Biological Effects of Electromagnetic Radiation

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A CENTURY OF ELECTRICAL PROGRESS

Foreword

This reprint volume first gleamed in the eye of Mark Grove, founding Chairman of the IEEE's Committee on Man and Radiation, in 1972. The aim of publishing a compendium of benchmark papers on the biological response to electromagnetic radiation at shortwave and microwave frequencies was approached with two objectives in mind: to provide the reader easy access to works that form the roots of Hertzian radiobiology, and to pay homage thereby to the engineers, physical scientists, and biologists whose creative works have shaped the investigative enterprise. The decade that elapsed between inspiration and fruition of the book were occasioned by several disappointments and delays. Reprints of some early works were difficult to obtain. The initial log of papers nominated for reprinting was large enough to fill several compendia. Also, with the passage of time, additional nominations were made. The need to reduce the page count to an acceptable number forced exclusion of many excellent papers, which posed a dilemma of choice often resolved by selection of the shorter of two works of equal merit.

The dilemma was resolved in 1979 by the strategem of appointing chapter editors and charging them with writing concise reviews in their areas of expertness in which benchmark papers could be cited, whether reprinted or not. Although this strategem gives less than their due to many deserving authors, it does provide them recognition and it does provide the reader indirect address and access to their works.

Some papers of high merit doubtless have not been included or cited in this collection; the later the year of the original paper's publication, the more likely its absence, which reflects the intent to illuminate the roots of the subject matter. I hope in years to come that the Committee on Man and Radiation will address, in subsequent reprint volumes, the trunk and foliage of this fascinating tree of technical and scientific knowledge. At such time as one of these books may appear, it should contain English translations of the original works of Western and Eastern European scientists, many of whom, like D'Arsonval of France, Schwan of Germany, and Presman of the Soviet Union, actually sowed the seeds of Hertzian radiobilogy. Their neglect in the present volume is a sorrowful testament to the semipermeable barrier of language: Most of those who superintended and most of those who will read this volume are not facile in French, German, and Russian. My European colleagues who read the material that follows—and *they* are facile readers of English—must accept an apology born of Yankee illiteracy, not Yankee hubris, for the absence of many important papers.

Many individuals have contributed to this volume. I thank the authors of chapters for their hard labors unrecompensed save for love of the subject matter. Peter Barber, Joan Breslin, Reed Crone, Allen Ecker, Richard Emberson, Om Gandhi, Edward Hunt, Richard Phillips, and Leo Young helped much in divers ways, as did past and present members of the Committee on Man and Radiation, from whose ranks chapter authors were recruited. I give especial thanks to John Osepchuk, the Editor, whose patience over the years was matched only by his dogged insistence on progress as he skillfully moved Mark Grove's brainchild from conception to completion.

Don. R. Justesen
Chairman, 1979, 1980
The Committee on Man and Radiation
Kansas City, MO
February 21, 1982

Preface

This book is the culmination of efforts begun in 1973 by the Committee on Man and Radiation (COMAR) to generate a collection of reprints useful to a broad audience interested in the scientific and technical literature on biological effects of non-ionizing radiation, or more popularly "microwave" and/or RF radiation (or electromagnetic radiation (EMR)). The idea was to present key reprints which would help the reader understand the bottom-line results and also some of the reports which have greatly influenced this field of research and its practical relevance. A collection of reprints cannot give the reader a coherent integrated history and overview of the field. What it can do is permit the reader to review for himself original literature and thereby permit more conviction in his own assessment of what the field is all about. The editors of the various chapters have tried to select *"key"* reprints to help the reader achieve the stated objective. Sometimes papers are chosen for their historical importance and not necessarily for scientific accuracy or validity as presently viewed. Some of the papers are chosen as representative of different schools of thinking, for example, the Eastern European bloc. Other papers are chosen because of their efficient summation of blocs of research.

This is a complicated and in some ways "murky" field with considerable controversy and growing relevance to practical political and regulatory questions. The chapter editors have found it nigh impossible to fulfill all the above objectives in one volume. The collective judgment of the irreducible minimum of *key* reprints amounted to 1,200 pages. After being forced to reduce this by more than a factor of two, the editors and I finally had to make some arbitrary choices and exclusions. These will not satisfy the expected critics. In our defense, we maintain that the final selection represents only *one* and not *the* collection of key reprints that will be useful. Furthermore, we point out that not only reprints are included but also quite extensive and updated lists of key references. Finally, the updated chapter introductions by the various editors help explain the bases and nature of the key reprint selections.

The reprints are presented in seven separate parts with associated references and editorial commentary. The apportionment of space to the various subjects is debatable, but the use of separate parts is of importance to the reader. The name of the game in this field has evolved into this three-task structure:

1) For a given biological body immersed in a given electromagnetic environment, determine the internal field distribution and resultant energy absorption and their most useful measures like "specific absorption rate" (SAR).
2) For a given internal field distribution or average indicators (average SAR) in animals or humans, determine the biological or medical effects.
3) Given the information from (2), evolve safety standards on exposure of people, susceptibility standards for electronic devices to be implanted into people and beneficial medical applications of EMR.

