MICROWAVE

AUDITORY EFFECTS AND APPLICATIONS

JAMES C. LIN, Ph.D.

Associate Professor of Electrical Engineering
Adjunct Associate Professor of
Physical Medicine and Rehabilitation
Wayne State University

Former Assistant Professor of Rehabilitation Medicine
and Assistant Director, Bioelectromagnetics Research Laboratory
University of Washington School of Medicine

This research monograph on the biological effects of microwave radiation concentrates on the pulse-modulated, microwave-induced, auditory phenomenon. Chapters are included on the auditory system, psychophysical observations, neurophysiological correlations, the interactive mechanism, and the spherical model. Earlier work done in this area is reviewed, and suggestions for further research into and potential applications of microwave radiation are given.

CHARLES C THOMAS • PUBLISHER • SPRINGFIELD • ILLINOIS

Microwave Auditory Effects And Applications

By

JAMES C. LIN, Ph.D.

Associate Professor of Electrical Engineering
Adjunct Associate Professor of Physical Medicine and Rehabilitation
Wayne State University

Former Assistant Professor of Rehabilitation Medicine
and Assistant Director, Bioelectromagnetics Research Laboratory
University of Washington School of Medicine

CHARLES C THOMAS • PUBLISHER
Springfield • Illinois • U.S.A.

Preface

THE SUBJECT OF MICROWAVE interaction with biological systems is drawing the attention of many scientists and engineers in life and physical sciences. While microwave radiation with sufficiently high power densities and sufficiently long exposure periods is known to produce hyperthermia and its associated adverse as well as beneficial effects, other effects especially those occurring at low average power densities with negligible, measurable tissue temperature rise remain distressingly out of focus. This monograph presents one of the most interesting and widely recognized phenomenon: microwave-induced hearing.

The purpose of the book is to bring a body of research literature, scattered in a large number of journals and reports, into some compact form for the convenience of students and researchers. It will deal with selected experimental and theoretical topics in an interdisciplinary field which is undergoing explosive growth. A few suggestions for research and potential applications are also included.

For the reader who is not familiar with the subject, some relevant information about microwave radiation and biological effects of microwaves is provided in Chapter 1. A brief description of the auditory system is outlined in Chapter 2 as a place of reference for the subsequent discussion of microwave effects on this system. Major experimental evidence of pulse-modulated microwave-induced auditory effects are presented in Chapters 3 and 4. The speculations and hypotheses regarding mechanisms are treated next. Chapter 6 examines in detail the implications of induced thermoelastic theory using a spherical head-model. The use of pulse-modulated microwave radiation as a tool in clinical medicine and laboratory investigations has been given special attention in Chapter 7. The reader who is less mathematically inclined may wish to skip some of the material of Chapter 5 and 6; however, the reader will probably be rewarded by a better understanding of the models if he or she elects to read at least the narrative portions of these sections.

Statements regarding microwave exposure parameters were left in the terms used in the originating report. No attempt was made to standardize these terms since assumptions concerning omitted details could easily lead to erroneous interpretation. The International System (SI) of units is used exclusively; conversion factors for selected quantities can be found in Appendix A.

It should be mentioned that some of the material, especially many of the hypotheses regarding the mechanisms involved, may become obsolete more rapidly than other; however, this represents current views on the subject. It is hoped that the information contained here will not only impart to the reader some basic knowledge of the subject but will also show that the subject area is relatively undeveloped at the present time and that further research is needed.

This book evolved from a set of notes prepared for a sequence of lectures at the University of Washington Center for Bioengineering. Subsequently, these notes were enlarged and used for a one-quarter special topics course offered as a part of the bioengineering program in the Department of Electrical and Computer Engineering at Wayne State University. The students were, for the most part, in their first or second year of graduate study.

The author would like to express his appreciation to Drs. Arthur W. Guy and Justus F. Lehmann of the University of Washington School of Medicine, who through their publications and personal contacts stimulated his interest in the use of microwaves in medicine and greatly influenced his point of view. He has also benefited from the casual encounters with his friends and colleagues from many parts of the country, and the manuscript profited from corrections and clarifications suggested by many students. The author would like to thank Ms. Joanne Juhl, Mai Hsu, and Anne Matthews for their assistance in the preparation of the manuscript and to acknowledge the National Science Foundation for their support of his research covered in this book. Finally, he would like to thank his wife, Mei Fei, without whose patience and understanding this monograph would not have materialized.

