in principle to what happened in the early days of World War II when people designed choke joints for wave guides. In this case the principal field components are radially out going and the choke is designed to contain that radially out going energy. However, it was found that if the flanges were off centered or if there were particles or various types of asymmetry one could excite ring modes in these chokes and cause perturbations in the transmission of these signals. Of course in those days they learned to damp these things out or to align them properly.

I would like to show you an example of some recent measurements with a Nardo 8100 probe and dependence with distance from a "hot spot" in an oven. Here (Fig. 1) a number of cases are shown with various types of loading conditions and although this doesn't show it because of some limitations of instrumentation at the time, generally speaking out a few feet one can roughly assume $1/r^2$ dependence. Sometimes closer to an oven one might suspect that there is more like a $1/r$ variation because in principle one could simply have normally incident energy on the door seal and thus a rather uniform slot excitation in which case the fields drop off as $1/r$ for the quasi-static or induction fields and radiation fields. These were adequately and thoroughly covered by Dr. Bowman and this indicates that there is a lot of distinction that has to be made in terms of how one calibrates the instruments. Mr. Crapuchettes pointed out that for practical purposes the Narda probe appears to provide a useful indication with a 10 or 20 percent accuracy of the level of the field. I don't think anybody claims to have a true near field calibration as Dr. Wacker points out, since this is somewhat meaningless unless one specifies the exact nature of the exciting field.

There are other possible effects besides the slot mode effects that Mr. Crapuchettes pointed out. It is conceivable that there are interaction effects in which one actually affects the incident power on the slot. In this connection some studies that are being planned by Dr. Rudge at ITT should be very useful in determining in a more standard experimental model than an oven, many of the parameters associated with near-field effects and calibrations. I am referring to a situation where one excites a slot but with a known slot excitation from a wave guide drive.

Another thing that should be pointed out, although this is a slight digression, in terms of interpreting how good our instrumentation is compared to other instrumentation used in biological research, it is apparent to me that it is very difficult to find out the characteristics of Russian instrumentation. I think there should be a great deal of effort to find out what the details of this instrumentation are and what their philosophy of measurement is.

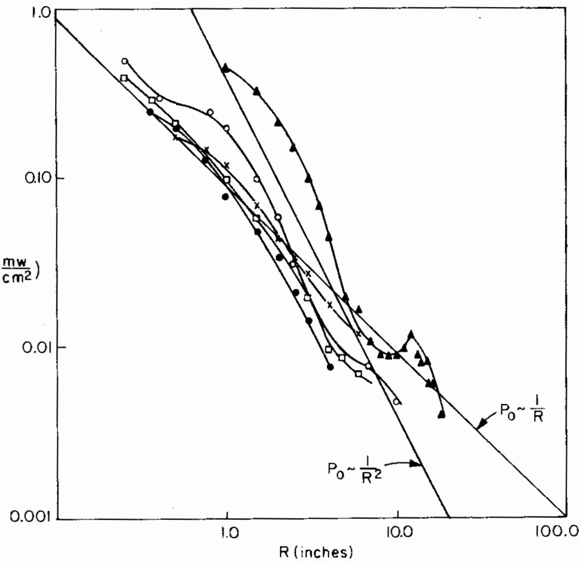


Figure 1. Microwave oven leakage as a function of distance from the oven door seal.

In conclusion I think that with a Narda probe and similar Ramcor probes that are near complete development, we have instruments that are practical, suitable indicators of hazard level. If one wants to get into more rigorous analysis there is a greater amount of work to be done and I think that we will have to stick with the practical probes in the oven field and the industrial field.

*Dr. Rosenthal:* Mr. Frank Lemaster, our next panelist, is with GEEIA, Rome, New York.

*Mr. Lemaster:* I would like to identify the organization I am associated with as GEEIA, which stands for Ground Electronics Engineering Installation Agency of the U.S. Air Force. It is a member of the AFLC Command and I thought this morning I would show you some slides depicting the equipment that we are responsible for performing surveys on. Before I do that though, I would like to explain the division of GEEIA. Headquarters for GEEIA is at Griffis Air Force Base, Rome, New York. Until last week it was organized into five regions . . . the European region at Wiesbaden is being removed.

Now I am going to show you a series of slides

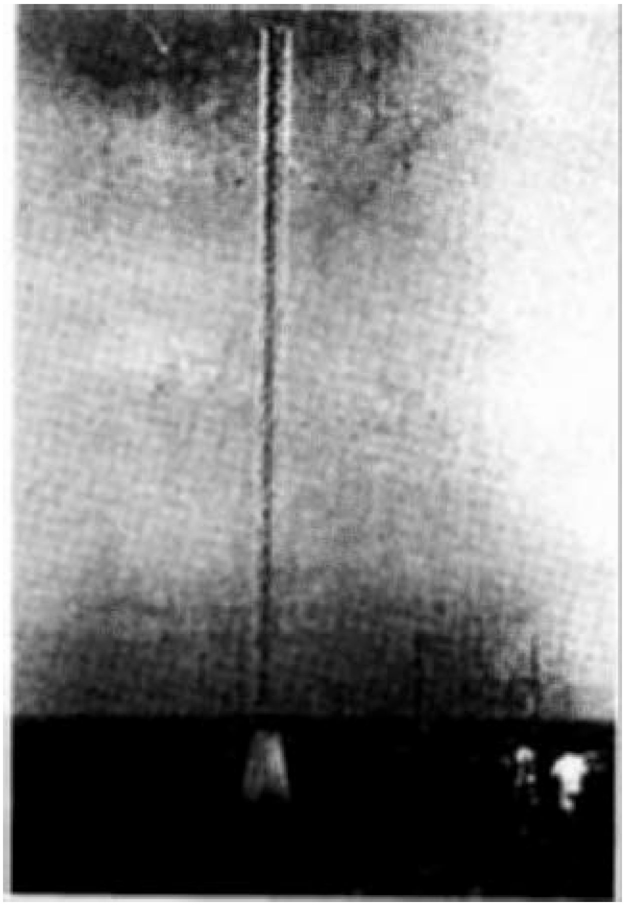


Figure 1. Low frequency, monopole antenna.

that depict the typical microwave equipment. The first slide shows a monopole, which is a very simple device. I show it to illustrate the fact that we are concerned with radiations at low frequencies.

The tropospheric scattering equipment shown in Slide 2 has some features that are quite interesting. It is quite often mounted on a mountain top which prevents personnel from getting into the beam of the equipment and therefore the hazard from such equipment is almost nonexistent even though the 10 mW/cm² limit sometimes extends hundreds of feet in front of the antenna.

Figure 2. Tropospheric scatter radar equipment.

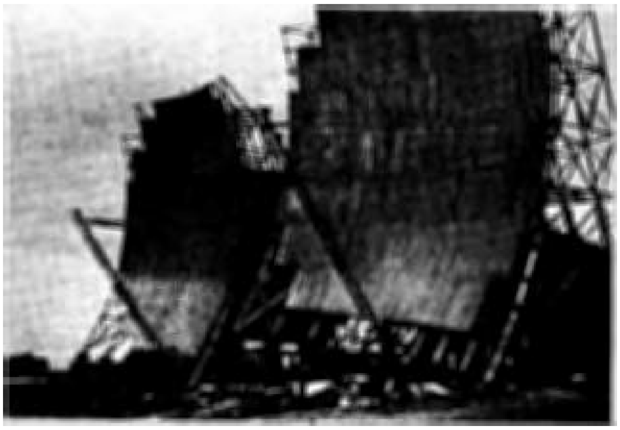


Figure 3. Tropospheric scatter radar equipment.

If the tropospheric scatter radar is mounted low to the ground, I would like to remind would-be measurers of r. f. energy that ground reflections may be significant. There are one or two cases that I know of where the theoretical 10 mW/cm² limit has been found to exist at almost twice the theoretical distance due to such phenomena.

Slide 3 depicts another type of tropospheric scatter equipment which sometimes is operated at very high power and in this case the area in front of the antenna is rather inaccessible. At ground level we seldom measure any hazard.

There would be a greater potential hazard to

Figure 4. Height finder radar located near ground level.

personnel from the device shown in Fig. 4 which is a height finder radar located very close to the ground. It is a tactical system meaning it can be moved anywhere and we do find hazards here. We find that there tends to be a little more carelessness or a need for regulation where tactical equipment is involved.

Figure 5 shows the Air Force FPS-6 height finder which operates at about 5 MW peak power with a 3500 watt average power. It has a negative declination capability. It poses definite hazards to personnel on adjacent towers, and, of course, if you should take any of this equipment into the shop for repairs there would be a lot of power there.

Figure 5. U.S. Air Force FPS-6 height finding radar: 5 MW peak power; 3.5 kW average power.

In the case of the radar shown in Fig. 6 we are getting into the super power equipment and when the equipment power goes up, special precautions are taken. In this case the radar is mounted on a 5 to 7 story building and it is virtually impossible for personnel to get in front of the beam. Extension towers are used to place the hazard from a particular radar well above any personnel.

Figure 7 illustrates a typical site layout involving four pieces of equipment. The distances between the towers is approximately two to four hundred feet. A hazard is sometimes presented from one tower to the next but, for one reason or another, we quite often find that the energy is blanked in the direction of adjacent towers so there really isn't a hazard to personnel on adjacent towers.

In the Air Force we have found no need to actually have personnel working in levels approaching 10 mW/cm², with but very few exceptions. It is operationally quite feasible to keep people out of the area where the power density even approaches the hazard level.

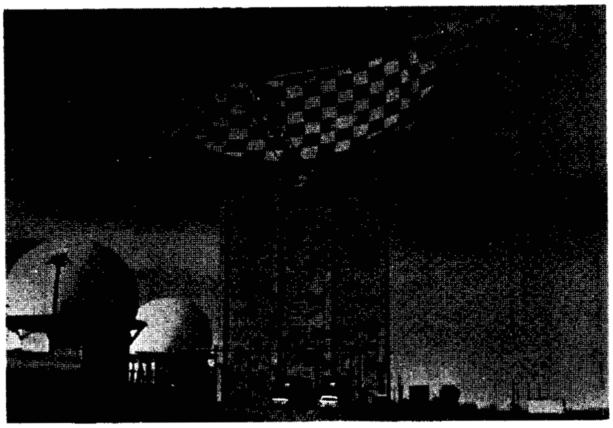


Figure 6. Super powered radar equipment mounted on a 5 to 7 story building to minimize personnel exposure.

We will now consider some modern test equipment. We are using the RAMCOR 1200 which, if I remember correctly, will cover up to 1 gigacycle; and we also use the NF157 power meter which I believe is no longer available. We are also using Hewlett-Packard equipment. We have radiation hazard problems that are not biological in nature but involve electronic devices and fuels and so we do get into many equipment configurations.