The first part, ably presented by an engineering pioneer of the field, Professor A. W. Guy, reflects the centrality of task (1) which falls within the professional scope of the IEEE—namely developing models for biological bodies, calculating internal distributions, absorption and scattering, and confirming or extending its knowledge by experiment. We have the privilege of including in Part 1 an original paper by E. L. Hunt *et al.* on the key technique of calorimetry which permits "wet-bench" scientists to determine averaged SAR values in experimental animals.

Parts 3 and 4, edited by D. R. Justesen and S. M. Michaelson, respectively, represent a necessarily abbreviated overview of the main bulk of the literature on "microwave bioeffects"—namely the interdisciplinary research on effects in animals and clinical or epidemiologic studies with man. We have devoted a separate part to effects on the central nervous system, as there is the general perception, especially in Eastern Europe, that these are the most sensitive and practically pertinent effects, whether this is right or wrong. Thus, these two parts represent task (2) in our above trilogy for the field.

Parts 5, 6, and 7, edited by O. P. Gandhi, J. C. Mitchell, and myself, respectively, reflect task (3), that is, practical applications to safety standards, whether on exposure, emission, or susceptibility, and medicine in diathermy, hyperthermia, and diagnostic techniques. This task is only now developing so that viewpoints are not necessarily definitive, particularly for medical applications.

Part 2 was left out of the review relative to tasks (1-3). Whereas the latter represent the areas of engineering, phenomenological or applied sciences, and practical arts, Part 2 represents the basic science efforts in this field. In sum, the most common working hypothesis on "mechanisms" of biological effects involves the role of localized energy absorption (that is, heat) in inducing biophysical or biochemical events triggering the chain of complicated events in the living creature. Even here, the true scientific model of biophysical interactions is not complete. The review by J. W. Frazer is an attempt to present some of the leading past and current views on mechanisms of interaction at the molecular and cellular level. This is a very controversial area with some excitment. It remains to be seen whether more accurate scientific models of interaction merely confirm the commonly accepted pattern of bioeffect data or suggest new effects, whether hazardous or beneficial.

Knowledge is never static and it is the privilege of COMAR to contribute to the professional and technical accomplishments of the IEEE by presenting the most up-to-date knowledge in this field in a form useful to not only scientific workers, but also others for whom this subject has practical relevance. As editors, we have tried to be scholarly and fair to the many contributors in this field. No doubt we have offended some, but we rest on our statement of noble intentions.

The reader may well question why a project like this begun in 1973 comes to fruition eight years later. I am afraid that we, COMAR, must confess the weakness of our operation (we are only a part-time voluntary committee). The task apparently is either too time consuming or too awesome. In any case, over the years various chapter editors suffered prodding or replacement; all the while, material needed updating. Personally, I am gratified at the completion of this project and, despite my hints of editorial agony, I am proud of the contributors to this volume and the resultant product.

I would like to express gratitude to Leo Young, Past-President of IEEE, who helped found COMAR and first suggested this project. We must acknowledge the important efforts of past COMAR chairman, Mark Grove; and Allen Ecker, Peter Polson, and E. L. Hunt; as well as the important roles of the present and immediate-past chairmen, Professor Gandhi and Dr. Justesen. Lastly, I must acknowledge the patience of W. R. Crone of the IEEE Press who persevered over the years in gently prodding us to completion.

John M. Osepchuk
Waltham, MA
June 4, 1981

Contents

Part I
Quantitation of Electromagnetic Fields in Biological Systems

The classical problem in studies concerning the biological effects of microwave radiation is the establishment of the relationship between physical characteristics of the fields and the magnitude of the effect. The first step in solving this problem is the quantitation of the relationship between the properties of the exposure fields and the absorbed energy (rate of energy absorption) or fields in the exposed tissues.

The need to solve this problem was not recognized until approximately a half century after d'Arsonval established the use of electromagnetics in medicine in 1890 [1]. As electromagnetics became popular in physical medicine in the form of short wave diathermy, the use of poorly conceived dosimetric techniques led to many improper assumptions and conclusions concerning field effects on tissues. The dose or dose rate available from various generators operating at different frequencies and power outputs during treatment of patients was quantified only in terms of output current to the electrode or coil applicators. It was implied in advertisements that the heating of deeper tissues would be enhanced with greater machine output. Since the tissue heating seemed to vary considerably with frequency, even with the same apparent output of various machines, many researchers jumped to the conclusion that there were selective and specific properties of the various wavelengths investigated. Finally, in 1941, an interdisciplinary research team of engineers and physicians, E. Mittleman, S. L. Osborne, and J. S. Coulter [2], conceived and developed the first true RF dosimetry by quantifying the temperature rise in exposed tissues in terms of the volume-normalized rate of absorbed energy expressed in units of watts per 1000 cc, surprisingly close to the now-accepted mass-normalized specific absorption rate (SAR) expressed in units of watts per kilogram.

