Microwave Auditory Effects And Applications

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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.

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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

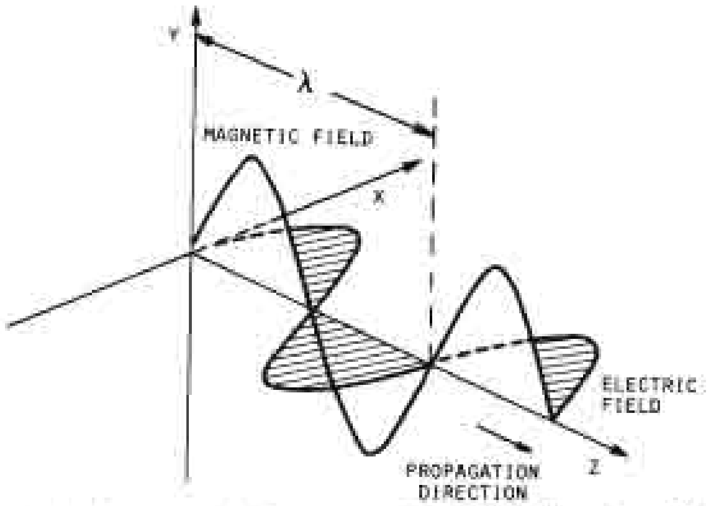

Figure 1. A plane wave of microwave radiation. The directions of electric and magnetic fields are everywhere perpendicular and both are perpendicular to the direction of propagation.

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

$$I = I_0 e^{-2\alpha z} \tag{1.2}$$

where I_0 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_0; 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 sine-wave 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.

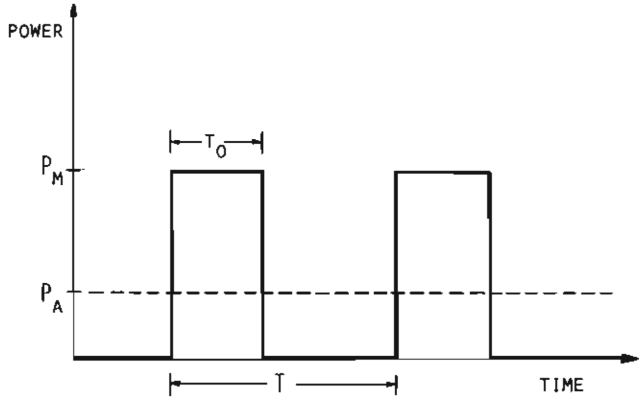

Figure 2. Waveform of rectangular pulses of microwave energy where t_o and T are the pulse width and period of each pulse. P_m and P_a are peak and average powers, respectively.

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^{5}	2.0×10^{-22}	1.24×10^{-3}
Radio frequency	10^{9}	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 or-

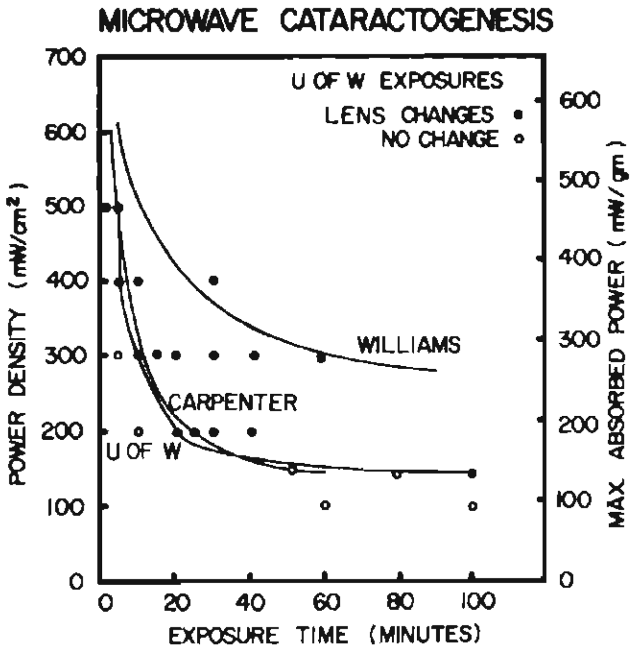

Figure 3. Cataractogenic thresholds for rabbits exposed to near zone 2450 MHz continuous-wave radiation. Note that the time and power thresholds reported by Williams nearly doubled those reported by Carpenter, while Carpenter's data practically coincided with that obtained by Kramar (U of W). (From Kramer et al.: The ocular effects of microwaves on hypothermic rabbits. Courtesy of *Ann NY Acad Sci, 247*:155-156, 1975.)

radiation virtually ceased, with only sporadic activity in the United States. Lehmann and Guy (Lehmann et al., 1962; Guy and Lehmann, 1966) experimentally verified Schwan's earlier theoretical prediction that microwave radiation at 900 MHz or lower would be better for therapeutic purposes than 2450 MHz because of its more desirable (deeper) heating patterns inside the tissue. Frey (1961, 1962) reported that pulsed microwave radiation elicited an auditory response in humans and animals. The effect occurred at average power densities as low as 100 μW/cm^2 and was described as a buzzing, ticking, or knocking sound within or immediately behind the head. The important parameters were reported to be peak power density, carrier frequency, and modulation. The optimum frequency for human perception was reported to be 1200 MHz.

Investigations in the Soviet Union and Eastern European countries, on the other hand, actually increased. Although many of these activities were unknown in the United States before 1964 (Dodge, 1965), most of the active research on the subject was being performed there (Dodge, 1970). For a complete description of the Soviet and Eastern European literature on the biological effects of high power electromagnetic radiation, the reader is referred to the books by Presman (1970) and Marha et al. (1971).

By 1966, substantial research in this area had been conducted, and it was generally believed that adequate understanding and practical control through safety standards had been achieved. In October, 1968, the United States Congress adopted the "Radiation Control for Health and Safety Act of 1968" (PL90-602), to protect the public from unnecessary exposure to potentially harmful radiation, including microwaves emitted by electronic products. This act and the Soviet and Eastern European countries' more conservative exposure standards for long-term irradiation (see Table II) have posed new questions on the adequacy of both our current knowledge of its biological effects and the protection afforded the general public from its harmful effects.

The last few years have seen a resurgence of research interest

TABLE II

SELECTED SAFETY STANDARDS FOR HUMAN EXPOSURE

Country	*Frequency*	*Standard*	*Remark*
USA (ANSI, 1974)	10 MHz to 100 GHz	10 mW/cm^2	0.1 hr or longer
		1 mWHr/cm^2	any 0.1 hr
Canada (1966)	10 MHz to 100 GHz	10 mW/cm^2	0.1 hr or longer
		1 mWHr/cm^2	any 0.1 hr
USSR (1965)	300 MHz or above	1 mW/cm^2	15 min/day
		0.1 mW/cm^2	2 hr/day
		0.01 mW/cm^2	6 hr/day
Poland (1961)	300 MHz or above	1 mW/cm^2	15 min/day
		0.1 mW/cm^2	2 hr/day
		0.01 mW/cm^2	6 hr/day
Czechoslovakia (1965)	300 MHz or above	0.025 mW/cm^2	8 hr/day, cw
		0.01 mW/cm^2	8 hr/day, pulsed

(Lin, 1975) in achieving a quantitative understanding of the relationships between the biological effects of microwave radiation and the physical variables that cause them. Because it is known that microwave radiation at sufficiently high power levels can produce heating and associated adverse effects, the emphasis of current research is on investigating both the effects of exposures at relatively low power densities and the mechanism underlying these effects. The following chapters will present an introduction to the information which has been gathered in the area of auditory effects induced by pulse-modulated microwave radiation–one of the most significant and most widely accepted low-level effects of microwave radiation on biological systems.

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Chapter 2

The Auditory System

THE AUDITORY SYSTEM receives information from the sound pressure waves in its surroundings and transmits this information to the central nervous system for processing and recognition. It is convenient to divide the auditory system into two components according to their anatomic and functional characteristics. The peripheral portion consists of the external ear, the middle ear, and the cochlea of the inner ear. The central portion is made up of the auditory nerve and pathways to various central neural structures.

EXTERNAL AND MIDDLE EARS

The external ear consists of the auricle or pinna, the external auditory meatus or canal, and the tympanic membrane or eardrum (Fig. 4). The function of the auricle is to direct sound waves into the external auditory meatus; however, it is relatively ineffective

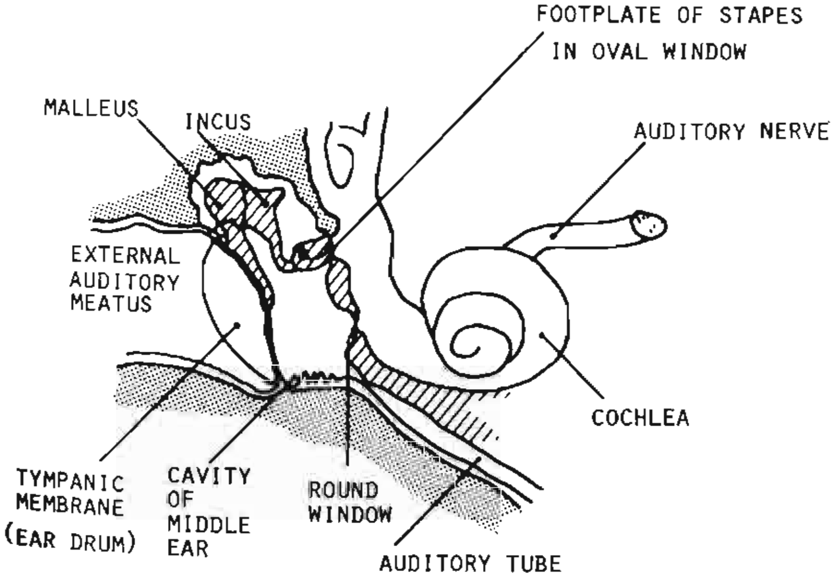

Figure 4. Anatomic features of the ear.

in man. The external auditory meatus is about 2.5 cm in length (Wever and Lawrence, 1954) and 7.5 mm in diameter (Shaw, 1974). Sound waves entering the external meatus are amplified by it much the same way as a tubal resonator, so that the sound pressure at the tympanic membrane is higher than the pressure at the entrance of the auditory meatus. A frequency response curve for the auditory meatus may be obtained by plotting the pressure difference between the tympanic membrane position and the center of the entrance of the auditory meatus against the sound frequency. An average frequency response curve in sound pressure level is shown in Figure 5. This curve is based on measurements by Wiener and Ross (1946) up to 8 kHz and by Djupesland and Zwislocki (1972) up to 10 kHz. The extrapolation to 12 kHz was inferred from measurements on a human ear replica and a model ear (Shaw, 1974). The maximum increase in sound pressure occurs first near 4 kHz, falls off on both sides of this resonant frequency, and peaks again near 12 kHz. The peaks are broad and round, indicating that the walls of the auditory meatus and the tympanic membrane are not rigid. The sound energy impinging on the tympanic membrane is partially reflected back into the air. Some of the incoming sound energy is also lost to the walls of the external auditory meatus.

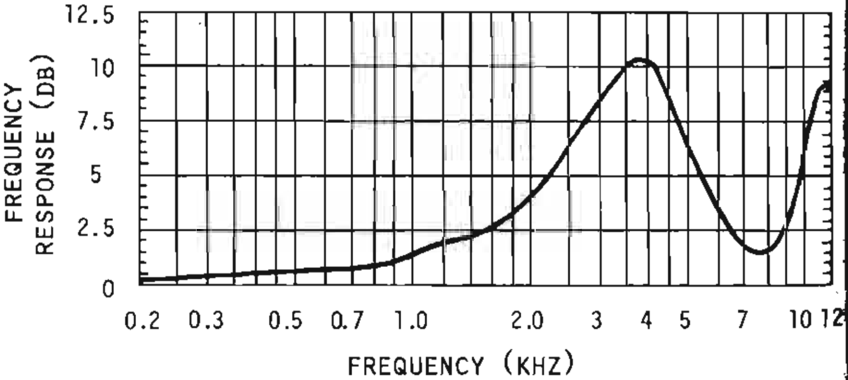

Figure 5. Frequency response showing the ratio of the sound pressure level at the tympanic membrane to the entrance of external auditory meatus. (Adapted from Shaw: The external ear. In Keidel and Neff [Eds.]: *Handbook of Sensory Physiology*, Vol. 5(1). 1974. Springer-Verlag, New York.)

The obliquely positioned tympanic membrane completely separates the external ear from the middle ear or tympanic cavity. The tympanic membrane is shaped like a shallow cone with its apex directed inward and somewhat below the center. Its anatomic area is about 65 mm^2 (Moller, 1974). The entire tympanic membrane vibrates in response to the impinging sound waves. The mode of vibration depends upon the sound frequency. At the threshold of hearing in man, the membrane displacement ranges from 10^{-6} cm for low frequencies to 10^{-9} cm at 3 kHz. (Bekesy, 1957).

The middle ear is an air-filled cavity in the temporal bone. It is separated from the external ear by the tympanic membrane and from the inner ear by the oval and round windows. The middle ear is connected with the nasopharynx by the eustachian tube or auditory tube. The tube is normally closed, but it opens during chewing, swallowing, and yawning, keeping the air pressure within the middle ear equalized with the atmospheric pressure. The passage between the middle ear and the nasal pharynx is a natural pathway for the spreading of infections of nose and throat to the middle ear. Such infections may impair hearing temporarily or permanently unless properly cared for.

The three small auditory ossicles–the malleus, incus, and stapes–are housed in the middle ear. The handle of the malleus is directed downward and attached to the upper part of the tympanic membrane. The head of the malleus is attached to the incus which in turn is connected by its long process to the stapes. The footplate of the stapes rests in the oval window. The malleus and the incus vibrate as a unit; movement of the tympanic membrane therefore causes the stapes also to move back and forth against the oval window. Two small muscles, the tensor tympani and the stapedius, are also located in the middle ear. The tensor tympani is attached to the handle of the malleus, and the stapedius is connected to the neck of the stapes. When the tensor tympani contracts, it moves the malleus inward and increases the tension on the tympanic membrane. The stapedius pulls the stapes outward upon contraction. Contraction of either or both muscles will therefore increase the stiffness of the middle ear mechanism and there-by decreases the low frequency energy transmission. These reflex muscle contractions are initiated only by relatively loud sounds and perform a limited protective function against them.

The most important function of the middle ear is to transform the sound pressure from a gas to a liquid medium without significant loss of energy. It can be easily shown that, at an air-water interface, only 0.1 percent of the sound energy is transmitted into water, the other 99.9 percent is reflected back to the air. The middle ear has two arrangements that practically eliminate this potential loss. The area of the tympanic membrane is approximately 65 mm^2 and the stapedial footplate has an anatomic area of about 3.2 mm^2. Since the mode of vibrations of the tympanic membrane is not simple, the ratio of the effective areas is around 14 to 1. In addition, the pressure exerted on the stapes is amplified by the lever action of the ossicles by a factor of 1.3 to 1 (Wever and Lawrence, 1954). Thus, there is a total gain factor of 18 between the pressure at the tympanic membrane and at the oval window.

The frequency response of the middle ear is not flat over the audible frequency range. The mass of the middle ear ossicles and the elasticity of the muscles influence the transmission of sound through the middle ear in different ways for different frequencies. The elastic property predominates at high frequencies, and the mass prevails at lower frequencies. Moreover, the mode of vibrations of the tympanic membrane is also frequency-dependent. Figure 6 is a plot of the frequency response of the middle ear of the cat as determined by measuring the stapedial displacement in response to sound pressures at the tympanic membrane (Guinan and Peake, 1967). It is seen that the ear is most sensitive in the region of 1 kHz for the cat. It is important to note that the middle ears of man and cat are not the same, although they are qualitatively similar in their functions.

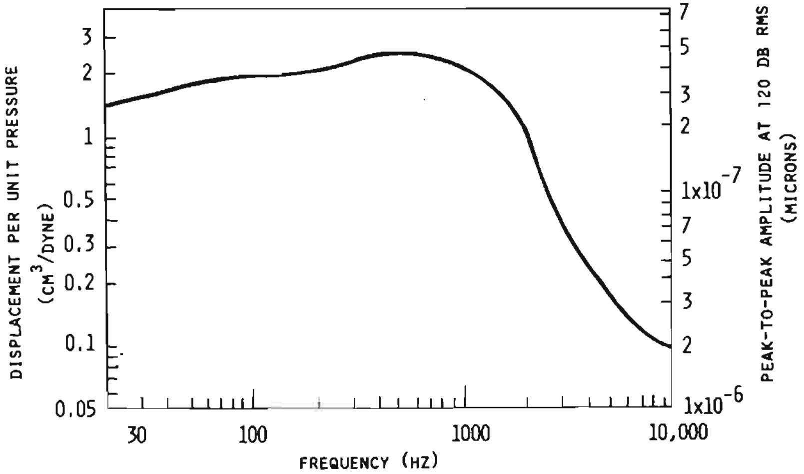

Figure 6. Amplitude of stapedial vibration in cats. (Adapted from Guinan and Peake: Middle ear characteristics of anesthetized cats. *J Acous Soc Am, 50:*1237-1261, 1967.)

THE INNER EAR

The inner ear or labyrinth consists of an osseous or bony labyrinth and a membranous labyrinth. The bony labyrinth is a series of canals and chambers in the petrous portion of the temporal bone. The membranous labyrinth lies within the bony labyrinth and is surrounded by the perilymph. Its inside is filled with endolymph. The labyrinth is divided into three parts: the vestibule, the semicircular canals, and the cochlea. The semicircular canals contain part of the sensory organ for balance. The vestibule is a chamber separated from the tympanic cavity by a thin partition of bone in which is found the oval window.

The cochlea is shaped like a snail shell which spirals for about two and three-quarter turns. The base of the cochlea is broad and tapers as it spirals to a narrow apex. The cochlea is divided by the basilar and Reissner's membranes into three chambers or scalae (Fig. 7). The upper scala vestibuli ends at the oval window. The lower scala tympani ends at the round window which is closed by the secondary tympanic membrane. Both of these chambers are filled with perilymph and they are separated by the scala media except at the apex of the cochlea where they are continuous. The scala media contains endolymph and is continuous with the membranous labyrinth. It is separated from the scala vestibuli by the Reissner's membrane and is cut off from the scala tympani by the basilar membrane. The essential organ of hearing, the organ of Corti, is located in the scala media.

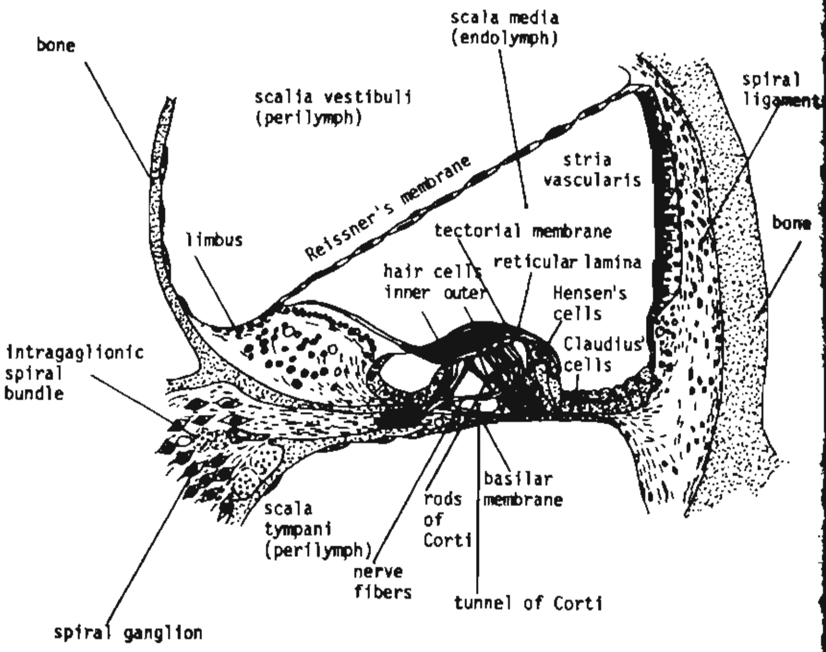

Figure 7. Cross section of the cochlea of a guinea pig. (Adapted from Davis
Energy into nerve impulses; hearing. *Med Bull St. Louis U*, 5:43-48, 1953.

The organ of Corti extends from the apex to the base of th cochlea and consists of a series of epithelial structures located o the basilar membrane, which is narrow and stiff near the oval win dow and comparatively wide at the apex of the cochlea. The cros section of a single turn of the cochlea of a guinea pig is shown i Figure 7. The auditory receptor hair cells are arranged in rows There are about 3500 inner hair cells placed in a single row alon the entire length of the cochlea, and there are about 20,000 oute hair cells arranged in three to four rows in the basal and apica turns of the cochlea. These cells have long processes (cilia) at o end and large basal nuclei at the other. The hair cells are covere by a thin but elastic tectorial membrane which makes contact wit the cilia of the hair cells. The fibers of the cochlear branch of th auditory nerve arborize around the hair cells. The cell bodies o these afferent neurons make up the spiral ganglia. The axons leav

ing the spiral ganglia form the auditory portion of the eighth cranial nerve which enters the dorsal and ventral cochlear nuclei of the medulla oblongata.

Mechanical Activity of the Cochlea

The Reissner's membrane is so thin and delicate that the scala vestibuli and the scala media probably function as a single unit in the passage of sound pressure waves. On the other hand, the basilar membrane is stiff and reacts in a characteristic manner to sound waves. When a sound pressure is transferred from the stapedial footplate to the cochlea, the oval window moves inward and pushes the perilymph of the scala vestibuli up toward the apex of the cochlea (Fig. 8). The sudden increase in pressure in the scala vestibuli forces the basilar membrane to bend toward the scala tympani, causing the round window to bulge outward. When the stapedial footplate is pulled backward, the process reverses. The vibrations of the basilar membrane are transmitted to the hair cells via the supporting cell structures of the organ of Corti and the tectorial membrane and cause the hair cells to activate the

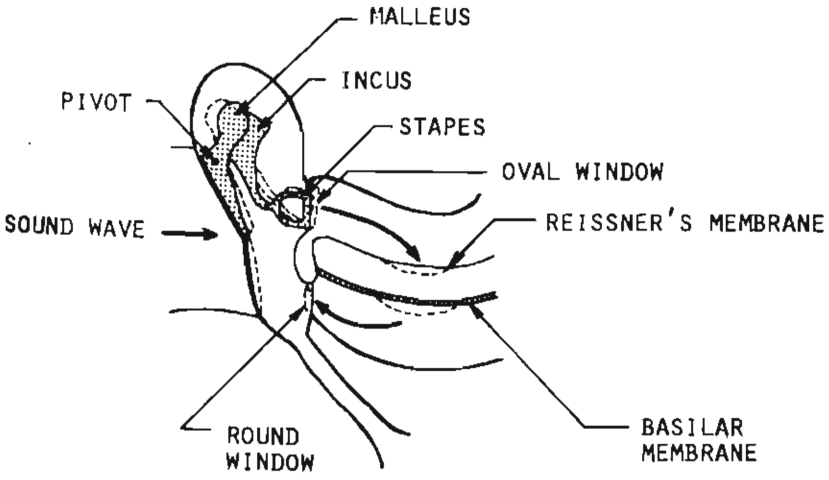

Figure 8. The auditory ossicles and the way their movement translates movements of the tympanic membrane into a wave in the cochlear fluid. (From Ganong: *Review of Medical Physiology*, 6th ed., 1973. Courtesy of Lange, Los Altos.)

Electrical Activity of the Cochlea

There are several characteristic electrical potentials in th cochlea. The endocochlear potential (EP) is a DC potential existing between the endolymph and the perilymph. At rest, this potential difference is about +80 mV relative to the perilymph. Th intracellular potential of the large cells in the organ of Corti, including the hair cells, is some 70 mV negative to the perilymph. The potential difference between the hair cells and the endolymp is therefore 150 mV. This potential is highly dependent on th oxygen supply. Bekesy (1952) suggested that this DC potential in the presence of a boundary membrane that could vary it electrical resistance as a function of mechanical stress, might b the source of cochlear phonics and microphonics. Building on thi suggestion, Davis (1953, 1957, 1961, 1965) has extensivel studied the mechanism of cochlear microphonic generation an postulated that the 150 mV DC potential could be modulated b resistance changes at the reticular laminar to produce cochlea microphonic oscillations with amplitude up to 3-10 mV. This resistance production mechanism has gained the widest acceptanc (Dallos, 1973; Horubia and Ward, 1970), and most experimenta observations are consistent with this hypothesis.

The cochlear microphonic is a potential that faithfully duplicates the waveform of the applied sound stimulus. It may be recorded from within or near the cochlea and a popular recordin site is the round window. The cochlear microphonic appears without threshold and has negligible latency (Wever, 1966). It i stable over long periods of time (Simmons and Beatty, 1962). I increases linearly with an increase in the pressure of the applie sound wave until the potential reaches 1 mV, and it then decrease with further increase in sound pressure (Wever and Lawrence, 1954). It is highly resistant to such changes in the physiologic state of the test animal as cold, fatigue, and drug administration. At death, the cochlear microphonic drops to a low level, but it persists at this level for up to thirty minutes or longer (Bekesy, 1960). Its existence, however, appears to depend upon the presence of normal hair cells (Butler et al., 1962).

Some examples of cochlear microphonics recorded from three sites along the cochlea of a guinea pig are shown in Figure 11. In Figure 11, the waveforms illustrated in A and B are typical for acoustic transients, and those shown in C and D are typical for acoustic tones. The cochlear microphonic responses to acoustic tones correspond closely to the waveform of applied sound energy. The microphonic shows increasing latency with distance from the oval window, consistent with the traveling waves described by Bekesy. The responses to bursts of tone at low frequencies are the largest at the apical turn but spread out over the entire cochlear duct. The cochlear microphonic generated is maximum in the basal turn when a burst of high frequency tone is used. Moreover, it is distorted and shows a strong asymmetrical nonlinearity in the second turn.

The peak-to-peak potentials for the cochlear microphonic re-

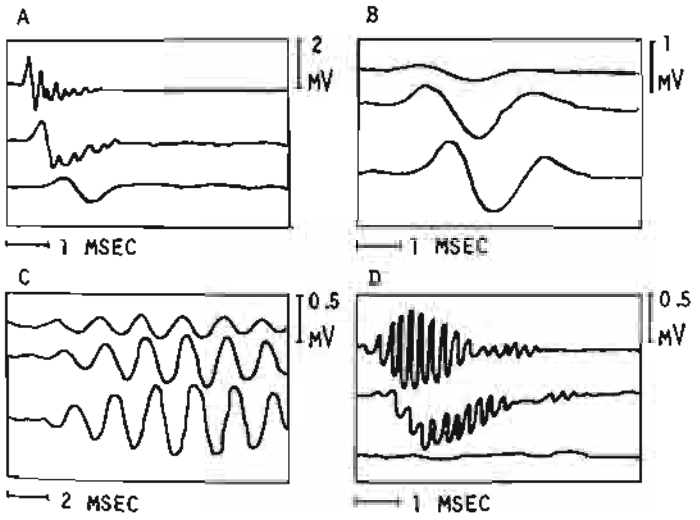

Figure 11. Cochlear microphonics recorded from the first (top), second (middle), and third (bottom) turns of the guinea pig cochlea in response to four different acoustic stimuli. A. Wide band click. B. 650 Hz click. C. 500 Hz pip. D. 4000 Hz burst. (Adapted from Eldredge: Inner ear. In Keidel and Neff [Eds.]: *Handbook of Sensory Physiology*, Vol 5(1). 1974. Springer-Verlag, New York.)

sponses to tones are shown in Figure 12 as a function of frequenc using the applied sound pressure level at the tympanic membran as a parameter (Engebretson, 1970). (Sound pressure level is described later in this chapter.) The solid curves are measuremen made with the auditory bulla (tympanic bone) opened. The increased stiffness due to the compliance of the small volume of ai enclosed behind the tympanic membrane would change the slop of each curve by the difference between the solid curve and th broken curve shown for the 30 db case. It is interesting to no that the cochlear microphonic response is almost frequency independent. The cochlear microphonic potential increases linearly a a function of applied sound pressure up to 80 db at any given frequency.

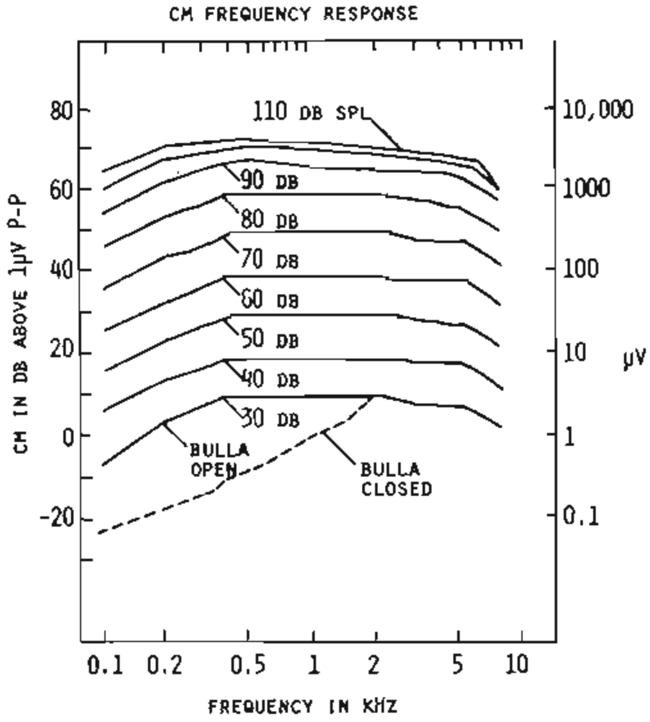

Figure 12. Peak-to-peak cochlear microphonic potential near the round window as a function of frequency in guinea pig. (Adapted from Engebretso *A Study of the Linear and Nonlinear Characteristics of Microphonic Vo age in the Cochlea*. Sc.D. dissertation, Washington U, St. Louis, 1970.)