Figure 8 is the standard DOD warning sign for r. f. radiation hazards. My Navy colleagues will recognize it immediately because it is their sign. Through the efforts of USASI and now through the Navy and Air Force, the Department of Defense

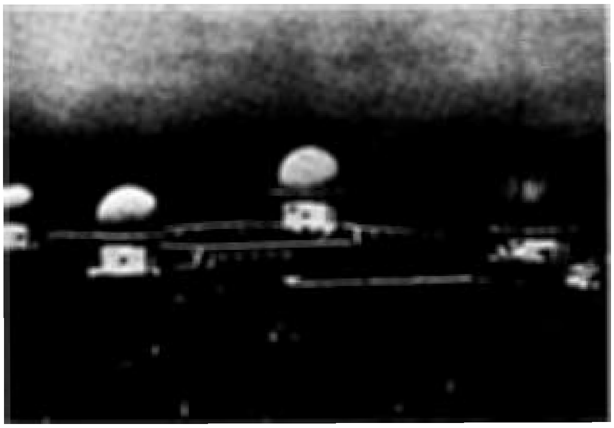


Figure 7. Typical site layout involving four radars. The distances between the towers are 200 to 400 feet.

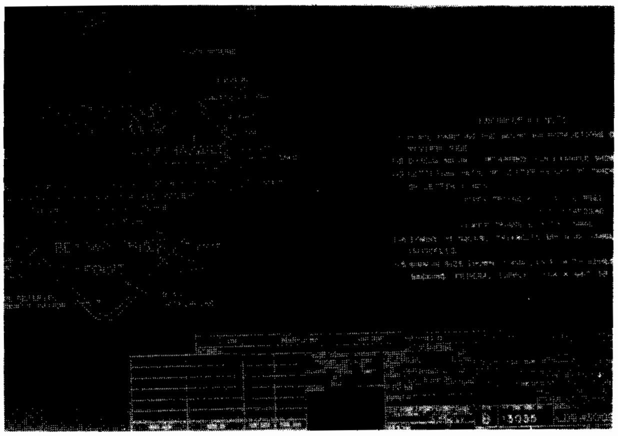


Figure 8. Standard Defense Department warning sign for r. f. radiation hazards.

some time ago adopted this sign as the official radiation hazard sign for microwave equipment.

The one comment I would like to make is that I have heard several interesting comments at the Symposium, but one that was particularly interesting to me. For several years I have fought a campaign to increase education in the field of radiation hazards. The one thing that is needed right now, out in the field, is more education. Education as to the extent of the hazard; education as to what can happen if the operators are careless.

*Dr. Rosenthal:* The next panelist is Dr. Ronald Bowman of the National Bureau of Standards, Boulder, Colorado.

*Dr. Ronald R. Bowman, National Bureau of Standards:* Fortunately the previous two speakers covered some points I wanted to make so my presentation can be cut a bit short. I'm happy to do that anyway because this audience has shown considerable capacity for formulating some very pertinent and sophisticated questions, and I am happy to donate some of my presentation time to an extended question and answer period at the end of the presentations. I would like to say, however, that the papers presented over the past two days have generated questions in people's minds as to the meaning of the results of the experiments. I think this confusion can be avoided in the future by more communication between the biological researchers and the physical scientists. These ambiguities could have been avoided in many cases by some very simple changes in the experimental situation. Certainly there needs to be and can be much better communication in the future between the disciplines.

My area of interest in this subject has been with respect to developing new instrumentation. As you know from the paper by Dr. Crapuchettes there are several new instruments on the market. Let me show a slide here to illustrate my particular slant on the measurement problem. (See Bowman in this volume, "General Characteristics".) My interest in developing a probe is with reference to a general purpose instrument that can be used to survey hazards and that could also perhaps be used in the laboratory. As I mentioned earlier, I believe that the probe ideally should be designed and constructed to respond to the total energy density of the field. Considering the problems involved in making a probe respond to the magnetic field energy density I think that most practical probes would be limited to measuring electric field energy density. At microwave frequencies knowledge of the electric field energy density is probably adequate anyway.

This characteristic that the probe should not cause significant scattering of the field implies that I am talking about a probe that is essentially a "high impedance" probe. It is true that the human body has an essentially "low impedance" and does not respond like a "high impedance" device in the field; however, I think it is impossible to mimic the body with a small "low impedance"probe. The hazards that exist for a given field configuration must be decided by some very careful experimentation. Once that is known then one can survey similar fields for hazards in terms of the energy density of the unperturbed field. However, if one tries to make a small probe that would respond as would a human body for a wide range of frequencies and a wide range of field configurations, I think that is a very serious problem and probably can't be solved. So I would myself rather employ a "high impedance" probe that would at least give an unambigous measurement of the unperturbed field.

Another important characteristic is that the probe be able to measure both peak and average values for complicated wave-forms. Certainly the papers presented the past few days have shown that there is a good possibility of nonthermal effects. People must then be interested in wave-form. The particular probe that I am working on at the Bureau of Standards is designed to measure rapid wave-form changes in the r. f. field. I don't know at this point how fast it will respond, but we have thrown away some ideas for practical probes that would only measure average values simply because we do feel that the wave-form question is important.

*Dr. Rosenthal:* With respect to the next panelist the crux of any standard is really measurement, obtaining research information, and then, of course, trying to measure a hazard. We will now hear from the man who is involved in setting up standards for the Public Health Service, Henry Rechen.

*Mr. Rechen, Bureau of Radiological Health, U.S. Public Health Service:* When I was fresh out of college my first sanitary engineering job was to build a two hole segregated privy on the side of the Panama Canal. At the time we built it we didn't yet need it but we anticipated needing it and I think that in the standards field we're doing the same thing. Let's hope we're building it before we need it.

In order for us to develop standards we have to first define what we mean by the control of public health. This is not just biological injury to man but it includes his food sources, his ability to use the environment around him that he is entitled to, and his ability to live without public health nuisances and also his ability to perform his duties without interfering with his neighbor's health. With reference to the so-called public health hazards or risks from microwave radiation, we have to have biological information in order to develop a standard. We have to decide whether the radiation is harmful or whether it is essentially innocuous or whether it can perhaps be beneficial.

There has to be a great deal of information about whether the effects are essentially of an acute threshold type, or whether they are cumulative. As we have heard over the last two days and previously, there is a great deal of information on threshold effects. There is also some evidence that there are cumulative effects. These are the results of dose—the delivery of energy in one form or another to a biological system. We cannot set up standards in the units of dose. The standards must be in units of exposure such as in terms of the microwave field power or energy density in free space. There is always the problem of converting an instrument reading made in free space to a meaningful dose interpretation.

Once we have biological information we can establish a series of standards including those for human exposure control. The biological data gives us information on the effects of radiation. We try to establish human control standards at levels that will not show effects. A person, for instance, measuring exposure should be able to refer his measurements to a recommended or legal human exposure control standard. If he finds himself referring to the occurrence or absence of biological effects, the standard is not adequate. The standard acts as a buffer between the person using or designing radiation sources or measuring them and the actual biological effects that are known to occur. Thus by having human exposure control standards it is not necessary for the user or the developer of the radiation source to argue whether or not this is going to hurt people, as long as he can meet the applicable standards.

Every source of microwave radiation either is powerful enough to cause biological damage or it is not. There is a grey area in between and I call effects in this area biological effects. If the source is harmful, human exposure controls must be exerted, for example, by totally enclosing that source so that access to it is impossible and the only radiation that emerges from the enclosure or the physically excluded installation is acceptable for human exposure. If physical barriers are used, there must be evidence of the physical barriers such as the door of the microwave oven. If, however, access to the dangerous areas is controlled by an operational procedure, a responsible operator must be provided.

There are thus two ways of controlling access to a dangerous source. One of them is by operator control and the other is by physical control barriers. If a source has no demonstrable biological harm connected with it these should not be necessary. There are, however, a large number of microwave sources that cannot be totally enclosed. Such equipment must be used in areas with people. Here the responsible designer comes first then the responsible operator. Now there are also uncontrolled uses of microwave sources by nonresponsible operators such as the child who buys the low power walkie-talkie, the housewife who buys a microwave oven, or the amateur who buys a high frequency radio transmitter.

We measure radiation for several reasons. If we are measuring a product or a device that is intended to prevent human exposure beyond some value, we are measuring to a performance standard. We normally would then not make any reasonable assumption about how people use this device. The performance standard would specify the leakage level for that product, and the product would have to meet that standard regardless of how the product was going to be used. There are usually two things connected with a microwave device. One is a useful beam and the other is unnecessary leakage. There would obviously then have to be a series of standards in addition to these physical factors such as wavelength and so forth. If we're checking on what you would call an installation where access control and human judgment is necessary to control the exposure of people, we have a much more involved standards problem because this now includes the technique by which the source is used and the judgment and training of the operators and designers of course. We cannot go into a design or into an operating installation and measure the technique that is used generally because we are only there for a short time. Nor can we directly measure the judgment that has gone into the control of exposure of people.

Now let me bring up the next factor that controls the application of standards. This is whether or not this source, from our viewpoint, provides a health risk, a health benefit or both. When I, as a member of the Public Health Service, speak of risk and benefit and usefulness and so on, I'm not speaking of industrial usefulness. I'm speaking of use to the individual whose health may be damaged by this radiation. Oddly enough at this Symposium and at the IMPI Symposium in Alberta last May and at the University of Surrey I heard no one claim a direct therapeutic benefit for microwave radiation for humans. You realize that if microwave radiation is absolutely necessary in our modern community, or if it is necessary for medical treatment or diagnosis, the human body does not differientiate in the effects on the body between the harmful radiation and beneficial radiation. The fact that the radiation exposure of our population may be necessary simply means that we must find means of reducing other concurrent or accumulative exposures. This means that every time a necessary or beneficial use of microwaves is found, all others who propose to expose humans must then meet a more restrictive standard. So that the more necessary uses for exposing people that are found, the more restrictive standards such as performance standards, leakage standards, and individual control standards must become.

Human exposure control involves the total exposure of that human and not just the exposure from a single device. We must concern ourselves with his total concurrent or accumulated exposure if there are cumulative effects. If there are medical uses of microwave radiation with direct application to humans we will have to have double standards. Here we have talked about the standards necessary to prevent biological effects or biological harm to humans. If someone is going to propose, describe, or defend the biological applications of microwave radiation to humans with a therapeutic or diagnostic benefit there must be a different standard for this exposure. All of this involves judgment. It's unfair of us to require that the designer and user of these sources, and especially the operators of these sources, apply all of this judgment without guidance. To me it has always seemed somewhat difficult for a large manufacturer to have to develop all of his own population exposure standards. He may, however, whenever challenged be able to show that there is no possible biological risk with what he is doing. But he has no community buffer who has established standards which if he meets them he no longer has to make his own arguments. This generally involves public officials as the people who promulgate various standards.