These investigators clearly demonstrated that the degree of tissue heating and therapeutic reaction was dependent solely on the rate of energy absorption and not on wavelength. However, subsequent research on clinical use of shortwave diathermy made little use of the techniques advanced by Mittleman *et al.*, and the microwave therapy and bio-effect research in the following two decades also lacked the application of volume or mass-normalized dosimetric concepts. Virtually all of the reported biological effects were related to incident power density so that it was difficult, if not impossible, to correlate data from different animal or human experiments so necessary for establishing human safe-exposure guides, or diathermy treatment doses.

Schwan [3-7] and Cook [8, 9] began to set the foundation in the early 1950's for later analytical work by characterizing the dielectric properties of biological tissues. This allowed microwave fields and their associated patterns of heating in exposed tissues to be analyzed later by Schwan through the use of simple models which consisted of plain layers of simulated muscle, fat, and skin [7, 10-13]. The existence of standing-waves within the tissues due to reflection at transitions of markedly different water content such as the fat-muscle or bone-muscle interface were predicted. The predictions were confirmed in the early 1960's by Lehmann *et al.* [14, 15]. It was also theoretically demonstrated by Saito and Schwan in the early 1960's that field-force effects can be elicited [16, 17]. These effects are the so-called *pearl chain* formations in which small particles of biological material, when suspended in a liquid of differing dielectric constant, are polarized by an electric field, which results in mutual attraction among the particles. Analysis indicated, however, that the field strengths required to produce pearl-chain formations are far in excess of those which would normally denature protein and thereby destroy tissue by excessive elevation of temperature.

During the period of the tri-services supported research in the late 1950's and 1960, preliminary work on experimental approaches to microwave dosimetry was done. Schwan and his colleagues described methods which could be used to fabricate tissue-equivalent phantom models of biological bodies and portions of the human anatomy [18] and to experimentally measure the energy absorption during exposure to microwave radiation [19]. In 1960, Mermagen reported his use of tissue equivalent phantoms to study energy absorption characteristics as a function of animal position in a near field [20]. He recognized the need for better microwave dosimetry and stated,

> "Since our group is interested in the absorption of microwave power rather than the incident flux, it should be more realistic to employ a unit of measurement commensurate with such power absorption. Therefore, if we measure W/cc in an absorber whose dielectric constant is similar to that of tissue and whose volume would represent a finite attenuation of microwave beams again similar to that of tissue, then a comparison might be achieved between experimental results from different investigators' laboratories."

In the early 1960's, the first analyses on biological models that revealed frequency dependencies in the coupling of electromagnetic fields to an intact electrically small body were performed by V. A. Franke in the Soviet Union [21] and discussed by Presman [22]. The models used in the theoretical analyses varied from circular cylinders to prolate spheroids of homogeneous dielectric with the same properties as muscle. Volume-normalized energy absorption rate and heat produced in prolate spheroid models of man was determined at lower

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RF frequencies in these studies through the use of quasi-static mathematical solutions. In other theoretical studies, spherical models were used by Schwan's group to determine relative absorptive cross sections as a function of frequency of the incident RF field [23]. It was found that the absorptive cross section—the surface area of the model's electrical "silhouette"—varies widely with frequency, reaching maximal values at the model's resonant frequency. From the mid through late 1960's, more realistic tissue-simulating models were developed and used for experimental measurements of field coupling by Guy and his colleagues [24, 25].

Finally, in the late 1960's, a true mass-normalized RF dosimetry using phantom models was introduced to actual practice in laboratory bio-effects research by Justesen [26]. This allowed the use of multi-mode cavities for exposing freely moving animals so that feeding, signaling, and stimulation for operant and classical conditioning experiments were possible.

During the same time period, distributive dosimetry—measures of the anatomical distribution of focal SAR's in biological models and bodies of small mammals—was developed by Guy through the technique of thermography [25, 27]. Finally, the first in a succession of analytical and empirical studies of the electrical and geometrical constraints on SAR was initiated by Gandhi [28-30]. The orientation of an animal with respect to the vectors of an incident plane wave was found to be a powerful controlling influence on the quantity of energy absorbed in an RF field. The importance of considering environmental factors, such as temperature and humidity, rather than focusing only on dosimetric quantities was pointed out by Mumford [31].

Paralleling the development of dosimetric concepts were the introduction in the early 1970's of twin-cell calorimetry by Hunt and Phillips—the "platinum rod" of whole-body dosimetry—[32, 33] and the development of continuous automatic integration of momentary energy absorption rates via differentiation of transmitted and reflected power-meter values in a special, environmentally controlled waveguide system developed by Ho *et al.* [34]. Ho's system provides an electrical, if indirect, means of determining in real time the whole-body SAR in a living unrestrained animal. Later, pharmacologically-induced ectothermia was introduced by Justesen's group (via steroids) [35] and Gandhi's group (via Na-Pentobarbital) [36]; this permits the whole-body SAR to be calculated directly from increments of body temperature in living animals.