JAMES C. LIN
Detroit, Michigan

Contents

Page

Preface v

Chapter

1. Introduction 3
    - Microwave Radiation 3
    - A Comparison of Electromagnetic Radiation 7
    - Biological Effects of Microwave Radiation 10
2. The Auditory System 19
    - External and Middle Ears 19
    - The Inner Ear 23
    - Action Potentials of the Auditory Nerve 31
    - Central Auditory Pathways 33
    - Transmission of Sound 34
    - Loudness and Pitch 36
    - Sound Localization 37
    - Deafness 39
    - Audiometry 40
3. Psychophysical Observations 45
    - Experimental Human Exposures 45
    - Detection in Laboratory Animals 57
4. Neurophysiological Correlations 68
    - Electrophysiological Recordings 68
    - "Threshold" Determination 88
    - Effect of Masking 95
5. The Interactive Mechanism 99
    - Site of Interaction 99
    - Mechanism of Interaction 100
    - Physical Properties of Biological Materials 106
    - A Quantitative Comparison 111
    - A Summary 122
6. The Spherical Model 135
    - Microwave Absorption 136
    - Temperature Rise 144

Chapter *Page*

Thermoelastic Equation of Motion 145
Sound Wave Generation in a Stress-Free Sphere . . . 146
Sound Wave Generation in a Sphere with Constrained Boundary 157
A Summary 168
7. Applied Aspects 173
Potential Applications 173
Maximum Permissible Exposure 178
Other Biological Effects 179

Appendix A. Units and Conversion Factors 193
Appendix B. Publications of Pertinent Conferences and Symposia 195
Author Index 197
Subject Index 201

Microwave Auditory Effects And Applications

Chapter 1

Introduction

THIS CHAPTER BEGINS with a consideration of microwave radiation and its relationship to other types of electromagnetic radiation. A brief historical introduction to the field of biological effects of microwave radiation is included to give an overview of early contributions. A variety of references to more comprehensive treatment of the general subject area will be found in the material that follows.

MICROWAVE RADIATION

Microwave radiation is a form of electromagnetic radiation which falls within the frequency range of 300 MHz to 300,000 MHz (megahertz = 10^6 Hz). It exists naturally as a part of the radiant energy given off by the sun; it is also produced by vacuum tubes and semiconductor devices. Man-made microwave energy may be conducted from the source by coaxial transmission lines or waveguides and emitted from transmitting antennas as a wave with oscillating electric and magnetic fields which pass into free space or material media. Microwave may be received by a receiving antenna and detected by diodes or similar devices. It propagates at the speed of light, which in free space is approximately 3×10^8 m/sec. The speed of propagation, v, is equal to the product of microwave frequency, f, and the wavelength, λ. That is

$$v = f\lambda \tag{1.1}$$

where the units of f and λ are, respectively, hertz (Hz) and meters (m).

At distances far from the transmitting antenna (usually ten wavelengths or more), microwaves may be considered as plane waves whose electric and magnetic fields are perpendicular to each other and both are perpendicular to the direction of propagation. Moreover, the electric and magnetic field maxima occur at the same location in space at any given moment, as depicted in Figure 1. In this case, the electric field strength in volts per meter is related to the magnetic field strength in amperes per meter through the constant known as intrinsic impedance, which in free space is approximately 377 ohms. For all other dielectric media, the intrinsic impedance is always smaller than that of free space. The power density (energy per unit time and per unit area) that impinges on a surface area normal to the direction of wave propagation is proportional to the square of the electric or magnetic field and is expressed in milliwatts per square centimeter (mW/cm^2) or watts per square meter (W/m^2). Most field strength measuring instruments for microwave frequencies are calibrated directly in mW/cm^2.

At distances less than ten wavelengths from the transmitting antenna (the near-field), the maxima and minima of electric and magnetic fields do not occur at the same location along the direction of propagation. That is, the electric and magnetic fields are out of time phase. The ratio of electric and magnetic field strengths is no longer constant; it varies from point to point. The direction of propagation is also not as uniquely defined as in the

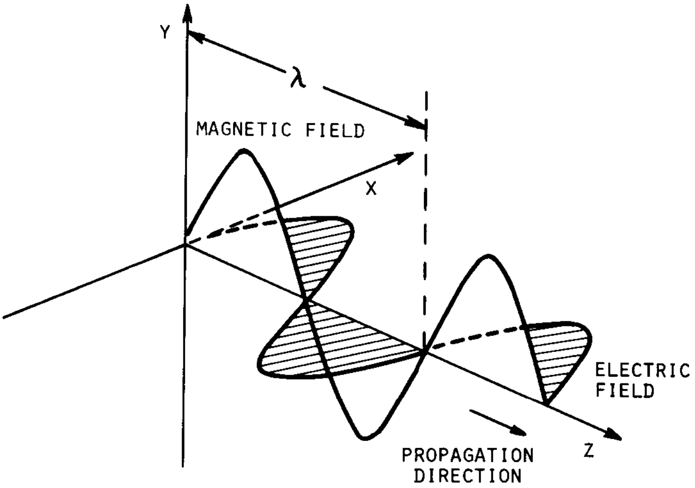

Figure 1. A plane wave of microwave radiation. The directions of electric and magnetic fields are everywhere perpendicular and both are perpendicular to the direction of propagation.