The standards include measurable exposures; they include design and construction of the installation; they include factors such as whether or not this type of radiation exposure is esthetically or biologically desirable. This is in an area of public health hazards or public health nuisances.

Finally, in establishing the standards we do need standard terminology and standard units of measurement. These were established in the radiation field initially by a meeting in Europe in 1928. I wonder what will be the corresponding year in the microwave field.

*Dr. Rosenthal:* The last panelist, Allan Frey, is going to talk about r. f. measurements and biological research. What I think he would like to do is to sum up good research practices. One of the problems is that we read a great deal of papers, particularly from other countries, and it is very difficult to ascertain exactly what would happen if one tried to reproduce this work since you don't know the exact conditions.

*Dr. Frey, Randomline, Inc., Willow Grove, Pennsylvania:* What I shall do is to suggest that we consider the specification of information needed for a paper in the microwave area to be considered satisfactory for publication. I will suggest some of the factors that should be reported and I will try to solicit comments and further factors which members of the audience feel should be reported.

In essence I think it would be useful if as a result of this Symposium it would be possible to write and publish a specification for investigators who are going to do research in the area of the biological effects of microwaves and high frequency radiation. This specification would consist of what they must report. For example, I see in my own research that one must report average power density and when it is appropriate peak power density should also be reported. Carrier frequency should also be reported. Although these things seem to be so basic, in my reviews of the literature, it is obvious that they are not. No paper should be allowed to be published without this minimum information. The nature of the modulation should also be reported. For example, things like pulse shape if the energy source is pulse modulated. We should also consider whether pulse rise time should be reported. The enclosure in which an experiment is done must also be reported. This often is not done.

One must also report what materials are in the field and the positioning of the materials that are in the field. There are times when it is mentioned in passing that the animals are enclosed in a cage with no further specifications of the cage.

The exact specification of the measuring equipment should be reported. For example, we heard in reports yesterday that the fields were going to be measured by use of a Simpson meter and a Hewlett-Packard meter. This is fine except there are accessories which are a part of the measuring instrument and without knowing precisely what these are it is hard to make any kind of an evaluation as to the validity of the measurements. These things should be specified as a minimum for publication of any paper in this area.

Where the measurements are made and under what conditions should also be specified. One should indicate whether he is putting the dipole in the field close to the back of the animal or whether he is replacing the animal with the dipole. Often it is not clear in a paper whether the measurements were made with the animal in the field. There should also be information on units of measurement. Should all papers report in terms of mW/cm$^2$? Sometimes it gets rather difficult when one investigator reports in one set of units and another investigator reports in another set of units. Should we have several sets of units or is one most appropriate? Should we report also the matter of exact exposure time, and exact exposure time to effects?

I would also suggest that it is important to give control data on things such as the use of electrodes in the field. One should specify exactly what has been done to insure that he is not inducing currents into the animal or measuring equipment. There is also the question of how one should measure. Should we standardize on measuring via the calorimetric route or should it be done via power meters with dipoles. Some investigators measure temperature in a glass of water, some investigators measure what is picked up on a half wave dipole. There is some comparison that can be made in theory but keep in mind that putting that glass of water in the field and what that does to the field is not exactly what the dipole does to the field. Can one really make any comparisons? Should there be a standard that specifies what is to be measured?

These are some of the factors that should be considered and should be in a specification as to what should be reported in any paper that is to be published. It may be helpful to suggest some of these things to our friends in the Soviet Union as useful information. I'd like to suggest possibly that other people in the audience might wish to add something to this list or consider deleting some of these factors.

*Dr. Rosenthal:* Before opening up the panel for discussion I would like to call on Dr. Allam from the University of Surrey who we would have liked to have included on the panel but unfortunately it was not possible.

*Dr. Derek Allam, University of Surrey, Guildford, England:* Most of what I was going to say has in fact been said. I won't labor on these points. Perhaps in the absence of a Wayne Kerr man I could come to the defense of the RAD 100, the so-called conversation item. This was developed by the Ministry of Technology in Britian as an EED monitor. It wasn't intended as a biological monitor. In fact its properties are extremely good, it is an extremely sophisticated instrument and it may well have some application. The RAD 200 monitor was initially developed by Wayne Kerr and the University of Surrey to measure leakage from microwave ovens and large drying presses. Coventry Evening Telegraph has a microwave device for drying ink so we developed this as a simple measuring instrument. I agree that it is not too cheap but the main reasons for this is calibration.

*Dr. Rosenthal:* The panel is now open for discussion. I would appreciate very much if you would indicate who you are and to which panel member your are addressing your question.

*Dr. Milton Zaret:* As some of you know, I have several different hats that I can wear at different times and usually when talking to engineers I prefer to wear the medical hat. When talking to physicians, I prefer to wear the engineering hat. Also, I have a little experience with management of medical research and when both groups are together, I can hide under that hat. Instead for the first time in my life I am going to talk under all hats.

I approached coming to this meeting with a great deal of trepidation and I'm sorry to say that I'll be going away with just about all of it. Partly, perhaps, because there has been a hiatus in time and I think at this point I would like to express publically, for the record, that the passing of Colonel George Knauf is really a loss that many of us here may not realize we had. This man, not fully trained in any of the disciplines that we are talking about, especially as the interface, took on an awful responsibility and formed it in what I consider a brilliant fashion against brick bats from every side. I thought I would make that one comment for the record because since he last formed a meeting of this sort there hasn't been one. Also, since he left the field there has only been fire fighting going on. All of us now are faced with the problem of trying to toy with the standard without any ammunition to speak of.

Getting back to the topic of this morning, I just want to make a few comments only because I dislike leaving statements left unchallenged because the Proceedings of this Symposium may, in some places, be held up as a Bible and it is nothing of the sort. The question of cumulative effects of microwave radiation. Now Dr. Carpenter and I, to some of you it may look like we are fighting, but we are not, we are approaching this problem from a different point of view. We are both taking the same route except he's talking about apples, at times, and I'm talking about pears. He's talking about basic research and sometimes I'm talking about applied research. When we talk about cumulative effects with microwaves, the only place that there has been any such thing as a cumulative effect of microwaves has been in the realm of lens injury and it's been in a situation where there has been an acute experiment and there is an immediate injury and the second insult is applied before the first one has healed. Now that can be one definition of a cumulative effect. Yet I talk at times about the lens in the eye being a cumulative tissue dosimeter with a history representing exposure to harmful effects of microwave radiation. I don't mean to say that if you take 10 exposures at 10 mW this is the equivalent of 1 exposure at 100 mW. There is no additive factor in this regard and this must be clarified.

In considering the question of the unnecessary burden on us due to the microwaves that are generated we have an r. f. burden coming to us from the sun and I wonder if we could live really if we had no r. f. background. If one wants to add a philosophical point about where does r. f. start and where does it end, there are a lot of things we don't know. There are questions that came to my mind as a result of a couple of the talks such as Frank Lemaster's. He said that it is virtually impossible for people to get exposed to these high powered radar sets. I have seen several hundred that have been exposed and these were the ones that were reported. We don't know about the people who were painting those towers. Some of the people I have seen were examined only because they were painters; they weren't in the radar field. They were up there painting a tower and someone saw them. If no one had seen them and reported it, we'd never know about it.

The question of education. I'm all in favor of education but we can't rely on it. The question that people can't get near equipment; I don't believe it. These are the people I see on the clinical side. Dr. Michaelson made some points that I would disagree with in some respects. That is that there is no single biological effect. There is one that is used to scan a spectrum and that is cataractogenesis. This is one that can be related if we would use the end point between Dr. Carpenter and myself. We are using different end points. People don't really understand this. We aren't disagreeing with one another, we are just using different end points. It looks like it is similar work to so many people because we have copied his instrumentation to a great extent. The people are still not clear on the fact that the end point is different. Also on the selection of animals, on some respects I agree with Dr. Michaelson, but on others I think we have to temper this because we cover the spectrum so to speak in experience. Some people are new at this and some have had a lot of experience at it. Some of us know, for example, that basic problems of biological effects must be investigated and they are willing to forego the applied research which is what is desperately needed today, and we know enough, in some instances, as in the cataract problem to start on the applied research. So you will have all different degrees of experience that can be applied to this research field.

The question of setting up a tissue model between frequencies by the cataract method, can also serve as average versus peak power, pulsing, modulation; you can do everything by this technique. Dr. Rosenthal has been involved with it and he can attest to this and perhaps talk about it if he cares to.

At any rate, I have probably said too much already at this meeting, and you'll forgive me because I just felt we just couldn't leave things unchallenged when there are issues of doubt and interpretation or even differences in defining the terms that we are talking about. We are not completely in the dark in this area. But it seems as if the people that manage the programs are afraid we are, so therefore, we have failed to communicate properly.

*Dr. Michaelson:* I suppose I should respond to Dr. Zaret. First I would like to go on record as agreeing with Dr. Zaret about the late George Knauf because I too feel that we all owe him a debt of gratitude for having the vision, the foresight, the honesty, and a little bit of temerity to go ahead and set up the research program against the wishes of his superiors in many respects. I think there are many people in this audience that feel the same way.

Now I would like to defend myself. Apparently I wasn't quite understood. I didn't say that there is no single biological indicator of exposure to microwaves. I said it is essential to realize that there is no universally accepted specific biologic indicator of exposure to microwaves. Although I did go on to say that there is no reason to believe that a single biological test would give a satisfactory indication of microwave exposure. I can't see how exposure of the eye can be used as an indicator of exposure of the testes; this is what I meant.

As far as the question of animal selection I didn't mean to imply that we should ignore basic research and tissue culture techniques. I think it is too bad that this was implied. I just didn't mention it because everyone realizes that these are basic techniques that have to be done, that have to be carefully worked at, carefully interpreted as I said yesterday. Cytogenetic studies are very important. Apparently some people misunderstood that point and someone thought I said they shouldn't be done. They have to be done but they have to be done critically, carefully and one has to be aware of the interacting variables and the implications involved in extrapolation of isolated cell systems to molecules in the whole organism.

*Dr. Rosenthal:* There is going to be a panel this afternoon on future research directions so I would like to try to keep this as much as possible to the measurements problem. Are there any other comments?

*Dr. Alan Shapiro:* There are two things I would like to comment on. One is Dr. Voss' comments made in the earlier part of the morning which also relates to Dr. Marha's paper of yesterday afternoon. This is the question of whether the exposure standard of 10 $\mu W/cm^2$ should be adopted. It appears to me that the argument for the adoption of that standard is based completely on an assumed cumulative effect. I've heard no other justification. I have heard no one who has observed a clinical effect at 10 $\mu W/cm^2$ nor have I heard anybody who has demonstrated a mechanism that is operative *in vitro* at 10 $\mu W/cm^2$. The argument is thus one of cumulative dosage. If one were exposed to this over a week's time for 8 hours a day, this would amount to something that would be comparable to 50 $mW/cm^2$; a level at which there is an issue that must be resolved as soon as possible; the question of cumulative dosage. Does it apply to microwave exposure? I've seen no evidence in the literature or at this meeting except for the cataracts of the eye which occur at higher levels and we have some better information in this case, which in any event does not involve exposures as low as 10 $\mu W/cm^2$. Unless such cumulative effects can be demonstrated, I see no justification for adopting that as a standard.