Later, Guy was to deploy circularly polarized, guided waves in specially equipped cylindrical waveguides which enable precise control of SAR's and virtually continuous irradiation of small animals that are fed, watered, and de-excremented with minimal disturbance of the field [37, 38].

Theoretical work and the development of instrumentation for quantifying electromagnetic-field interactions with biological materials increased substantially in the 1970's with many important developments. Interaction of plane-wave sources with layered tissues were studied [39-42]. New and novel instruments were developed for better characterization of exposure fields [43-47]. More sophisticated mathematical and physical models of biological tissues and anatomical structures generated a much better understanding of absorptive characteristics in tissues of differing composition and geometry. Theoretical models of the human head that consisted of a brain and spherical shells for simulation of the skull and scalp led to the observation by Shapiro that electrical *hot spots* (localized regions of intensified energy absorption) could occur deep within the brain at frequencies associated with resonance [48]. Absorption of RF energy at the surface of the head was considerably less due to focusing of the field, which results from the high dielectric constant and the spherical shape of the head. The theoretical results were expanded and verified experimentally to predict energy absorption by animal and human bodies of a wide range of sizes exposed at various frequencies [49-55]. Better and more detailed analyses were developed for various geometric objects which simulate bodies of man and animals, that is, cylinders [56-60], prolate spheroids [61-63], and ellipsoids [64-66]. Theoretical analyses were verified experimentally via thermography [49, 67, 68], newly-developed calorimetric techniques [69-71], and special temperature-sensing probes composed of microwave-transparent materials such as fiberoptics guides [72-75] and high-resistance leads [76, 77]. Cetas has reviewed and discussed the relative merits of these different techniques [78]. Probes were also developed for direct measurement of electric fields within exposed tissues [47, 79, 80]. Paralleling the use of microwave transparent materials for new dosimetry instrumentation was the adoption of these materials for use in recording physiological signals from live laboratory animals under microwave exposure [49, 81-83].

Finite-difference techniques and other numerical studies, in conjunction with high-speed computers, were developed along with sophisticated programs for calculating the EM fields and associated heating patterns in arbitrarily shaped bodies [84-91]. Mathematical models were also developed to include the effects of convective cooling via blood flow in calculating steady-state temperatures for the various parts of the body, including critical organs such as the eyes and brain [92-94]. The continued development and use of phantom models has contributed significantly to our understanding of energy absorption in biological bodies [27, 67, 68, 83, 95-101].

The simultaneous applications of these new developments of the 1970's in various laboratories was the stimulus needed to allow the microwave auditory effect to be quantified and understood as a complex thermal acoustic phenomenon which was quantified for nonbiological materials by the physicists more than a decade earlier [81, 102-105].

The collective advances in analytical solutions and experimental studies, in improved devices for measuring field strengths of plane-wave fields and for determining SAR's in exposed animals, and in non-perturbing thermal and electrical sensors culminated in publication of the first *Dosimetry Handbook* for RF radiation by Curtis Johnson and colleagues, of the University of Utah and the Air Force School of Aerospace Medicine [106, 107]. These collective results have been empirically cast in a succinct form by Durney *et al.* [108].

I have mentioned major analytical, experimental, and instrumental advances that have taken place during three decades of work on the biological response to RF waves. While much work remains to be done, especially in distributive dosimetry of experimental animals and man, a solid base for further advancement has been constructed.

My selections for this volume reflect some of the more important developments; because of limitations on space, I have selected works that for the most part are most informative from both a historical and a technical standpoint to the investigators of the 1980's who, it is hoped, will continue to advance the field.

Arthur W. Guy, Ph.D.
Associate Editor

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THE ABSORPTION OF ELECTROMAGNETIC ENERGY IN BODY TISSUES[1]

A Review and Critical Analysis

HERMAN P. SCHWAN, PH.D., AND GEO. MORRIS PIERSOL, M.D.

PART I

BIOPHYSICAL ASPECTS

In recent years, considerable interest has been shown with regard to the frequencies at which ultrahigh frequency electromagnetic waves produce the most effective therapeutic results (1–5). Furthermore, concern has developed over the effects of powerful electromagnetic radiation sources on personnel (6–9). The purpose of this review is to evaluate the existing literature, to discuss the biophysical mechanisms by which electromagnetic radiation is absorbed in tissue, and to describe its medical applications.

The discussion is divided into: A) Classification of various effects of high frequency currents and radiation. B) Brief outline of the limitations of ultrashort wave diathermy. C) Summary of the physical laws which characterize the absorption and propagation of electromagnetic waves in tissue. D) Consideration of electrical properties of various body tissues. E) Analysis of their influence on the propagation of the radiation in tissue. F) Studies of physiological character concerning the effects of electromagnetic radiation on tissue material. G) Hazards associated with the absorption of electromagnetic radiation. H) Clinical applications. Sections F–H will appear in Part II of this review.