At higher pressures, the cochlear microphonic response becomes nonlinear and the deviations from linearity increase as a function of both frequency and sound pressure (Eldredge, 1974). Cochlear microphonics up to 100 kHz have been recorded from bats, cats, rats, and guinea pigs (Vernon and Meikle, 1974).

There are two additional cochlear potentials generated when sound impinges on the ear (Davis, 1958). Moderate to strong sound pressure decreases the potential difference between the scala media and the scala vestibuli, and this decrease is maintained as long as the applied sound pressure persists. Similar to the cochlear microphonic, this negative summating potential shows no threshold and negligible latency. Unlike the microphonic, its amplitude continues to increase with increasing sound pressure. It is generally more resistant to drugs and anoxia and depends on the integrity of the inner hair cells. Under certain circumstances (namely, in fresh animal preparations and low sound pressures) the direction of change of the potential in the scala media is positive with respect to the scala tympani: It is then called the positive summating potential. The summating potential recorded in the basal turn when low frequency sound is used is usually small and positive.

ACTION POTENTIALS OF THE AUDITORY NERVE

The manner by which movement of the basilar membrane converts sound energy into nerve impulses is not completely known. It is believed that the cochlear potentials elicit action potentials in the nerve fibers that arborize around the hair cells, and that from these nerve fibers the action potential passes through the auditory nerve into the brain. The action potential of the auditory nerve as a whole can best be recorded following stimulation by an acoustic click. It consists of two distinct components, N_1 and N_2, each about one millisecond in duration (Fig. 13). The latency of the action potential relative to cochlear microphonic is a function of sound pressure amplitude, of the rate of rise of sound pressure, and of the frequency (Pestalozza and Davis, 1956). The minimum latency for N_1 is about 0.55 milliseconds and the maximum is about 2.3 milliseconds (Davis et al., 1950). The amplitudes of N_1 and N_2 are nonlinear functions of sound pressure (Rosen-

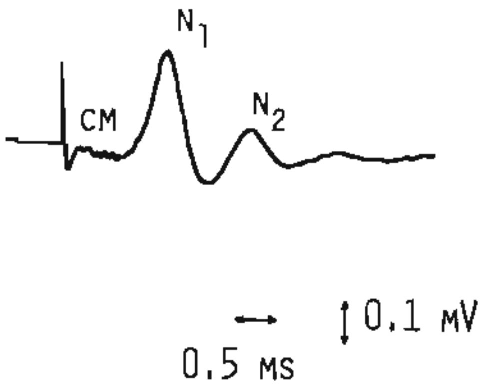

Figure 13. Auditory nerve response in cats following an acoustic click sti ulation. CM, cochlear microphonics. N_1 and N_2, nerve responses.

blith, 1950). N_1 grows slowly at first, then suddenly becomes mo rapid and N_2 appears. The discontinuity indicates the existe of two different sets of excitable elements with different thresho of excitation (Davis, 1957).

The nerve response is vulnerable to almost all adverse con tions. It is more sensitive to anoxia than cochlear microphon and recovers less readily. Quinine has been shown to abolish nerve responses selectively (Davis et al., 1950). The latency N_1 is increased by cold (Bornschein and Krejei, 1955). The ne response can also be reduced by the activity of the efferent inhi tory fibers (Galambos, 1956). A slowing of the nerve discha in single fibers during constant stimulation has been reported Tasaki (1954). The neural components of the round window sponse have also been shown to decrease as a result of either multaneous or previous stimulation. The masking effect is parti larly sensitive if the frequency spectrum of the masking noise ov laps that of the stimulus (Derbyshire and Davis, 1935; Ros blith, 1950). It is interesting to note that the polarity of the neu components of the round window response remains the same wh the phase of the stimulus is reversed. The cochlear micropho potential, on the other hand, reverses polarity with the change stimulus phase. The same observation is true when the cochl location of the recording electrode is changed (Davis et al., 19 Rosenblith and Rosenzweig, 1951).

CENTRAL AUDITORY PATHWAYS

The auditory action potentials generated in the nerve fibers ascend from the spiral ganglia via the eighth cranial nerve to the dorsal and ventral cochlear nuclei. These nuclei project both to the superior olivary complex unilaterally and bilaterally through the trapezoid body and the superior olivary nuclei and to the lateral lemniscus nuclei (Fig. 14). The superior olivary complex also sends fibers to the lateral lemniscus. The inferior colliculus

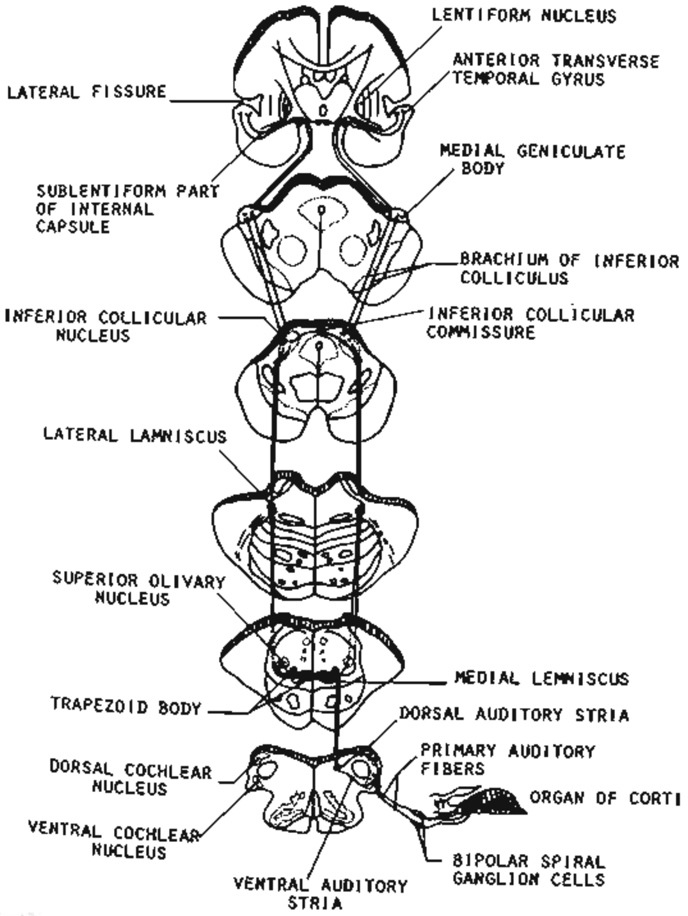

Figure 14. Schematic representation of the central auditory pathways. (Adapted from Everett: *Functional Neuroanatomy*, 6th ed., 1971. Lea & Febiger, Philadelphia.)

receives axons from the cochlear nucleus, the superior oliva complex, and the lemniscus. At this level, the axons may cro over to the contralateral inferior colliculus nucleus via the co missure. The major ascending connection runs, bilaterally, fro the inferior colliculus to the ventral division (principal nucleu of the medial geniculate body of the thalamus via the brachia. is important to note that recent studies have indicated lesions the lemniscus did not produce degeneration in the brachia geniculate body (Goldberg and Moore, 1967; Van Noort, 1969 This is contrary to the old idea that lemniscal axons also contri ute to the medial geniculate body.

After forming synapses in the medial geniculate body, the cending axons radiate in a diffused fashion to the cerebral cort and project to the transverse temporal gyri and insular cortex cated in the superior portion of the temporal lobe, near the flo of the lateral cerebral fissure. The crossings at the levels of superior olivary complex, lateral lemniscus nuclei, and inferi colliculi are responsible for the bilateral representation which lows auditory impulses arising in either ear to be projected both sides of the auditory cortex.

The olivocochlear bundle, or the bundle of Rasmussen, is prominent bundle of efferent (descending) auditory nerve fibe that originate in the superior olivary complex. These axons cro the brain stem to reach the hair cells of the organ of Corti of opposite ear. Stimulation of this olivocochlear bundle of Rasm sen produces an inhibitory effect on the action potential respo to click (Galambos, 1956). The cochlear microphonic is un fected by the procedure, but the auditory nerve response is grea reduced. This efferent inhibitory action is an expression of central nervous system's regulation of the sensitivity of heari mechanisms.

TRANSMISSION OF SOUND

When a sound pressure wave impinges on the ear, it is amplif by the external auditory meatus and causes the tympanic me brane to vibrate in a characteristic manner. This vibration transformed by the auditory ossicles into movements of

stapedial footplate. These movements create pressure waves in the fluids of the inner ear which displace the basilar membrane of the cochlear duct and cause the hair cells located on top of the basilar membrane to generate electrical potentials. The endocochlear potential elicits impulses in the auditory nerve. After the auditory nerve, the nerve impulses are transmitted through the cochlear nuclei, the trapezoid body, the superior olivary complex, the inferior colliculus, the medial geniculate body, and finally the auditory cortex. The primary auditory cortex receives the nerve impulses and interprets them as different sounds. The impulses are also conveyed to the surrounding auditory associative areas for recognition.

In addition to the usual course through the external auditory meatus and the middle ear ossicles described thus far, hearing may also be mediated by way of the bones of the skull. The latter has been designated as bone conduction to distinguish it from the air conduction route reserved for the former. Under ordinary conditions, sound pressures in the air cause almost no vibration in the skull bones, therefore bone conduction is less significant than air conduction in hearing. Tapping the jaw or holding vibrating devices such as a tuning fork against the skull can cause vibrations of sufficient amplitude in the skull to elicit bone-conducted sound. Intense air-borne sound can also impart sufficient energy to the skull bones to initiate bone-conducted hearing. In this case vibration of the skull is transmitted directly to the fluid of the inner ear and causes the basilar membrane to move. After it reaches the organ of Corti, the transmission of sound to the auditory cortex is the same as that for air conduction.

There are three widely accepted routes by which bone-conducted sound stimulates the cochlea: These are the compressional, inertial, and osseotympanic theories of bone conduction.

Compressional bone conduction implies that the cochlear shell is compressed slightly in response to the pressure variations caused by sound. The mechanism was first described in some detail by Herzog and Frainz in 1962 (see Tonndorf, 1962). Because the cochlear fluids are relatively incompressible, because there are

volume differences between the scala vestibuli and scala tymp
and because the oval window is stiffer than the round windo
pressure difference may develop across the basilar membrane
sulting in its displacement and the production of a traveling wav

The inertial wave bone conduction theory (Barany, 1938)
gests that, for low frequency vibrations, a relative motion is se
between the ossicular chain and the temporal bone. The temp
bone containing the cochlea vibrates as a whole. The middle
ossicles, because of their inertia and flexible attachment to
temporal bone, move in opposition to the cochlea. The net
of this action is an apparent movement of the stapedial footp
in and out of the oval window, leading to cochlear stimulatio
much the same manner as in air conduction. An additional
ertial effect may be due to a relative motion between the
lymphatic fluids and the cochlear shell (Wever, 1950).

The osseotympanic theory refers to a mechanism by whi
relative movement of the skull, with respect to the mandible,
up pressure variations in the air present in the auditory me
(Bekesy, 1960). When the bones of the skull are driven by
brating device, the mandible attached to the lower jaw lags be
or does not move at all. This results in relative displacemen
the cartilaginous skeleton of the auditory meatus, causing so
to be generated in the auditory meatus and transmitted to th
ner ear via the ossicles.

LOUDNESS AND PITCH

The perceived loudness of a sinusoidal sound wave is
termined by both its amplitude and its frequency. Loudness
with sound intensity, which is proportional to the square of
sure amplitude. Figure 15 shows the threshold of audibility
tactile sensation in terms of the weakest intensity of sound
can be heard or felt as a function of frequency. At any given
quency, the loudness varies as the logarithm of intensity.
threshold intensity for tactile sensation is about 10^{12} times h
than that for hearing at 1kHz. It is interesting to note that he
is keenest in the range of 1 to 4 kHz and decreases sharply
lower and higher frequencies. On the other hand, the threshol

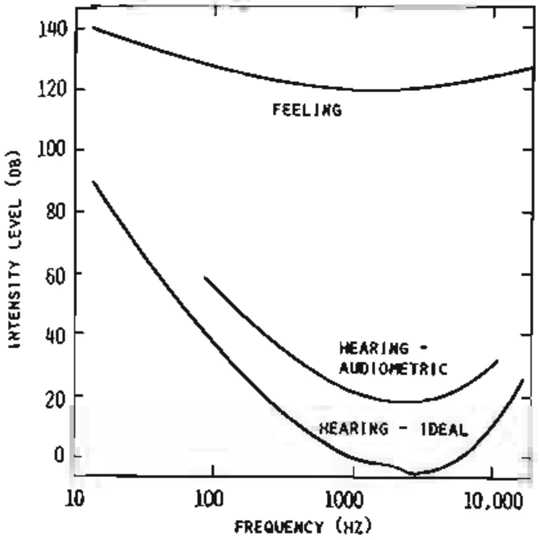

Figure 15. Audibility curve and threshold of tactile sensation in man. (Adapted from Ruch et al., *Neurophysiology*, 2nd ed., 1965. Saunders, Philadelphia.)

feeling is fairly constant. The fundamental and major overtones of the human voice are all at lower frequencies. Middle C is about 260 Hz. Sound intensity must be about 100 times greater to "just" hear 260 Hz rather than 1000 Hz.

Although the pitch of sound is determined primarily by the sound frequency, loudness also plays a part. In general, tones below 500 Hz seem lower and tones above 4 kHz seem higher as the loudness increases. The pitch rises as the duration increases from 0.01 to 0.1 second, and the pitch of a tone cannot be perceived unless it lasts for 0.01 second or longer.

SOUND LOCALIZATION

The problem of projecting a sound to its source is referred to
localization. Although the difference in time between the ar-
ival of the sound wave in the two ears is most important in de-
mining the direction from which a sound impinges, the differ-
ces in phase of the sound waves and the loudness on the two
are also important. At frequencies below 1 kHz the time dif-

ference is a determining factor, and at frequencies above 1 k the loudness difference appears most significant. The auditory c tex is necessary for sound localization in many experimental a mals and in man.

For sound sources in the vertical plane, located at an equal d tance from the two ears, the sound waves arriving at the right a left ears are identical functions of time for all angles of elevat of the sound source. The ability to locate the sound source curately in this case requires the following: The sound must complex; the sound must include frequencies above 7000 Hz; a the auricles must be present (Roffler and Butler, 1968). This s gests that when a complex sound with a broad spectrum impin on the head it is diffracted by the head and the auricles. T auricles selectively increase the high frequency sound intens For each direction, characteristic changes are superimposed on incident sound wave which are recognized and utilized to de mine the location of the sound source.

This hypothesis is supported by the observation that if no ot directional cues are present, irrespective of the actual directi sound waves with energy predominantly around 1 kHz are lo ized behind the listener. Frequencies below 500 Hz and arou 3 kHz appear in front of the subject. Sound waves with most their energy centered around 8 kHz are localized overhead (Fig. 16).

The experience of hearing sound as originating from within head when listening over earphones has previously been explai on the basis of the adaptive nature of sound coming through earphones, because earphones follow head motions. Further, earphone sound waves arrive at the two tympanic membranes approximately the same instant of time. The phenomenon has n been attributed to the difference in spectral characteristics betw earphone listening and free-field listening (Schroeder, 197 With earphones, standing waves are created in the auditory mea between the tympanic membrane and the membrane of the phone. These standing waves have time-varying spectra which different from those caused by diffraction at the subject's head a free-field listening situation. Thus, the subject can associate external location with earphone listening and consequently associates the sound sources with inside the head, which is the only alternative location. Recent demonstrations, in which earphone listeners externalized the sound sources when the standing waves are effectively removed from the external auditory meatus and the effects of head diffraction in a free-field are accounted for, lend considerable credence to the spectral theory.

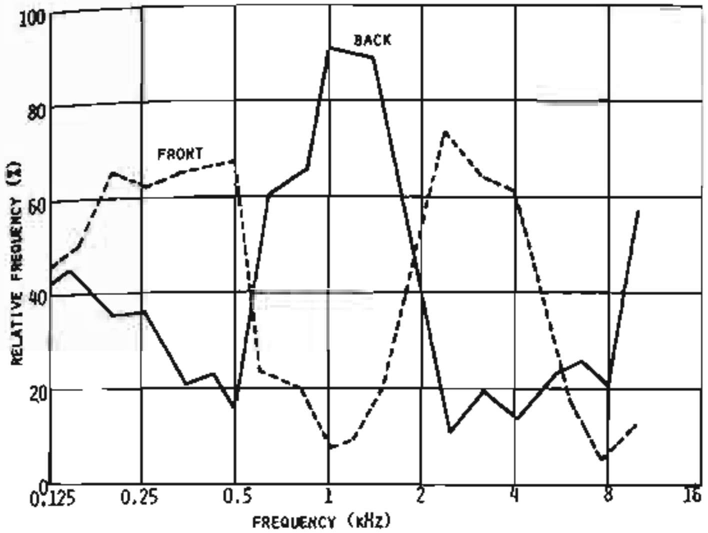

Figure 16. Plane wave sound localization in the median plane by sound spectrum. Sound waves with frequencies predominantly around 1 kHz and above 8 kHz are localized behind the listener (back). Sound waves below 500 Hz and 3 kHz produce front localization. Sound waves containing mostly 8 kHz energy appear to originate from overhead. (Adapted from Schroeder: Models of hearing. *Proc IEEE, 63:*1332-1350, 1975.)

DEAFNESS

Deafness, including partial hearing loss, is classified into two major categories: conduction deafness and nerve deafness. Any condition which interferes with the transmission of sound through the external and middle ears to the cochlea is classified as a conductive hearing loss. Common causes are wax or foreign body in the external auditory meatus, repeated blockage of the auditory tube, destruction of middle ear ossicles, thickening of the tymp membrane as a result of infection, and abnormal rigidity of the tachments of the stapes. Nerve deafness means failure of the a tory nerve impulses to reach the cerebral cortex because of d age to the cochlea itself or to the central neural pathways for a tory signals. Causes of nerve deafness include chemotoxic de eration of the auditory nerve produced by streptomysin, tu of the auditory nerve, and damage of the hair cells induced by posure to excessive noise. Neural hearing loss has also been tributed to viruses such as mumps, as well as to old age. Alm all older people develop some degree of neural hearing loss e cially for very high frequency sound.

AUDIOMETRY

Auditory activity is commonly measured with an audiom This device is also used clinically to distinguish conduction nerve deafness. It presents the subject with pure tones which from 250 to 8000 Hz at octave or half-octave intervals. The so intensity used can vary from zero db to 100 db.

The decibel (db) scale is a relative measure of the root-m square (RMS) sound pressure. The standard reference so pressure is 0.0002 dyne/cm^2 in air. This reference was adop by the Acoustic Society of America and it approximates the a tory threshold of the average young adult at 1000 Hz. The sou pressure-level (SPL) in db is therefore given by

$$\text{SPL(db)} = 20 \log P/P_o \qquad ($$

where P is the RMS sound pressure, P_o is the reference so pressure, and log is the logarithm to base 10. It is useful to n that because sound intensity is proportional to the square of so pressure, equation 2.1 may also be written as

$$\text{db} = 10 \log (S/S_o) \qquad ($$

where S and S_o are the measured and reference sound intensi respectively.

The reference sound pressure value used in audiometry, h

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ever, differs from the above threshold value by 15 to 20 db. This is because the audiometric reference is the average of normal hearing for different pure tones and the measurements were made in less than ideal conditions (see Fig. 15).

An audiogram is a plot of a subject's auditory threshold for various frequencies relative to normal hearing. It provides an objective measurement of the degree of deafness and an assessment of the total frequency range affected. Figure 17 shows the audiogram of a subject with normal hearing. Figure 18 displays the audiogram of a subject who has conductive hearing loss. Approximately 50 db of extra sound intensity had to be used in order for the subject to hear the sound at 4000 Hz through air conduction. However, the hearing was even better than normal for bone-conducted sound, which means that the cochlea and central auditory pathways were normal. The conduction of sound through the ossicular system must therefore have been impaired. If both air and bone conduction routes showed considerable loss, some degree of nerve deafness would have been indicated.

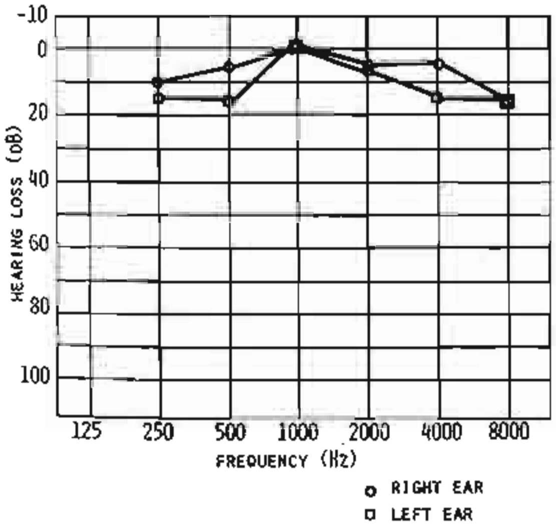

Figure 17. Audiogram of subject with normal hearing.

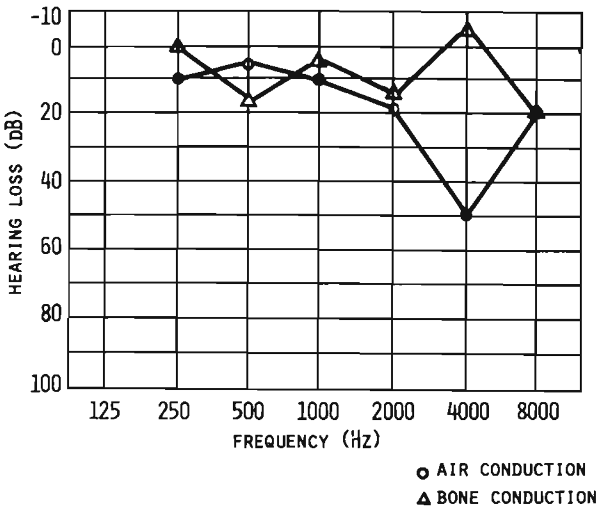

Figure 18. Audiogram of a subject with conductive hearing loss.

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Chapter 3

Psychophysical Observations

In Chapter 1, the perception of pulse-modulated microwave radiation via the auditory system was discussed. The responses were often described as clicking, buzzing, or chirping sounds and occurred instantaneously at low average incident power densities. The effect was at first dismissed by most investigators in the United States as an artifact. After repeated demonstration, however, it is now firmly established and fully documented (Frey, 1961, 1963, 1965; Frey and Messenger, 1973; Guy et al., 1975; Rissmann and Cain, 1975). Some of these studies will be outlined.

EXPERIMENTAL HUMAN EXPOSURES

Human Perception

Frey (1961) first reported that human beings can hear pulse-modulated microwave energy transmitted through the air. He found that human subjects exposed to 1310 MHz and 2982 MHz microwaves at average power densities of 0.4 to 2 mW/cm^2 perceived auditory sensations described as buzzing or knocking sounds. The peak power densities were on the order of 200 to 300 mW/cm^2 and the pulse repetition frequencies varied from 200 to 400 Hz. Subjects blindfolded with tight-fitting blackened goggles reported perception which correlated perfectly with microwave irradiation. When earplugs were used to attenuate the ambient noise level by 80 db, the subjects indicated a reduction in ambient noise level and an apparent increase in the level of microwave-induced sound. Moreover, in a paired test, it was found that persons shielded from the impinging microwave radiation ceased to report perception. Subjects who were not shielded continued to report hearing microwave-induced sound. This experiment showed that the human auditory system can respond to pulse-modulated microwave radiation, although the mechanism was unknown.

Frey referred to this auditory phenomenon as the RF (radio frequency) sound. The sensation occurred instantaneously at average incident power densities well below that necessary for known biological damage and appeared to originate from within or near the back of the head; the orientation of the subject in the microwave field was not an important factor. It was found that one person with an average air conduction hearing loss of 50 db, but with good bone conduction, could hear the microwave-induced sound at approximately the same average incident power densities as normal subjects could. On the other hand, another subject with clinically normal hearing was unable to perceive pulse-modulated microwave energy. An audiogram taken from this subject is shown in Figure 19. It can be seen that although the individual's hearing mechanism for air conduction was fairly normal, he had about a 60 to 80 db bone conduction loss. Furthermore, his hearing was very poor for frequencies above 5 kHz. A second finding was that subjects who were asked to compare the perceived sound with conventional acoustic energy invariably choose their parallels from the higher frequencies and eliminated all frequencies below 5 kHz

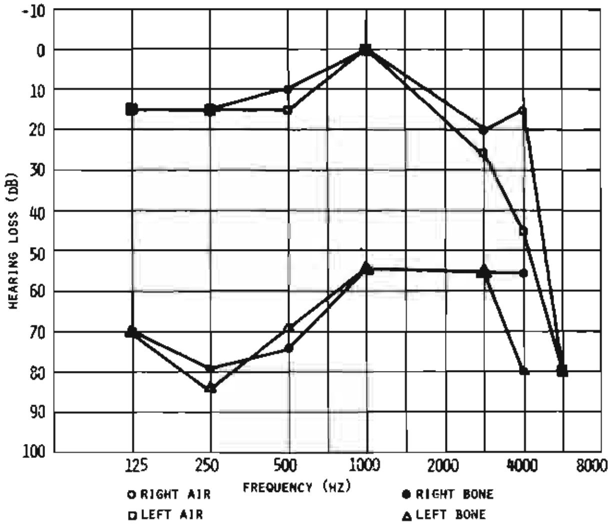

Figure 19. Audiogram of a subject with clinically normal hearing but with substantial bone conduction loss. (Adapted from Frey: Auditory system response. *Aerospace Med, 32:*1140-1142, 1961.)

(the limit of loudspeaker's frequency response). These two observations suggested that a necessary condition for perceiving the microwave-induced sound was the ability to perceive acoustic energy above approximately 5 kHz through the bone conduction route.

In the following year, Frey (1962) reported that people with a notch in their audiogram around 5 kHz may also fail to perceive microwave-induced sound. He has extended his observations down to 425 MHz microwaves. Using a fairly wide range of microwave parameters, Frey attempted to establish a threshold relationship for microwave-induced hearing. The results of this experiment are presented in Figure 20. It can be seen that the peak incident power is a critical factor: With nearly 90 db of ambient acoustic noise, a peak incident power density of approximately 275 mW/cm^2 was needed to elicit auditory response at frequencies be-

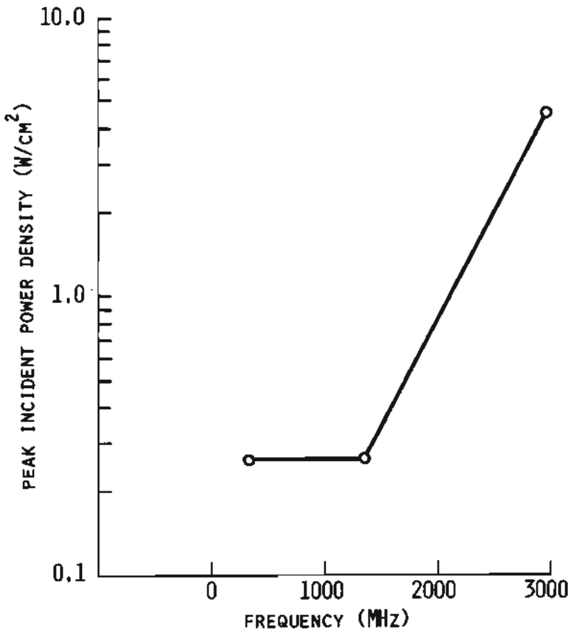

Figure 20. Peak incident power density required for auditory perception of pulse-modulated microwaves. (Adapted from Frey: Human auditory system response. *J Appl Physiol, 17:*689-692, 1962.)

tween 425 MHz and 1310 MHz. The high value for 2982 MHz was attributed to the difference in the penetration of microwave energy into the head at various frequencies. In two subsequent papers (Frey and Messenger, 1972, 1973), additional data was presented which indicated that the perception of microwave-induced sound was primarily a function of the peak power density and secondarily dependent on pulse width. They also reported that a band of optimal pulse widths seems to exist for the auditory sensation.

Guy et al. (1973, 1975) conducted a similar study for the purpose of more precisely measuring the exposure parameters. Two co-investigators served as subjects. The microwave energy was derived from an Applied Microwave Laboratory pulse signal source (PH 40k). The source was capable of providing up to 10 kW peak power pulses with the pulse width varying from 0.5 to 32 μsec and was used to feed a 2450 MHz (32 cm × 26 cm) aperture horn by means of an RG8 coaxial cable. The incident power to the horn and reflected power were monitored by means of a Hewlett-Packard 477 bolometer and 430C power meter combination connected to a Microlab FXR 30 db bidirectional coupler inserted between the coaxial cable and the horn. The pulse width and pulse repetition frequency were controlled by an external pulse generator and monitored on an oscilloscope.