The second comment is on frequency specificity which is more pertinent to the subject of the panel. The question is whether frequency specific effects exist and whether the standard should be broken down into different frequency regions with different measurements in these regions. It seems to me that one must distinguish between two kinds of frequency specific effects. Physically these are those that are frequency specific because of the boundary conditions. That is the case when the geometry of the boundary conditions of the whole surround that is establishing the field is taken into consideration. There are then frequency specific effects for different geometric arrangements; the induced field in the specimen will be different. I have made some calculations for a model of the cranium of the head which was a seven layer model just to get some feeling for what the differences in tissue dielectric constants and resitivities would do. It was a means of testing the assumption that Dr. Schwan had made and stated again the other day, that the boundary conditions would not lead to any highly nonuniform heating within the cranium. I found on the basis of my calculation that that is not true. When the Mie parameter (i.e., the scattering parameter) is of the order of one, which can occur very often in this frequency range, one could get highly nonuniform induced fields within the cranium which would be very different in a cat, a monkey, or a man, at the same frequency. In particular one could have the condition where at 10 mW/cm$^2$ irradiation, the average heating in the whole cranium was below the active metabolic level but there would be hot spots in the mid-brain region where the heating would be above the active metabolic level. The frequency specific effects due to the geometry of the boundary conditions, even in the free field, can play a very important role. On that basis the standard should take into consideration the differences from one portion of the radio frequency spectrum to another and also in extrapolating from animal measurements to man.

The second type of frequency specific effect is the sort of thing that Dr. Illinger referred to in his talk and this is on the level of mechanisms of interaction. On the level of mechanisms of interaction the problem is even more difficult to explore analytically. It seems to me that the basic question is whether the energy levels that are excited by the radio frequency photons are immediately thermalized or thermalized so rapidly that the various levels that can be excited in the chemistry of a system lie so close to one another that the energy that is put in at one level is distributed in a Boltzmann fashion throughout all of the energy levels such that one need not consider any resonance or any specific bond in some molecule being excited and thus contributing some special effect but instead all of the levels are excited in a thermal fashion. I looked into this question very briefly and the time constants that I have been able to determine and those in the literature of microwave spectroscopy are such that I can't find resonances in any biologically significant molecule, that is where resonance phenomena would be significant and where thermalization doesn't occur immediately.

*Comment from the floor:* I want to interject something since a lot of this discussion seems to be going into things that are presumably going to be discussed this afternoon. I'm afraid there might not be any consensus about the measurement problem or the instrumentation problem which I thought was the original purposes of this panel discussion. For this purpose I would like to present an idea that occurred to me as I listened to this discussion and that concerns the Russian instrumentation. It is pretty clear to me that we put a lot of emphasis on what the Russians are doing in biological research but we don't have much information, or at least it hasn't been reported here, on what instrumentation the Russians are using. The instrumentation that I have read about they very clearly emphasize far field instrumentation. In this particular case they show loop sensors and, of course, they emphasize, probably naturally enough, a lot of integration for the dosimetry. Never have I seen any discussion or any near field instrumentation to go along with the application of these standards. When we heard Dr. Marha speak yesterday about measurements at one foot this makes me think that if we have to consider their research in the biological area, maybe we should consider their method of operation by measuring at one foot at likely sites of exposure. Perhaps they don't like to get bogged down with all the ambiguities of near fields at 2 inches. I would like to hear some response to these questions with respect to how they measure the near field or fields near objects.

*Dr. Zaret:* I would like to add one thing about biological tissues as dosimeters. In 1961 when lasers were first discovered, frequently the only way we could tell whether a laser had really lased was to put a rabbit in front of that laser and look for the lesion, and the physical scientists were happy to have that method at that time. We have some tissue models that can be used in this field.

*Dr. Moris Shore:* I have one comment that I would like to make and also possibly ask one question. The comment is relative to the problem of communication that we have at a meeting such as this. I was very glad that Dr. Zaret, in talking about his views on cumulative effects, made it a point to define what he considers cumulative effects, for example, by indicating that 10 exposures at 10 mW/cm$^2$ might be equivalent to one exposure at 100 mW/cm$^2$, and saying that unless you have a condition like this you have no cumulative effect. I think that such a statement is one that most of us would be in agreement with. However, the views that some people have with respect to cumulative effects of many agents, microwave radiation for one, ionizing radiation for another, are not based on such simple addition because it is generally recognized that repair does occur following injury. In the case of ionizing radiation this is true and from what we have been able to see from Dr. Carpenter's work with cataracts and Dr. Van Ummersen's work, I think it would be true in that case as well, although it is only one end point that has been examined and perhaps we should examine many more. I believe that the same problem occurs when we talk about mechanisms of injury and I think that considerable controversy has been generated relative to that particular point. I'm sure that people are disagreeing as much in terms of what the mechanisms actually are, as they are disagreeing because they don't use the same words to describe the same things. I think it is very important that we define the terms that we use so that when we agree or disagree we know what we are agreeing or what we are disagreeing about.

Now the question that I would like to ask is this. With respect to measurement as it applies to biological experimentation, I think that is is very well to characterize the field that you are working with, and whether you measure with the animal in place or without the animal in place, to specify conditions of the experiment and exposure. But what about the problem of energy absorption, dosimetry in an experimental situation, whether we're talking about man or whether we're talking about tissue culture? What are the possibilities that we could develop at least the kind of sophistication that we have been able to develop in other areas such as, for instance, ionizing radiation?

*Dr. Michaelson:* I can't talk about absorption and instrumentation. I'm afraid I'm not competent to discuss instrumentation in that aspect. I think we ought to clarify one point on the question of cumulative damage. Dr. Shore is very right. We are confusing terms and there is a lot of semantic difficulty. Quite often we confuse ionizing radiation with microwaves. This question of cumulative damage in relation to ionizing radiation is not in any way the same as the suggested cumulative effects of microwaves. When we talk about cumulative damage in ionizing radiation, if there is not enough energy that is incompatible with life there is a recovery. However, based on mathematical determinations and considerable experimental data, there is definite evidence of residual injury and from the basis of residual injury or incomplete recoverability you have cumulative damage. If we increase the interval between multiple microwave exposure we don't get the effects that are seen by compressing the time interval. This is not the same as cumulative damage in the area of ionizing radiation.

*Dr. Zaret:* I think that all the tissue phantoms that have been used so far for microwave determination are wrong. For example, fat was formerly a layer of fat in the physiological condition and now it is a piece of dead fat. We're dealing in a body with a hemodynamic system. All the measurements are under hemostatic conditions. A phantom resembling living tissue can be made but it has to be made with hemodynamic specifications.

# PANEL DISCUSSION II: FUTURE NEEDS IN RESEARCH ON THE BIOLOGICAL EFFECTS OF MICROWAVE AND R. F. RADIATION

*Panel Moderator:* COLONEL ALVIN M. BURNER

*Headquarters, USAF*

*Col. Burner:* On February 13 Dr. Cleary asked me to serve on a program committee for this meeting. At that time I was Chief of the Radiobiology Division, Technical Director of Radiobiology, and the Director of Research and Development of the Aerospace Medical Division at Brooks Air Force Base. This is no longer my affiliation. I am now assigned to Headquarters, USAF. I must emphasize that the opinions which I will express today are my own and quite evidently not those of the Air Force.

In my invitational letter, I asked each of the panelists to address the question from his own particular viewpoint, but not to limit his statement to this narrow position. I hope that the summary of these deliberations will form a distillate of the sense of this fine meeting. As a scientist I have a great deal of interest in the problems as they range from a subcellular level of reaction in flora and fauna on up through the reaction of advanced organisms. However, as a person who has had primary concern for the individual as he reacts with the microwave field, my views tend to concentrate on the whole human body and the limits which should be placed on his exposure to such fields.

There are many questions that have been touched on in these sessions as to the directions our future research should take. These include continous wave versus pulsed microwaves. Is there a difference and if so what is the significance thereof? Other problems include the effects of frequency specificities, low frequencies (below 300 MHz) where relatively little experience is available, and instrumentation as we previously discussed. As I have said before, we would like to have a single instrument that will permit accurate measurements both in the laboratory and in the field so that we can translate the information that we obtain in the laboratory to the environment in which the man will work in the field. The importance of effects which produce no measurable temperature rise, and I am avoiding saying thermal versus nonthermal effects, long term versus short term effects and many others must be determined.

I am here today as a moderator and I am not here to make speeches so I will terminate my remarks by saying that unfortunately, because of pressing academic business, Dr. Schwan who was to be present and serve on this panel will not be here today. He sends his regrets. Our first speaker today will be Dr. Charles Susskind, Professor of Engineering Sciences, the University of California, Berkeley.

*Dr. Susskind:* We haven't heard many kind remarks about the so-called Tri-Service program on the biological effects of microwaves that was active for about a decade beginning in about 1956. The program gathered together research workers who had been concerned with these and allied problems—some of us had even been working in the field even before—and brought them under the benevolent eye of the Department of Defense, mainly the Air Force, although the Navy also took a hand (through the Office of Naval Research) and the Army mounted a smaller effort mainly "in house" research. The main overall idea was to gather and disseminate information and to coordinate and stimulate new work. The program did an excellent job of getting together data and getting them out to all hands. What is known in the United States about our problem is to a considerable extent the result of the Tri-Service Program. These results are certainly not limited to "thermal" effects. The Program also did a good job in stimulating research and incidently of training people. Many of the researchers, scientists, and engineers who are doing work now and will be doing work in the future earned their spurs (and their research assistant salaries) under the Tri-Service sponsorship.

The Program didn't do quite so well in the matter of coordinating research. To a considerable extent this lack of direction was due to a very proper diffidence on the part of the main champion of this work, the late Col. George Knauf, whose name has been mentioned at this meeting before. Despite the misgivings of our colleagues in the social sciences the scientific agencies of the Department of Defense had, in my experience, been much more respectful of this aspect of academic freedom; the freedom to pursue the truth no matter where it will take you, than many other government agencies. There is a lesson in that for the U.S. agencies now concerned with initiating additional work on biological effects of nonionizing radiation and their health implications, which are notably the Technical Electronics Products Radiation Safety Committee of the Department of Health, Education, and Welfare and the President's Electromagnetic Radiation Management Advisory Council. The lesson is that we must evolve methods of managing and coordinating research without inhibiting the investigator's freedom.