CLASSIFICATION OF VARIOUS EFFECTS OF HIGH FREQUENCY CURRENTS AND RADIATION

Effects on biological material can be placed in three categories (3): 1) thermal, 2) specific thermal, and 3) nonthermal. Volume heating is the general heating which any type of conductor or semiconductor, such as tissue, may receive under the influence of electrical currents or waves. Specific thermal effects (structural heating) exist when boundaries between different types of tissues or particles on a microscopic scale, such as small cell complexes or even bacteria, etc., can be selectively heated without substantial heating of the surrounding material. Those effects, which cannot be explained on a thermal basis, are classified as nonthermal effects. We are not attempting to discuss the literature dealing with the existence of nonthermal effects. To the best of our knowledge, none of the statements about these can withstand criticism. (See for example, the summaries of Krusen (10) and Osborne and Holmquest (11)). Therefore, we will confine our consideration to thermal effects of high frequency currents and radiation.

It has been shown that specific thermal effects, such as the selective heating of bacteria, are not possible. The selective temperature rise which a particle may experience by developing internal heating due to absorption of electrical energy is inversely proportional to the square of the particle size. Even under favorable conditions for selective heating in particles of microscopic size and colloidal dimensions, the temperature rise is less than 1/1000° C. (12–15). The analytical investigations upon which this statement is based are substantiated by experiments with water droplets in oil (14), yeast cells (16), fruit flies (17), and paramecia (18). Selective heating may occur only when the particle size is at least 1 mm. in diameter. On this basis, it may be possible to heat groups of cells of sufficiently large size. This is especially true in the transient period, i.e., while the particle or cell complex approaches the final temperature. Then the ratio of particle temperature rise to environmental temperature rise is especially great. Since this fact has not been recognized generally, it may be illustrated by figure 1. If a water particle, 2 mm. in diameter, is immersed in oil, it is heated selectively to 100° C. within 3 seconds by a field strength of about 10 kilovolts per cm. Equal heating occurs at first in 24 seconds when about 6 kilovolts per cm. are applied, and it requires 2 minutes with 5 kilovolts per cm. However, during the 3-second pulse the oil surrounding the water droplet has heated up only 3°, while during the 24-second pulse about 23° C. are reached and in the case of permanent application of the electrical field, 50° C. are obtained[2]. Similar examples can be given for larger objects, i.e. selective heating can be achieved especially if it is possible to apply short pulses of high power in objects of macroscopic size. It must be emphasized that a water in oil preparation is especially suitable for selective heating and that in the biological field such possibility of favorable circumstances does not exist. More favorable conditions might be created by overlapping the beams of two different sources of radiation, thereby creating a volume in which more heat is developed than in the surrounding medium. In conclusion, it may be said that although there is a future possibility of improving techniques for selective heating of cell complexes of at least cubic cm. volume, no possibility exists on physical grounds for selective heating of submacroscopic particles. This permits us to restrict our following discussions solely to volume heating.

There are two possible approaches to the study of the effects of radiation. In animal experiments, conclusions are based on the study of temperature changes in the animal in the radiation field. A more basic approach lies in the study of the fundamental tissue properties responsible for the conversion of the "primary"

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[2] These values hold if we choose for convenience the temperatures in oil at a distance $2R$ from the center of the sphere, as representative for the heating of the oil. For a more detailed discussion, see reference 14.

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radiation energy into heat. Furthermore, if one understands how such data may be interpreted in terms of the molecular components of tissues, it is possible to extrapolate this information to experimentally unexplored frequency ranges, thereby predicting more suitable techniques.

In the chain of events which lead from the application of the radiant energy to its therapeutic effect, it is possible to distinguish the following steps:

Absorption of radiant energy. The absorption of radiant energy is dependent upon the various electrical constants of the individual tissues. Energy absorption leads to the development of heat. This we define as "primary heat" developed in the irradiated body. Primary heating produces temperature differences between various tissues and even differences within homogeneous material. This happens