The subject sat with the back of his head directly in front of the horn, 15 to 30 cm from the aperture (Fig. 21). Placement of the subject's head in the near zone field of the horn was necessary in order to obtain the full dynamic range of pulse widths and power levels necessary for evoking an auditory sensation. The average power density at the location of the exposed surface of the subject's head was measured with a Narda 8100 power monitor at high pulse repetition frequencies and at low peak power levels as a function of incident power to the horn with the subject absent. The values for higher power and lower pulse repetition frequency were obtained by linear extrapolation from the monitored incident power to the horn. Microwave absorbing materials (Emerson & Cuming, Inc., Eccosorb® CH490) were placed around the vicinity of the subject to eliminate reflections. The horn antenna, absorbing material, and test subject were situated in a shielded room completely isolated from the power generating equipment and experimenter in order to eliminate disturbing noises. Cable-connectors to the horn and bidirectional couplers were made through bulkhead connections on the wall of the shielded room. The subject used a light switch to signal the experimenter when an auditory sensation was perceived.

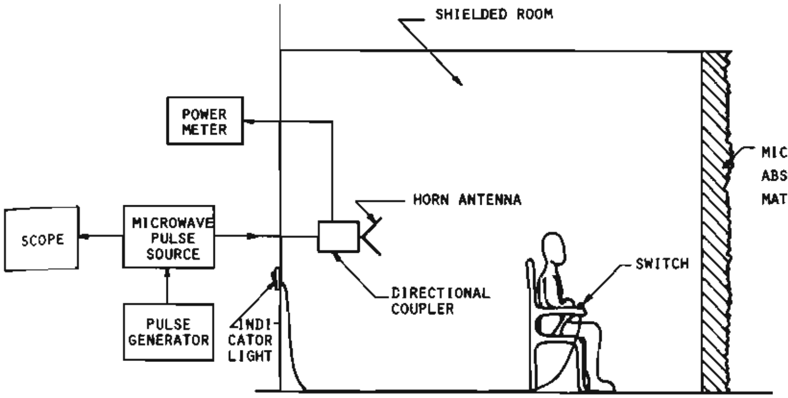

Figure 21. Experimental arrangement for measuring the threshold of microwave-induced auditory sensation.

Prior to the tests, standard audiograms of the subjects were taken. The first subject had normal hearing, while a pronounced notch at 3500 Hz was noted for both ears of the second subject. Similar results were obtained for both air and bone conduction. The ambient noise level in the exposure chamber was measured as 45 db, re 0.0002 dyne/cm^2, with a sound level meter (General Radio 1551-A). Each subject was exposed to a range of microwave pulse widths varying from 1 μsec to 32 μsec. The pulses were presented as a train of three pulses 100 msec apart every second, to maintain an average power density well below 1 mW/cm^2.

It was reported that each individual pulse could be heard as a distinct click originating from somewhere within or near the back of the head. Short pulse trains could be heard as chirps with the tone corresponding to the pulse repetition frequency. When the pulse generator was keyed manually, transmitted digital codes could be accurately interpreted by the subject. The auditory sensation perceived for two pulses within several hundred microseconds of each other was the same as one pulse with the same total energy as the pulse combination. It is significant to note that the energy required for audition by the subject with normal hearing was approximately a third to a quarter of that required for the subject with sensori-neural conduction impairment. The determination of incident power and modulation characteristics at the threshold for auditory sensation in humans will be discussed in the following section.

Rissmann and Cain (1975) also investigated the microwave-induced auditory sensation in humans. Before the experimental session, standard audiograms were obtained for each of the eight volunteer subjects. Although there were some variations in hearing ability, none of the subjects had a pronounced hearing loss greater than 25 db. Each subject was asked to place his or her head under a horn antenna which was driven by a 15 μsec pulse of 3000 MHz microwave energy. Five subjects reported hearing a click which seemed to originate from inside the head. Three subjects had difficulty in perceiving a microwave-induced sound when the maximum power output of the microwave source was used with a pulse width of 15 μsec, but they had no difficulty in hearing a click when the pulse width was increased to 20 μsec. This indicated that, although the audiograms revealed no significant differences in hearing ability among the subjects, they only gave information up to a maximum frequency of 8 kHz. It is possible that microwave-induced sound in humans contains a significant portion of its energy above 8 kHz (see Chapter 6). Thus it is possible that the three subjects had an inordinate amount of hearing loss at higher frequencies. This has in fact been documented recently (Cain and Rissmann, in Press).

The results of the above studies confirm the claims made by Frey that humans can hear pulsed microwave radiation. Specifically, human beings receive an auditory sensation when the head is exposed to 200 to 3000 MHz pulse-modulated microwave energy with a peak power density in the range of 100 to 300 mW/cm^2 and an average incident power density as low as 0.4 mW/cm^2. The pulse width varied from 1 to 100 μsec. Although some measurements were attempted at 8900 MHz, the results were negative at the power densities used (Frey, 1962). The microwave-induced sound appears as an audible click, buzz, or chirp depending on such factors as pulse width and pulse repetition frequency of the impinging radiation and usually is perceived as originating from within and near the back of the head. When the pulses are delivered manually, transmitted digital codes could be reliably interpreted by the human.

In addition to the above reports, there have been qualitative accounts of auditory sensation generated in pulse-modulated microwave fields (see, for example, Meahl, 1961; Ingalls, 1967; and Justesen, 1975).

Threshold Determination

Since the first report that pulse-modulated microwave radiation induces an auditory sensation in the human, several investigators have attempted to assess the thresholds for sensation as a function of microwave parameters. Frey (1962) had obtained an approximate threshold for perception in a high ambient noise environment (70-90 db, General Radio Model 1551-13 sound level meter) for frequencies between 425 and 1310 MHz. The threshold peak power density stayed fairly close to 257 mW/cm^2 and the average power density was 0.4 mW/cm^2. Guy et al. (1973, 1975) found that the threshold of audibility of 2450 MHz microwave-induced sound in humans was about 40 μJ/cm^2 per pulse. Psychophysical tests with four human subjects indicated that the auditory threshold for 1245 MHz microwave pulses was around 80 mW/cm^2 and was primarily dependent upon peak power density. Thresholds for pulse-modulated 3000 MHz radiation varied from 225 to 2500 mW/cm^2 of peak power density and 2.3 to 2.0 μJ/cm^2 of energy per pulse (Rissmann and Cain, 1975). The following paragraphs will describe in detail some of these efforts to establish the threshold of microwave-induced auditory sensation.

In the Frey and Messenger (1973) study, four trained subjects with clinically normal hearing were tested individually in a microwave anechoic chamber. Each subject sat on a wooden stool with his back to the horn antenna. Microwave energy was derived from a laboratory pulse source (Applied Microwave Laboratory, Model PG5K) which operated at 1245 MHz. A pulse repetition rate of 50 pulses per second was used. At this rate, a buzzing sound was perceived by the subjects. The subject's head was fixed in space by placing his chin on an acrylic rest mounted on a wooden pole. He communicated the loudness of microwave-induced sound using a small multi-key hand switch.

The method of magnitude estimation (Stevens, 1961) was used in this experiment. The subject was told to consider the loudness of the first microwave-induced sound to have a value of 100. The "standard sound" was presented for two seconds. A silent period of approximately five seconds followed, and then a microwave pulse of some combinations of peak power density, average power density, and pulse width was presented for two seconds. The subject was asked to assign to each microwave-induced sound a number proportional to the apparent loudness. The order of presentation of microwave pulses was determined with a table of random numbers and there were three randomized repetitions in each series.

The results are shown in Figures 22 and 23. Each point in these figures represents the median of the estimates. In Figure 22 the peak power density was varied while holding the average power density constant by changing the pulse width. It can be seen that the perceived loudness is clearly a function of peak power density. Furthermore, the threshold peak power density required for perception is somewhere around 80 mW/cm² for this experiment. Figure 23 presents the perceived loudness for the same subjects. The average power density was increased by increasing the pulse width while holding the peak power density constant. It appears that the average power density did not significantly affect perception of pulse-modulated 1245 MHz radiation.

The experimental arrangement and general conditions of the test room used by Guy et al. (1973, 1975) were described in the

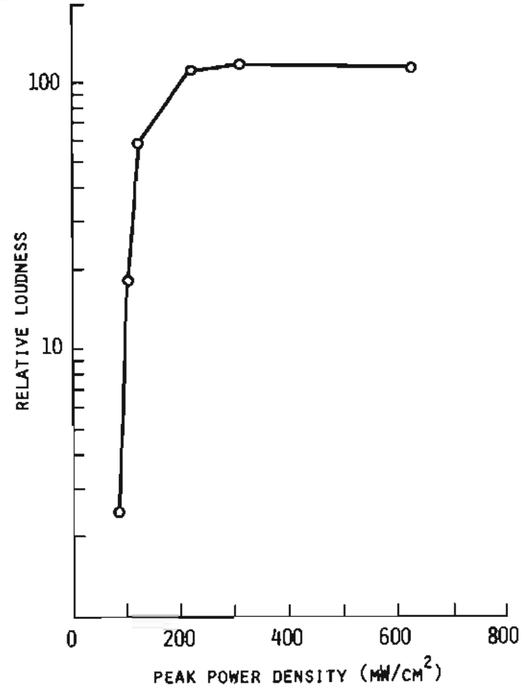

Figure 22. Loudness of microwave-induced sound as a function of peak power density for constant average power density (0.32 mW/cm^2) and average energy density per pulse (26.3 μj/cm^2).

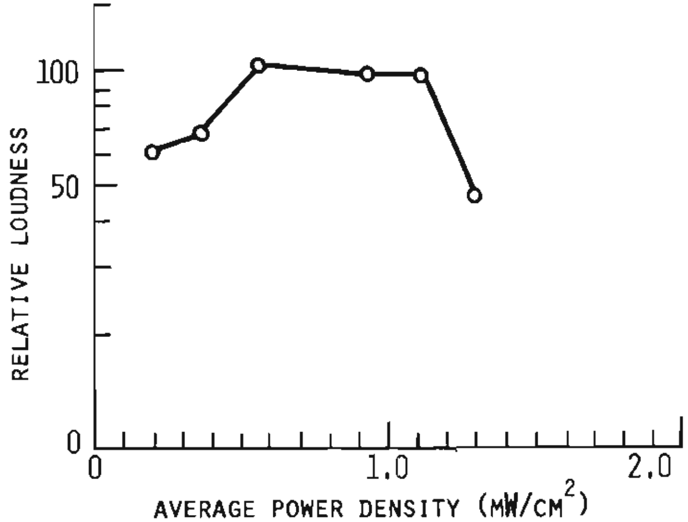

Figure 23. Perceived loudness as a function of average power density for varying pulse width but constant peak power density (370 mW/cm^2).

previous section. Although two subjects were involved, most of the data were obtained from one subject who was thirty years old and had close to normal hearing as indicated by a standard audiogram. Each subject was seated with his back toward the microwave horn approximately 30 cm away, with his ears at approximately the same height as the center of the horn.

The psychophysical method used was closely related to the method of limits or minimal change (Sheridan, 1971). The subjects responded to each microwave stimulus separately by depressing a light switch. In order to guard against any ordering effect, both ascending and descending series were employed. The threshold values given in Table III are average figures of three ascending-descending series. The data suggested that the threshold for a 2450 MHz microwave-induced sound was related to an energy density of 40 μJ/cm^2 per pulse, regardless of the pulse width or peak power density for pulses 1 to 32 μsec wide.

The apparent discrepancy among the various studies of threshold parameters of microwave-induced auditory sensation may be partially accounted for by the different frequencies used by various investigators. Also, different psychophysical methods of threshold determination have been known to give somewhat different results (Sheridan, 1971). On the other hand, we would expect the functional dependence of observed phenomenon upon the incident pulse characteristics to stay the same. The above studies clearly indicate the lack of any agreement as to which of the following quantities are of prime importance: average power density, peak power density, pulse width, or energy density per pulse. Guy et al. (1975) suggested that the threshold of microwave-induced auditory sensation for pulses shorter than 30 μsec is proportional to the energy density per pulse regardless of pulse-width or peak power density. Frey and Messenger (1973), however, maintained that the perceived loudness of microwave-induced sound is a function of peak power for 1245 MHz pulses whose width ranged from 10 to 70 μsec. Guy et al. indicated that their results are consistent with Frey and Messenger's when pulse width is taken into consideration.

TABLE III

THRESHOLD OF MICROWAVE-INDUCED HEARING SENSATION IN AN ADULT HUMAN WITH NORMAL HEARING (2450 MHz, 3 pps, 45 db BACKGROUND NOISE)

Pulse Width (μsec)	*Peak Incident Power Density (W/cm^2)*	*Incident Energy Density per Pulse (μJ/cm^2)*	*Average Incident Power Density (μW/cm^2)*
1	40	40	120
2	20	40	120
4	10	40	120
5	8	40	120
10	4	40	120
20	2.15	43	129
32	1.25	40	120

Figure 24 presents the perceived loudness of microwave-in-

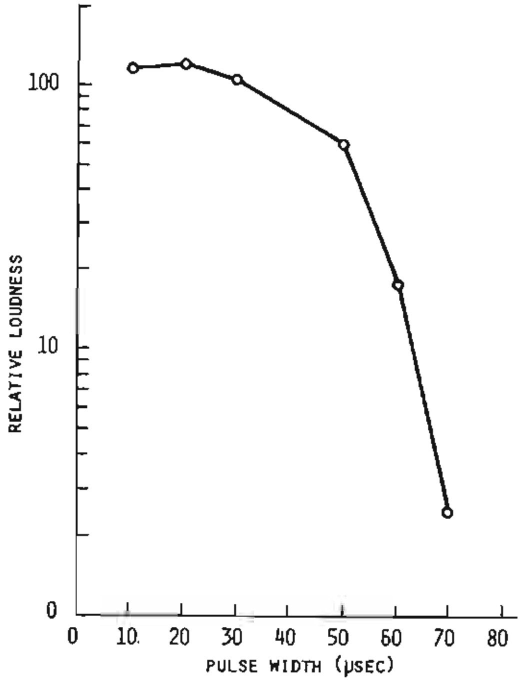

Figure 24. Variation of perceived loudness as a function of pulse width as the peak power is changed to keep the average power constant (0.32 mW/cm^2).

duced sound in humans as a function of pulse width. This curve is based on measurements made by Frey and Messenger (1973). It can be seen that for pulse widths between 10 and 30 μsec, loudness did not vary as a function of pulse width when the peak power density was decreased to keep the energy density per pulse constant, in agreement with Guy et al.'s observation. For pulse widths greater than 30 μsec, however, the loudness decreased as the peak power density was decreased to maintain a constant applied energy density per pulse. Furthermore, Figure 25 shows that the perceived loudness stayed approximately the same when the peak power density was held constant while allowing the energy density per pulse to increase with the pulse width, indicating that the perceived loudness is a function of peak power density rather than energy density per pulse. This result is clearly at variance with Guy et al.'s observations, even for pulse widths shorter than 30 μsec.

The above studies illustrate the need both for further investigation into the functional relationships between the physical characteristics of the impinging pulse-modulated microwave radiation and the induced auditory sensation and for more precise measures of the threshold of sensation. It seems that a larger sample space is the most important consideration, along with quality control of test conditions.

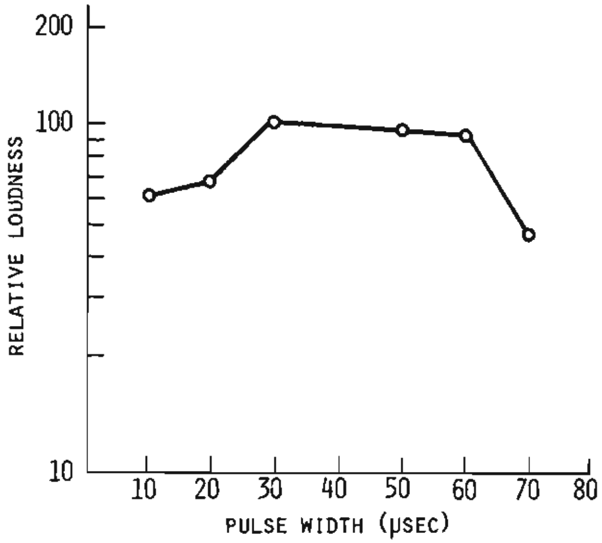

Figure 25. The perceived loudness is approximately the same as the energy per pulse increased with pulse width.

DETECTION IN LABORATORY ANIMALS

We have described in the previous section that humans, under certain conditions, can perceive pulse-modulated microwave energy at low average power densities. Because the auditory perception studied here involves a discrimination response to differential characteristics of impinging pulsed microwaves, this avoids a common issue in studies involving human subjects: the possibility of subjective responses. Corroborating observations in lower animals will, however, substantially enhance the acceptance of a microwave-induced auditory sensation.

Considerable efforts have been devoted to acquiring confirmatory data in lower animals. Early studies (Justesen and King, 1970) attempted unsuccessfully to present modulated microwave energy to rats as a cue for obtaining sugar water, since none of the rats discriminated the cue. Frey (1971; Frey and Feld, 1972, 1975) has reported successful use of pulsed microwaves as a cue in avoidance conditioning of cats and rats. More recently, Johnson et al. (1976) demonstrated a discriminative control of appetitive behavior by pulse-modulated microwave energy in rats. The following sections will discuss in detail the efforts to establish the behavioral basis for microwave-induced auditory sensation in mammals.

Detection in Rats

King et al. (1971) reported evidence that rats can detect the presence of modulated, 2450 MHz microwaves at absorbed power densities of 0.5-6.4 mW/gm. They used microwaves as a conditioned stimulus in a conditioned suppression experiment involving six male albino rats. The modulation was a rectified sine wave approximately 8 msec wide with a pulse repetition frequency of 60 Hz. The exposure was accomplished in a multimodal cavity (Modified Tappan® R36 microwave oven) fitted with a Plexiglas® conditioning chamber. The absorbed power densities were determined by measuring the total power delivered to the cavity when equivalent water phantoms were used and dividing the power measurement by the body weights of the rats.

The operant response was a tongue lick (which was monitored photoelectrically), and the rats were rewarded by discrete volumes of sugar water. After the initial operant response, reinforcement was scheduled intermittently at two-second intervals until the response occurred frequently and consistently. Modulated microwaves were then presented from time to time as a warning signal against an impending electric shock to the foot, which constituted the unconditioned stimulus. After repeated presentation of the warning signal and the unconditioned stimulus, the subjects responded stably except when the warning signal was present. One-minute periods of microwave exposure and 0.5-second periods of electrical shock were presented. The number of licks that occurred during sixty-second "safe" periods and during ensuing sixty-second warning periods (which usually terminated in shock) were tallied by digital counters and cumulative recorders. They found that microwave exposure caused a suppression of tongue licks.

Although lacking the saliency of a conventional auditory stimulus, which was also used, pulse-modulated microwaves can function as a highly reliable cue. The detection efficiency was strongly dependent upon the amount of microwave energy to which the rats were exposed. These observations are in opposition to earlier findings regarding microwave control of appetitive behavior (Justesen and King, 1970). In the earlier case, in which pulse-modulated microwaves were not effective as a cue for obtaining sugar water, it was theorized that the appetitive methodology was not sufficiently sensitive (King et al., 1971). Another possibility is the less than optimum pulse shape used in the form of a half-sine wave.

Frey and Feld (1972, 1975) conducted a study to determine whether rats would perceive low-level pulse-modulated microwave energy and respond to it behaviorally. Eight 125-day-old Sprague-Dawley male rats, each weighing approximately 150 g, were tested in a darkened microwave anechoic chamber which contained two acrylic barrier boxes (Fig. 26) mounted on wooden tables. The tables were arranged in such a manner that mutual field interaction between the two boxes was minimized. Each box consisted of two halves (compartments). The right half of one was shielded and the left half of the other was shielded from the impinging microwaves using microwave absorbers (Eccosorb FR340, Emerson & Cuming) to minimize microwave exposure of the respective sides of the boxes and to exclude any possible effect due to side preference. Opaque paper was attached to the side of both boxes facing the horn antenna so that the experimental subjects did not have any visual cue as to which half of the box was shielded. The location of the subject was monitored using a switch affixed to the bottom of each compartment of the barrier box. Rectangular microwave pulses (30 μsec wide, 1245 MHz) were derived from a pulse source (Applied Microwave Laboratory, Model PG 5K) at the rate of 100 pulses per second and were fed to the horizontally polarized standard-gain horn antenna via air lines, coaxial cables, and a waveguide adapter. The incident power density at 5 cm above the floor of each half of the boxes, when the animal was absent, was measured using a half-wave dipole, and a thermister and

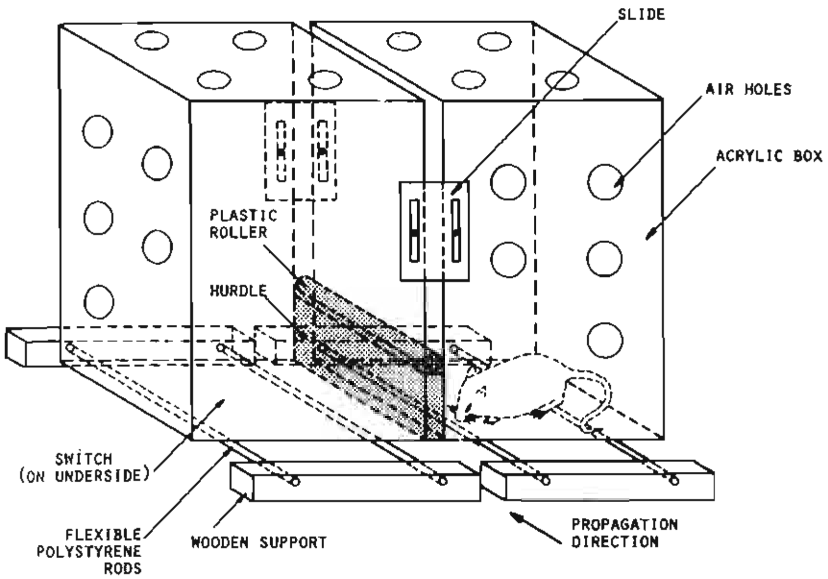

Figure 26. Barrier box used to investigate the avoidance by rats of pulse-modulated microwaves.

power meter combination (Hewlett-Packard Model 4MB and 430C, respectively). The average power densities in the unshielded half were less than 1.0 mW/cm². The shielded half had a value of 7 percent or less of the unshielded side.

After acclimation to the barrier boxes, place-avoidance conditioning was initiated with pulse-modulated microwaves as the discriminative stimuli. During each ninety-minute session, cumulative measurements of residence time in shielded and in unshielded compartments was taken to reflect the course and status of conditioning. Rats were assigned to either an experimental or a control group. Control sessions were run with all equipment turned on but without output. The means of each subject for all seven sessions were first computed. The means for the experimental and control groups were then computed.

Figure 27 shows the means of cumulative crossings. It can be seen that rats crisscrossed between the two compartments at a relatively high rate in the beginning of each session and then tended to settle down to a lower rate of crossings. It is significant to note that the number of crossings was reduced substantially in the experimental group over the entire session. Figure 28 illustrates the difference in residence preference which resulted from exposure to rectangular-pulse-modulated microwaves. It is easily seen that the animals did not exhibit a preference between the compartments in the absence of microwaves (control group). Rats exposed to 0.4 or 0.9 mW/cm² (133 or 300 mW/cm² peak power density) exhibited an avoidance of the unshielded compartment. Evidently, the animals no longer moved randomly between the shielded and exposed sides but spent most of their time in the shielded side (see Fig. 27).

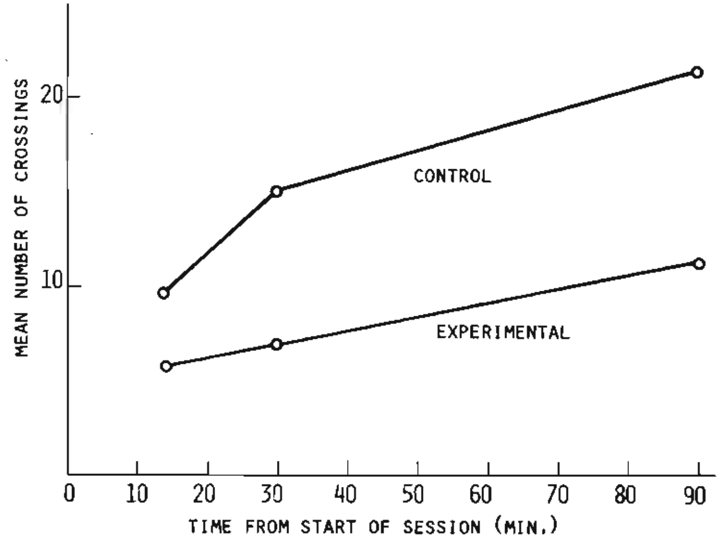

Figure 27. Means of cumulative number of crossings for rats in a free-choice, microwave-induced avoidance conditioning experiment.

Every effort was made in this investigation to eliminate all possible differential cues, other than pulsed microwaves, that the rat might use to discriminate between the exposed and the shielded sides of the barrier box. The possibility of odor cues was controlled by keeping a small amount of litter of the same type that was used in the home cages in the barrier boxes and removing it at the end of each session. The daily order of control and experimental runs were randomized, as was the box used each day. The occurrence of avoidance behavior in the absence of explicit loca-

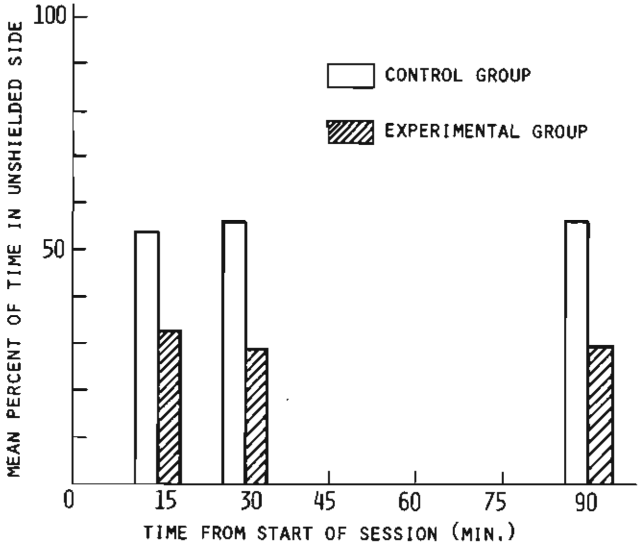

Figure 28. Residence preference of rats tested during pulse-modulated microwave exposure.

tion cues led the investigators to conclude that the rats could perceive pulse-modulated microwave energy. This perception would depend on pulse-modulated microwaves possessing some stimulus properties. Frey and Feld reported that rats seemed to find the pulsed microwave to be aversive and are motivated to actively avoid it. Furthermore, they observed comparable weight gain in both the control and experimental group, suggesting that the animals remained in comparable good health throughout the entire experiment.

Additional investigations of microwave-induced auditory sensation involved a discriminative control of appetitive behavior by pulse-modulated microwaves in rats (Johnson et al., 1976). The aim of this investigation was to substitute pulse-modulated microwave for the previously well-discriminated tone cue (acoustic click).

The subjects were six female white rats (Wistar-derived strain) from 300 to 350 g in weight. The animals were partially deprived of food until their weight fell to 80 percent of that before deprivation. They were then placed in a body-movement restrainer and trained to perform a head-raising response for food pellets. During daily ninety-minute sessions, individual rats were presented alternating five-minute stimulus-on/stimulus-off periods during which food was made available as a reward for responding only during stimulus-on periods. The initial stimulus was a 7.5 kHz acoustic click produced by a high frequency speaker driven by a 1 volt, 3 μsec wide rectangular pulse at the rate of 10 pulses per second.

The general arrangements for the behavioral test are shown in Figure 29. The rat holder shown in Fig. 30 was designed to provide necessary restriction of body movement to control for energy dosing during experimentation, while permitting sufficient movement of the animal's head and neck for the collection of behavioral data. The holder was constructed of acrylic to reduce the amount of distortion of the incident microwave field. The spaced bar construction provided adequate ventilation for control of the animal's surface temperature and permitted easy placement of the animal. After the first few sessions, the rats learned to position themselves in the holder by running into the cone and extending their heads through the opening. The holder with the rat was then placed in a receiver as shown in Figure 31. The receiver positioned the rat in such a way that the rat could move its head in a short vertical arc. The small head movement, allowing its nose to interrupt the light beam, constituted the operant behavior. The in-

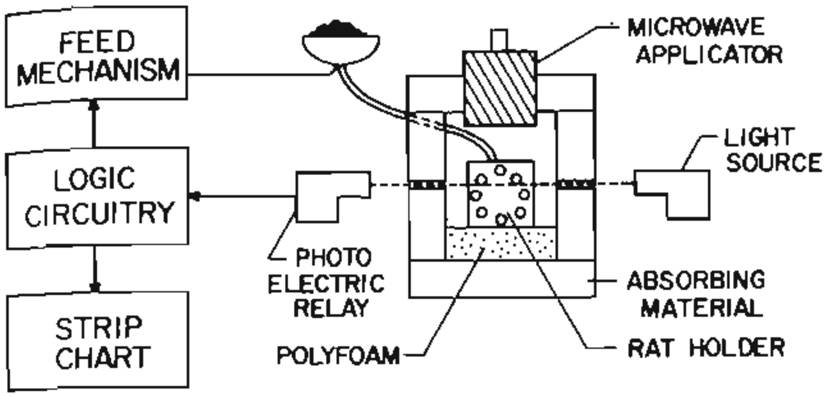

Figure 29. Schematic diagram of apparatus for testing head-raising-for-food response of rats.