That is, of course, a general problem wherever research is directly sponsored by outside funds and everybody including the members of the ERMAC and HEW committees are aware of it. It is of particular importance when basic research pertains to a matter of public interest. You must have independent research if you expect to get results that can be believed. At the same time you have to be able to channel the efforts in a direction most likely to produce the necessary results. This is an important and rather delicate task but I have full confidence in the committee members' importance and delicacy.

There is one minor problem that nevertheless might be useful to bring to their attention. If the work that remains to be done, for instance the vexing task of replicating some of the Soviet results, and more generally of building conceptual bases for the possibility of effects at lower frequencies and intensity levels than have concerned us to date, is in the public interest, the mechanisms must be found to channel support for such work that falls outside the ordinary schemes of research support. It is all very well to say that what Dr. Frey or Dr. Vogelhut or Dr. Illinger proposes for investigation is very interesting and certainly worth doing. It is another thing to expect them to go home and submit applications for grants to the National Institutes of Health, where the review procedure takes 5 to 8 months, where the chance of getting any research proposal funded is about 1 in 5, and where the chance of getting support for bio-engineering research is even slighter. There is very little money for bio-engineering research as such at NIH and virtually none at NSF.

Without belaboring the point let me simply reiterate that if we decide that we need more research, with a distinctly utilitarian end in view, we must figure out a way of getting that research funded regardless of the probable contribution to science that will result, and without submitting the proposal to the same sort of scrutiny that a proposal in theoretical physics would receive. This is not a trivial problem. I have full confidence not only in the importance and delicacy of the committee members concerned, but also in their ability to deal with the practical world. This is just a word to the wise.

*Col. Burner:* Thank you, Dr. Susskind. Our next speaker will be Dr. Sol Michaelson, from the University of Rochester, Rochester, N.Y.

*Dr. Michaelson:* The greatest need today in the assessment of biological effects of microwave exposure is to maintain a realistic perspective on the nature of microwave fields and the possible effects from exposure. The mechanisms by which cell damage is produced, the biological tolerance of the most susceptible tissue, and the safe levels of intensity must be established in an organized fashion.

Something that concerns us very much is the development of adequate and operable standards which requires comprehensible evaluation of information obtained from animal experiments and surveys of individuals exposed either occupationally or while engaged in military activity. The criteria to be used in evaluating experimental results of microwave exposure and the interacting variables in such assessments, requires the exercise of informed judgment. Since there is such a clear cut dichotomy in the criteria used in the United States and the U.S.S.R., these have to be understood and evaluated. As of right now we don't have any better idea of what the U.S.S.R. situation is than we had before the Symposium. How, in fact, do the Soviets measure, if they actually do, the levels that they say they adhere to? This is a critical activity for all of us. How can we find out this information? What can we do to obtain it? The question of central nervous system effects, which preoccupies the Soviets as much as it does, must be resolved by quantitative experimentation and good biomedical investigation and the implications of such effects should be intelligently defined. I beg to differ with some of the people at the Symposium in that we shouldn't try to replicate the Soviet experiments. In this country we have enough competent, interested neurophysiologists and we are as far advanced, if not more so technologically, in neurophysiological and bio-engineering, as the Soviets are. We may be as much as a generation ahead of them. There is no reason why we can't set up our own criteria, our own concepts, and approach the problem within a framework of our own interest, our own ideas, our own needs.

The question of possible genetic effects from low-level microwave exposure has still not been answered. The resolution of the controversy concerning thermal, nonthermal, and microthermal effects is extremely important in the development of realistic maximum permissible levels of exposure. We have to do this to avoid placing undue restriction on industry, the military, and medical applications of microwave energy. The problem is how to determine tolerance limits. The parameters that have to be studied include the physical factors such as frequency and average power. I won't go into all of these because they have been hashed over and over again. Many biological, chemical, and physical phenomena have been noted in the past but as of now these are inadequately understood and explained. I would like to caution again, as I did earlier, that what is extremely important is that we critically analyze the information that we have. There is a lot of information, but a lot of it is misunderstood, a lot is confusing, and a lot of it is interpreted incorrectly.

An aspect of the work that must be kept in mind in the planning of experiments is the effect of temperature increase. As long as we realize that there is a thermal burden in these experiments, I don't care if it is tissue culture, isolated cells, single cells, organs, tissues, whole animals, parts of bodies, whole bodies, there is no difference. We have to have thermally corrected controls. Ambient temperature has to be considered. Interacting variables have to be understood; they have to be defined; they have to be appreciated.

I feel it is essential to develop a definition of what we mean by hazard. Are we talking about biological effects? Should these be considered in setting up standards or should we talk about injury and hazards? The question of repairability or irrepairability, and the whole question of cumulative effects is up in the air. It is a controversy that has to be resolved, and here we cannot look to ionizing radiation for the concept of injury, repair, residual injury. These are quite different and we can't confuse the two. We have to determine if there are irreversible changes. Is there repair? What are the rates of repair?

In general fresh approaches must be used to develop newer concepts and understanding of the biological effects of microwaves. Well planned controlled animal studies should be undertaken. Tissue culture studies, isolated cell studies are extremely important, but they have to be approached with understanding and intelligence. Representative species of different orders, not of the extent of isolated cell systems, but concurrently, in parallel, with basic biological research and biophysical research must be utilized to provide extrapolation factors for predicting the response of man. Microwave frequencies with calibrated beams should be used. Such studies are best developed through direct collaboration of biomedical and engineering personnel.

Since evidence indicates that the eye and the testes may be the most "critical" organs in the assessment of microwave hazards, it is essential that the effects on these organs be critically and quantitatively evaluated on a sequential basis, not as we have done in the past to a large extent. Investigation of long term effects on large enough numbers of suitable animal species is mandatory.

In conclusion it should be emphasized that more critical evaluations of the existing information, more sophisticated conceptual approaches, and more vigorous restrictive experimental design must be developed.

*Col. Burner:* Our next speaker this afternoon is Dr. John H. Heller, of the New England Institute of Medical Research, Ridgefield, Conn.

*Dr. Heller:* I plan to take the role of the Devil's advocate. It's not hard. Listening to the talks here is not just mixing apples and bananas; you throw in kitchen sinks and plumbing supplies. I have never heard so many people, with the possible exception of certain immunological meetings, talking about more different things at a single meeting, all of which are supposed to be relevant to the same things. This panel discussion is supposed to be oriented to future needs. One of the most important needs is to know what we are talking about. I suggest that none of us do, including myself. I think it is about time that we did.

We have to begin with the phenomenological because the purely theoretical, physical, up to now has left things thoroughly wanting. The kind of elegant theoretical thinking that Paul Vogelhut has done from physical and chemical data, at least gives us the kind of models that we can look for. We need at least straw men to set up and tackle. If we can get fundamental information, at this level, we can go to the cell, or to the animal. If we take some fascinating phenomena like Dr. Tanner's bird feathers; I don't know that this is a piezoelectric effect, it may be organic semi-conduction. Whatever it is these are the kinds of things that I think need stringent examination physically, and chemically as well as biologically. If there ever was an interdisciplinary problem the effect of r. f. on not just living tissue, but on matter, is an interdisciplinary one of the first order. I think we need groups of people representing not only different expertise in engineering, physics, chemistry, and biology, but they should be interdisciplinary enough so that they can cross communicate among themselves. A group of us is trying to set up an ad hoc committee representing many of these disciplines. We plan to meet in a group far smaller than this and sit down for three to four days to hammer out a program so that when an experiment is done in Alberta it can be replicated in Kankakee or anywhere else.

The problem of dosimetry is an absolute stinker. It is in my view a macro-Heisenbergian nightmare. It's going to have to be solved somehow. I suggest that it will be solved somehow.

I don't like the concept of hazard. Any physical change or stress can be considered a hazard. If I should suddenly get an acute swift kick in the aft end, this would be a stress. All kinds of things would happen to my adrenals and so on, but I am sure that this would be reversible and then I would survive without a problem. It should be borne in mind that any physical force which can induce any kind of a change may also be used as a useful change. It has already been found that insects can be killed without any damage to corn, grain, and other things of this nature. What we have to do is to examine effects from a broad spectrum from low frequencies up to the multigigahertz region. The fact that there seems to be frequency specificity must be verified. If there are frequencies to which the body, or mammalian tissue, or plant tissue, are transparent we have to know about them. We have to do this in a systematic way. There is no quick and dirty way. It is going to be costly. The hardware is going to be expensive. It is going to cost a lot of dollars which will have to come from somewhere. Until we have a coordinated effort, from the government, industry, and academia, and until there are funds to implement this sort of thing, we may have a meeting ten years from today (the way we had ten years back) and leave with essentially static and light noise.

My recommendation is that the future need to evaluate what happens in a biological system is going to depend upon understanding the physics and chemistry of large ranges of r. f. and being able to extrapolate this into not only cells but enzymes and molecules and then into organs and intact organisms. In this way and only in this way are we going to find out what the story really is. To get some phenomenological information there are physicians who have examined, in the aerospace industry, tens of thousands of patients who have been exposed to this. One of the things that we know how to do best is a routine epidemiological survey and I urgently recommend that the USPHS, if it can get the funds, undertake this forthwith because this can probably put more useful data into our hands on a phenomenological basis, in man, than any other single factor.

*Col. Burner:* Next I would like to call on Dr. Allan Frey, from Randomline, Inc.

*Dr. Frey:* I will make my comments very brief. First of all let us not worry about the Russian work, or replicating it. No one can replicate the Russian work because there is not enough information there in terms of methodology. No matter what you do in terms of experimentation to replicate you still cannot say that you have done exactly what any of the Russian investigators have done. You cannot draw a conclusion as to your "replication" of their work. On the other hand let's look at the Russian work and use it for purposes of hypothesis generation. It can serve a very useful purpose in this way. Second, let's do parametric studies; let us establish some of these factors like modulation, frequency, and such, as to what importance they have. Third, let us look at the Tri-Service material some of which is very good. Certain areas have been explored and researched quite well.

We should not research to death the details that we already have. Fourth, let us consider functional change, change in the function of the organism, and explore how r. f. energy can affect function. And last, no matter what you do experiments on, please give some data on methods, rather complete data, so someone else can replicate your work and evaluate and organize it and draw conclusions from the studies that are undertaken.

*Col. Burner:* I would now like to call on Dr. Russell L. Carpenter, of the Northeast Radiological Health Laboratory of the Public Health Service.

*Dr. Carpenter:* As I have been listening to the papers given in this Symposium I have also been thinking of what we should do next. I am going to make a couple of proposals. I think I would like to call for a moratorium, perhaps of two years duration, on any discussion as to whether effects are thermal or nonthermal. We need research which will produce information, well documented information, and out of that information there may hopefully come understanding. When the day arrives when we can understand what microwave radiation does to living tissue, then perhaps we can sit down and discuss the question of thermal versus nonthermal effects. I suspect that when that day arrives we will no longer be interested in the question.