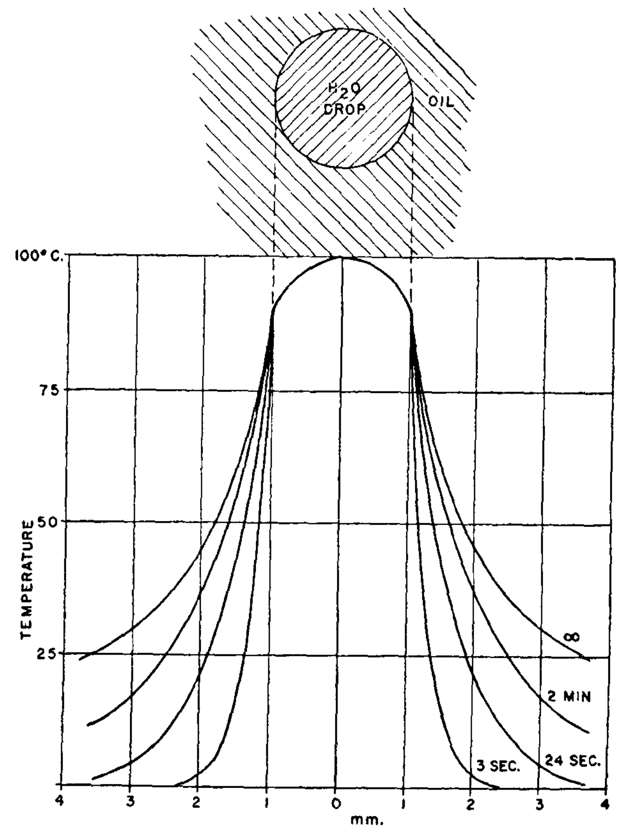

FIG. 1. Temperature rise in water droplets suspended in oil, plotted inside and outside the water. The curves hold for the case in which a high frequency field is applied for 3 seconds with a field strength of 11 Kilovolts/cm. *in oil, for 24 seconds* with 6 Kilovolts/cm., for 2 minutes with 5 Kilovolts/cm. and for unlimited time (∞) with 4.5 Kilovolts/cm. They illustrate how it is possible to obtain highly selective heating with short pulses of high intensity.

because primary heat development is most pronounced where the radiant energy is strongest, i.e. near the surface to which the radiation is applied. *The next mechanism of importance is the flow of heat from warmer to cooler areas.* This depends on the ability of the matter under consideration to conduct heat, i.e. its heat conductivity. It is also affected greatly by the blood flow, which may carry heat from one body area to another. It is important to realize that heat flow will diminish temperature differences. This means that final temperature distributions are characterized by curves which are flatter than those of primary heat development. It is the final heat distribution which produces the reaction observed by the clinician.

It is the task of the biophysicist to establish the basic laws governing primary effects. He and the physiologist work together and study actual heat distribution and associated phenomenon, such as blood flow. The clinician records the final results. All three groups cooperate to obtain a complete, clear picture of the effects of radiation. From a practical viewpoint, the actual temperature curve, i.e. the combined results of primary heat development and heat flow are more important than the mechanism of absorption. However, in the majority of cases, we can ascertain a complete knowledge of actual temperature distributions only in animal experiments. Extrapolation of this information to the human body is difficult because the amount of heat which can be absorbed by any body depends on the volume and surface of the irradiated body[3]. Here knowledge of the fundamentals of the absorption mechanism is most helpful. It permits us to predict how much radiant energy will be absorbed in the body; how far it penetrates; and the kind of tissue which will experience special heat development. We may then estimate the difference between primary heat absorption curves and actual heat distribution curves. If these conclusions agree with those derived from animal experiments, we arrive at well founded results to be applied to mankind.

It should be pointed out that the mechanism by which heating is brought about by microwave radiation is fundamentally different from that which takes place when so-called short wave diathermy is applied. Only in the latter instance the patient becomes a part of either a high frequency condensor or an induction field. The principal difference between the application of short wave diathermy and radiation diathermy is illustrated in figure 2. In short wave diathermy[4] ultrahigh frequency currents are passed through the body. Kirchoff's law of current conduction states that the sum of all currents $(i_1, i_2 \cdots i_n)$ at any given cross section

[3] Under normal conditions the human body transmits on its own about 0.01 watt/cm.^{2} energy in the form of heat through radiation, sweating, and heat convection to the outside. Under extreme conditions, this amount may be increased as much as 10 times. If similar figures hold for other animals, an animal with one-tenth the body surface of the human can absorb only one-tenth as much radiant energy as a human, before continuously raising the total body temperature as a result of absorption of thermal energy. Heat dissipation in this case would be less than heat absorption.

[4] The term "ultrashort wave diathermy" is misleading. Short wave diathermy has nothing to do with short waves. It utilizes high frequency currents produced by equipment which is potentially able to emit ultrashort waves, if equipped with proper radiation devices.