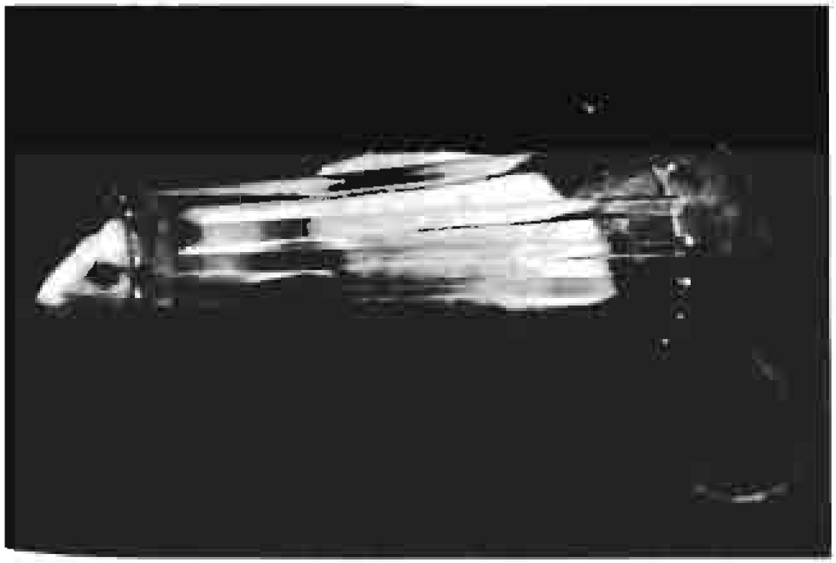

Figure 30. Rat in a conical body restrainer.

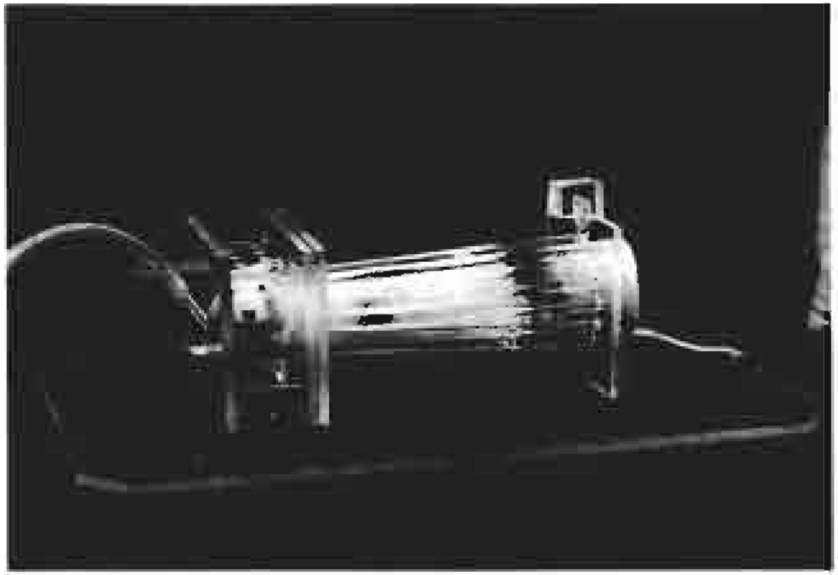

Figure 31. Rat in a restrainer placed on a baseplate receiver with head extended into operant device.

terrupted light beam caused a switch to close which led to the delivery of food. An external feeder caused a small, 45 mg food pellet to be delivered via a polyethylene tube to a receptacle which was constructed of the same material as the holder and located directly below the rat's head. The rat was able to eat the food-pellet with only a slight downward movement of its head. Standard relays, counters, and recorders were used to program the stimuli and record the responses. A closed circuit television system was used to observe the animal's behavior during each test session. This system provided a consistent means of investigating behavior adaptable to the special requirements of microwave radiation in the exposure chamber (Lin et al., 1974; Johnson et al., 1976; Lin et al., 1977).

After these animals learned to inhibit their responses so that 85 to 90 percent of a given session's total responses were made during the appropriate stimulus-on periods, individual animals were then exposed to thirty seconds of pulse-modulated 918 MHz microwaves at the same pulse width and pulse repetition rate as the acoustic stimulus at average incident power densities less than 5 mW/cm^2. These animals began to respond immediately (Fig. 32). During subsequent sessions in which microwave, not the acoustic click, was present during the stimulus-on periods, all animals demonstrated a continued ability to respond at the 85 to 90 percent level. This clearly suggested an auditory component in the microwave control of this behavior.

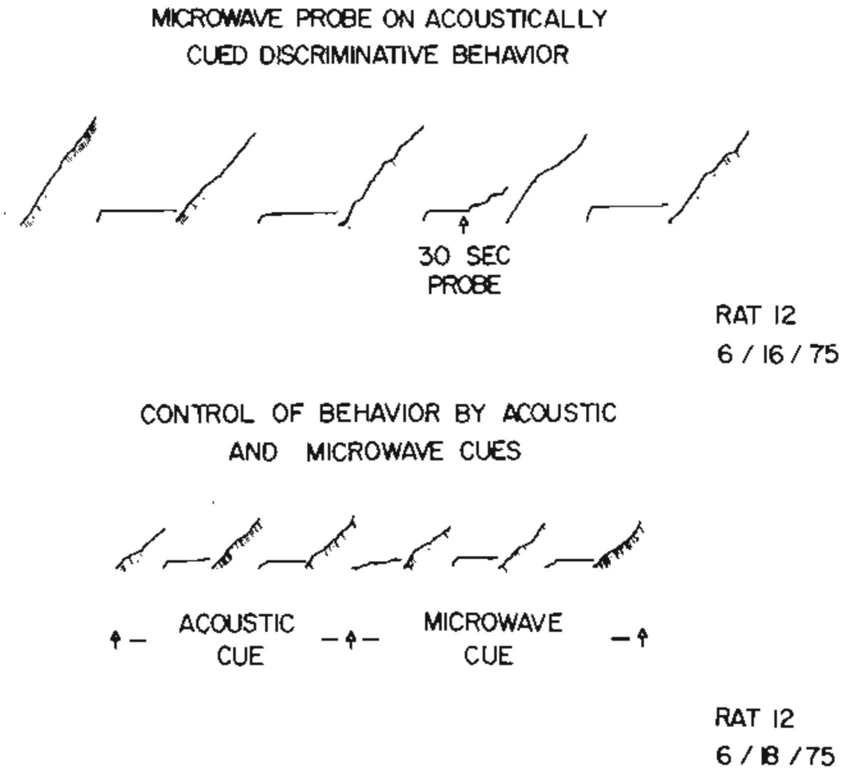

Figure 32. Cumulative record showing an animal's performance. Top: In response to thirty-second microwave probe, rat begins to respond as if acoustic cue had been presented. Bottom: Rat responds equally well during presentation of acoustic and microwave stimulation. (From Johnson et al.: Discriminative control. In Johnson and Shore (Eds.): *Biological Effects of Electromagnetic Waves*, HEW Publication, 1976.)

Detection in Cats

Detection of pulse-modulated microwaves in cats has been reported by Frey (1966, 1971). He indicated that cats can use pulse-modulated microwave radiation as a cue in avoidance conditioning experiments. Unfortunately, he did not give any details regarding the experimental protocol nor did he present any detailed results.

Certain facts seem clear from the above studies. The immediate detection of microwaves can be mediated by the auditory system. The auditory detection occurs only if the microwave energy is modulated. Rectangular pulses seemed more effective than other pulse shapes. In neither human nor animal detection is it understood if the action is on the receptor cell (nervous system, neural structures) or on some accessory tissues. Pulse-modulated microwaves could be having a direct effect on the primary auditory nerve. It is also possible that something in the head is vibrating in the presence of pulsed microwaves and that this detection is mediated by the normal bone conduction hearing route. Evidences for and against various interaction mechanisms will be presented in a later chapter.

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Chapter 4

Neurophysiological Correlations

MICROWAVE-INDUCED auditory sensation has been described in several laboratories in terms of its ability to excite the peripheral and central nervous systems of laboratory animals and of the similarity between its evoked electrical potentials and those produced by conventional acoustic stimuli. Any quantified experimental findings that are related to these characteristics will further the understanding of pulsed microwave interactions with the auditory system and may confirm or refute hypotheses about direct neural excitation. A number of interesting studies designed to establish the site of interaction and the mechanism involved in the pulsed microwave-induced auditory sensation have appeared.

In this chapter, experimental observations on the electrical events that occur along the auditory pathways in response to pulse-modulated microwave exposure will be summarized. Studies such as those of Frey (1967) and Guy et al. (1973) showed that appropriately modulated microwaves evoke electrical activities from the brains of laboratory animals. The compound potentials recorded from the auditory nerve (Taylor and Ashleman, 1974) and observations made in the more central portions of the auditory system (Guy et al., 1975) implied that acoustic stimuli and pulsed microwaves are affecting the nervous system in the same manner. This interpretation was reinforced by the finding that bilateral cochlear destruction resulted in total loss of thalamic and cortical evoked potentials due to pulsed microwaves and acoustic inputs (Taylor and Ashleman, 1974), suggesting that the perception of pulsed microwave energy was a bona fide auditory effect. Recent observations (Chou et al., 1975) of cochlear microphonics in guinea pigs under higher incident power conditions also corroborated this suggestion.

ELECTROPHYSIOLOGICAL RECORDINGS

There are several different types of electrical activity which may be recorded from the ear and the brain during stimulation by sound. These electrical phenomena include the action potentials of the auditory cortex, thalamus, and auditory nerve, and the cochlear microphonics. If the electrical potentials evoked by pulsed microwaves are found to have characteristics similar to those evoked by conventional acoustic stimuli, this would vigorously support the observation that pulse-modulated microwaves could induce auditory sensation in mammals. Further, if pulsed microwave-evoked potentials are recorded from each of these sites, it would support the contention that microwave-induced auditory sensations are mediated at the periphery, as are the sensations of conventional acoustic inputs.

Primary Auditory Cortex

Several investigators have reported evoked auditory responses in the cortex of laboratory animals exposed to pulse-modulated microwaves. Using scalp electrodes affixed to the top of the head and the side of the head under the ear, Rissmann and Cain (1975) reported recordings of similar electrical activities in two cats, a beagle puppy, and two chinchillas irradiated with rectangular pulses 5-15 μsec wide at 3000 MHz and acoustic clicks from a speaker.

In another study (Taylor and Ashleman, 1974), three cats weighing 2.0 to 3.4 kg were anesthetized with sodium pentobarbital (50 mg/kg) following premedication with Acepromazine® and were administered atropine sulfate (0.2 mg) after induction of anesthesia. The cats were placed on a heating pad controlled by a rectal temperature monitor. Each cat was fitted with a piezoelectric crystal transducer for the presentation of acoustic stimuli via bone conduction. A ring of Rexolite® plastic 18 mm in diameter and 2 mm thick was fitted to the dorsal surface of the frontal bone just anterior to the coronal suture and was held rigidly in place by nylon screws and dental acrylic cement (Fig. 33). The interior of the ring was threaded to facilitate installation and to allow easy removal of the crystal during microwave exposure. This prevented possible artifacts from excitation of the transducer by the microwave field or from energy concentration at the point of contact.

Next, the cats were placed in a head holder constructed of low

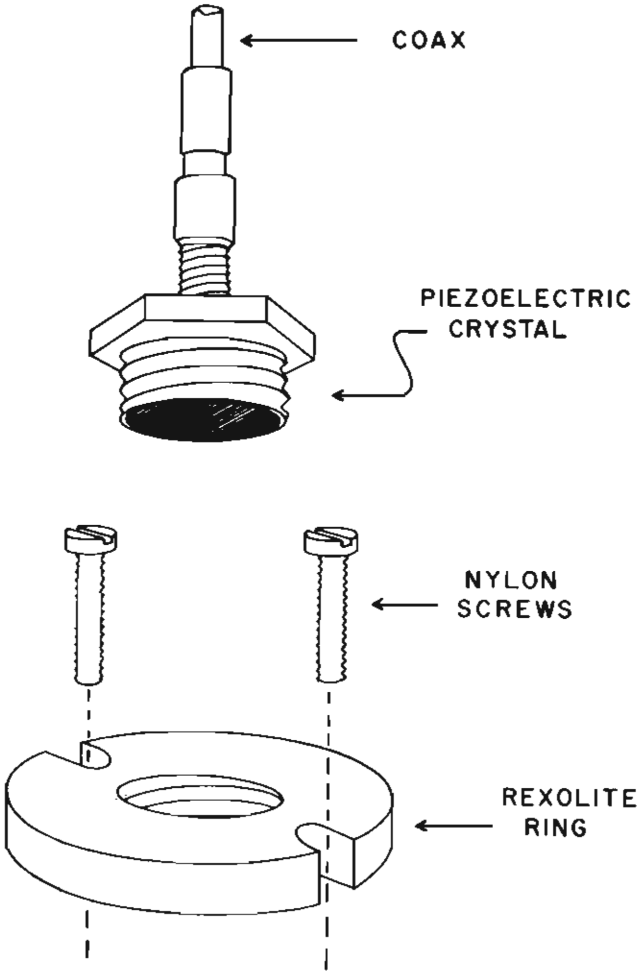

Figure 33. Schematic of piezoelectric transducer for providing bone-conducted acoustic stimuli to the animal. (From Guy et al.: Microwave induced acoustic effects. Courtesy of *Ann NY Acad Sci, 247:*194-218, 1975.)

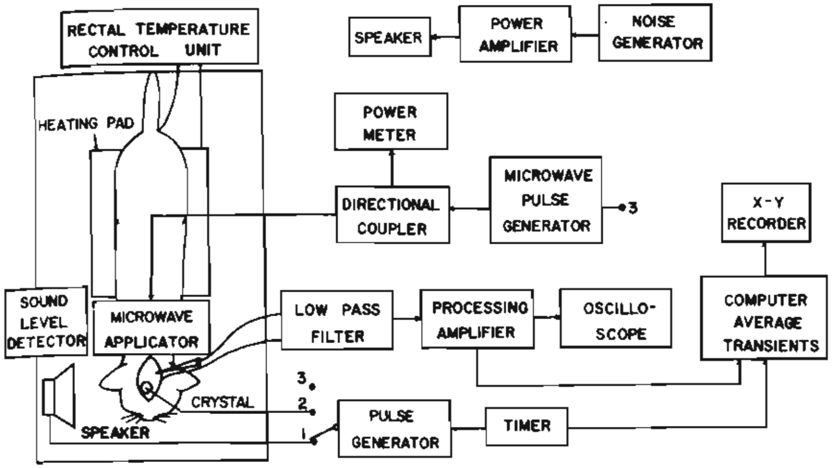

Figure 34. Block diagram of equipment used to test the microwave-induced auditory effect in the cat. (From Guy et al.: Microwave induced acoustic effects. Courtesy of *Ann NY Acad Sci, 247:*194-218, 1975.)

loss dielectric slabs (Fig. 34). Skin and soft tissue were excised to expose the temporal bone and lateral portion of the parietal bone. Portions of these bony elements were removed to expose the ectosylvian gyrus. A microwave-transparent carbon electrode was then placed, under direct observation, on the surface of the anterior ectosylvian gyrus. The evoked responses were led from the active electrodes through high resistance carbon leads to a microwave filter and then to a Tektronix 2A61 amplifier and an oscilloscope (Tektronix 565). Some of the signals were further processed with a signal averaging computer (TMC400C). The averaged signal was printed out on an X-Y plotter (Moseley 7000 AM).

Following surgical exposure of the auditory cortex, the animal was allowed to stabilize until there was a consistent response waveform and latency as evoked by a piezoelectric transducer driven with 10 μsec wide square pulses at a rate of one pulse per second. The transducer was then removed from the mounting ring and the microwave stimuli applied at the same rate but at an increased pulse width of 32 μsec. The microwave stimuli consisted of rectangular pulses of 2450 MHz energy produced by a signal generator (AML model PH40K) and was fed through a coaxial cable to a directional coupler and a vertically polarized horn antenna. The antenna was positioned posterolaterally to the cat's head at a distance of 10 cm and an angle of 30° from the sagittal plane. The incident power levels were measured by a thermister mount and power meter combination (HP 477 and 430C, respectively).

Figure 35 shows typical evoked signals recorded from the auditory cortex following conventional acoustic and pulsed-microwave stimulation. It is interesting to note the remarkable similarity between these responses. During the surgical procedures, most of the lateral and ventral surface of the bulla was exposed by reflection and removal of the overlying soft tissue. The lateral wall of the bulla was perforated with a drill and the hole was then enlarged with a small rongeur until both round windows could be clearly visualized. When clear-cut responses were established, the cochlea was disabled by careful perforation of the round window with a microdissecting knife and aspiration of perilymph. Aspiration of the contralateral cochlea led to marked reduction of the amplitude of the evoked potentials. Disablement of the remaining cochlea in these animals resulted in total loss of the signal, as shown in Figure 35. Taylor and Ashleman were unable to detect activity following cochlear manipulation even though they took additional steps, such as increasing numbers of successive signals averaged.

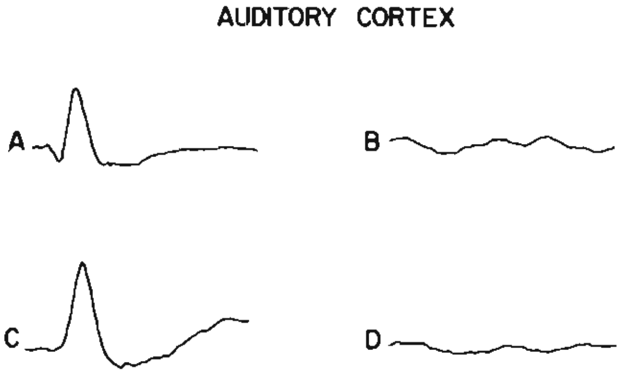

Figure 35. Cortical responses in the cat to acoustic (A & B) and pulsed microwave stimulation (C & D) before and after cochlear ablation. A & C recorded before and B & D after bilateral destruction of the cochlea. (From Taylor and Ashleman: Analysis of central nervous system involvement in the microwave auditory effect. Courtesy of *Brain Research, 74*:201-208, 1974.)

Brain Stem

Pulsed microwave-evoked potentials have also been recorded from the brain stems of cats. Frey (1967) implanted a coaxial electrode in the brain stem of eleven cats with the help of a Kopf stereotaxic instrument. The electrode was affixed to the skull by nylon screws and dental acrylic plastic while the cat was under Fluothane® anesthesia. After a four to six week recovery period, the cat was placed in a polystyrene head holder which was located inside an Eccosorb AN-77 (Emerson & Cuming, Inc.) lined wooden exposure chamber. The electrode previously implanted was connected via coaxial cable to a preamplifier, oscilloscope, transient signal averager, and recorder. Pulses of 10 μsec wide acoustic and 1200-1535 MHz microwave energies were applied at five-minute intervals. The evoked potentials are shown in Figure 36 for four brain stem locations. Because of the similarity of the acoustic and microwave evoked activities, and because the responses were seen immediately before but not immediately after death, Frey concluded that the signals were neural rather than an artifact of the experimental protocol. He had also suggested that the effect might be the result of direct stimulation of the auditory nervous system at a site central to conventional sound perception. He based this suggestion mainly on his failure to observe any apparent cochlear microphonics associated with pulse-modulated microwaves in cats and guinea pigs (Frey, 1967, 1971) even with incident power densities far above that needed to induce the auditory effect in cats.

Considerable caution must be taken in accepting Frey's results, however, because of the recording technique used. In his experiment, the evoked potentials were sensed by a metal coaxial electrode. Despite the fact that the coaxial electrode was developed with the intent to avoid microwave energy induced on the electrode, and despite his reports that during extensive testing the electrode had shown no indication of energy pickup (Frey, 1968), coaxial electrode of similar construction has been shown to increase the peak microwave absorption in the brain tissue surrounding it by as much as two orders of magnitude (see Fig. 37

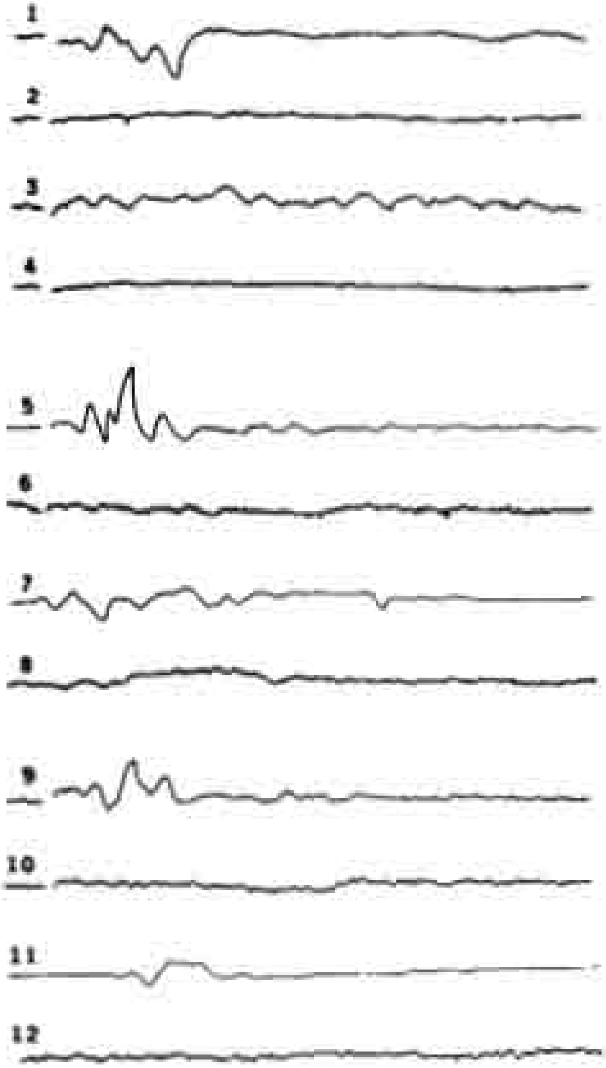

Figure 36. Averaged brain-stem-evoked response data. Electrode tip was in the area of the subthalamic nucleus, 1, 2; reticular formation, 3, 4; inferior olivary nucleus, 5-8; and paramedian reticular nucleus, 9-12. Traces 1, 3, 5, and 9 were obtained during irradiation with pulsed RF energy a few minutes after death. Substituting pulsed acoustic energy for RF energy, traces 7 and 11 were obtained before death and 8 and 12 after death. (From Frey: Biological function as influenced by low-power modulated RF energy. Courtesy of *IEEE Trans Microwave Theory Tech*, 19:153-164, 1971.)

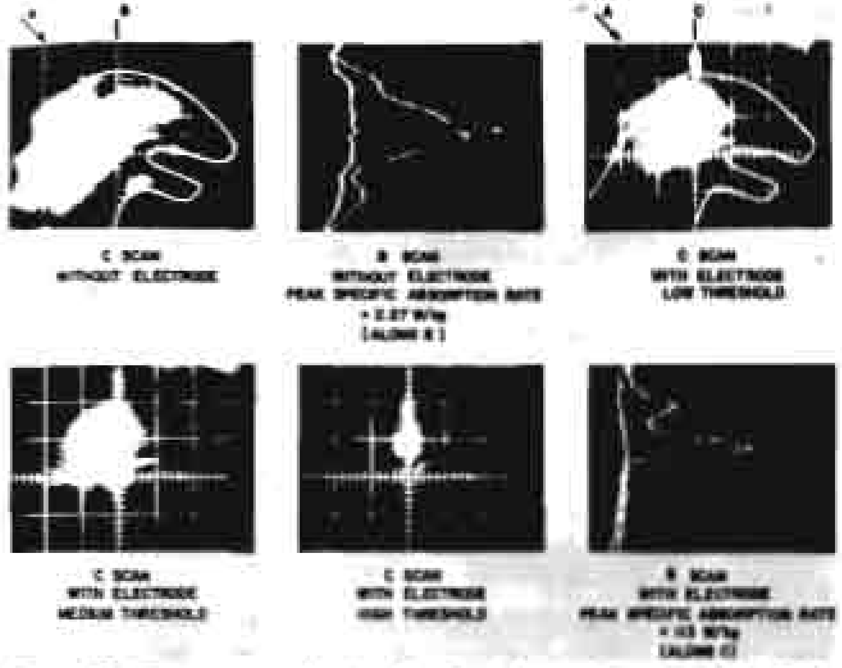

Figure 37. Thermograms showing the effect of a metallic coaxial electrode, similar to those used by Frey, on the microwave absorption pattern in the brain of a cat irradiated with near zone 918 MHz continuous wave radiation. The bright spots on the C-scans show patterns of microwave absorption. The C-scan obtained with a high-threshold shows clearly the increased energy absorption in the region where the tip of the electrode is located. The differences between the curves in the B-scans are proportional to absorbed energy. The incident power density is 2.5 mW/cm^2 and is directed along A with the electric field oriented in the plane of the paper. Scale: 1 div = 2 cm. (From Guy et al.: The effect of microwave radiation. *Proc Int Microwave Power Symp*, May 1972.)

and Guy et al., 1972). Therefore, by using this electrode, the possibility of brain tissue stimulation by microwave current directly induced on the electrode cannot be completely ruled out.

Much stronger evidence for pulse-modulated microwave-evoked electrical activities in the brain stem came from the electrophysiological data reported by Guy et al. (1973, 1975) and Taylor and Ashleman (1974). Using a glass microelectrode filled with Ringer's solution and with a tip diameter of 80 to 100 micrometers, these investigators recorded compound action potentials from the medial geniculate body of cats exposed to 918 and 2450 MHz microwave pulses. Because the dielectric properties of Ringer's solution and brain tissues are similar, the glass pipettes filled with Ringer's solution were essentially transparent to microwaves when used for recording bioelectric signals from the depth of the brain (Guy et al., 1972; Johnson and Guy, 1972).

Cats were anesthetized intravenously with alpha-chloralose (55 mg/kg) in Ringer's solution (20 cc), and 0.2 mg of atropine sulfate was administered intramuscularly after induction of anesthesia. Cats were paralyzed with Flaxedil® (20 mg) and then maintained on artificial respiration. The body temperature of the cats was held constant at 38°C by a heating pad connected to a rectal temperature control unit. A pair of wooden ear bars was used to hold the cat in a Kopf stereotaxic instrument. In order to minimize the distortion of the fields around the cat's head, all metal pieces for fixing the inferior orbit and the upper jaw were replaced by wooden pieces.

Following exposure of the dorsal surface of the skull by conventional methods of skin incision and reflection of the underlying muscle, a burr hole was made in the parietal bone. Before insertion of the electrode, each cat was fitted with a piezoelectric crystal transducer for providing acoustic stimuli by bone conduction (see previous section). The electrode was directed toward the medial geniculate body by the standard stereotaxic method (Snider and Niemer, 1961). The electrode and accompanying ground connection were coupled via high resistance 1000 ohms/cm carbon-loaded plastic conductors which are transparent to microwaves in air, through a low pass microwave filter, to a high input impedance physiological signal processing amplifier, oscilloscope, computer of average transients, and X-Y plotter (see Fig. 34). The responses evoked by acoustic clicks from a loudspeaker were continuously monitored as the electrode was advanced vertically. Proper placement of the electrode tip was assumed when the evoked responses displayed the proper latency period. The electrode placement was verified in some of the animals by histological examination of the brains.

Acoustic clicks were presented to the animal by exciting either the loudspeaker placed 17 cm to the right of the center line of the cat's head for air conduction or the piezoelectric transducer with square pulses 1 to 30 μsec in duration at 1 pulse per second from a Hewlett-Packard Model 214A pulse generator. Microwave pulses 918 or 2450 MHz of the same pulse characteristics were provided by horn or aperture antennas located 8 cm away from the occipital pole of the cat and driven by an AML PH 40K signal source. In the absence of the cat, a Narda 8100 power monitor was used to measure the average incident power density to the location where the cat's head was placed, and the bi-directional coupler and power meter were used to measure incident power to the antennas.