I must confess to being to a slight degree responsible for this myself because at the Second Tri-Service Conference in Rome, New York, I reported some of our experiments and suggested that because the results bore no constant relation to the temperature conditions obtained, that perhaps some explanation was needed other than the effect of heat. I wonder, too, how much the desire to explain microwave effects on a thermal basis isn't a desire for security. If we can say, as I have seen it stated in one book on microwave cataracts, that of course, this is a thermal effect, then of course the whole thing was settled. If we can say it is a thermal effect and we know all about thermal effects so therefore we understand everything. On the other hand if we can't say that then we need to learn something. I think it might be a good idea to go ahead and learn and of course keep the data as to thermal conditions and in fact all of the data we can on experiments. But let us not try to aim for one or another interpretation. Instead I would suggest that we need to work at low power levels under conditions of repeated exposure. This is what is liable to happen, if we are going to talk about this as a hazard, to the housewife or someone in industry. Let us see what we can find out about low level exposures. In so doing I thing we can and should determine whether there are effects which we can call additive or effects that we can call cumulative. I suspect that if an individual suffers from either one that he may have no interest in the academic question of which it is. I think this is a field to which we should devote some time.

We should learn whether there are frequency dependent effects. It may well be that one tissue will respond differently to a certain frequency, or to a certain power level than does another organ. In the case where we are talking about hazard or health conditions then, of course, one has to set the standard at that level which will not affect the most susceptible tissue or organ. I think particularly we need to do experiments in which we can analyze the effects of the radiation on the cellular and metabolic level. I have been encouraged by the papers given by Dr. Vogelhut and Dr. Illinger which suggest very strongly that effects can be brought about at the molecular level with relatively small amounts of energy involved.

I would, finally, second Dr. Frey's plea for complete information when the experiments are reported. I would add the one that should be reported is whether the animal was under anesthesia or not and if so, what the anesthetic was and how much of it was used. Also, we should specify the instruments, including the model number, that were used to monitor and for dosimetry. Finally, I think a future need is that we get together once in a while, as we have at this most valuable and interesting meeting, where we can in a sense let our hair down and discuss, criticize, and argue in a friendly fashion.

*Col. Burner:* Next I would like to call on Dr. Norman C. Telles, Division of Biological Effects, Bureau of Radiological Health, United States Public Health Service, Rockville, Md.

*Dr. Telles:* When my colleagues and I at the Bureau of Radiological Health were first considering asking the Medical College of Virginia and Dr. Cleary and Dr. Ham to put on this Symposium for us, we were at a point where we had just been given the responsibility under the New Public Law 90–602 which, as you heard from Dr. Hanlon earlier this week, is an act for radiation safety and control of electronic devices. To be perfectly candid, while our Bureau and more specifically my colleagues and I in the Division of Biological Effects were quite familiar with the biological effects and therefore the health problems related to ionizing radiation, we really had only a "book" knowledge of the effects of microwaves and even that was really fairly limited.

We felt, therefore, that a meeting of this kind would be very useful for several reasons. First, we thought it would be of general interest to many scientists working in this area to have the opportunity, as Dr. Carpenter just suggested, to get together to discuss their work since there has been no such meeting of this kind since the early 1960's when the last Tri-Service conference was held. Secondly, we hoped that the meeting would bring out discussion which would indicate what the deficiencies and strengths of past research efforts were and where research relatable to the responsibilities of our Bureau might be developed. Thirdly, we hoped that the meeting would generate enough interest in these problems so that the apparent slow down in research in these problem areas would not continue.

At the same time we recognize that part of the reason for the slow down was due to a continually reduced availability of funds to support research in this area and I think again Dr. Susskind has alluded to that problem. Fourth, we thought a meeting might provide a forum whereby scientists could exchange facts, opinions, and theories, and where they could also engage in discussions on points of agreement and disagreement on these subjects of vital interest. I must say that we have not been disappointed in the least on this latter score. And fifth, we hoped this meeting might lead to the suggestion that another meeting of this sort takes place, as it was just suggested again by Dr. Carpenter, and you have already heard this morning from Mr. Villforth that the Bureau does hope to see another meeting of this type in about 2 years.

If any of us had any illusions that this Symposium would provide us with a clear cut basis on which to proceed to develop a new health program related to nonionizing radiation, I think that this meeting has certainly served to clear away these illusions. Very clearly, there is much that is unknown and remains to be done. Much is still unknown and it would appear as if we are really just beginning to attack an immensely complicated problem. This area of health is further complicated by a wide divergence of existing knowledge, and research and protection standards as exemplified by the U.S. and Western countries and Europe and the U.S.S.R. and Eastern European countries. I will defer to what the other panelists, who are truly experts in this area, have already said or will say and leave it to them in the following discussion to outline the need for future biological research. I do want to make one or two comments however, about some research needs as I see them. These remarks largely stem from the comments made previously by Dr. Susskind.

First and foremost, I see a need for economy of effort. I do not believe, for example, that we should necessarily embark on research programs which would repeat in their entirety the types of programs that were developed during the 40's and 50's for ionizing radiation. We simply do not have the financial support and resources which would be required to do this, nor do I think we are likely to get them. For this reason I think that we should be highly selective about what we want to do as well as what we support. I do not mean by this that we should stifle or fail to support new ideas or new approaches. I do think that we don't have to start out by doing for example, acute lethality studies on every last strain of rat, mouse, or what have you. I really don't think we would be buying ourselves enough that was new to make it worthwhile. I say this, however, within the limitations suggested by Dr. Michaelson earlier today as he discussed the need for doing research on various animal types.

Next, research needs are met only when one has enough well trained people in the various disciplines and people who will gravitate naturally to the problems existing in the field. We, therefore, need to support training programs which will provide an opportunity for interested young men to branch out into research on microwave effects, applications, and technology. I would hope, however, that such training would not be so narrow or constrained that the individuals in these programs would not be able to move from one field of interest to another. In other words, I think broad training, keeping in mind some of the limitations and precautions raised just last evening by our banquet speaker, Dr. Brandt, would be the most desirable type of training.

Finally I would like to make one more less specific recommendation which probably reflects my training as a physician and public health physician and which is really a reiteration of Dr. Heller's remarks made just a few moments ago. And this is the need in the U.S. as well as in other Western countries to do well designed and well controlled clinical and epidemiological surveys of microwave workers. I think that the Russians have been justifiably criticized by individuals at this meeting and at other times for making claims about clinical or biological effects for which they do not provide us with a complete basis for evaluation. On the other hand, many Western scientists have disclaimed any possible microwave effects on microwave personnel, pointing out that very little has been reported in the way of adverse biological effects. I would like to suggest that this may be true only because we have not looked hard enough. It is clear that if we do look hard enough on occasions, such as Dr. Zaret has done, we can often find things that we did not anticipate. Now apart from Dr. Zaret's work I know of only three published U.S. reports in which efforts were made to assess the possible effects of microwaves on radar workers. The combined total of people in these three studies were, I think, fewer than 400 individuals whose average exposure I think was something less than three years. I couldn't even begin to do a definitive study with these few people on something like, let's say the relationship between smoking and lung cancer or sodium intake and hypertension, with these few man years of experience to go on. Therefore, I think that these types of studies should represent some of the most urgently needed studies for the future and I wish you would be looking ahead for possible delayed or cumulative effects of microwave exposure.

*Col. Burner:* It is my pleasure at this time to introduce Dr. Edward Alpen, Batelle Northwest Laboratories, Richland, Washington.

*Dr. Alpen:* It is very hard to follow such a distinguished panel as anchor man because there is so very little left to say, but I think there are one or two things that remain and I have rarely been caught without words. I think one can distill out of a lot of what has just been said a requirement which I have seen from the very first opening minutes of the meeting and going on almost to the end. That is the necessity for the scientist to again become a scientist. The scientist when he acts in the role of an experimenter is not a standards maker or a standards setter. He may sometime in his career choose or opt to take the route where he sits on panels which make standards or he may provide his professional judgment. But repeatedly in this meeting we have heard individuals who have presented data then turn and say to us that this data either does or does not support an existing standard. It is really not any of their business when they are acting in the role of experimenter.

My principal plea here is the need for us to re-establish the requirements for good quality science. That is a distillation of what all the panelists have said before me. When we say we need thermal control, that is merely an extension of saying we need good control, we need a well designed experiment. We've been really in a morass of judgmental intellectualism which is unrelated to factual data. We don't have the factual data yet to make a lot of decisions. Many of us in the audience who have ionizing radiation backgrounds are sure we are looking at the same cross-eyed horse we looked at some twenty years ago. We're looking at the same problems of a multi-disciplinary approach. I might even say that we are looking at the same problem of what the significance is of the Russian literature we're having to deal with. I would like to report to all of you, who have not been in the ionizing radiation field, that the Russian literature that we all laughed at in the 1940's and 50's is a standard of performance today. We have yet to find them in error in their low level radiation work. I certainly remember back in the 50's laughing when a Russian reported a crossed extensor reflex which as adduced by something like 1 R to the other leg, and when milliroentgens were reported to produce responses. These were in fact valid findings. I would like you to accept your Russian colleagues as co-equal scientists of integrity equal to your own. They may have used different methods and they may have been reported or misquoted in ways which, let us say, are unusual to us. I think that we have to start off, as some of the other panelists have said, by doing good science; using what they have shown as a lead to go on in the behavioral area as we are starting to do now and to continue the research.

I don't agree with some of the panelists on the scope or breadth of the program which they are suggesting. I agree more with Dr. Telles in that we need a well ordered set of scientific priorities. We have to do it carefully and well and I don't think it is a cataclysmic event at the moment which is facing us. We need to set our requirements and our time table and then in orderly and quiet fashion approach this end. I think that there are some steps that could be taken in approaching the problem right now. One of these is to spend a bit more time and money in developing and using exposure facilities which avoid many of the dosimetric mousetraps that one gets into with the use of the varied exposure systems one has today. Admittedly to go into anechoic r. f. chamber and suitable exposure set-ups represents many thousands of dollars in investment, but at least they are model systems which are understandable and can be used.