far-field case, making the situation extremely complicated. It should be noted that various field regions generally do not affect the basic mechanisms by which microwave radiation acts on biological systems, although the quantitative aspect of the interaction may differ somewhat due to changes in energy absorption.

Microwave radiation, like visible light, is reflected, scattered, refracted, and absorbed by physical and biological materials. These properties are governed by the electromagnetic properties of the media, specifically its dielectric constant and conductivity. They change as the frequency of the microwaves changes. In general, when considering the interaction of microwave radiation with biological systems, it is necessary to account for the frequency or wavelength of the radiation and its relationship to the physical dimensions of the biological system.

When microwave radiation impinges on a planar tissue structure, over 90 percent of the incident energy is reflected at the surface (see Chapter 5). The transmitted fraction is attenuated exponentially as it penetrates into the tissue according to the formula

$$I = I_o e^{-2\alpha z} \tag{1.2}$$

where I_o is the transmitted power at the surface and I is the transmitted power at a depth z. The depth of penetration, $1/\alpha$, is defined as the depth at which I has been reduced to 14 percent of I_o; it is a function of the tissue and microwave frequency involved and is a measure of the lossy character of the medium.

In addition to frequency, the amplitude of microwave radiation may also be altered in a definite pattern corresponding to the requirements of a given application. However, for more efficient information transmission via a microwave communication system, it is often necessary to use pulse modulation in which the amplitude, width, or position of a set of pulses that modulate a sinewave carrier (cw microwave) is altered in accordance with the information to be transmitted. In the case of continuous-wave (cw) operation, a sine wave with constant amplitude is transmitted from the instant the power is switched on until it is switched off.

One of the more familiar applications of cw microwave energy is the microwave oven that can cook a hamburger in just a few seconds. A classical example of the applications of pulse-modulated microwave radiation is radar capable of detecting and locating a target many kilometers away. Today, radar exists in many varied forms, such as missile-guidance radar, weather-detecting radar, air-traffic-control radar, etc. Even though such uses of microwave energy are of great importance, the applications of microwaves extend much farther into a variety of areas of everyday use and into basic and applied research in medicine, chemistry, and agriculture.

In this book we are concerned mainly with pulse-modulated microwave radiation. Figure 2 shows the waveform of rectangular pulses of microwave energy with a pulse width of t_o and a period of T. The pulse repetition frequency or rate is given by 1/T. It is customary to characterize a microwave pulse by its duty cycle, which is defined as the ratio of pulse width to the period, i.e. t_o/T. A duty cycle of 1.0 corresponds, therefore, to cw operation. In subsequent discussions of microwave-induced auditory effects, the pulse width involved is generally in the microsecond range, and the pulse repetition rate is around 1 Hz. The average power, P_a (averaged over a period), is given by the product of the peak power, P_m, and the duty cycle. For short pulses with low pulse repetition frequency, the average power can therefore be very low, even though the peak power may be in the kilowatt (kW) region.

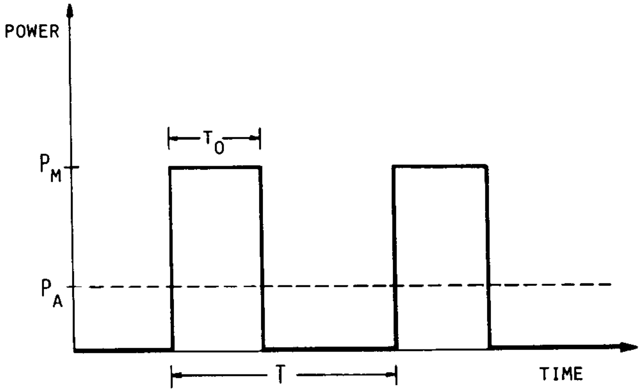

Figure 2. Waveform of rectangular pulses of microwave energy where t_o and T are the pulse width and period of each pulse. P_m and P_a are peak and average powers, respectively.