Figure 38 presents some typical evoked responses recorded from the medial geniculate body due to acoustic and 2450 MHz

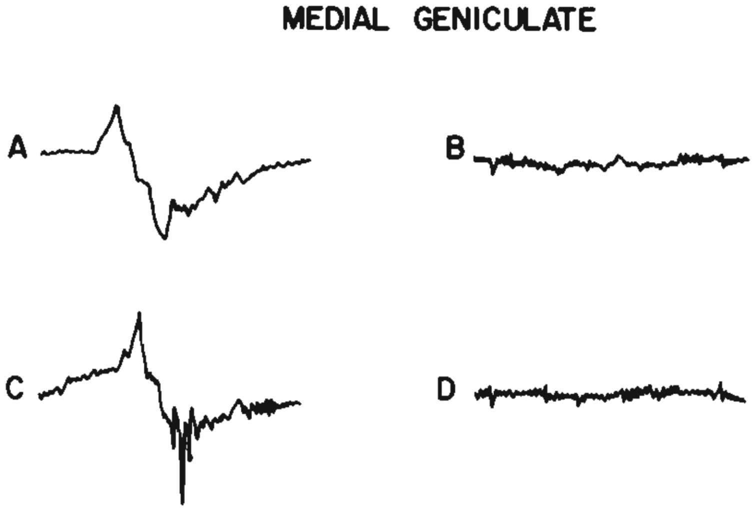

Figure 38. Evoked responses from medial geniculate body of the cat to acoustic (A & B) and pulsed microwave stimulation (C & D) before and after cochlear ablation. A & C recorded before and B & D after bilateral destruction of the cochlea. (From Taylor and Ashleman: Analysis of central nervous system involvement in the microwave auditory effect. Courtesy of *Brain Research*, *74*:201-208, 1974.)

microwave pulse stimulation. The recordings were made on the X-Y recorder based on forty averages taken with a signal averaging computer (Technical Measurements Corporation Model 646). The similarities between the evoked responses are apparent, and cochlear damage led to total loss of these responses to both acoustic and microwave stimuli.

The late slow wave in the general somatosensory thalamic region (VPL) was the same for both conventional acoustic click and pulsed microwave stimulation (Fig. 39). That such pulses were eliciting similar responses in regions of the brain other than auditory areas indicated that the microwave-evoked response was not merely an artifact generated in either the animal preparation or the recording equipment.

Evoked responses from the medial geniculate body of the cat were also obtained for two animals using X-band pulses at frequencies between 8.67 GHz and 9.16 GHz. The required energy per pulse to elicit the responses was significantly higher than required for the other frequencies. For this case, the X-band horn had to be placed within a few centimeters from the exposed brain surface of the animal (through the 1.0 cm diameter electrode access hole in the skull). No response could be elicited for an animal in which the electrode access port through the skull was limited to a diameter slightly larger than the electrode. When the skull was bared, there was still no elicited response; when the hole in the skull was enlarged, however, a response was obtained.

Rissmann and Cain (1975) also reported recordings of evoked electrical activities from the inferior colliculus of cats exposed to 10 μsec wide 3000 MHz microwave pulses. They also used glass microelectrodes filled with Ringer's solution. The experimental procedures were closely related to those just described. They found that the evoked potentials in response to acoustic and pulsed microwave stimuli disappeared in these animals following replacement of the antenna with a dummy load and following death.

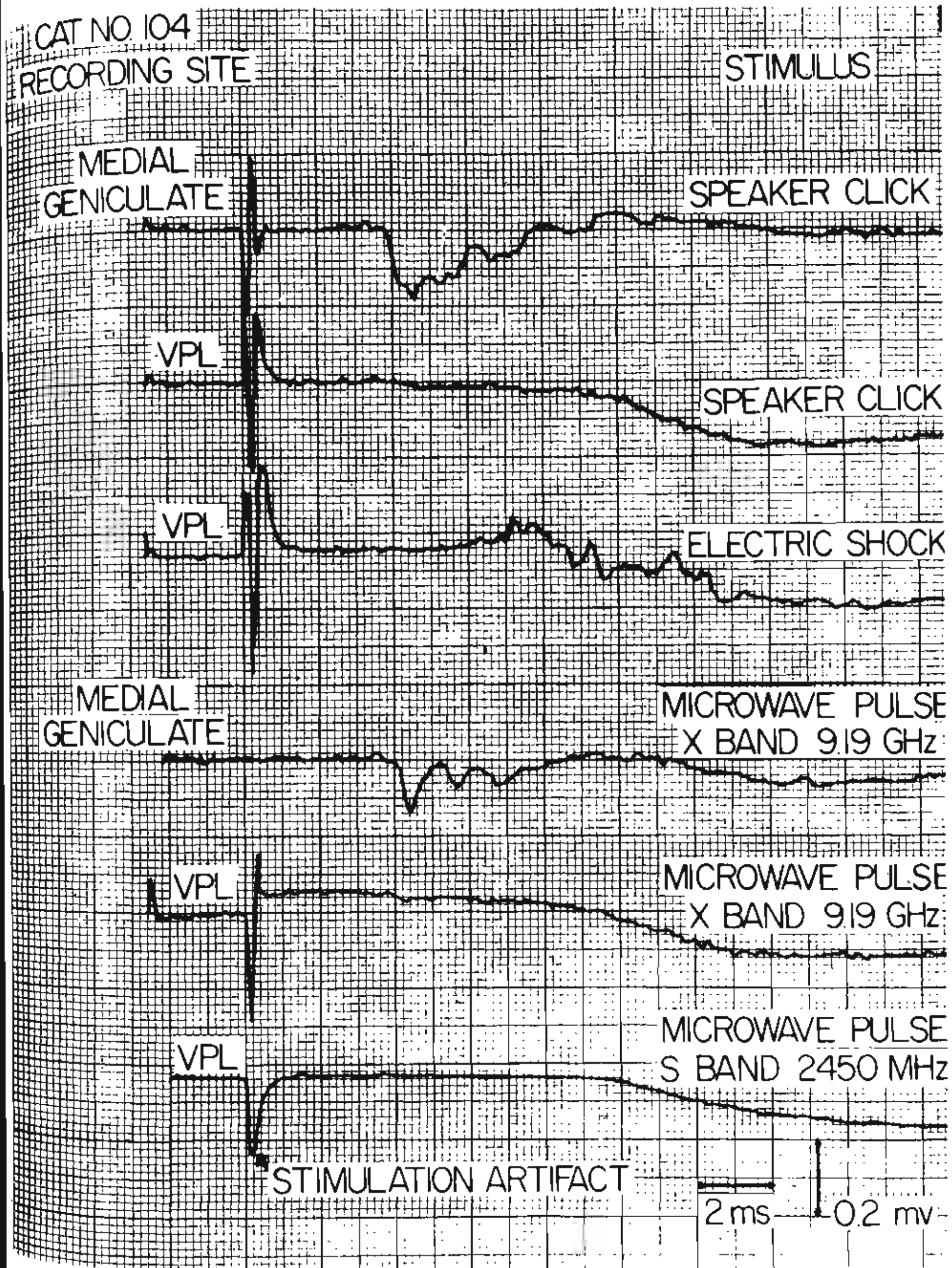

Figure 39. Evoked cross-modal brain responses due to acoustic and microwave stimuli. (From Guy et al.: Microwave induced acoustic effects. Courtesy of *Ann NY Acad Sci. 247*:194-218, 1975.)

Eighth Cranial Nerve

Three cats, from a group of nine cats weighing from 2.0 to 3.4 kg used to establish the site of interaction of microwave-induced auditory sensation (Taylor and Ashleman, 1974; Guy et al., 1975), were anesthetized with sodium pentobarbital (50 mg/kg) following premedication with Acepromazine®. The cats were placed in the head holder described previously. After reflection of the auricle and removal of the underlying muscles to expose the temporal bone, a hole was drilled to remove most of the squamous portion and a portion of the parietal bone. Through this opening, brain tissue was removed to expose the tentorium cerebelli. Using a drill and rongeur, an opening approximately 1.5 cm in diameter was made in the tentorium. The dissection was then continued with the aid of a B & L dissecting microscope. Cerebellar tissue was removed to expose the eighth cranial nerve as it emerged from the internal auditory meatus. A dissecting microscope and a micromanipulator were used to insert a Ringer's solution filled 100 μ diameter tip glass microelectrode within the nerve. The exposure apparatus and recording instrumentation were similar to that shown in Figure 34. During recording, the auditory nerve and surrounding tissue were covered with warm mineral oil.

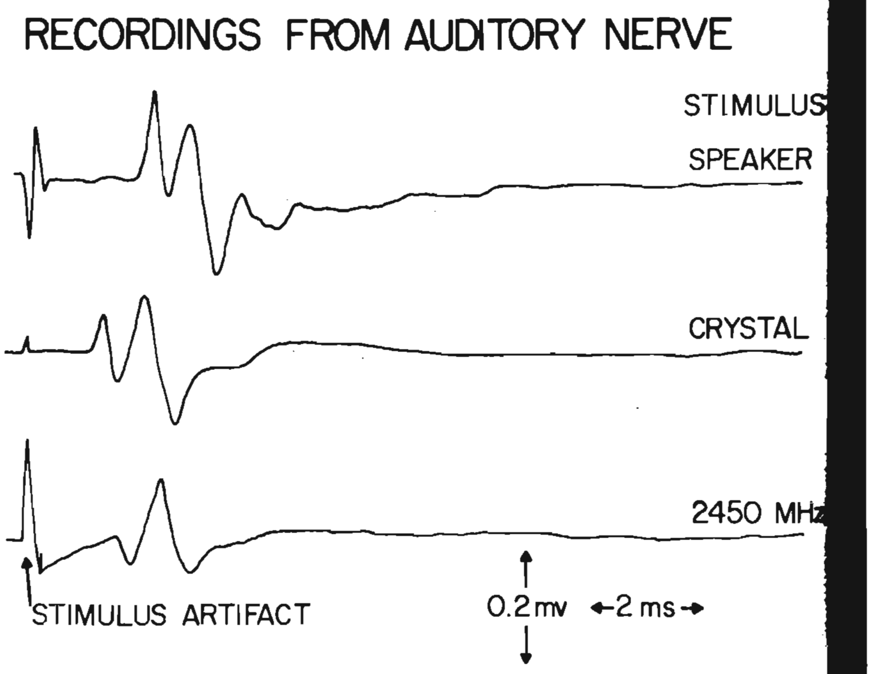

Figure 40. Auditory nerve responses of cat irradiated with acoustic and microwave pulses.

Acoustic-click- and microwave-pulse-evoked signals in the eighth cranial nerve are shown in Figure 40. Unilateral ablation led to total loss of these evoked potentials to both acoustic and microwave stimuli. It can be seen that microwave-induced activity is very similar to that evoked by a conventional acoustic click from a piezoelectric transducer.

Cochlear Round Window

In another series of experiments (Guy et al., 1972, 1975) a high resistance carbon electrode similar to that employed in the cortical recordings was applied to the round window of the cochlea to record activity evoked by acoustic clicks and microwave pulses.

Before the cats were placed in the stereotaxic instrument, the lateral and ventral surface of the auditory bulla as exposed by reflection and removal of the overlying soft tissue. The lateral wall of the bulla was perforated with a drill and was enlarged with a small rongeur until the round window of the cochlea could be clearly visualized. A carbon electrode was cemented to the round window and connected to a low pass microwave filter for further signal processing (Fig. 34). The remaining surgical procedure was similar to that performed for the medial geniculate experiments, including the attachment of the piezoelectric transducer.

It can be seen from Figure 41 that both acoustic stimuli and microwave pulses elicited activity at the round window. The first trace shows the composite cochlear microphonic and N_1 and N_2 auditory nerve responses elicited by a loudspeaker pulse from an animal. The cochlear microphonic was quite strong in amplitude. When the auditory system of the same animal was stimulated by microwave pulses, a microwave artifact pulse and clear N_1 and N_2 auditory nerve responses were elicited, but there was no evidence of a cochlear microphonic as seen from the second trace in Figure 41. The cochlear microphonic in this case is either extremely brief and lost in the microwave artifact, greatly attenuated, or absent completely.

The role of the cochlea in microwave-induced auditory phenomena has been discounted, partly on the basis of not observing a microphonic in either cats or guinea pigs (Frey, 1967, 1971). Guy et al., however, have found in some animals that the cochlear microphonic is considerably reduced (third trace in Figure 41) or not present at all (fourth trace in Figure 41) when the auditory system of the animal is stimulated by an acoustic click. It is interesting to note that Wever (1966) has pointed out a number of factors that would prevent the observance of a cochlear microphonic, especially at low stimulus intensity. These were reported in studies in which the auditory thresholds of cats, as determined by behavioral tasks, were established as being 40 db below the first stimulus level effective in eliciting cochlear microphonics of sufficient amplitude to be observed with the conventional oscilloscopes. Thus, considering the fact that the microwave pulse generator used was capable of only providing 10 to 17 db gain in peak power over that corresponding to the threshold of evoked responses, the absence of a microwave-evoked cochlear microphonic does not necessarily rule out the hypothesis that microwave-induced auditory sensation is mediated at the periphery as are conventional acoustic stimuli.

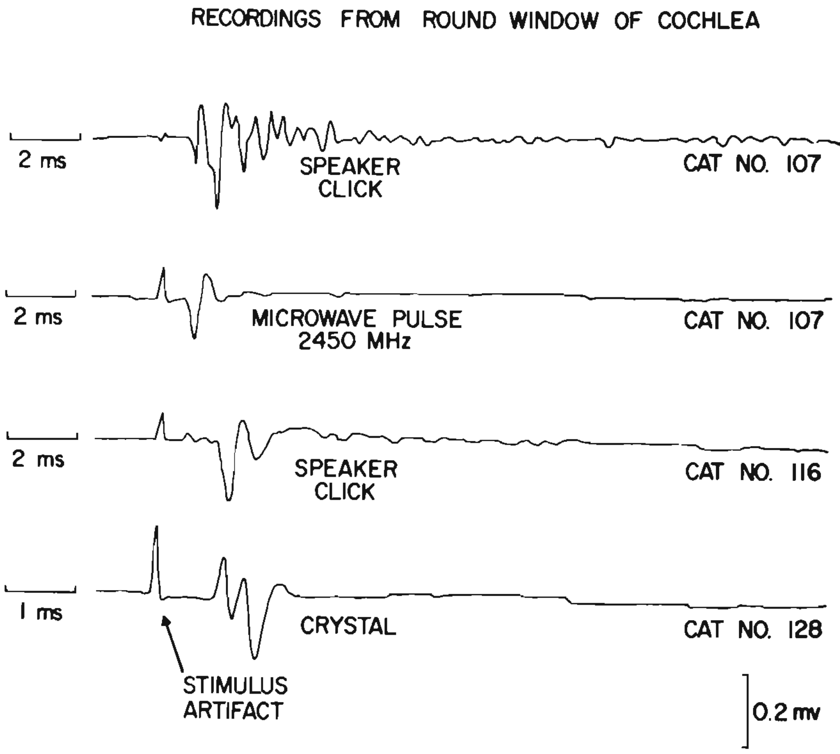

Figure 41. Recordings from the round window of the cat cochlea elicited by acoustic and microwave stimuli. (From Guy et al.: Microwave induced acoustic effects. Courtesy of *Ann NY Acad Sci, 247:*194-218, 1975.)

Cochlear Microphonics

The findings in the eighth cranial nerve, the brain stem, and the primary auditory cortex described in the previous sections indicated that the microwave-induced auditory effect is exerted on the animal in a manner similar to that of conventional acoustic stimuli. Also, the elimination of the first stage of sound transduction affected the central nervous system's response to acoustic and microwave energy in the same way, i.e. the evoked electrical activities of all three sites were abolished by cochlear disablement, suggesting that the locus of initial interaction of pulse-modulated microwave energy with the auditory system resides peripherally with respect to the cochlea. On the other hand, cochlear microphonic, the signature of mechanical distortion of cochlear hair-cell, has never been observed under experimental situations. This has led to the suggestion that pulsed microwaves, in contrast to conventional acoustic stimuli, might not act on any sensor prior to acting directly on the inner ear apparatus.

As mentioned in the previous section, failure to observe any microwave-induced cochlear microphonic in experimental animals may have been due to limitations of the output of the microwave pulse generator or a large microwave-pulse-artifact which concealed the cochlear microphonic. Chou et al. (1975) have successfully demonstrated the existence of microwave-induced cochlear microphonics in laboratory animals with clearly visible acoustically evoked cochlear microphonics by minimizing the problems just mentioned.

Five guinea pigs weighing 400 to 600 g were anesthetized with sodium pentobarbital (40 mg/kg) and allowed to breathe normally through a trachial cannula. After clearing either the left or right auditory bulla, a fine carbon electrode was inserted against the round window and cemented onto the bulla. The animals were then screened on the basis of whether the amplitude of the cochlear microphonic evoked by an acoustic click exceeded 0.5 mV. If the answer was positive, the guinea pig's head was then placed in the cylindrical cavity through an opening on the side of the waveguide (Fig. 42). The head was supported by a microwave-transparent polystyrene foam block inside the cavity. With the animal's head inside, the cavity was tuned for maximum power to the head by adjusting the position of a sliding short located on one end and the depth of penetration of the animal's head. Since only 0.1 percent of the input power was detected to be leaking around the neck of the guinea pig, the available power was assumed to be completely absorbed by the subject. It was estimated that the average energy absorbed per pulse was an order of magnitude greater than those used in all previous experiments. The microwave pulse artifacts were greatly reduced by locating the microwave source (AML model PH 40K), the cavity, and the animal in a shielded room (Fig. 43) and recording the cochlear potentials via coaxial cables connected to differential amplifiers outside the shielded room.

Figure 42. Guinea pig with head inserted in the circular waveguide exposure chamber. (From Chou et al.: Cochlear microphonics generated by microwave pulses. Courtesy of *J Microwave Power, 10*:361-367, 1975.)

The animals were intermittently exposed to 918 MHz micro-

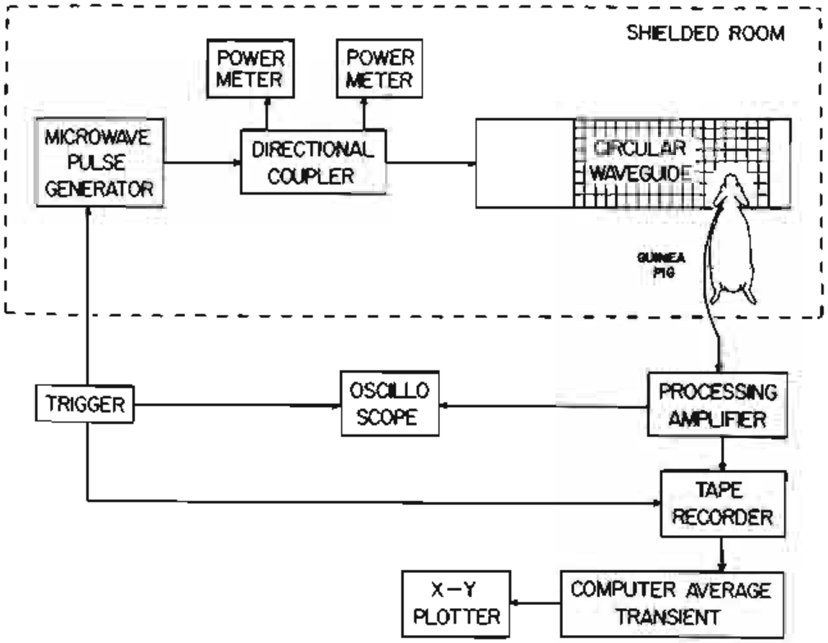

Figure 43. Schematic of experimental apparatus for recording microwave-induced cochlear microphonics in guinea pigs. (From Chou et al., Cochlear microphonics generated by microwave pulses. Courtesy of *J Microwave Power, 10*:361-367, 1975.)

wave pulses, 1 to 10 μsec in duration, for ninety second intervals at a pulse repetition frequency of 100 Hz and at peak powers up to 10 kW. The evoked electrical activities were stored on a magnetic tape system having a frequency response to 80 kHz. The responses were then processed either on-line or off-line using a signal averaging computer. Figure 44 illustrates the evoked potentials recorded from the round window of a guinea pig. It can be seen that the responses due to single acoustic clicks derived from a speaker driven at 10 kHz consisted of a cochlear microphonic which preceded the N_1 and N_2 auditory nerve responses. The polarity of the cochlear microphonic changed with a change in the polarity of the electrical energy driving the speaker, confirming the authenticity of the cochlear microphonics observed. When the same guinea pig was exposed to pulsed microwave, in addition to the well-defined N_1 and N_2 nerve responses, a high frequency (50 kHz) oscillation was seen preceding and immediately following the microwave stimulus artifact. Clearly, cochlear microphonic responses similar to that evoked by conventional acoustic stimuli can be induced by pulse-modulated microwave energy.

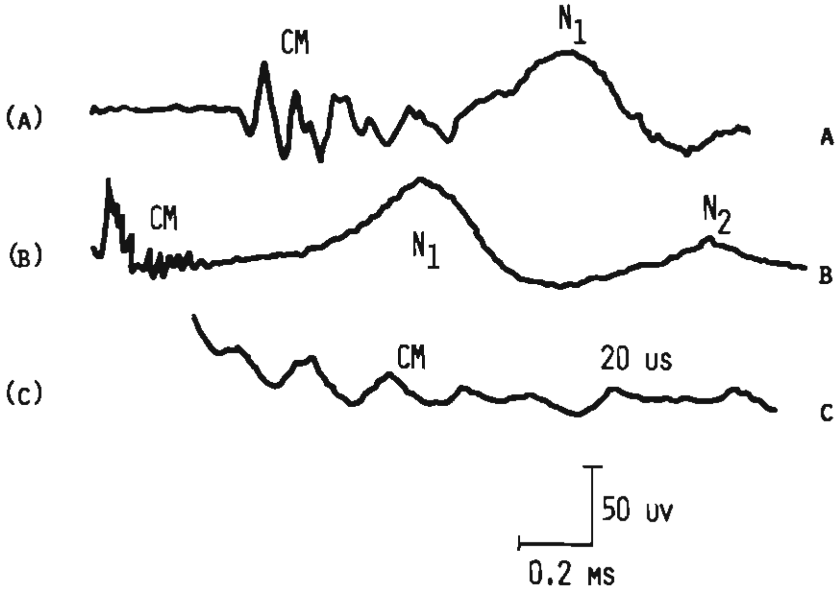

Figure 44. Evoked round window response in the guinea pig. (a) Acoustic click stimulus. (b) Single 918 MHz microwave pulse 10 μsec wide. The absorbed energy density is 1.33 j/kg. (c) Time expansion trace of (b). Initial 200 μsec. (From Chou et al.: Cochlear microphonics generated by microwave pulses. Courtesy of *J Microwave Power, 10*:361-367, 1975.)

Figure 45 compares the cochlear microphonic induced by microwave pulses of 1 μsec, 5 μsec, and 10 μsec at the same peak power (10 kW). Each trace is the average of 400 responses

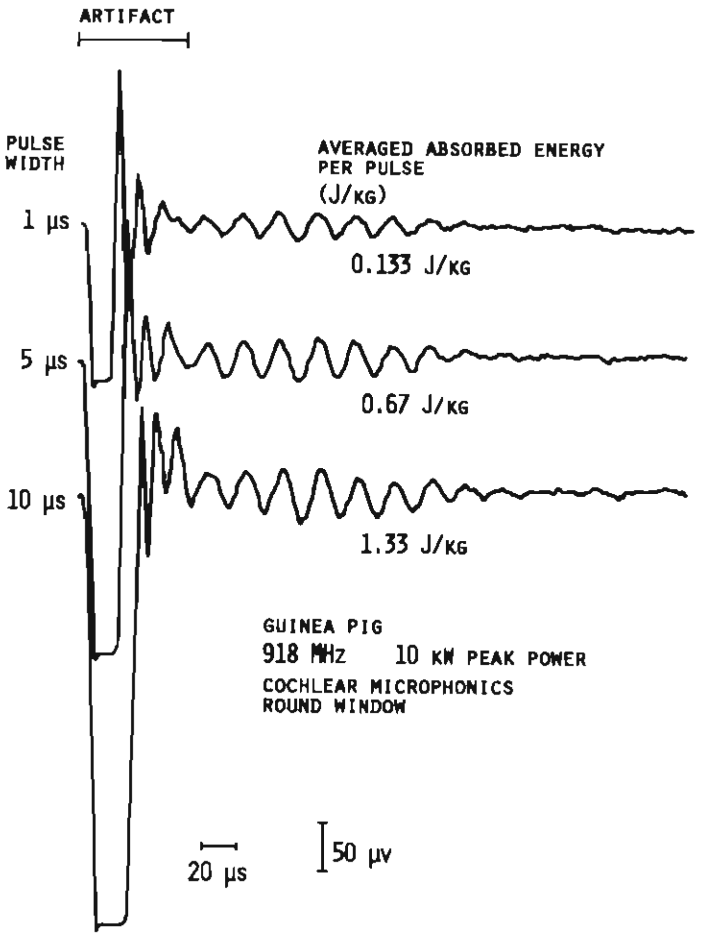

Figure 45. Cochlear microphonics evoked by 918 MHz microwave pulses at a peak power of 10 kW, but variable pulse width. (From Chou et al.: Cochlear microphonics generated by microwave pulses. Courtesy of *J Microwave Power, 10*:361-367, 1975.)

played back from the tape. It can be seen that, while the frequency of the cochlear microphonic remained constant, its amplitude increased as pulse width increased, and the energy absorption correspondingly increased. Further, latency of cochlear microphonic occurrence was nearly the same for all three cases. Following the death of the animal, whether by anoxia or by drug overdose, microwave-evoked nerve responses disappeared before the cochlear microphonic. Similar disappearances occurred during acoustical stimulation of the dead animal. After many minutes, the CM also disappeared, but the artifact persisted, indicating that the 50 kHz oscillatory signal is a genuine physiological response. More recently, Chou et al. (1976, 1977) have recorded 38 kHz cochlear microphonics from the round window of cats irradiated with 918 MHz microwaves.

In summary, the electrophysiological evidence presently available indicates that an auditory sensation can be induced in laboratory animals by pulse-modulated microwave energy. The results of the above studies suggest that microwave-induced auditory sensation is detected by the animal in a manner very similar to conventional sound detection and that the site of conversion from microwave to acoustic energy resides somewhere peripheral to the cochlea. It is not known, however, what structure in the head transduces the microwave energy to acoustic energy. The mechanism of interaction and the physiological implication are still not clear.

"THRESHOLD" DETERMINATION

In Chapter 3 a brief account of psychophysical efforts to establish the "threshold" of microwave-induced auditory sensation in humans was given. Several investigators attempted to ascertain the minimally effective magnitudes of pulsed microwave energy for evoking auditory system responses in laboratory animals. These "threshold" determinations, however, must be considered incomplete because measurements were usually attempted with too few subjects and at only a single frequency.

Using potentials from the medial geniculate body of the cat Guy et al. (1973, 1975) studied the threshold of pulse-modulated microwave-evoked auditory response. The experimental protocols were analogous to those described in the "Brain Stem" section. Tables IV and V present the threshold of 918 and 2450 MHz microwave-pulse-evoked thalamic responses. The peak absorbed energy density per pulse in these tables was measured with a thermographic method discussed previously by Guy (1971) and the results compared favorably with that calculated using a spherical model of the head (Johnson and Guy, 1972).

TABLE IV

THRESHOLD OF EVOKED AUDITORY RESPONSES IN CAT EXPOSED TO 918 MHz MICROWAVE PULSES AT ONE PULSE/SEC. BACKGROUND NOISE 64 DB

Pulse Width (μsec)	*Peak Incident Power Density (W/cm^2)*	*Avg. Incident Power Density (μW/cm^2)*	*Incident Energy Density per Pulse (μJ/cm^2)*	*Peak Rate of Absorption (W/g)*
3	5.80	17.4	17.4	4.1
5	3.88	19.4	19.4	2.76
10	2.26	22.6	22.6	1.6
15	1.37	20.6	20.6	0.97
20	1.17	20.6	20.6	0.83
25	0.97	24.3	24.3	0.69
32	0.80	28.3	28.3	0.63

TABLE V

THRESHOLD EVOKED AUDITORY RESPONSES IN CAT EXPOSED TO 2450 MHz MICROWAVE PULSES AT ONE PULSE/SEC. BACKGROUND NOISE 64 DB

Pulse Width (μsec)	*Peak Incident Power Density (W/cm^2)*	*Avg. Incident Power Density (μW/cm^2)*	*Incident Energy Density Per Pulse (μJ/cm^2)*	*Peak Rate of Absorption (W/g)*
0.5	35.6	17.8	17.8	20.2
1	17.8	17.8	17.8	10.1
2	10.0	20.3	20.3	5.3
4	5.0	20.3	20.3	2.4
5	4.0	20.3	20.3	2.32
10	2.2	21.6	21.6	1.23
15	1.9	28.0	28.0	1.06
20	1.7	33.0	33.0	0.94
25	0.6	15.2	15.2	0.35
32	1.5	47.0	47.0	0.83

It can be seen from these tables that as the pulse width was increased, the peak incident power density required to elicit an auditory response in the cat decreased almost proportionately, except at a pulse width of 32 μsec for the 2450 MHz case. Although the average incident power density and the incident energy density per pulse also increased with pulse width, the increases were more gradual and not as clear cut. This observation has led Guy et al. (1975) to conclude that the threshold for the pulsed microwave-evoked auditory response was related to the incident energy density per pulse, at least for pulse duration shorter than 10 μsec. The incident energy density per pulse appeared to be at a level about one-half of that which produced audible sensations in humans (Chapter 3). On the other hand, one cannot easily rule out the possible connection between the pulsed microwave-evoked auditory responses and the peak incident or absorbed power density, as well as the pulse width of the incident microwave pulses.