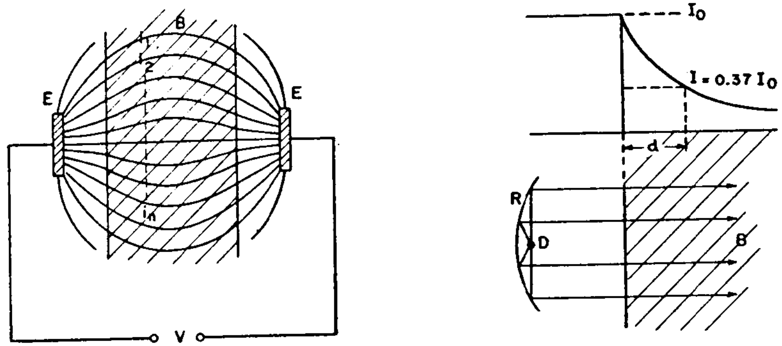

FIG. 2. Figures a (*left*) and b (*right*) illustrate the fundamental difference between current and radiation therapy. In high frequency current therapy (known as short wave therapy) high frequency currents are used for heating purposes. In electromagnetic radiation therapy, electromagnetic waves are absorbed and converted into heat. The laws for current conduction and radiation propagation are completely different. *a, left:* A segment of the body (*B*) is passed by high frequency currents as produced by the high frequency voltage *V* and made available to the body by the two electrodes *E*. Current heating necessitates always two electrodes and the sum of all currents entering and leaving the body is the same. *b, right:* A part of the body (*B*) is exposed to high frequency radiation. The radiation is generated by a dipole *D*, which in turn is energized from a high frequency generator. The dipole radiation is focused by one reflector *R* and directed into the body, where it is absorbed. The upper figure shows how the radiation intensity *I* is reduced in the human body due to conversion into heat and how the depth of penetration of the radiation *D* is defined.

through the body is independent of the location of that cross section[5]. Consequently, the strength of the current entering and leaving the body is equal. Because the current has a tendency to spread, its concentration per square cm. diminishes as the distance from the electrodes is increased. Therefore, the surface may be expected to have greater heating than areas inside the body. If two condensor electrodes are used to send high frequency currents through a body, concentration of the field intensity may be effectively reduced by spacing the electrodes away from the body, thereby creating a more uniform field (19–22). Radiation, on the other hand, consists of electromagnetic waves and is transmitted into the body by a reflector (fig. 2). Radiation energy is reduced by absorption. Its intensity decreases according to an exponential law when applied to a homogeneous material. The term "depth of penetration" can be applied correctly only in the case of radiation. Figure 2B shows how the intensity is reduced due to absorption. It is always optimal on the surface.

LIMITATIONS OF ULTRASHORT WAVE DIATHERMY

Esau was the first one abroad to recognize the value of UHF currents in effectively increasing the penetration of the heat into the human body (23), as did Schereschewsky in this country (24). Early claims of selective heating with

[5] This statement is correct only if all the currents are ohmic ones, i.e. due to ionic conduction. Where significant capacitive currents exist, as they do in the ultrahigh frequency field, this statement must be amended to read that the vector sum of all currents is constant.

this form of diathermy were based on investigations by McLennan and Burton (25) and by Paetzold (26). They found that a high frequency current of a given value will produce optimal heating of either an electrolyte or any other conductor, when the conductivity is altered to fulfill the relationship

$$60\lambda \kappa = \epsilon \quad (1)$$

(λ = wavelength of oscillator producing high frequency current, κ = specific conductance, and ϵ = relative dielectric constant of electrolyte). Some investigators concluded erroneously from this that by proper choice of a wavelength which fulfills equation 1 for any given type of tissue a maximum amount of heat in this body tissue could be developed. However, Schaefer (27) and, more recently, Higasi (28) showed that this is not the case. The practical value of Paetzold's principle of selective heating in a series combination of various tissues (skin, fat, muscle, body organs) depends on the variation of the electrical properties of different types of tissue. Determinations of the electrical properties of tissues with high water content prove that their data are very similar to each other. Hence, the distribution of heat in all tissues with high water content is fairly uniform, provided that equal current density is assumed. Schaefer gave a detailed analysis of this problem which substantiates the impossibility of selective heating of any type of muscular or organic tissue (27, 29–31).

However, fat and bone have very different dielectric properties. Analysis shows, therefore, that the heat which is developed per volume unit of subcutaneous fat is much greater than that produced in deep tissues which have a higher water content (31, 32). Furthermore, it was recognized that the ratio of the total amount of heat developed in fatty tissue per unit volume to the heat development in muscle decreases as the frequency is increased. This statement, which was originally based on an analytical argument utilizing knowledge of the dielectric data of fat and muscle, has been corroborated in experimental studies by actual temperature measurement. It may be concluded, therefore, that even at the highest frequencies which are practical for current therapy, i.e. about 100 Mc., fatty tissue is heated more than muscular tissue. In figure 3A and 3B the ratio of heat developed in fat to that in muscle is shown as calculated from dielectric data and as determined from temperature measurements.

Concurrently with the use of ultrahigh frequency currents applied to the human body for therapeutic purposes by means of two current electrodes (capacitive heating), another method was proposed for the production of deep heating with ultrahigh frequency currents. It was suggested that an induction field produced by coils energized from an ultrahigh frequency generator be employed for this purpose (inductive heating (23, 33, 34)). Electric currents (Eddy currents) are set up by the rapidly oscillating magnetic field surrounding the windings of the coil. This is a direct consequence of one of Maxwell's equations, which states that the electrical potential created by an alternating magnetic field is proportional to the product of magnetic field strength and frequency. It was hoped that it would be possible to obtain much more uniform deep heating than with the capacitive heating technique. This was anticipated on the basis that the magnetic