The preceding discussion has intentionally been kept brief and is included only to facilitate the understanding of later material. The reader who wishes to obtain a more detailed knowledge of the physical aspects of microwave radiation is referred to many readily available texts on the subject (for example, see Collins, 1966).

A COMPARISON OF ELECTROMAGNETIC RADIATION

Electromagnetic radiation is generally classified either by frequency or by wavelength. The energy carried by electromagnetic radiation may be expressed in terms of the energy required to eject or promote electrons from materials exposed to electromagnetic radiation. Each ejected or promoted electron receives a definite amount of energy that is characteristic of the frequency of the impinging radiation. Electromagnetic energy can therefore be thought of as being divided into bundles or photons. The energy, ϵ, of a photon is related to the frequency by

$$\epsilon = hf \tag{1.3}$$

where h is the Planck's constant, 6.625×10^{-34} joule-sec, and f is the frequency of the radiation in hertz. Therefore, the higher the frequency, the higher the energy per photon. The frequency and maximal energy for all radiations from radio-frequency waves to gamma rays are shown in Table I.

Gamma rays and X-rays have a great deal of energy and are

TABLE I

ENERGIES OF ELECTROMAGNETIC RADIATIONS

Type of Radiation	*Wavelength (nm)**	*Frequency (MHz)*	*Energy per Photon (joules)*	*(eV)†*
Gamma	10^{-4}	3.0×10^{24}	2.0×10^{-12}	1.24×10^{7}
X-ray	5×10^{-4}	6.0×10^{23}	3.98×10^{-13}	2.48×10^{6}
Ultraviolet	15	2.0×10^{17}	1.33×10^{-17}	82.7
Visible	390	7.7×10^{17}	5.1×10^{-19}	3.18
Infrared	780	3.8×10^{17}	2.55×10^{-19}	1.59
Microwave	10^{6}	3.0×10^{6}	2.0×10^{-22}	1.24×10^{-3}
Radio frequency	10^{8}	3.0×10^{2}	2.0×10^{-26}	1.24×10^{-7}

* 1nm (nanometer) = 10^{-9} meter. A nanometer is the recommended measure for the wavelength of light.

† eV (electron volt) = 1.602×10^{-19} joules.

capable of ionization, that is, producing ions by causing the ejection of orbital electrons from the atoms of the material through which they travel. The biological effects of gamma rays and X-rays are therefore largely the result of the ionization they produce. The minimum photon energies capable of producing ionization in water and in atomic carbon, hydrogen, nitrogen, and oxygen are between 10 and 25 eV. Inasmuch as these atoms constitute the basic elements of living organisms, 10 eV may be considered as the lower limit for ionization in biological systems. Although weak hydrogen bonds in macromolecules may involve energies less than 10 eV, energies below this value can generally be considered, biologically, as nonionizing (Metalsky, 1968). Nonionizing radiation present in our environment includes ultraviolet, visible light, infrared, microwaves, and radio-frequency waves as indicated by Table I.

Ultraviolet radiation is important for a number of biological processes and has also been shown to have deleterious effects on certain biological systems. One effect of ultraviolet radiation that everyone has experienced is sunburn. Ultraviolet radiation is known to kill bacteria, and it is also reported to have carcinogenic effects. Ultraviolet rays transmit their energies to atoms or molecules almost entirely by excitation, that is, by promotion of orbital electrons to some higher energy levels. Consequently, some of the effects produced by ultraviolet rays may resemble the changes resulting from ionizing radiation.

Although the photons of visible light with relatively low energy levels, 1.59 to 3.18 eV, are not capable of ionization or excitation, they have the unique ability of producing photochemical or photobiological reactions. Through a series of biochemical reactions, green plants, for example, are able to use light energy to fix carbon dioxide and split water such that carbohydrates and other molecules are synthesized. Visible light is also transmitted through the eye media without appreciable attenuation before reaching the retina. There it is absorbed by light-sensitive cells which initiate photochemical reactions whose end result is the sensation of vision. Retinal injury and transient loss of vision may occur as a result of exposure to intense visible light.

The infrared radiation of the sun is the major source of the earth's heat. It is also emitted by all hot bodies. There is little evidence that photons in the infrared region are capable of initiating photochemical reactions in biological materials. Although thermochemical reactions may follow photochemical reactions, changes in vibrational modes are responsible for absorptions in the infrared region. The absorbed energy increases the kinetic energy of the system, which is in turn dissipated in the form of heat. Thus, the primary response of biological systems to an exposure to infrared radiation is thermal.