Chou et al. (1975) had exposed guinea pigs to 2450 MHz microwave pulse in a cavity and found that the threshold peak absorbed power density for producing an identifiable cochlear microphonic response was nearly 2 W/g for a 10 μsec wide square pulse. The peak absorbed power density was determined by measuring the induced temperature in the guinea pig's head using a thermographic procedure (Chou and Guy, 1975). One would expect the threshold value to be higher than those determined using evoked responses from the thalamus. It is known, at least in cats, that the auditory threshold determined by behavioral tasks is 40 db below the sound levels first effective in producing cochlear microphonic potentials of sufficient amplitude to be identified with conventional oscilloscopes (Wever, 1966).

Rissmann and Cain (1975) determined the microwave-induced auditory thresholds in several different laboratory animals. Their experimental protocol was very similar to that employed by Guy et al. (1973, 1975), with the exception that they placed the recording electrode in the inferior colliculus of the cat and placed scalp electrodes on the top and side of the head of other animals. The threshold peak incident power densities were determined as a function of the pulse width of the impinging 3000 MHz micro-

TABLE VI

THRESHOLD OF 3000 MHz PULSE-MODULATED, MICROWAVE-EVOKED AUDITORY RESPONSES IN CATS, CHINCHILLAS, AND DOGS

	Cat		*Chinchilla*		*Dog*	
Pulse Width (μsec)	*Peak Incident Power Density (W/cm²)*	*Energy Density per Pulse (μJ/cm²)*	*Peak Incident Power Density (W/cm²)*	*Energy Density per Pulse (μJ/cm²)*	*Peak Incident Power Density (W/cm²)*	*Energy Density per Pulse (μJ/cm²)*
5	2.5	12.5	2.5	12.5	1.80	9.0
10	1.3	13	1.5	15	0.30	3.0
15	0.58	8.7	0.54	8.1	0.20	3.0

waves for two cats, two chinchillas and one dog. The results of this study are presented in Table VI. It can be seen that the peak incident power density required to elicit an auditory response decreased as the pulse width increased in all cases, although not proportionately. The threshold energy density per pulse seemed to stay relatively constant for cats and chinchillas in agreement with the results reported by Guy et al. (1973, 1975) for the pulse widths used. There was, however, no apparent relationship between audible threshold and energy density per pulse for the dog, although in this case an increase in pulse width was accompanied by a decrease in peak power density required.

The threshold parameters required to elicit a response from the medial geniculate body of the cat were assessed in two animals for X-band pulses at frequencies between 8670 and 9160 MHz (Guy et al., 1973, 1975). Table VII shows that the incident power density and the energy density per pulse required were much higher than those required for other frequencies.

The results of the above studies strongly indicate a "threshold" in microwave-induced auditory sensation, but the exact numerical value must await further experimentation. If the available threshold data are analyzed as a function of microwave frequency (Table VIII, Figs. 46 and 47), it becomes clear, both in terms of peak incident power density and peak rate of energy absorption, that the threshold differs for different frequencies even in the same animals. Changes in efficiency of absorption of microwave energy and variations in the ambient noise condition may contribute to the difference. It is interesting to note the nonlinear nature of thresh-

TABLE VII

APPROXIMATE THRESHOLD OF EVOKED AUDITORY RESPONSES*
IN CAT EXPOSED TO X-BAND MICROWAVE PULSES AT
ONE PULSE/SECOND, BACKGROUND NOISE 64 DB

Pulse Width (μs)	32
Peak Incident Power (W/cm²)	14.8 to 38.8
Avg. Incident Power (μW/cm²)	472 to 1240
Incident Energy Density/Pulse (μJ/cm²)	472 to 1240

* Application of power directly to top of exposed skull required to elicit responses.

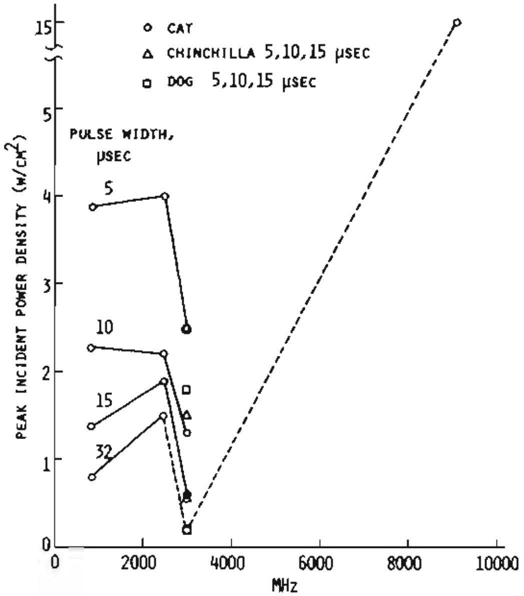

Figure 46. Threshold peak incident power for cat, chinchilla, and dog irradiated with pulse-modulated microwaves for various pulse widths involved. Note the rapid decrease of incident power required with increasing pulse width.

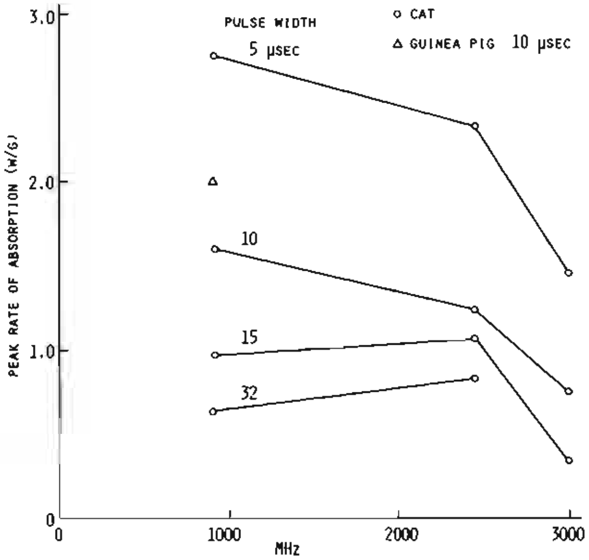

Figure 47. Threshold peak rate of absorption (absorbed power density) for cat and guinea pig with pulse width as a parameter for different microwave frequencies. Note the rapid decrease of required absorption with increasing pulse width.

TABLE VIII

PEAK INCIDENT AND ABSORBED POWER DENSITIES REQUIRED FOR PULSED MICROWAVE-INDUCED AUDITORY EFFECTS IN ANIMALS

Species	*Freq. (MHz)*	*Pulse Width (μsec)* *Peak Incident Power Density (W/cm²)* 5	10	15	32	*Peak Absorbed Power Density (W/g)* 5	10	15	32
Cats	918	3.88	2.26	1.37	0.80	2.76	1.60	0.97	0.63
	2450	4.00	2.20	1.90	1.50	2.32	1.23	1.06	0.83
	3000	2.50	1.30	0.58		1.45	0.73	0.32	
	9000				26.80				
Guinea Pigs	918						2.00		
Dogs	3000	1.80	0.30	0.20					
Chinchillas	3000	2.50	1.50	0.54					

old as a function of pulse width, which seems to indicate the existence of a minimum or optimum pulse width for efficient conversion of microwave to acoustic energy in the mammalian cranial structure. This has been suggested previously by Frey and Messenger (1973; also see Chapter 3, section on "Detection in Laboratory Animals"); however, experimental confirmation has yet to come.

EFFECT OF MASKING

Guy et al. (1975) have investigated the effect of ambient noise level on the threshold of the microwave-induced auditory effect in cats. Animals weighing 2.2 to 3.3 kg were prepared under alpha-chloralose anesthesia for recording electrical responses from the medial geniculate body evoked by pulsed microwaves and conventional acoustic inputs. The electrode used was a glass pipette filled with Ringer's solution with a tip diameter of 80-100 μm. The detailed experimental procedures were similar to those described earlier in the "Brain Stem" section. Each cat was fitted with a piezoelectric transducer for providing sound stimuli via the bone conduction route (see Fig. 33). A loudspeaker located 17 cm to the right of the cat's head centerline was used to deliver the air-conducted acoustic clicks. Microwave pulses were provided by a 2450 MHz horn antenna placed 8 cm away from the occipital pole of the cat and driven by a pulse power generator (AML Model PH4OK). The average incident power density was measured in the cat's absence using a Narda 8100 power meter and the peak power density was calculated from the known duty cycle. A noise generator (General Radio, Model 1390-B) was used in combination with an audio amplifier (Hewlett-Packard Model 467A) and a speaker to provide 50 Hz to 15 kHz artificial ambient noise levels up to 90 db, as measured with a sound level meter (General Radio 1511A).

The averaged thresholds of evoked responses due to all three stimulating modalities are presented in Figure 48 as a function of ambient noise level. Each point represents the threshold averaged over three to five cats. It can be seen that there was no noticeable increase in the threshold for the microwave stimuli as the ambient noise level was increased. A moderate rise, however, was seen in

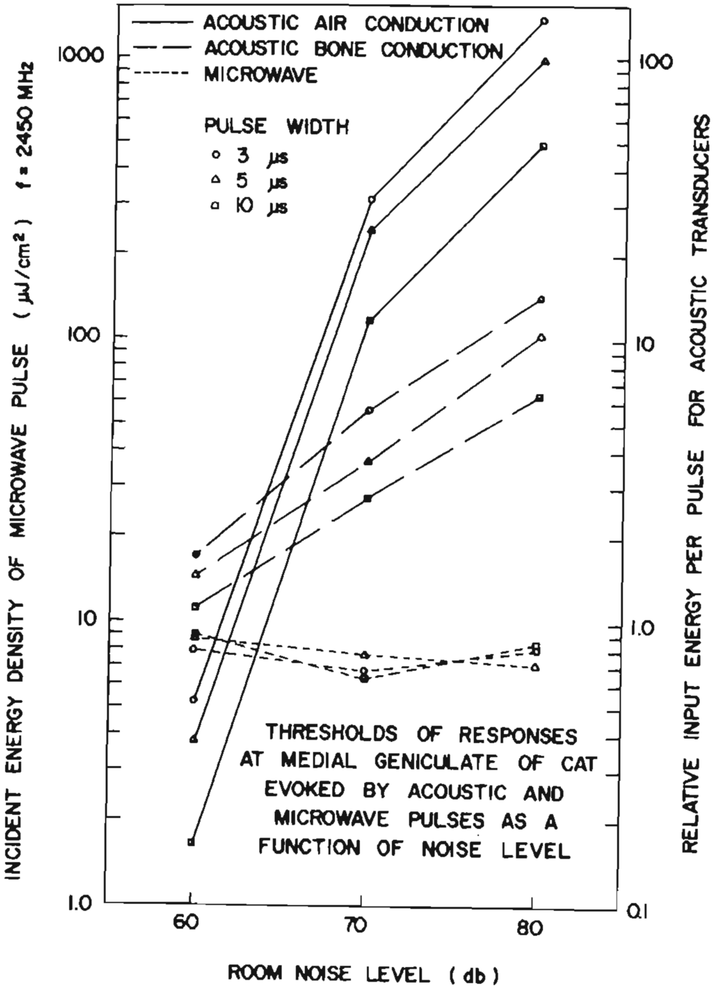

Figure 48. Evoked medial geniculate response thresholds as a function of background noise. (From Guy et al.: Microwave induced acoustic effects. Courtesy of *Ann NY Acad Sci, 247:*194-218, 1975.)

the threshold for the piezoelectric transducer attached to the skull. There was also a large increase in the threshold response evoked by the loudspeaker. These results suggest that the acoustic energy produced by pulse-modulated microwaves probably lies predominately in the frequency range above 15 kHz in cats, since the cat's "threshold of audibility" for microwave pulses was not raised by the presence of masking background noise (50 Hz to 15 kHz). This estimate is consistent with the observation that 38 kHz cochlear microphonic oscillations were induced in cats by pulse-modulated microwaves.

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Chapter 5

The Interactive Mechanism

THE MECHANISM RESPONSIBLE for the pulse-modulated microwave-induced auditory effect is not clearly understood. Many investigators have attempted to account for the effect from physical and physiological considerations. We will describe some of the mechanisms that have been suggested whereby auditory responses might be induced by pulse-modulated microwave radiation.

SITE OF INTERACTION

Early proposals maintained that the auditory system could perhaps be directly responsive to pulsed microwaves. The suggestion (Frey, 1961, 1962) that the auditory response might be the result of direct cortical or neural stimulation was based upon observations that the response was instantaneous and occurred at low average incident power densities and upon the failure to record any cochlear microphonic in cats and guinea pigs at incident power densities much higher than those required to elicit a well-defined auditory nerve response. Subsequent investigators (Guy et al., 1973, 1975; Taylor and Ashleman, 1974; Rissmann and Cain, 1975; Chou et al., 1975) have shown that auditory activities may be evoked by exposing the heads of cats, chinchillas, and guinea pigs. Responses elicited in cats both by conventional acoustic stimuli and by pulsed microwaves were similar and disappeared following disablement of the cochlea and following death (Taylor and Ashleman, 1974; Guy et al., 1975). More recently, cochlear microphonic oscillations have been recorded from the round window of guinea pigs during irradiation by pulse-modulated 918 MHz microwaves. These results suggested that the microwave-induced auditory sensation is transduced by a mechanism similar to that responsible for conventional sound perception and that the primary site of interaction resides somewhere peripherally with respect to the cochlea.

MECHANISM OF INTERACTION

While there is considerable evidence for the existence of microwave-induced auditory effects in mammals, the questions of where and how the transduction occurs have not been satisfactorily answered. The results summarized in the previous section seem to indicate that the effect was exerted on the peripheral portion of the auditory system. A peripheral response to microwave pulses should involve mechanical displacement of the bones of the skull with resultant dynamic effects on the fluids of the cochlea.

Several transduction mechanisms have been suggested involving vibrations of the skull for microwave-induced auditory sensation. Sommer and von Gierke (1964) have considered radiation pressure exerted by the pulse-modulated microwave on the surface of the irradiated cranium, which may then launch an acoustic signal of sufficient amplitude to be detected by the inner ear through bone conduction. Although the radiation pressure computed using Frey's data (Frey, 1961, 1962) was found to be slightly above the free-field air conduction threshold, it was almost two orders of magnitude below the sound pressure required for threshold bone conduction hearing (see Fig. 49). Nevertheless, considering the fact that some of Frey's observations point toward bone conduction mediation, Sommer and von Gierke concluded that there was no evidence of any direct stimulation which cannot be explained on the basis of microwave-induced vibrations in tissue and normal reception in the cochlea.

On the other hand, Frey (1971), favoring a direct microwave-neural interaction, rejected the radiation pressure transduction mechanism because the computed radiation pressure (see Fig. 49) for his lowest threshold incident power density necessary to evoke activities from the brain was approximately two orders of magnitude below the bone conduction threshold. In general, according to the radiation pressure hypothesis, higher microwave frequencies (say 10 GHz) would be more effective in producing the auditory effect; however, Frey (1961, 1962) had observed the contrary in his experiments. Evidence for peripheral mediation described in previous sections, however, tends to discount a direct microwave-neural interaction theory. The quantitative arguments presented by both Frey and Sommer and von Gierke have suffered from imprecisions which made radiation pressure less attractive as a possible transduction mechanism. Later we will deal with this in further detail.

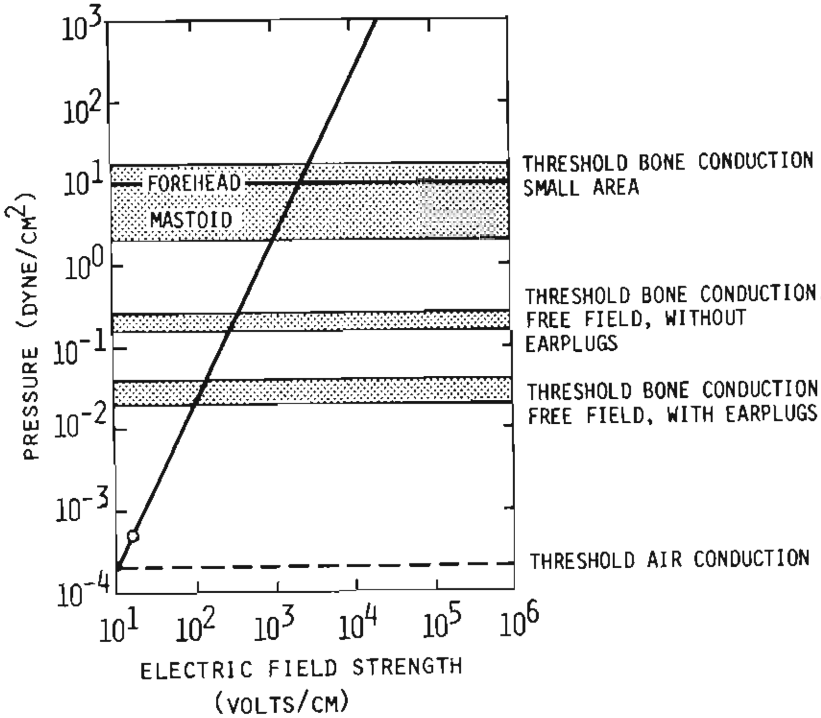

Figure 49. Radiation pressure on the head in an electric field. Approximate pressure ranges for the human auditory thresholds for air and bone conduction at 1000 Hz are indicated. The straight line indicates the radiation pressure on a conducting sphere in a plane electromagnetic wave with a wave length that is small compared to the diameter of the sphere. "o" indicates the range of the field strength in Frey's experiments. (Adapted from Sommer and von Gierke: Hearing sensations in electric fields. *Aerospace Med, 35:* 834-839, 1964.)

Guy et al. (1973, 1975) introduced a microwave-induced electrostrictive force theory based on a mathematical theory on the expansion of a dielectric body in response to an applied electrostatic field (Stratton, 1941). At the frequencies where the auditory effect can be easily detected, microwaves can penetrate deeply and are absorbed in tissues of the head. The absorbed energy produces a volumic strictive force which sets up a pressure wave that travels in the cranial tissue structure and initiates movement of the cochlear partition. They assumed that the equations derived for electrostatics were also valid for microwaves and calculated the pressure within the brain that would be expected. The acoustic pressure calculated in this way was of the same order of magnitude as the computed internal threshold pressure (Guy et al., 1974). Later, Guy et al. (1975) indicated that earlier estimations of electrostrictive forces may well be below the threshold of hearing.

Foster and Finch (1974), after examining the available information on the conversion of electromagnetic to acoustic energy by the surface heating of a liquid (White, 1963; Gournay, 1966), suggested a thermoelastic theory for pulsed microwave-induced auditory sensation. They observed that microwave pulses in water produced acoustic pressure transients with peak amplitude within the audible frequency range of 200 Hz to 20 kHz–well above the expected threshold for perception by bone conduction. According to the microwave-induced thermoelastic theory, during microwave absorption by tissue materials, a portion of the incident energy is converted into heat which generates a spatial temperature gradient normal to the surface. This temperature gradient, as a result of rapid thermal expansion, produces strains in the dielectric (tissue) material and leads to the generation of acoustic stress waves that propagate away from the surface. After the acoustic signal is detected by the cochlea via bone conduction, it is then perceived in the same manner as that for conventional auditory stimuli. Because, as we shall see in a later section, the calculated acoustic pressure at the surface of the head is well above the established threshold of hearing and is much higher in amplitude than that due to either radiation pressure or electrostrictive force mechanisms (Foster and Finch, 1974; Guy et al., 1975; Lin, 1976), the thermoelastic converting mechanism has been viewed as the most probable cause of microwave-induced auditory sensation in mammals.

Interestingly, the first experimental observation suggesting a thermoelastic transduction mechanism appeared nearly a year before Foster and Finch's report. In an attempt to elucidate the mechanism responsible for microwave-induced auditory sensation, Sharp et al. (1974) found that carbon-impregnated polyurethane microwave absorber (Eccosorb WG4, Emerson and Cuming) acted as a transducer from microwave energy to acoustic energy. They reported that if the microwave absorber was placed between the observer and the pulsed microwave generator the apparent locus of the audible click moved from the observer's head to the absorber. Using a microphone and sound level meter, they were able to detect sounds produced by pulsed microwaves in absorbers of different sizes and shapes and as small as 4 mm square by 2 mm thick. Several other kinds of microwave absorbers also produced audible sound. However, aluminum foil had to be crumbled before audible sound was detected from it. They attributed the observed phenomenon to radiation pressure and implicated a connection to pulsed microwave-induced auditory sensation in humans.

A careful examination of the results revealed that the radiation pressure explanation becomes doubtful since physical requirements and simple calculations indicated that the radiation pressure exerted on highly reflective smooth surfaces such as a sheet of aluminum foil should be greater than that exerted on the surfaces of microwave absorbers or tissue materials. This is contrary to the results reported by Sharp et al. Instead, the present results seem to support the thermoelastic hypothesis which requires the absorption of microwave energy in a short time over a significant distance inside the surface of the exposed object. Since the penetration depth (the distance over which 85% of the energy in the impinging microwave is lost) is extremely small, on the order of one micrometer for aluminum, compared with microwave absorbers or tissue materials, one would therefore expect the acoustic energy generated in aluminum foil to be much smaller than that generated in the other materials used. On the other hand, crumpling the aluminum foil presumably increases the effective penetration depth and amount of microwave energy absorption so as to produce an audible sound when it is exposed to pulse-modulated microwaves.

Although there is no direct physiological evidence confirming the existence of pulsed microwave-induced thermoelastic pressure in viable preparations, Foster and Finch (1974) have recorded acoustic transients in water, physiological saline, blood, muscle, and brain samples irradiated with pulsed 2450 MHz microwave energy. They used a large polystyrene container filled with 0.15N KCl solution at 25°C and exposed to pulse-modulated 2450 MHz microwaves at a constant energy density per pulse of 80 $\mu J/cm^2$, while varying the pulse width from 2 to 25 μsec in a microwave anechoic chamber. Microwave energy was derived from a pulse source (Applied Microwave Laboratory, PH40) coupled to a standard gain horn antenna (Waveline, 299). The average incident power density was measured with an isotropic radiation monitor (Narda, 8300). The peak sound pressure generated in the solution was measured using a sensitive, electrically shielded hydrophone (Chesapeake Instrument). The results are shown in Figure 50. Each curve in the figure corresponds to the pressure level measured with a variable band-pass filter which ranged from 200 Hz to the upper frequency limits indicated on the figure. It can be seen that for short pulses the peak pressure stayed nearly constant, signifying a dependence on the product of peak power density and pulse width or energy density per pulse. The peak pressure, however, was directly proportional to the peak power density for longer pulses. In general, the change between the two types of peak pressure dependence occurred at a pulse width of 20 to 25 μsec. It is interesting to note that the peak pressure also varied as a function of filter bandwidth. At shorter pulse widths the dependence of peak pressure upon the filter bandwidth was almost one-to-one in decibels. The correspondence was not as direct at the upper end of pulse widths used.

Foster and Finch, using distilled water, have also shown that between 0 and 4°C the recorded pressure wave was inverted from that at higher temperatures, and at 4°C the signal disappeared completely. This agrees with the known behavior of water as a function of temperature. At 4°C the coefficient of thermal expansion of water is zero. This observation argues strongly for a microwave-induced thermoelastic mechanism of sound wave generation in water. Since similar signals were observed in biological tissues exposed to pulse-modulated microwaves with pressure amplitudes approximately 90 db relative to 0.0002 dyne/cm², which is above the estimated threshold for perception by bone conduction, it is reasonable to conclude that a similar mechanism may be at work when humans and animals sense pulsed microwaves impinging on their cranium.

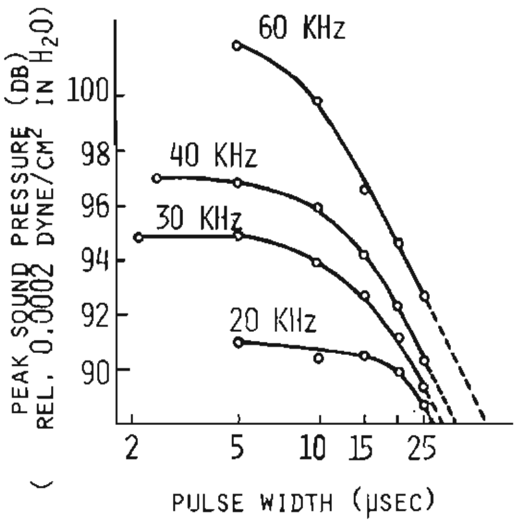

Figure 50. The peak sound pressure of the microwave-generated acoustic transient as a function of pulse width. The incident energy density per pulse was 80 $\mu j/cm^2$. (Adapted from Foster and Finch: Microwave hearing. *Science, 185*:256-258, 1974.)

A number of other peripheral transduction mechanisms for a pulsed microwave-induced auditory effect have also appeared in the last few years. Most of these hypotheses were qualitative and lacked specific details, consequently they remain as highly speculative proposals wanting experimental and theoretical verification. Sharp et al. (1974) suggested that it is conceivable that more than one mechanism may be operating when humans and animals hear microwave pulses. For example, they put forward a piezoelectric theory in which the potential difference possibly resulting from bone deformation caused by microwave pulses was suggested as a candidate for electrically mediated response. This is contrary to later work on cochlear microphonics. They have also mentioned a direct coupling mechanism between the incident microwave energy and the basilar membrane without qualification. This hypothesis seemed to make the detection of microwave-induced auditory sensation highly dependent on the subject's orientation, which was contrary to psychophysical observations.

Lebovitz (1973, 1975) has advanced several interesting hypotheses regarding possible mechanisms, including caloric vestibulo-cochlear stimulation, waveguide tuning, and dielectrophoresis. Although more complete experimental data on the absorbed energy distribution and frequency dependence are needed for a better judgment of his hypotheses, the data now available tend to discount these mechanisms, and other widely discussed theories such as thermoelastic transduction seem much more attractive in comparison. For example, in addition to the requirement of subject orientation for optimal detection sensitivity, the waveguide tuning hypothesis neglected the physical fact of cut-off frequency. For a mean external auditory meatus diameter of 7.5 mm, assuming the skin and musculature are fairly good conductors at microwave frequencies (which they are), the waveguide theory (Ramo et al., 1965) predicts a lowest cut-off frequency for an air-filled waveguide of 23.45 GHz. That is, microwaves with a frequency below 23.45 GHz would not be able to propagate within the auditory meatus. Conversely, in order for the waveguide hypothesis to hold, the impinging microwave energy must be above 23.45 GHz, which is in direct contradiction to available experimental information.

PHYSICAL PROPERTIES OF BIOLOGICAL MATERIALS

A number of transduction mechanisms have been presented in the preceding section. Three of the most popular peripheral microwave-to-acoustic energy converting schemes will be quantitatively examined in the following material. Before proceeding to a detailed discussion of these derivations, it is important to review the acoustic, microwave, and thermal properties of those biological structures that will be considered in our mathematical model or that are otherwise important in biological investigations.

Acoustic Properties

The acoustic properties that determine the propagation of sonic energy in tissues are the sound velocity and the absorption coefficient. We may also express the acoustic properties in terms of Lamé's constants and the density of the material.

Many investigators (Goldman and Hueter, 1956; Dunn et al., 1966; Lang, 1970; Fallenstein et al., 1969) have determined the numerical values of these parameters for various tissue structures. It should be emphasized that detailed information on specific tissues is continually being sought. A brief summary of some of the available data is given in Table IX. Bone absorbs ten times more sonic energy than brain. In general, the velocity of sound wave propagation is frequency independent while the absorption coefficient varies rapidly as a function of sonic frequency (Schwan, 1965).

Microwave Properties

The microwave properties of biological structures are characterized by the dielectric constant ϵ_r and the effective conductivity σ due to both conduction currents and dielectric loss. These two parameters together determine the amount of microwave energy transmitted into and absorbed by tissue media. Characterization of these parameters for various tissues has been a subject of intense investigation by Schwan and others. A number of review articles (Schwan and Piersol, 1955, 1956; Schwan, 1957, 1958, 1963; Johnson and Guy, 1972) have appeared over the years summarizing dielectric property measurements for tissues from a variety of species at different temperatures and frequencies.