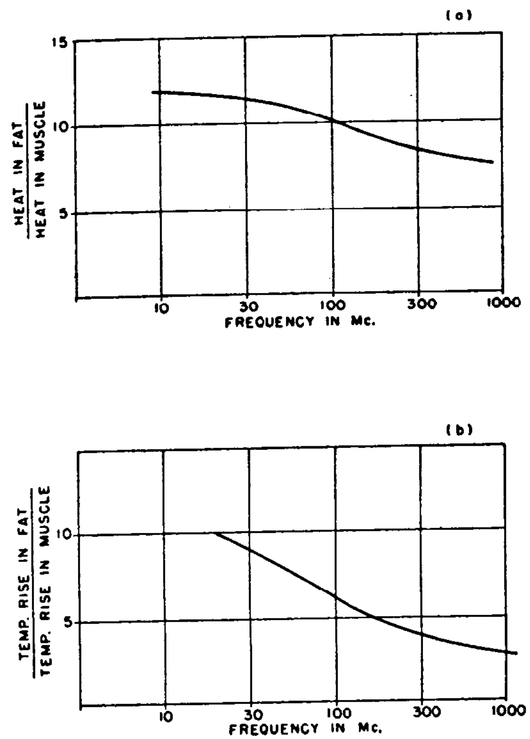

FIG. 3. Illustrates the strong tendency of high frequency current therapy to heat selectively subcutaneous fatty tissue. *a, upper:* Heat development in fat compared to that in muscle as calculated from dielectric data at various frequencies. *b, lower:* Temperature rise in fat compared to that in muscle at various frequencies (taken from Paetzold, ref. 1). The ratios of heat development and temperature rise in fat and muscle are in both cases much greater than one. They decrease with increasing frequencies. Differences in actual values between calculated and observed results may be partially due to heat conduction and in part due to variation in fat impedance data.

field is influenced only by the magnetic properties and these do not vary within the human body.[6] However, in view of the proportionality of the electric current with the frequency, either extremely powerful and expensive equipment or very high frequencies are necessary to produce sufficiently great currents useful for heating purposes. The use of very high frequencies is the only feasible way to proceed, but this in turn leads to another predicament (35–37). If coils of low inductance are used, nonuniform magnetic fields result with high magnetic field strength in the immediate neighborhood of the windings and consequent preference for surface heating. On the other hand, capacities which exist between the windings of longer coils produce capacitive currents which are conducted by the

[6] The magnetic permeability of all biological material is equal to that of vacuum within a fraction of 1 per cent and the magnetic losses of biological substances may be neglected likewise in our discussion.

surface of the body and cause consequent surface heating. In summary, it may be stated that the situation with the induction field is more complicated than with the capacitive electrode arrangement. However, it has been possible to work out a compromise which gives somewhat improved deep heating at frequencies in the neighborhood of about 20 to 30 Mc. The presently used frequency of 27 Mc. was chosen largely on this account. But it must be stated that even with this compromise, fat heating is still substantially stronger than the heating of deep tissues. So far, no data exist which permit conclusive comparative evaluation of the effectiveness of currents applied with electrodes (capacitive heating), and currents generated by coils (inductive heating). However, it is safe to state that while short wave diathermy, employing high frequency currents for heating purposes, definitely provides better deep heating than is obtainable with surface heating (hot pack, infrared) it certainly does not yet provide a good tool capable of bringing the major part of the available energy into the deep tissues below the subcutaneous fat.

RADIATION DIATHERMY

Attempts to reduce the undesirable fat heating by employing sufficiently high frequencies with the condensor field method are limited. This is due to the fact that the highest possible frequency at which the patient circuit can resonate, without excessive radiation losses, is in the neighborhood of 300 Mc.[7] (Paetzold (38) and Osswald (39)).

Successful employment of higher frequencies requires the use of the radiation field which was first proposed by Esau (23) and later in greater detail by Hollman (40–42) and Paetzold (43, 44). The first radiation experiments with small power were carried out by Bruenner-Ornstein and Randa (45) and by Denier (46). It was hoped that the low conductivity and consequent high penetration of radiation in fat would permit significant heating of the deep body tissues. Using a plane fat layer in series with muscle Hollman presented a mathematical analysis of the problem. The results of his analysis are very encouraging with regard to the value of the ultrahigh frequency electromagnetic radiation field for therapeutic purposes. However, Hollman's evaluation is incorrect because he assumed incorrect data for the dielectric properties of tissues. He obtained his dielectric data by extrapolation from material which had been obtained by others (47–50) at lower frequencies. Also, he did not take into account the marked changes in dielectric properties which occur at ultrahigh frequencies. These occur at frequencies above 300 Mc. due to polarity of water (see details in following section).

Hollman was the first to point out the advantages of impedance matching device or material between radiation source and body surface. When radiation strikes the surface of the body, part of it is absorbed and the remainder is reflected. If a coupling material with electrical properties identical to those of the body is placed between the source of energy and the body surface, no energy loss due to reflection will occur. Unfortunately, however, under such circumstances the coupling medium will absorb energy and the body will not receive the total

[7] The "patient circuit" is the lumped circuit which is used to energize the patient.