If I were to set for myself a set of personal priorities of what needs to be done in the laboratory I would follow the following list or set of guidelines and I don't mean to impose these on anyone else. I would feel that the principal objective at the moment is for good science. To go into the laboratory to design and conduct behavioral experiments using behavioral and physiological performance end points which will explore this area. We have seen enough to titillate the imagination at this particular meeting to tell us there is something there worth looking at. Let's do it with as little bias as possible, although if we have no bias we probably wouldn't be scientists in the first place. But we have among us good behavioralists and good physiologists. There are a number of adequate end points which are available to us. The physiological function methodology has been used very little in microwave phenomena to date. Such things as work performance, swimming tests, work to exhaustion, treadmill tests; these sorts of thing have not yet been fully exhausted, and they are inexpensive and reasonably easily controlled experiments. I would put high on my list of personal priorities the exploration of the question of genetic effects of microwaves. When one makes a personal decision then one is faced with the dollar problem. How do you do it? I really don't know. If you are doing it with some of our classic systems such as with the *Drosophila* or related small insects it can be done for a moderate price. But there comes a day, as it did in the radiation business, when this has to be tested in a mammallian system and then we are looking at the Russell mega-mouse, mega-buck experiment all over again. I hope that day never comes and that we can demonstrate in *Drosophila* that it is not important. But we should keep an open mind and look at it carefully and admit when we do so that we are facing a monumental problem of experimental work.

Other important fields that I feel need to be worked on are the mechanisms of cataractogenesis; more work on the threshold levels; more work on the nature of the lesion. I think we all have to be more careful, as all the other individuals on the panel have said, to very specifically explore all the parameters which need to be examined such as frequency, pulse width, repetition rate, wave form, and all the other considerations that we have just barely touched upon.

I would like to take very strong objection to the suggestion that Dr. Heller made of an ad hoc committee to formulate the progress and direction of microwave research. I think myself, as a personal judgment, this is 180 degrees out of phase with what we should do. We should do everything we can to develop the independence of thought which is required to produce new leads and new bias in this field; new ideas without putting ourselves in a straight-jacket of preformed judgments of an ad hoc committee who have been in the field and who have their own opinions.

*Col Burner:* I think it is only appropriate to ask Dr. Heller if he wants to rebut Dr. Alpen's speech.

*Dr. Heller:* Yes, I think the virtues of the ad hoc committee are the following: first, it appears as though there is going to be a very limited amount of money. I think one should try to use this as judiciously as possible. Secondly, we do not yet have a method of intercommunication among all the people that are interested. They publish in all kinds of journals all over the world. It is terribly difficult to stay on top of the literature. One of the functions of an ad hoc committee is communication among all of us and others who may be interested. Finally, I think it would be a very useful idea when there are various ways of approaching such problems as dosimetry systems and methods, particularly since we are going across many disciplines; that these things can be made available in a broad way. And in the same regard since there are a variety of vested interests such as in the military, and in industry, and so forth, where there may be certain monies for certain areas, that we do not replicate these things with the limited amount of funds that we have but that we try to do as intelligent a job as we can. In so doing, I don't think that such an ad hoc committee will be terribly different from the policy decisions the National Academy, or other comparable groups who make recommendations of areas that ought to be looked at.

*Col. Burner:* Thank you, Dr. Heller.

*George Wilkening, Bell Telephone Laboratories:* There seems to be unanimous or almost unanimous agreement that one of the things that should be done is to perform repeat insult type of experiments at low levels and I think there has been near unanimous agreement for some time that this low level type of study should be done. I am particularly interested in the remarks of Dr. Carpenter who I think reiterated the need for these low level studies and in that connection, since Dr. Carpenter is a consultant to the Public Health Service on these matters, I would like to ask the very practical question as to whether or not any of the panel members believes that with present knowledge of bioeffects, limitations and instrumentation, etc., it is premature to set standards at the relatively low levels. Of course, I have some specific interest in reference to the case of the microwave oven and setting of standards for that type of device. I would like to hear some opinion about whether or not you are in fact saying it is premature to consider the proposal of such standards.

*Dr. Carpenter:* I don't know as I said I think it is premature, but I do think so. I don't think we know enough right now to warrant taking another stab in the dark. We have lived pretty comfortably with the first stab. I don't think it has proved to be a very great handicap to developments. So far we have been very comfortable with it. My own feeling is let's stay with the ten milliwatts per square centimeter level and meanwhile do experimentation to find out whether this is good or do we have to lower it or should we raise it.

*Dr. Heller:* I think it is premature.

*Dr. Michaelson:* Since I'm the culprit who wrote the "definitive" Air Force report in which we supported the 10 mW/cm$^2$ level, I was hoping in some way we might come out of this Symposium with some new ideas and perhaps, if necessary, change my opinion. I said before there's no indication at this point that would ask us to lower this standard. I have reviewed the literature very carefully, reviewed our own work, and looked very critically at other people's work and I can't see any basis now for not living with this 10 mW/cm$^2$ level. I would like to take 30 seconds, since the late Col. Knauf has been mentioned several times and I support those people who have expressed a certain admiration for this gentleman and as I said before, we really don't know any more now than we did in 1960 and 1961 and I would like to read the conclusion that Col. Knauf made at the end of the Tri-Service era:

1. "No serious injury or death can be attributed to exposure to the beam of any radar set.
2. In no instances were cataracts produced by exposure to power levels below 120 mW/cm$^2$ no matter how extended the duration of the exposure.
3. Although there is some suggestion of a cumulative effect as far as cataracts themselves are concerned it is essential that each exposure in a series be conducted at power levels near 100 mW/cm$^2$.
4. No data were obtained to invalidate the safety level of 10 mW/cm$^2$.
5. At this level equipment operators can function effectively.
6. There was virtually no disagreement in the United States that this level insures a safe environment.
7. SHAPE and NATO which represent some important European countries after due consideration and discussion have adopted and published the standard of 10 mW/cm$^2$."

*Col. Burner:* I join your sentiments and admiration for Dr. Knauf.

*Dr. Alpen:* I'd like to say that I do not believe that it is premature to set a standard. You must always set a standard based on the presently available information but this is not something which stays fixed and engraved in granite for all future times. It is subject to readjustment as your knowledge tells you to move it up or down. Remembering also that in any environmental control standard, the standard is not something that you live at but is something that you managerially live below because when you are approaching the standard you have managerial problems. There is thus some built-in safety in the existence of a standard. You set it with the best information you have at any time even though you don't have one experiment.

*Dr. Frey:* With regard to Dr. Michaelson's comments, indicating that Dr. Knauf's conclusions still hold and that there has been no reason to change, we should also keep in mind that one of the reasons that there is no reason to believe that there should be a change is that there has been no data collected since that time either.

*Dr. Zaret:* One of the things I like to add to Dr. Frey's criteria for reporting is that all negative results be reported also. So many times if you don't have positive results the work is not mentioned anywhere, even at meetings like this. As I see it it will be years before, at the molecular level, we are ready to move on up into the cellular levels, tissue levels, whole body levels. Perhaps this is the way it should be for basic research. I think it is very important to the users of microwave radiation not to wait for this kind of information. To those listed already this morning, NASA and the FAA, I think, should also be invited to participate in discussions at a meeting such as this and be apprised of what the conclusions are. The question was raised that we should somehow take the medical application of microwaves and exempt them from consideration. As a physician, it is very hard for me to accept this. The usual use of microwaves in medicine is to relieve soreness in muscle tissue and we can do this with mustard plasters, hot packs, aspirins, steroids, and a lot of other things. I think that if physicians were alerted to the potential hazards of microwave radiation many of them would be quite reluctant to use microwave therapy for self-limiting conditions which is perhaps the major use of microwave radiation in medicine. I see no reason to exclude medical devices.

*Col. Burner:* I would like to add a comment of my own in that regard, which is that in 1956 to 1959 I was commander of a dispensary in France and during that period of time the Air Force came out with an edict saying that only qualified and trained physiotherapists would use microwave producing devices. This was at a time when every small dispensary had its own microwave device and everybody and his brother was using it. So perhaps the Air Force isn't at all that backward.

*Dr. Heller:* In reply to Dr. Michaelson, if I have understood him correctly that there has been essentially no known data since those standards came out, if this is correct, I wonder what we are all doing here. I don't believe the mutagenic effect was elaborated then or was Dr. Vogelhut's indication that 75 $\mu$W could make considerable changes in colloids which are physical systems. Such effects were not, and still are not understood, except for our hypothesis concerning the interaction of microwave and one micron spheres. Dr. Vogelhut and Dr. Illinger pointed out that small amounts of energy may indeed affect membranes and this may be important and it is certainly one effect induced at less than the 10 mW/cm$^2$.

*Dr. Telles:* I would like to add one additional comment to the point raised by Mr. Wilkening. I would agree with Dr. Alpen that it is not too premature to consider the setting of standards. I would add, however, that from my point of view I can't afford to sell public health short. I think we have to look at this standards setting matter always keeping in mind that we are considering the public at large. You have to keep in mind the setting of the lowest possible practical standards. If this can be achieved I think we should shoot for it.

*Dr. Susskind:* Just to reassure Dr. Zaret, I believe there are representatives of NASA and FAA at this meeting, I see several from scanning the list of attendees. I believe also that they are represented on the ERMAC council.

. *Dr. Michaelson:* In reference to Dr. Heller's comment, on this mutagenic effect, if I remember correctly, Dr. Heller first reported this mutagenic effect in 1959; so there is nothing new since 1961. Also it is very hard for me as a mammalian physiologist to extrapolate from some physical phenomena in macromolecules to a human being as much as it is fairly hard to extrapolate from mega-mouse experiment that costs millions of dollars in an isogenic strain to a heterogenic animal like man.

*Col. Burner:* I would like to make one comment in connection with Dr. Knauf's statement. I think that Dr. Knauf would be the first one to want to see the records corrected on that matter and I think that Dr. Zaret's work with cataractogenesis from microwave generators, at Cape Canaveral, is a monumental work in that direction.

*Dr. Heller:* Chromosomal aberrations were reported by us in 1959. Mutations not until just a few years ago. Going to the problem of ionizing radiation, I remember well, considerable years after the war, when the radiologists got together and said we as physicians know everything there is to know about radiation and we are not misusing it and you biophysicists and physicists don't know what you are talking about when you talk about atomic and molecular levels. The next speaker got up and pointed out that radiologists have 1000 percent higher incidence of leukemia than all the other physicians combined.

*Col. Burner:* A very well stated point.