Table X presents the dielectric constants and conductivities for brain, muscle, bone, and fatty tissues summarized by Schwan and others. The data were mostly obtained at 37°C and represent average values for humans and animals. It is seen that the dielectric constant decreases with increasing frequency while the conductivity in-

TABLE IX

MEASURED ACOUSTIC PROPERTIES OF BIOLOGICAL MATERIALS

Material	*Temperature* °*C*	*Density* Kg/m^3	*Bulk Velocity m/sec*	*Shear Velocity m/sec*	*Lamé's Constant,* λ nt/m^2	*Lamé's Constant,* μ nt/m^2	*Absorption Coefficient m-1*	*Frequency*
Water distilled	20	998.2	1483				2.5×10^{-2}	1 MHz
	40	992.2	1529				2.5×10^{-2}	1 MHz
Normal saline	20	1005	1493					
	40	998.4	1539					
Brain	37	1030- 1050	1460- 1540				11	1 MHz 1 MHz
	37			0.100	2.24×10^9	1.052×10^3		10-100 Hz
Muscle	37	1070	1575- 1585	1.78			13-25	1 MHz
Fat	37	970	1440	1.78			5-13	1 MHz
Bone	37	1700	3360-	1576	2.25×10^{11}	5.5×10^{10}	90	0.8 MHz
			3380-				40	0.6 MHz

TABLE X

MICROWAVE PROPERTIES OF BIOLOGICAL MATERIAL

	Frequency, f (MHz)	*Dielectric Constant* ϵ_r	*Conductivity,* σ *mho/m*	*Attenuation Coefficient,* α cm^{-1}
Brain	100	46.6	0.76	0.15
	200	42.9	0.76	0.18
	300	40.4	0.77	0.20
	433	38.4	0.77	0.22
	750	36.1	0.81	0.25
	915	35.6	0.85	0.26
	2450	32.0	1.32	0.43
	3000	31.1	1.60	0.53
	5000	28.8	3.02	1.04
	8000	26.4	6.19	2.20
	10000	25.1	9.08	3.26
Muscle	100	72	0.889	0.15
	200	56	1.28	0.25
	300	54	1.37	0.30
	433	53	1.43	0.33
	750	52	1.54	0.38
	915	51	1.60	0.40
	2450	47	2.21	0.60
	3000	46	2.26	0.62
	5000	44	3.92	1.10
	8000	40	7.65	2.23
	10000	40	10.3	3.00
Bone or fatty tissue	100	7.45	19.1-75.9	0.013-0.042
	200	5.95	25.8-94.2	0.020-0.062
	300	5.7	31.6-107	0.025-0.075
	433	5.6	37.9-118	0.030-0.080
	750	5.6	49.8-138	0.039-0.106
	915	5.6	55.6-147	0.044-0.113
	2450	5.5	96.4-213	0.077-0.169
	3000	5.5	110-234	0.088-0.186
	5000	5.5	162-309	0.130-0.247
	8000	4.7	255-431	0.221-0.372
	10000	4.5	324-549	0.287-0.484

creases in the frequency range of interest (100 to 10000 MHz). It is interesting to note that tissues of different species exhibit similar electric behavior, at least around 2450 MHz (Lin, 1975). The computed attenuation coefficient α, using ϵ_r and σ as functions of frequency, is also given in the table. It shows that for higher frequencies, attenuation increases rapidly, and, therefore, most energy is absorbed at the surface.

TABLE XI

MAGNITUDE OF THE MICROWAVE POWER TRANSMISSION AT AN AIR-TISSUE INTERFACE

Frequency (MHz)	*Power Transmission Coefficient*
100	0.224
200	0.288
300	0.319
433	0.355
750	0.393
915	0.404
2450	0.431
3000	0.436
5000	0.439
8000	0.446
10000	0.448

The fraction of incident microwave energy transmitted into biological media is illustrated in Table XI for soft tissue structures such as brain and muscle; both are characterized by high water content. It is evident that the transmitted energy is substantial and is strongly frequency dependent.

Thermal Properties

The thermal properties of biological structures, namely, specific heat and thermal conductivity, are required to predict the transient and steady state temperature distributions and heat transfer due to microwave exposure. Thermal properties for various tissues have been summarized in detail by Chato (1966, 1969) and other data were presented by Lehmann (1965) and Cooper and Trezek (1972). Table XII is an abbreviated collection of existing information on the thermal properties of biological materials. The coefficients of thermal expansion for a number of materials are also included in the table. Because values for biological structures do not seem to have been measured, the values for tissues with high water content, i.e. brain and muscle, were assumed to be 60 percent of the corresponding value for water (Weast, 1974), whereas bone and fat were assumed to have a value approximately 40 percent of that for water, reflecting their lower water content.

TABLE XII

THERMAL PROPERTIES OF BIOLOGICAL MATERIALS

Material	*Thermal Conductivity cal/m sec°C*	*Specific Heat cal/g°C*	*Thermal Diffusivity 10^{-7} m^2/sec*	*Coefficient of Thermal Expansion 10^{-5} $(°C)^{-1}$*
Distilled water	0.15	0.998	1.50	6.9
Brain	0.126	0.88	1.38	4.14
Muscle	0.122	0.75	1.52	4.14
Fat	0.0525	0.62	0.873	2.76
Bone	0.35	0.49	4.20	2.76

A QUANTITATIVE COMPARISON

In the foregoing section, we have described a number of transduction mechanisms suggested by various investigators. We present here a first order calculation comparing three possible physical mechanisms which are the most likely to be involved in the peripheral interaction of microwave pulses with the auditory systems of animals and humans.

Several investigators (Guy et al., 1975; Lin, 1976; Borth and Cain, 1977) have reported comparative data on the amplitude of the acoustic energy generated through radiation pressure, electrostrictive force, and thermoelastic stress. The results indicated that thermally produced forces greatly exceed radiation pressure. While the strictive forces are high compared to radiation pressure, they are much smaller than those generated by rapid thermal expansion, based on an exposed semi-infinite medium of brain material. Moreover, the amplitude of the induced thermal stress pressure is clearly above the established threshold of hearing in humans via bone conduction. Thus, while all three mechanisms may be operating in a given exposure situation, the large values due to thermal expansion may completely mask the effects of the others.

Let us consider a simple one-dimensional model in which a plane wave impinges normally on the boundary of a semi-infinite region of homogeneous tissue material (Fig. 51). We assume uniform microwave absorption at and near the surface of the dielectric (tissue) medium. The power density at the surface is I_o. The power density at a distance z from the surface is given by

$$
\begin{aligned}
I &= I_o e^{-2\alpha z}, \quad 0 < t < t_o, \\
&= 0, \quad \text{elsewhere}
\end{aligned}
\tag{5.1}
$$

where α is the attenuation coefficient which describes the absorbing characteristics of the medium. This microwave energy corresponds to a rectangular pulse with pulse width t_o. It may exert a radiation pressure on the surface of the absorbing medium and launch an acoustic wave, or it may generate sufficient body forces via dielectric expansion, or it may be absorbed by the lossy dielectric and converted to an acoustic wave as a result of rapid thermal expansion.

We assume the dielectric medium possesses linear, isotropic elastic properties characterized by Lamé's constant λ and μ and a volume density ρ. Allowing particle displacement u only along the z direction, the equation of motion of the particles (Love, 1927; Sokolnikoff, 1956) in the medium responding to an applied force or pressure obtained from Newton's second law of motion is

$$
\frac{\partial^2}{\partial t^2} u(z,t) - c^2 \frac{\partial^2}{\partial z^2} u(z,t) = G(z,t) \tag{5.2}
$$

where $c = [(\lambda + 2\mu)/\rho]^{1/2}$ is the bulk velocity of acoustic wave propagation in the medium, and G(z,t) is the generating function proportional to force per unit mass in newtons per kilogram. For the development presented here the temperature variations of ρ and c are neglected. Although an acoustic wave is, in general, attenuated as it progresses through the medium, we will neglect attenuation in formulating the mathematical description of the response. That is, we assume the fraction of acoustic energy dissipated in the medium to be relatively small. However, in analyzing the data, we should take attenuation into consideration.

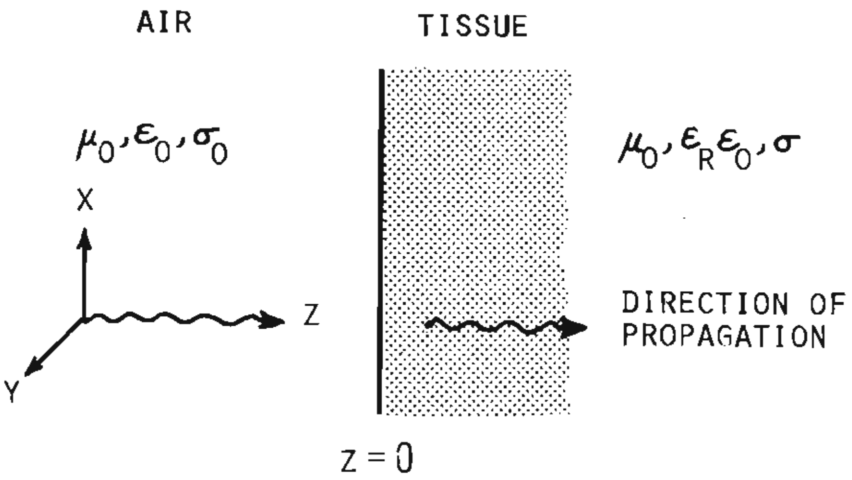

Figure 51. A plane wave impinging normally on a semi-infinite tissue medium.

In what follows, the D'Alembert's method of solution (Tychonov and Samarski, 1964) of the governing differential equation (5.2) is used to obtain displacements and pressures for the one-dimensional response of a half-space due to power deposition. The method is very useful for obtaining results for many types of volume-force excitation. Most of the development appears here for the first time. Previous results have all been derived using the usual transform techniques, which required considerable mathematical manipulations.

If equation (5.2) is solved by assuming that the surface is rigidly constrained* and is initially at rest, that is, at z = 0,

$$
u(0,t) = 0 \tag{5.3}
$$

and

$$
u(z,0) = \frac{\partial}{\partial t} u(z,0) = 0 \tag{5.4}
$$

then the displacement as a function of z and t for a generating function G(z,t) is given by

$$
\begin{aligned}
u(z,t) &= \frac{1}{2c} \int_0^t dt' \int_{z-ct+ct'}^{z+ct-ct'} G(x,t')dx, \quad t < z/c \\
&= \frac{1}{2c} \int_0^t dt' \int_{|z-ct+ct'|}^{z+ct-ct'} G(x,t')dx, \quad t > z/c
\end{aligned}
\tag{5.5}
$$

---

* Only the case of a rigidly constrained surface is considered because the resulting pressure for a constrained surface is greater than that given by a stress-free surface (see Gournay, 1966 or Chapter 6).

It is readily verified by substitution that equation (5.5) formally satisfies the equation of motion and the auxiliary conditions.

Radiation Pressure

When a plane wave impinges on an infinite plane surface, a pressure is exerted by the impinging microwave on the medium (Stratton, 1941; Smythe, 1968). If the surface is entirely within a medium that supports essentially no shearing stress ($\mu/\lambda << 1$), which is the case in soft tissues, the total pressure P is given by

$$P(z,t) = (\mu_o \epsilon_o \epsilon_r)^{1/2} I(z,t) \tag{5.6}$$

where I(z,t) is that expressed by equation (5.1), ϵ_r is the relative dielectric constant of the medium, and ϵ_o and μ_o are the vacuum permittivity and permeability, respectively. The net force acting on a differential volume shown in Figure 52 is seen to be $A\Delta P(z,t)$. Therefore, the total force per unit mass is

$$G(z,t) = -\frac{1}{\rho} \frac{\partial P(z,t)}{\partial z} \tag{5.7}$$

or equivalently

$$G(z,t) = \begin{cases} 2\alpha I_o \left(\frac{1}{\rho}\right) (\mu_o \epsilon_o \epsilon_r)^{1/2} e^{-2\alpha z}, & 0 \leq t \leq t_o \\ = 0, & \text{otherwise} \end{cases} \tag{5.8}$$

where ρ is the density of the medium. The displacement, obtained by evaluating the integrals in equation (5.5) with the generating function given by equation (5.8) for radiation pressure, is

$$u(z,t) = \frac{I_o (\mu_o \epsilon_o \epsilon_r)^{1/2}}{\alpha \rho c^2} e^{-2\alpha z} \begin{cases} F1, & t < t_o;\ t < z/c \\ F2, & t > t_o;\ t < z/c \\ F3, & t < t_o;\ t > z/c \\ F4, & t_o < t < t_o + z/c;\ t > z/c \\ F5, & t > t_o + z/c;\ t > z/c \end{cases} \tag{5.9}$$

where

$$F1 = \sinh^2 \alpha c t \tag{5.10}$$

$$F2 = \sinh \alpha c t_o \sinh \alpha c (2t - t_o) \tag{5.11}$$

$$F3 = \frac{1}{2} [1 - e^{-2\alpha z} - \sinh 2\alpha z\, e^{-2\alpha c t}] \tag{5.12}$$

$$F4 = \frac{1}{2} [1 - \sinh 2\alpha z\, e^{-2\alpha c t} - \cosh 2\alpha c (t - t_o) e^{-2\alpha z}] \tag{5.13}$$

$$F5 = \sinh 2\alpha z \sinh \alpha c t_o\, e^{-\alpha c (2t - t_o)} \tag{5.14}$$

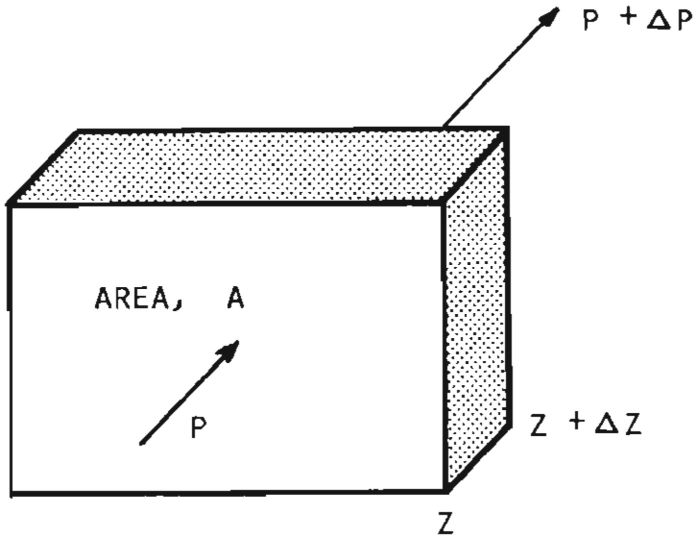

Figure 52. Force (pressure) acting on an elemental segment of tissue material having a surface area A and depth Δz.

The pressure distribution is given by

$$p(z,t) = (\lambda + 2\mu) \frac{\partial u(z,t)}{\partial z} \tag{5.15}$$

Thus, upon completion of the indicated differentiation process, we have

$$p(z,t) = \frac{2(\lambda + 2\mu) I_o (\mu_o \epsilon_o \epsilon_r)^{1/2}}{\rho c^2} e^{-2\alpha z} \begin{cases} -F1, & t < t_o;\ t < z/c \\ -F2, & t > t_o;\ t < z/c \\ F6, & t < t_o;\ t > z/c \\ F7, & t_o < t < t_o + z/c,\ t > z/c \\ F8, & t > t_o + z/c,\ t > z/c \end{cases} \tag{5.16}$$

where

$$F6 = \frac{1}{2} [1 - \cosh 2\alpha z\, e^{-2\alpha c t + 2\alpha z}], \tag{5.17}$$

$$F7 = \frac{1}{2} [\cosh 2\alpha c (t - t_o) - \cosh 2\alpha z\, e^{-2\alpha c t + 2\alpha z}], \tag{5.18}$$

$$F8 = \cosh 2\alpha z \sinh \alpha c t_o\, e^{-\alpha c (2t - t_o) + 2\alpha z}, \tag{5.19}$$

Electrostrictive Force

A dielectric body exhibits tendencies to contract or expand in an applied electromagnetic field. The force associated with the elastic deformation is called strictive force. Although a complete derivation of the strictive force in a microwave field is difficult to obtain, an approximate expression may be obtained by considering the pressure increase in a fluid (which is an approximation of most soft tissue structures) exposed to a microwave field. The pressure increase at any interior point due to microwave exposure, according to Stratton (1941) and Smythe (1968), is given by

$$p(z,t) = \frac{1}{3}(\epsilon_r - 1)(\epsilon_r + 2)\, I_o \left(\frac{\mu_o \epsilon_o}{\epsilon_r}\right)^{1/2} e^{-2\alpha z} \tag{5.20}$$

It is readily seen from Figure 52 and the presentation in the previous section that the total strictive force per unit mass inside the dielectric fluid is

$$G(z,t) = \frac{2\alpha I_o}{3\rho}(\epsilon_r - 1)(\epsilon_r + 2)\left(\frac{\mu_o \epsilon_o}{\epsilon_r}\right)^{1/2} e^{-2\alpha z} \tag{5.21}$$

The generating function corresponding to an incident rectangular microwave pulse with pulse width t_o is therefore given by

$$\begin{aligned} G(z,t) &= \frac{2\alpha I_o}{3\rho}(\epsilon_r - 1)(\epsilon_r + 2)\left(\frac{\mu_o \epsilon_o}{\epsilon_r}\right)^{1/2} e^{-2\alpha z}, \quad 0 < t < t_o \\ &= 0, \quad \text{otherwise} \end{aligned} \tag{5.22}$$

The displacement due to strictive force, after substituting equation (5.22) into the integral solution of equation (5.5), is

$$u(z,t) = \frac{I_o}{\alpha\rho c^2}(\epsilon_r - 1)(\epsilon_r + 2)\left(\frac{\mu_o \epsilon_o}{\epsilon_r}\right)^{1/2} e^{-2\alpha z} \begin{cases} F1, & t < t_o;\ t < z/c \\ F2, & t > t_o;\ t < z/c \\ F3, & t < t_o;\ t > z/c \\ F4, & t_o < t < t_o + z/c;\ t > z/c \\ F5, & t > t_o + z/c;\ t > z/c \end{cases} \tag{5.23}$$

where F1, F2, F3, F4, and F5 are given in equations (5.10) to (5.14). The pressure due to strictive force using equations (5.15) and (5.23) becomes

$$p(z,t) = \frac{2I_o}{3\rho c^2}(\lambda + 2\mu)(\epsilon_r - 1)(\epsilon_r + 2)\left(\frac{\mu_o \epsilon_o}{\epsilon_r}\right)^{1/2} e^{-2\alpha z} \begin{cases} -F1, & t < t_o;\ t < z/c \\ -F2, & t > t_o;\ t < z/c \\ F6, & t < t_o;\ t > z/c \\ F7, & t_o < t < t_o + z/c;\ t > z/c \\ F8, & t > t_o + z/c;\ t > z/c \end{cases} \tag{5.24}$$

where F6, F7, and F8 are specified by equations (5.17) to (5.19).

Thermoelastic Stress

In the process of microwave energy absorption, a portion of the incident radiation is converted into heat which generates a temperature gradient normal to the surface. As a result of thermal expansion occurring within a few microseconds, this temperature gradient produces strains in the dielectric material and leads to the generation of stress waves which propagate away from the surface.

For the power distribution described by equation (5.1), the energy absorption occurs only during the short microwave pulse application between $t = 0$ and $t = t_o$. Neglecting any heat loss due to conduction and radiation, a solution of the equation of heat conduction (Carslaw and Jaeger, 1959; Gournay, 1966) gives a simple approximate temperature distribution $v(z,t)$ inside the medium as

$$v(z,t) = 2\alpha I_o t e^{-2\alpha z}/(\rho c_h) \tag{5.25}$$

where c_h is the specific heat of the medium. It is interesting to note that equation (5.25) predicts extremely rapid temperature rise and large temperature gradient when the peak input power is close to the magnitude observed for microwave-induced auditory sensation.

In biological materials, as in many nonmetallic media, the cooling curve for $t > t_o$ is a slowly varying function of time and becomes appreciable only for times greater than milliseconds. Moreover, the times for production and propagation of stress waves are short compared with temperature equilibration. Thus we assume for $t > t_o$

$$v(z,t) = 2\alpha I_o t_o e^{-2\alpha z}/\rho c_h \tag{5.26}$$

In the medium, the temperature rise produces a strain

$$\epsilon_z = \frac{\partial u(z,t)}{\partial z} = \beta v(z,t) \tag{5.27}$$

where $u(z,t)$ is the particle displacement and β is the coefficient of linear thermal expansion. We have also assumed negligible strains along the x and y directions. The strain of equation (5.27) could also be produced in the absence of any heating by a mechanical stress of

$$P_z = (3\lambda + 2\mu)\, \beta v(z,t). \tag{5.28}$$

In the presence of both heating and stress, the stress-strain relationship (Love, 1927; Sokolnikoff, 1956) requires

$$P(z,t) = (\lambda + 2\mu)\frac{\partial u(z,t)}{\partial z} - (3\lambda + 2\mu)\,\beta v(z,t) \tag{5.29}$$

where P(z,t) is pressure or stress.

Referring to Figure 52 we see that the net force due to rapid heating acting on the differential volume is AΔP(z,t). Thus, the total force per unit mass as a result of rapid heating of the elastic dielectric medium is

$$G(z,t) = -\frac{1}{\rho}\frac{\partial P_z(z,t)}{\partial z}\,. \tag{5.30}$$

Substituting equation (5.28) in equation (5.30) produces

$$G(z,t) = -(3\lambda + 2\mu)\frac{\beta}{\rho}\frac{\partial v(z,t)}{\partial z}\,. \tag{5.31}$$

By combining equations (5.25), (5.26), and (5.31), the generating function due to rapid heating by a short microwave pulse with pulse width t_o under the approximation of negligible heat transfer becomes

$$\begin{aligned} G(z,t) &= (3\lambda + 2\mu)\beta I_o t(2\alpha)^2 e^{-2\alpha z}/(c_h\rho^2), \quad t < t_o \\ &= (3\lambda + 2\mu)\beta I_o t_o(2\alpha)^2 e^{-2\alpha z}/(c_h\rho^2), \quad t > t_o \end{aligned} \tag{5.32}$$

We now substitute equation (5.32) into equation (5.5) and perform the simple integrations to obtain, for the displacement,

$$u(z,t) = \frac{(3\lambda + 2\mu)\beta I_o}{2\alpha c_h\rho^2 c^3}\,e^{-2\alpha z}\begin{cases} \sinh 2\alpha ct - 2\alpha ct, \quad t < t_o;\ t < z/c \\[2ex] \sinh 2\alpha ct - \sinh 2\alpha c(t - t_o) - 2\alpha ct_o\cosh 2\alpha c(t - t_o), \\ \qquad t > t_o;\ t < z/c \\[2ex] \sinh 2\alpha z e^{-2\alpha ct + 2\alpha z} + 2\alpha c(t - z/c)e^{-2\alpha z} - 2\alpha ct, \\ \qquad t < t_o;\ t > z/c \\[2ex] \sinh 2\alpha z e^{-2\alpha ct + 2\alpha z} + 2\alpha c(t - z/c)e^{2\alpha z} - \sinh 2\alpha c(t - t_o) \\ \qquad - 2\alpha ct_o\cosh 2\alpha c(t - t_o), \quad t_o < t < t_o + z/c;\ t > z/c \\[2ex] 2\sinh 2\alpha z\, e^{-2\alpha c(t - z/c) + \alpha ct_o}(\alpha ct_o e^{\alpha ct_o} - \sinh \alpha ct_o), \\ \qquad t > t_o + z/c;\ t > z/c \end{cases} \tag{5.33}$$

From equation (5.29), using the results of equation (5.33), the pressure or stress is found to be

$$p(z,t) = (3\lambda + 2\mu)\frac{\beta I_o}{\rho c_h c}e^{-2\alpha z}\begin{cases} -\sinh 2\alpha ct, \quad t < t_o;\ t < z/c \\[2ex] \sinh 2\alpha c(t - t_o) - \sinh 2\alpha ct - 2\alpha ct_o \\ \qquad + 2\alpha ct_o\cosh 2\alpha c(t - t_o), \quad t > t_o;\ t < z/c \\[2ex] \cosh 2\alpha z e^{-2\alpha ct + 2\alpha z} - e^{2\alpha z}, \quad t < t_o;\ t > z/c \\[2ex] 2\alpha ct_o\cosh 2\alpha c(t - t_o) + \sinh 2\alpha c(t - t_o) - e^{2\alpha z} \\ \qquad + \cosh 2\alpha z\, e^{-2\alpha ct + 2\alpha z} - 2\alpha ct_o, \\ \qquad\qquad t_o < t < t_o + z/c;\ t > z/c \\[2ex] 2\cosh 2\alpha z(\alpha ct_o e^{\alpha ct_o} - \sinh \alpha ct_o)\,e^{-2\alpha c(t - z/c) + \alpha ct_o} \\ \qquad - 2\alpha ct_o, \quad t > t_o + z/c;\ t > z/c \end{cases} \tag{5.34}$$

The above expressions represent a complete analysis of the displacement and pressure generated by microwave-induced thermal expansion in a semi-infinite elastic medium. A few special cases have previously been obtained using the usual transform technique in solving the equation of motion (White, 1963; Gournay, 1966; Chou and Guy, 1975). As mentioned earlier, it is considerably simpler to solve the problem using the integral solution of equation (5.5) obtained through D'Alembert's method.

A Numerical Example

It is instructive to examine quantitatively the explicit expressions describing the formation of acoustic waves in a semi-infinite biological medium. For a 2450 MHz microwave pulse impinging normally on the surface of brain material the physical parameters required are given in the section on "Physical Properties of Biological Materials." The results of computer calculations made with $t_o = 10$ μsec and $I_o = 1000$ mW/cm² are shown in Figures 53 to 64.

In Figures 53 and 54 the development and propagation into the medium of displacement and pressure, induced by radiation pressure, is shown as a function of time and depth. Note that the displacement is zero while the pressure is the highest at $z = 0$ (con-

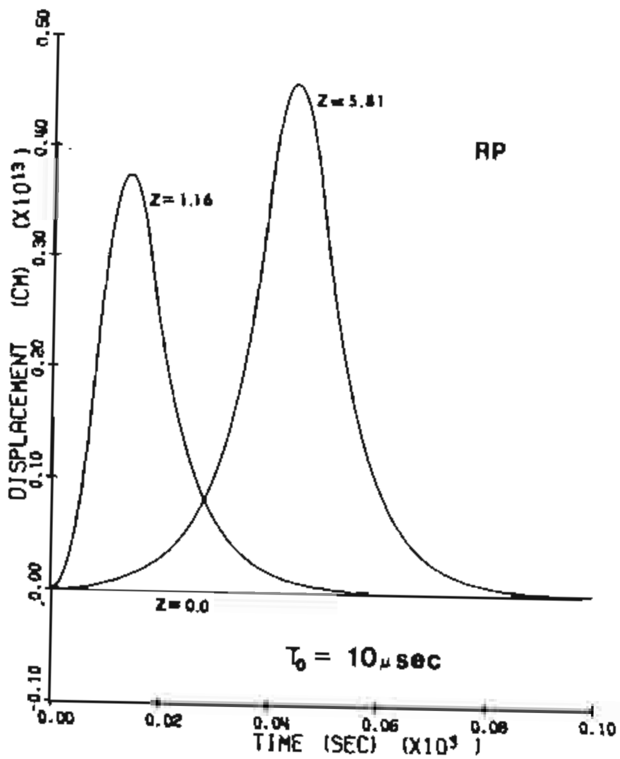

Figure 53. Displacement induced by radiation pressure in a semi-infinite brain model exposed to 2450 MHz microwave radiation. $t_o = 10$ μsec and $I_o = 1000$ mW/cm².

strained-surface). The displacement close to the surface is characterized by a rapid rise-time and a slightly slower fall-time. These times become increasingly symmetric as the distance into the medium increases. The pressure wave is initially monophasic and becomes diphasic with increasing penetration into the medium. Both displacement and pressure attain the asymptotic traveling waveform after passing out of the region of effective energy deposition (depth of penetration). This is shown clearly by Figures 55 and 56 where the maximum displacement and pressure are plotted as a function of distance. It is seen that the maximum displacement increases to a limiting value and the maximum pressure decreases to a minimum value after $z = 1/\alpha = 2.32$ cm.

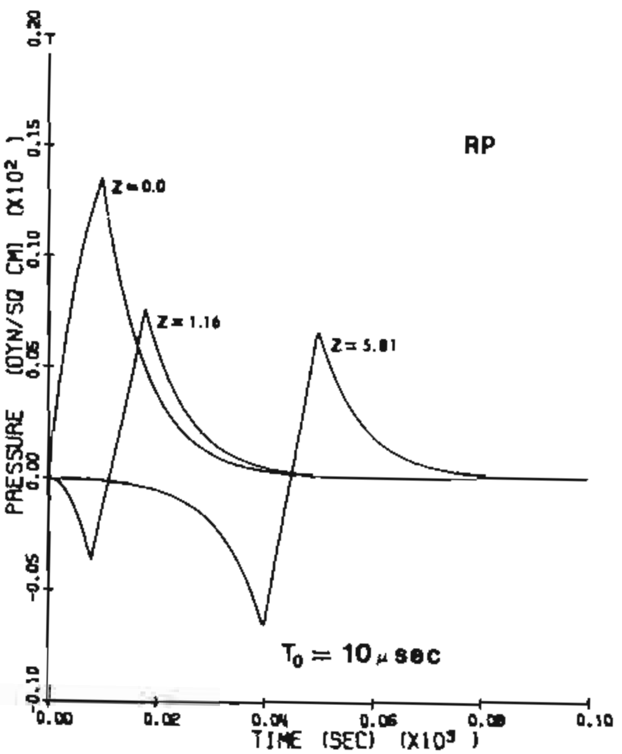

Figure 54. Pressure induced by radiation pressure in a semi-infinite brain model exposed to 2450 MHz microwave radiation. $t_o = 10$ μsec and $I_o = 1000$ mW/cm².

The results of calculations made for electrostriction are given in Figures 57 to 60. As expected, the waveform and the dependence of maximum displacement and pressure on distance are almost the same as for radiation pressure, except that the magnitudes are greater by approximately a factor of ten.

Figure 61 shows examples of displacement elicited in the planar brain model by microwave-induced thermoelastic stress. The curves are qualitatively similar to those obtained from radiation pressure and electrostriction, except that the peak displacement is greater by a factor of one thousand. Figure 62 depicts typical pressures developed as a result of thermoelastic expansion. In this case, we choose to show only the traveling component of the pressure wave by removing from equation (5.34) terms proportional to $2\alpha ct$ or $2\alpha ct_o$ wherever appropriate. It is seen that the traveling component of the thermoelastically generated pressure wave is similar to radiation pressure and electrostriction, but with a peak pressure greater by two to three orders of magnitude. Figures 63 and 64 illustrate the variation of peak displacement and pressure as functions of distance from the surface of the semi-infinite brain model.