Microwave radiation is known to increase the kinetic energy of the system when it is absorbed by the biological media. In this case the increased kinetic energy is due to changes of rotational energy levels which dissipate in heat. Perhaps the term *nonionizing radiation* is an oversimplification for denoting microwave and radio-frequency radiation, since it can be readily demonstrated that strong microwave and radio-frequency as well as AC current fields will light a fluorescent bulb without direct connection. The point is that microwave and radio-frequency waves have low-energy photons; therefore, under ordinary circumstances, this radiation is too low to affect ionization or excitation. Consequently, microwave radiation may be referred to as low-energy electromagnetic radiation.

Another point of distinction between ionizing and nonionizing radiations is that the effects of ionizing radiation on man is cumulative, as is the photochemical reaction produced by absorbed light. That is, if the radiation intensity and time of exposure are varied in such a way that the product of the two is always the same, the biological effect is the same. There is currently no definitive scientific evidence indicating any cumulative effect due to exposure to electromagnetic radiation in the microwave region. Available information suggests that the observed effects diminish as the radiation intensity is reduced to a low level and that repeated exposures do not alter this observation. At low levels the organism apparently has a chance to effect some recovery simultaneously with any injury.

BIOLOGICAL EFFECTS OF MICROWAVE RADIATION

In 1892, shortly after Hertz's demonstration of sustained high-frequency oscillation, d'Arsonval, a physician in France, applied the high-frequency (10 kHz) current to himself and found that it produced a sensation of warmth without any accompanying muscle contraction. He also observed flushing of the skin and increased sweating. (See Licht, 1965, for historic introduction.) In spite of d'Arsonval's inclinations toward specific physiologic effects, heating reactions in tissues exposed to high-frequency became the primary therapeutic application. In 1908, Nagelschmidt introduced the word diathermy to describe the relatively uniform heating produced throughout the tissues as high-frequency current was converted directly into heat. The use of high-frequency diathermy persisted for about a third of a century; its frequency range was between 1 and 3 MHz (longwave diathermy).

The vacuum-tube amplifier was developed by deForest in 1907. In 1928, using vacuum-tube amplifiers, Esau produced shortwave diathermy machines capable of generating electromagnetic radiation as high as 100 MHz with several hundred watts of output power. Schliephake at Giessen used the new machines first on himself and reported that he cured himself of a furuncle on the nose in less time than other treatments required. Overenthusiasm and lack of experience resulted in many moderate and some severe burns in patients in the early days of shortwave diathermy. Like the longwave diathermy, shortwave therapy was immediately involved in the decades-old controversy over possible specific effects apart from heating.

In 1937, physicians in America and Europe were immediately interested in William's report (1937) that electromagnetic radiations having wavelengths of a few centimeters could be focused, and in Southworth's report (1937) that such radiation could be directed along metallic pipes. Hemingway and Stenstem (1939), Krusen (1956), and Hollmann (1938) suggested the possible applications of microwaves of 25 cm wavelength for therapeutic purposes and predicted that these radiations could be focused to produce heating of the tissues without excessive heating of the skin. However, equipment with sufficient output power to allow medical investigation was not available at that time.

Microwave sources with sufficient power for therapeutic uses were developed rapidly under the stimulus of an intensive wartime research program. All such sources, however, were unavailable for medicinal research since they were reserved solely for military use during World War II. The introduction of radar as a defense measure soon caused concern over the biological effects and potential hazards of microwave radiation. Stimulated by this concern, the United States military services conducted some clinical studies to determine whether or not rumors (such as sterilizing effects) might be based on factual ground. Reports by Daily (1943) and by Lidman and Cohn (1945) failed to record any clinical change resulting from exposure to radiation from radar. These were the first studies on the effects of microwave radiation on the human body.

As the war ended, Raytheon Company provided two microwave generators to the Mayo Clinic for medical research in June 1946. Thus, almost a decade after they first became interested in the medical use of microwave energy, the staff of the Mayo Clinic were able to begin their first studies of microwave diathermy. They began their study with living animals and discovered that microwave diathermy could cause severe tissue burns within a short time of application. Nevertheless, with the proper selection of power and treatment duration, it was found that deep tissues could indeed be heated to therapeutically effective levels. It was noted by Krusen et al. (1947) that the initial temperature rise was greater in the skin and subcutaneous fat than in deeper musculatures. The final temperature in the muscle, however, was higher. These and other works conducted by the Mayo Clinic staff initially established the uses and limitations of microwave diathermy and led to its acceptance as a therapeutic agent by the American Medical Association in December, 1947 (Moor, 1965).

Some of the early reports which showed microwave diathermy to be of definite benefit include Mirault's (1950) finding that mi-