*Dr. Illinger:* I should like to make a brief comment on something that has been touched upon several times in the experimental aspect of this field and that is the necessity, in order to put reasonable interpretation on the experiments, for having a definitive statement of the power profile of the microwaves that are interacting with the organisms. This is to say the power as a function of time. One of the certainly undisputed mechanisms of coupling between a biological system and microwaves is the dielectric relaxation of water. We may dispute more specific molecular effects but surely this one is without doubt. Now as a function of power and whether the power is pulsed or continuous or what have you, a number of different effects emerge and as was pointed out earlier this morning, at low power levels one can assume of course that there is thermal equilibrium, one deals with the kind of Boltzmann distribution that leads to the dielectric relaxation of water that is well understood. Nevertheless, as power levels increase in a pulsed system and indeed the powers that have been reported here in some instances are very high; the collisional effects in the system, purely in a molecule system, are not going to be able to follow the power change and in fact it is a temperature jump. As a matter of fact in a quite different area, the area of chemical kinetics, people use r. f. discharges and microwave discharges to put a pulse of temperature change which they then look at in the decay time and look at the kinetics of the system. This is an entirely different thing from the thermal equilibrium problem. Finally, at very high powers there may also be dielectric breakdown. There may in fact be electronic changes in the molecules and then the system becomes quite similar to ionizing radiation, that is to say x rays stripping off electrons from molecules. In any case, in order to look at the more subtle biological effects which, from the physical-chemical standpoint can only be projected, one can only ask how the electromagnetic radiation couples with the system. What happens biologically is much more complicated and much more subtle. With regard to the physical-chemical problem, it is clear that entirely different effects may occur at different power levels.

*Dr. Kamet:* The participation of Soviet scientists at meetings such as this would have been desirable, and I would very much appreciate it if the panelists would express their opinions about inviting the leading Soviet scientists to meetings such as this in the future.

*Dr. Frey:* I can tell you a little about this matter of inviting Soviet scientists to this meeting. I was handling this and there have been a few problems with regard to inviting them. I know that there was interest. They had expressed interest and they were invited. However, we had an interesting situation. There was no answer to the formal invitation. We followed it up, sending them programs and such with again no answer. I do not know why.

*Dr. Susskind:* We have of course had contact with Soviet scientists before, both by trips behind the Iron Curtain and by their coming to international meetings such as the one on bioengineering in London some years ago. Dr. Gordon, who is one of the chief workers in the Soviet Union and certainly one of the most influential, was at that meeting. We had some questions put to her which had to do with a particular detail of one of her papers. However, we got nothing out of her or her colleagues beyond what was in the paper. I understand that other colleagues have had this same experience that where you probe a little bit deeper for additional data you find that you are told what is published and that is all that we are going to say about it. There seems to be genuine difficulty on their part of getting more into print than they are able to get.

*Col. Burner:* I think you are probably very fortunate, Dr. Susskind, because in the meetings that I have gone to they have sent someone else to read the original author's paper and he says he has no knowledge of other information.

*Dr. Carpenter:* At that meeting in London, there were several of us who wanted to talk to Dr. Gordon and I think she wanted to talk to us but she was accompanied by a nonscientist who explained to us that she was very tired and needed a rest and if we would write our questions out and leave them, she would be happy to send answers. Well, we didn't want that, we wanted a discussion. We couldn't have it, as Dr. Susskind said.

*Dr. Zaret:* I had the good fortune to meet the Soviet scientists at the International Aerospace Medical Association Meeting where our entire conversation was carried on through an interpreter. One year later this same individual appeared in the United States at a meeting being the interpreter for someone else.

*Dr. Frey:* This experience with not being able to have direct discussions and this mention about it being suggested that you write your questions out and submit them. . . . I suggest that if you write your questions out and submit them you should not wait around for an answer. You may wait for a very long time.

*Dr. Akery:* One subject that hasn't been covered in these last three days is the problem of induced currents in implants in the human body. There have been one or two medical papers in England on this subject including one where a patient receiving therapeutic diathermy went into ventricular fibrillation. I don't have any details on this but no doubt you have had similar cases reported in your literature over here. Does the panel feel that this aspect is covered or should be covered by this Symposium? Certainly from the point of view of the individual who has this implant, ventricular fibrillation is far more important than anaphase bridges in somatic cells.

*Dr. Frey:* I have done a good bit of experimentation exploring the matter of electrodes implanted into the body, the effects of r. f. energy on them. This I did from the standpoint of developing recording electrodes rather than for clinical work. There are wild effects you can get with conventional electrode system and it is a very difficult problem. We had quite a development program to work out electrodes which do not have induced currents that cause all kinds of interesting effects. I believe that in a clinical situation that one has to use considerable care with electrodes if a person is going to be in an r. f. field of certain frequencies. There can be a very real danger to them.

*Dr. Susskind:* In the paper by Schwan and Lie going back to the early 1950's, there are several cases in which the authors warn about the application of microwave therapy. One of them, if I recall correctly, has to do with pins that might be present in a person's body or in a surgical intervention such as in the correction of borken bones, and another one is pregnant women, because of the large amount of water that is involved. We were interested to hear yesterday that Dr. Marha told us that in Czechoslovakia there is a prohibition also against pregnant women working at even subhazardous levels because of the increased difficulties. I think this sort of thing is in the literature as a warning at least and perhaps ought to be revived in formal warnings.

*Col. Burner:* As opposed to induced electrical currents from marrow pins, I believe the major problem is local tissue heating because of the intense heating of the metal object.

*Dr. Heller:* Dr. Jose Delgardo at Yale, who is very well known for the electrodes which he puts into the brains of various animals to get behavioral changes, energizes them with r. f. at a distance.

*Dr. Griffins:* We are doing dielectric research from the standpoint of using the heat that is generated and I have noticed that there is a problem sometimes with r. f. burns when you are in a strong field with ungrounded metallic objects. Is this reported in the literature and is it something that is well known?

*Col. Burner:* Dr. Suskind called my attention to this problem when I was out in San Francisco several years ago in connection with some EEG or EKG work. Dr. Susskind, would you care to comment?

*Dr. Susskind:* We had a case of a baby being burned in a military hospital. It was a dependent of a military person and the military doctor brought it to us asking, since it was in the vicinity of radar equipment, could there have been enough induced currents to cause this sort of thing during EEG when the front electrodes of the eight electrodes produced burns on the baby's head. The conclusion at that time was that they were probably chemical burns but we could not entirely exclude the possibility of a freak accident in which the loop of the EEG created enough resonance intercept from an aircraft overhead, or something like that, enough energy to produce such a burn.

*Col. Burner:* That goes along with the opinion that I got from a dermatologist in the Bay area with whom I discussed this problem also.

*Dr. Frey:* I have seen in some high power r. f. fields nails in wood which had sparks jumping between them. You can get fair amounts of damage from situations of this type.

*Col. Burner:* We recently tested an r. f. protection garment with the help of the Bureau of Standards and while we didn't expect to get it in fields this high although we might have, it was very interesting to note that one of the real hazards from this suit was the arcing that would occur between the folds of the cloth when you got it up to levels of 200 and 250 mW/cm$^2$. As one of my predecessors used to say about the super-sonic low altitude missile, when it comes near Mach 2½ at 500 ft. it tends to make the natives restless. Are there any other comments from the floor?

*Dr. Glaser:* Your just mentioning the r. f. protector garment leads me to ask if there is any hope for eye protection from r. f.

*Dr. Carpenter:* There have been suggestions to wear a metal screen over the eye which you can see through. This has been tried to some extent, but I don't know if it has ever been fully evaluated. It would give some protection.

*Dr. Michaleson:* Some of you may know that in the Soviet standards there is a qualification that protective goggles be worn at some of the higher permissible levels for certain periods of time.

*Dr. Rosenthal:* There actually are goggles that have been developed. In fact, they do exist and they do provide quite a bit of protection.

*Dr. Telles:* I want to add the comment that if you do use protective elements such as screens they would in all probability go completely around the head. One of the people down at our Southeastern laboratories had in fact developed such a protective eye screen. They found that unless they were facing towards the source at all times the amount of radiation at the point where the eyes would be could actually increase due to reflections.

*Dr. Frey:* These goggles make me unhappy. I can see one being in a worse situation with them on than with them off.

*Dr. Deichmann:* It was not my intention to make a comment because my friends here on the panel and I have worked together on the program which Col. Knauf initiated to get things well in hand. I would like to join those who made the comment that we should not modify the 10 mW/cm$^2$. I very much feel that it is premature to make any changes because the effects of the field do not depend solely on milliwatts per square centimeter, they depend on the whole battery of other factors. I don't want to belabor the point but just let me mention a few: namely, the wavelength, the air flow, the air current, the temperature of the flow, which is very important for the individual who is in the field, the covering of the body and I am not only thinking of the type of covering but whether it is reflecting, refracting, or absorbing. When I think of all the studies we conducted years ago there's all the difference in the world between rat hair and rabbit hair and we learned a little bit more yesterday about the feathers. There are other factors: the size of the body is terribly important, considering two bodies of the same unit weight makes all the difference in the world whether the body is tall and skinny or whether the individual is short and fat. Again I don't want to go into the details but the composition of the body, the part that water and fat play, is of tremendous importance when it comes to effects in the field. The position in the field is terribly important. Whether the person is sitting, lying, or standing, whether he's got his arms and legs and fingers extended or not are all factors that play a role. I could also add the factors that we used to refer to as the irradiation cycle rate. Namely, the relationship of periods of exposure to periods of nonexposure. It's terribly important, for instance, if an individual or an animal is exposed for 30 seconds in one minute, this is one thing if this is repeated. For instance, by this type of exposure to a certain power density it is very easy to kill animals in a very few minutes. On the other hand, if the exposure is a second on, a second off, again the total exposure per minute is 30 seconds but you can carry this on indefinitely without any harmful effects. The part of the body which is exposed is terribly important; whether it is the head, or belly, or the abdominal region, not to speak of those parts of the body which are especially susceptible such as the eyeball, or the testes. I would like to briefly refer to one effect that I have not heard about at this time even though I'm sorry to say that I missed the first day of the meeting. When I talked about microwave radiation, some ten years ago, there was one doctor who said that what you are talking about is very interesting and I want to tell you about a patient I had, a lady who suffered from hallucinations. There was nothing that kept her under control, except heavy sedation. Finally, he said, one day the sedation wore off and she came to me and said that it wasn't the music so much that was bothering her, it was the commercials. Now the reason why I'm bringing this up is because I repeated this at a meeting we had in Berkeley and at that time there were several engineers that told us that this was nothing new to them, so perhaps there are others who have had similar experiences.

*Col. Burner:* I can remember as a child reading about a report coming out of Schenectady as to the same effect. Time is growing very rapidly short. Do we have any other final comments from the members of the audience? If not, let me thank the audience for their enthusiastic and intelligent and well oriented comments and discussions and the panel members for their excellent participation.

*Dr. Cleary:* I'd like to thank the program committee for helping to put the program together. I think they did a very good job. I would also like to thank the foreign visitors who have come to this Symposim and who have contributed so much to it. I think it would be presumptuous of me to try to reiterate the things that have been said here this afternoon or during the past two days. I think that enough has been said. We are in a position of needing more information; particularly I think, on the level of basic effects. I might say that I think the problem is extremely difficult and I don't think it is likely that all of the basic mechanisms will be worked out in the very near future. I think that work carried out in the next few years will certainly be a big help in elucidating the mechnisms which will eventually enable us to establish with finality, realistic permissible levels of microwave exposure.

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