A SUMMARY

Three different physical transduction mechanisms for converting microwave pulses to acoustic waves have been analyzed. Explicit expressions describing the formation of acoustic waves via microwave-induced radiation pressure (5.16), electrostriction (5.23), and thermoelastic expansion (5.34) have been obtained using the D'Alembert method of solution. The development and propagation of the displacement and pressure waves into a brain half-space irradiated with a 10 μsec-wide 2450 MHz microwave pulse are shown in Figures 53 and 54 for radiation pressure, in Figures 57 and 58 for electrostriction, and in Figures 61 and 62 for thermoelastic expansion.

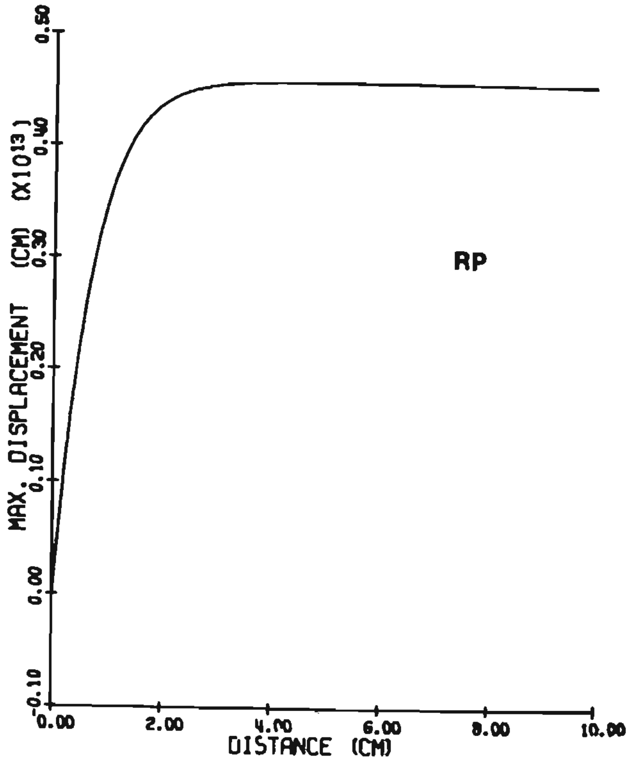

Figure 55. Spatial dependence of peak displacement induced by radiation pressure in brain materials irradiated with 2450 MHz microwave pulses. $t_o = 10$ μsec and $I_o = 1000$ mW/cm^2.

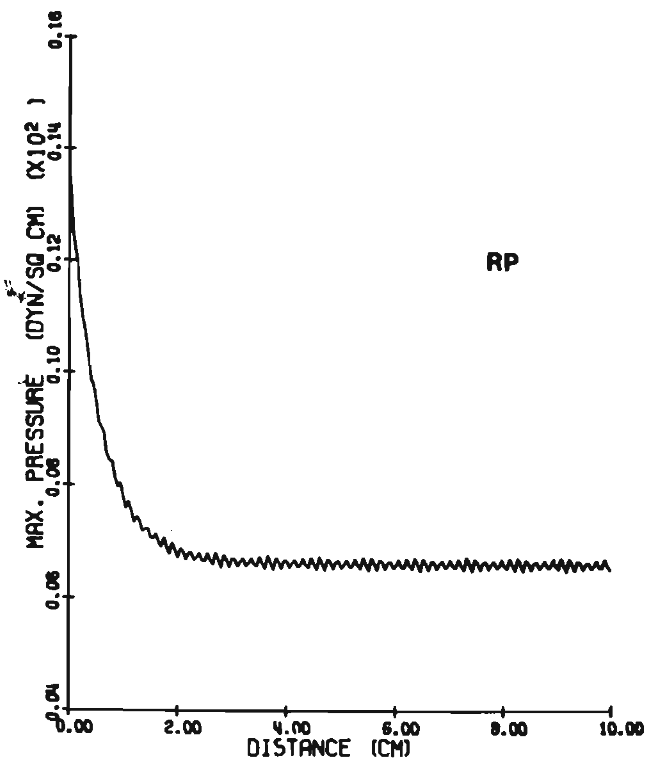

Figure 56. Spatial dependence of peak pressure induced by radiation pressure in brain materials irradiated with 2450 MHz microwave pulses. $t_o = 10$ μsec and $I_o = 1000$ mW/cm^2.

It can be seen from the results of the previous section that the peak compressive or tensile stress (pressure) always occurs at the

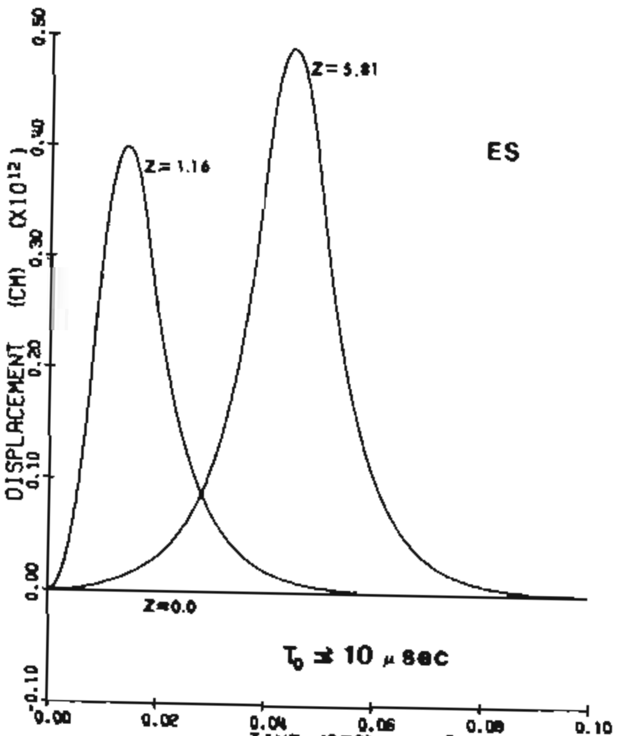

Figure 57. Displacement induced by electrostriction in a semi-infinite brain model exposed to 2450 MHz microwave radiation. $t_0 = 10$ μsec and $I_0 =$ 1000 mW/cm^2.

surface regardless of which mechanism is involved in its development. In fact, a direct comparison of the maximum pressures shown in Figures 56, 58, and 62 indicates that microwave-induced thermoelastic stress exceeds radiation pressure by almost three orders of magnitude; pressure generated by electrostriction is about ten times as high as that produced by the radiation pressure mechanism. Thus, while the electrostrictive force mechanism is effective in comparison with radiation pressure, it is much less effective than thermoelastic expansion in developing acoustic waves in brain matters.

It is instructive to obtain a simple relationship among the pressure magnitudes predicted by the three mechanisms for producing acoustic energy. Comparing equations (5.24) and (5.16) we have

$$\frac{\text{magnitude of pressure due to electrostriction}}{\text{magnitude of pressure due to radiation pressure}} = \frac{\varepsilon_r}{3} \tag{5.35}$$

where we have assumed $\epsilon_r >> 1$. A consideration of equations (5.34) and (5.16) yields

$$\frac{\text{magnitude of pressure due to thermoelastic stress}}{\text{magnitude of pressure due to radiation pressure}} = \frac{3}{2}\,\frac{c\beta}{c_h(\mu_o\varepsilon_o\varepsilon_r)^{1/2}} \tag{5.36}$$

where we have made use of the fact that $\mu/\lambda << 1$. These ratios are tabulated in Table XIII for brain, muscle, and water. They

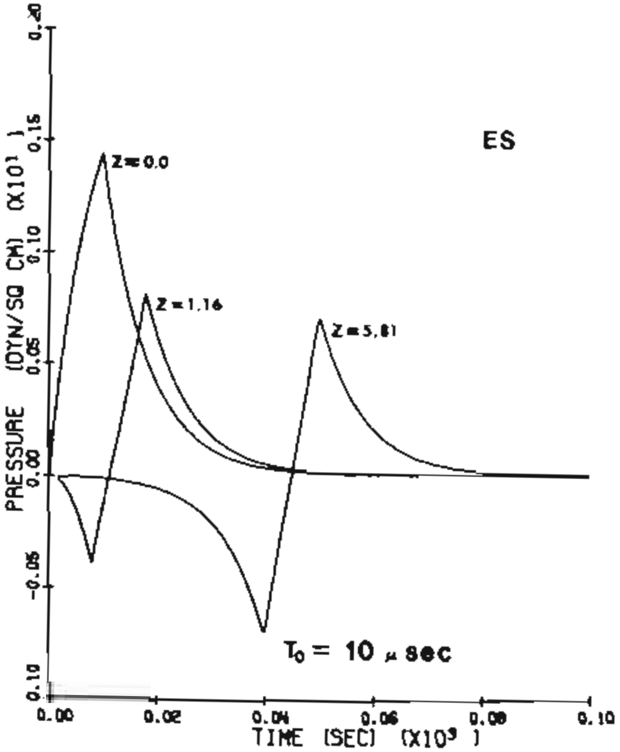

Figure 58. Pressure induced by electrostriction in a semi-infinite brain model exposed to 2450 MHz microwave radiation. $t_0 = 10$ μsec and I_0 1000 mW/cm^2.

TABLE XIII

A COMPARISON OF THREE PHYSICAL MECHANISMS OF ACOUSTIC ENERGY PRODUCTION IN SEMI-INFINITE MODELS OF BIOLOGICAL MATERIALS EXPOSED TO SHORT MICROWAVE PULSES[*]

Material	*Electrostriction/ Radiation Pressure*	*Thermoelastic Stress/ Radiation Pressure*	*Thermoelastic Stress/ Electrostriction*
Brain	10.67	1301	122
Muscle	15.67	1290	82
Water	26.0	1225	47

[*] Given as the relative amplitude of acoustic waves generated by impinging 2450 MHz microwave pulses.

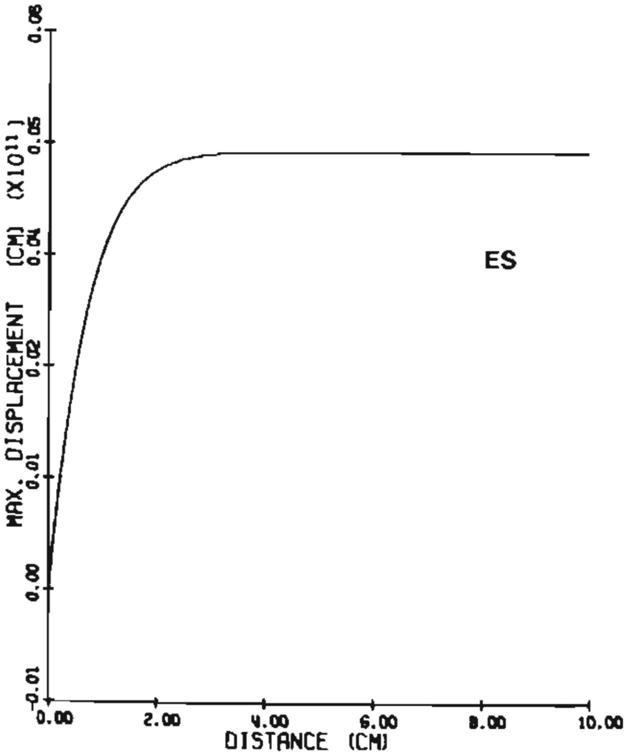

Figure 59. Spatial dependence of peak displacement induced by electrostriction in brain material irradiated with 2450 MHz microwave pulses. $t_o = 10\ \mu sec$ and $I_o = 1000\ mW/cm^2$.

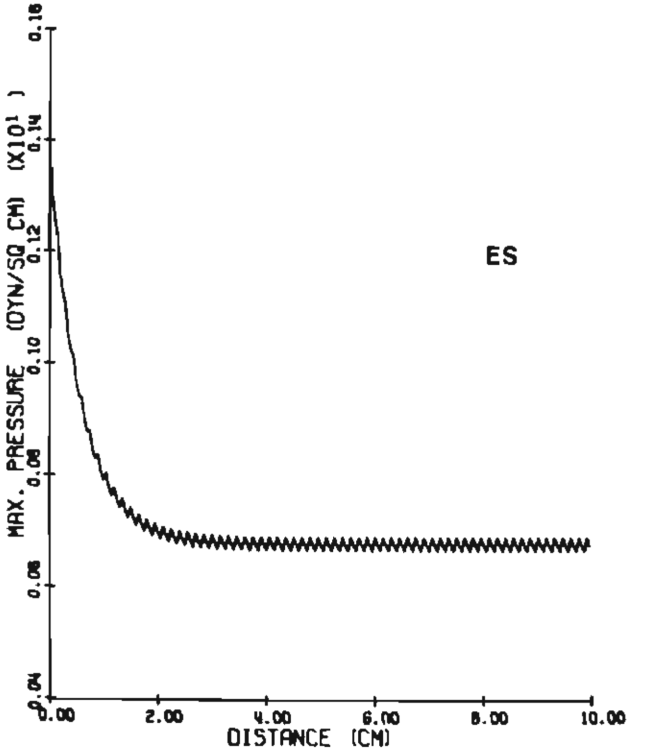

Figure 60. Spatial dependence of peak pressure induced by electrostriction in brain material irradiated with 2450 MHz microwave pulses. $t_o = 10\ \mu sec$ and $I_o = 1000\ mW/cm^2$.

represent measures of the relative amplitude of acoustic waves generated by impinging 2450 MHz microwave pulses via the three mechanisms. It is readily observed that, in all cases, thermoelastically generated stress exceeds the others by a large margin. Thus, while all three mechanisms may be operating at given incident power density, the large values due to thermoelastic expansion may completely mask the effect of the others.

If we assume a 6 percent coupling coefficient (see Table XI) and a peak incident power density of 4000 mW/cm² (which was found to be the minimally effective value for 2450 MHz microwave radiation to produce audible signals in an adult with normal hearing), the computed maximum thermoelastically generated pressure is approximately 0.15 dyne/cm^2 for brain, which is clearly above the established threshold of perception by bone conduction (see Fig. 49). Thus, if the acoustic wave is produced in a human head, it may reach the inner ear via bone conduction causing a distinct auditory sensation.

It should be mentioned that the human head is not a semi-infinite medium of brain material, but rather an inhomogeneous spheroidal body with a semirigid surface. The calculations made in this chapter are therefore not expected to be accurate predictions of the precise magnitude of microwave-induced acoustic waves in the human head. They do, however, show the importance and applicability of various transduction mechanisms. In particular, the analysis indicates that the amplitude of a thermoelastically generated acoustic signal is of such magnitude that it is likely to be the most attractive physical mechanism to explain the microwave-induced auditory effect in humans.

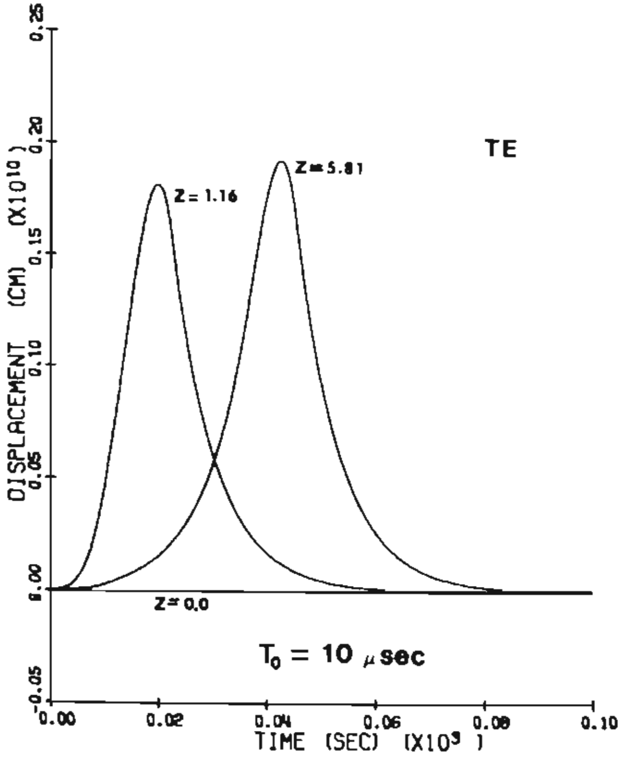

Figure 61. Displacement induced by thermoelastic expansion in a semi-infinite brain model irradiated with 2450 MHz microwave pulses. $t_0 = 10$ μsec and $I_0 = 1000$ mW/cm^2.

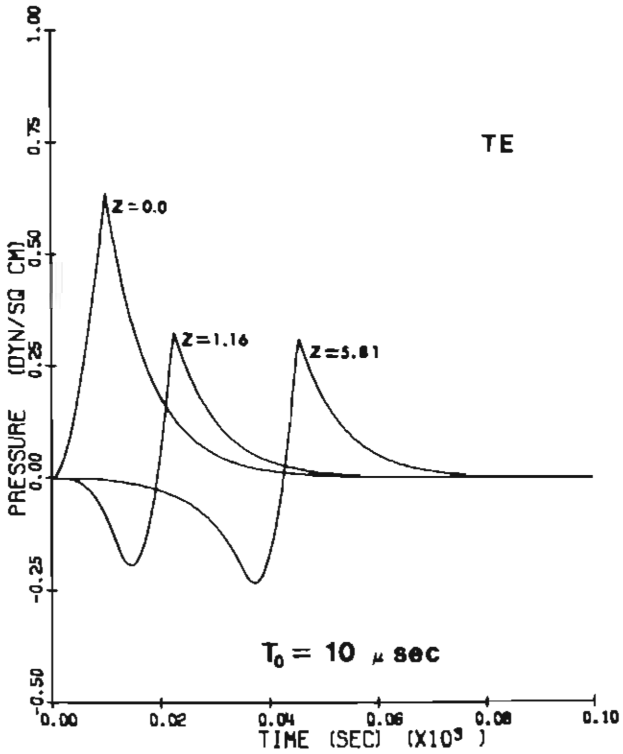

Figure 62. Pressure induced by thermoelastic expansion in a semi-infinite brain irradiated with 2450 MHz microwave pulses. $t_0 = 10$ μsec and $I_0 = 1000$ mW/cm^2.

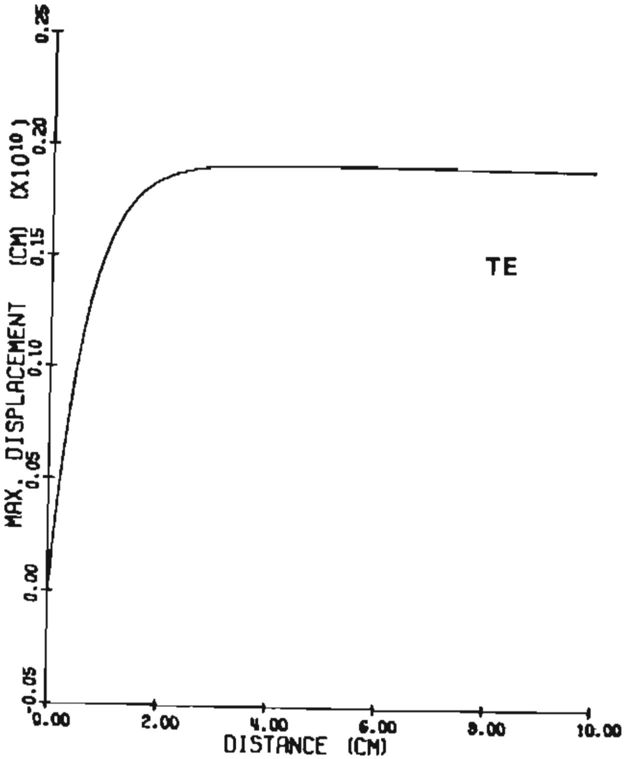

Figure 63. Spatial dependence of peak displacement in a semi-infinite brain model exposed to 2450 MHz microwave pulses. $t_o = 10$ μsec and $I_o = 1000$ mW/cm^2.

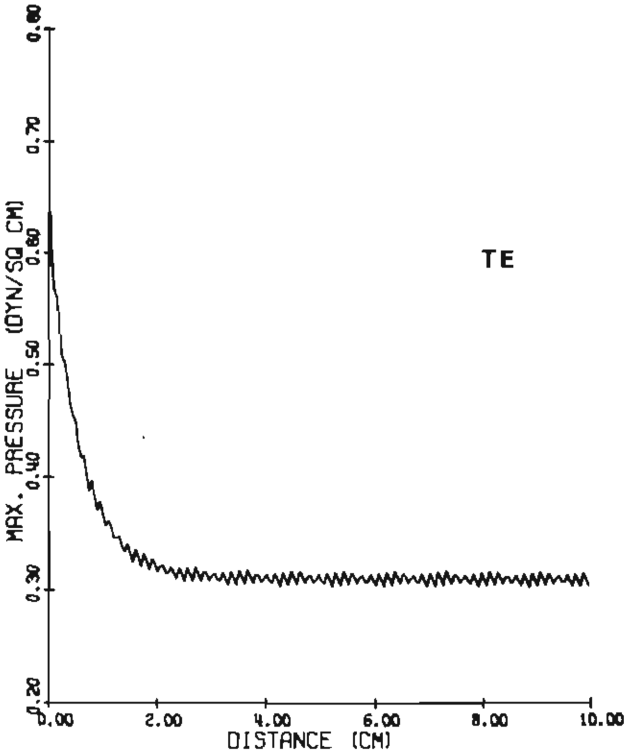

Figure 64. Spatial dependence of peak pressure in a semi-infinite brain model exposed to 2450 MHz microwave pulses. $t_o = 10$ μsec and $I_o = 1000$ mW/cm^2.

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Chapter 6

The Spherical Model

THE PRECEDING CHAPTERS have demonstrated that an audible sound occurs when human subjects are exposed to pulse-modulated microwave energy which appears to originate from within or immediately behind the head, and that immediate detection of pulsed microwaves can be mediated by the auditory system of laboratory animals.

It was also shown that auditory activities may be evoked by irradiating the heads of cats, chinchillas, and guinea pigs with pulsed microwave energy. Electrophysiological responses elicited in cats by both conventional acoustic stimuli and by pulsed microwaves disappear following destruction of the round window of the cochlea, and following death. Furthermore, cochlear microphonics have been recorded from the round window of guinea pigs and cats exposed to pulsed microwaves at 918 MHz. These results indicate that microwave-induced audition is transduced by a mechanism similar to that responsible for conventional acoustic reception and that the primary site of interaction resides peripherally with respect to the cochlea. It is therefore reasonable to conclude that the microwave-induced auditory effect is a cochlear response to acoustic signals that are generated, presumably in the head, by pulsed microwaves.

While the effect is widely accepted as a genuine biological effect occurring at low average power densities, some controversy exists regarding the mechanism by which pulsed microwave energy is converted to sound in humans and animals. Several physical mechanisms were advanced in Chapter 5 for the conversion of microwave to acoustic energies, including radiation pressure, electrostriction, and thermoelastic expansion. A comparison of these three mechanisms revealed that the thermoelastic expansion is the most effective mechanism, since pressures generated by thermoelastic stress may be one thousand or more times greater than by the other possible mechanisms. Consequently, thermal expansion has become the most generally accepted transduction mechanism.

A detailed analysis of the acoustic waves generated in spherical human and animal cranial structures exposed to pulsed microwave radiation is considered here. We assume that the auditory effect arises from the miniscule but rapid rise of temperature in the head as a result of the absorption of microwave energy. The rise of temperature occurring in a very short time is believed to create thermal expansion of the brain matter, which then launches the acoustic pressure wave that is detected by the cochlea.

We consider the head to be perfectly spherical and consisting only of brain matter. The impinging radiation is assumed to be a plane wave of pulsed microwave energy. The absorbed microwave energy inside the head is obtained first. The accompanying temperature rise is then derived, and finally the inhomogeneous thermoelastic motion equation is solved for the acoustic wave generated in the head.

The reader who is less mathematically inclined may wish to omit the sections regarding "Solution for $F_t(t) = 1$," "Solution for Rectangular Pulse," and "Theoretical Analysis"; their numerical interpretations appear in "Computed Frequency of Sound," "Computed Displacement and Pressure," "Computed Frequency of Sound," and "Computed Pressure and Displacement." However, the reader will probably be rewarded by a better understanding of the model if he or she elects to read at least the narrative portions of these sections.

MICROWAVE ABSORPTION

Let us consider a homogeneous spherical model of the head exposed to a plane wave of pulsed microwave energy (Fig. 65). The rate of absorbed microwave energy per unit volume W(r,t) at any point inside the head is given by

$$W(r,t) = \begin{cases} \frac{1}{2}\sigma|\overline{E}|^2, & 0 \leq t \leq t_o \\ = 0 & t > t_o \end{cases} \tag{6.1}$$

where σ is the electrical conductivity of brain matter and t_o is the

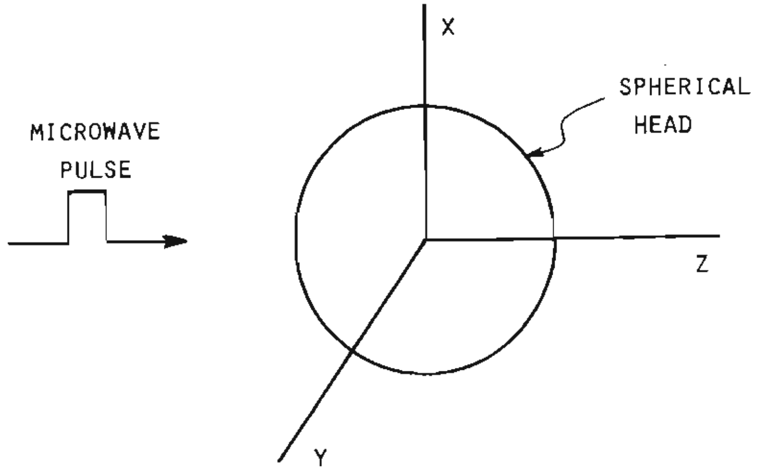


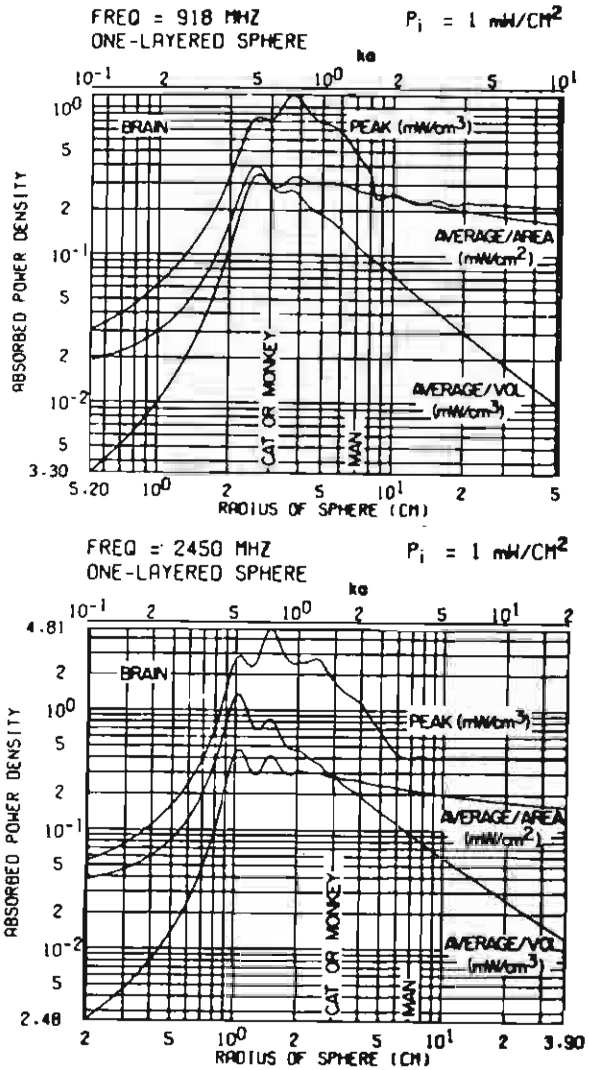
Figure 65. A rectangular pulse of microwave energy impinging on a spherical model of the head.

pulse width. The induced electric field $\overline{E}$ is given by

$$\overline{E} = E_o e^{-i\omega t} \sum_{j=1}^{\infty} i^j \frac{2j+1}{j(j+1)} \{a_j \overline{M}_{olj} - ib_j \overline{N}_{elj}\} \tag{6.2}$$

where E_o is the incident electric field strength; $\omega = 2\pi f$, f being frequency, a_j and b_j are magnetic and electric oscillations, respectively; and $\overline{M}$ and $\overline{N}$ are vector spherical wave functions. A derivation of equation (6.2) is given by Stratton (1941). The basic idea is that for a plane wave linearly polarized in the x direction and propagating along the positive z direction, the incident and induced fields may be expanded in terms of vector spherical wave functions. The expansion coefficients a_j and b_j are then found from boundary conditions at the surface of the sphere. Since the general formulation is readily available, we shall refer the interested reader to the above mentioned reference. It is emphasized that the idealized model does not account for the effect of the neck and the rest of the body.

Several investigators have presented results of computer calculations of microwave energy absorption using spherical head models (Shapiro et al., 1971; Kritikos and Schwan, 1972, 1975;



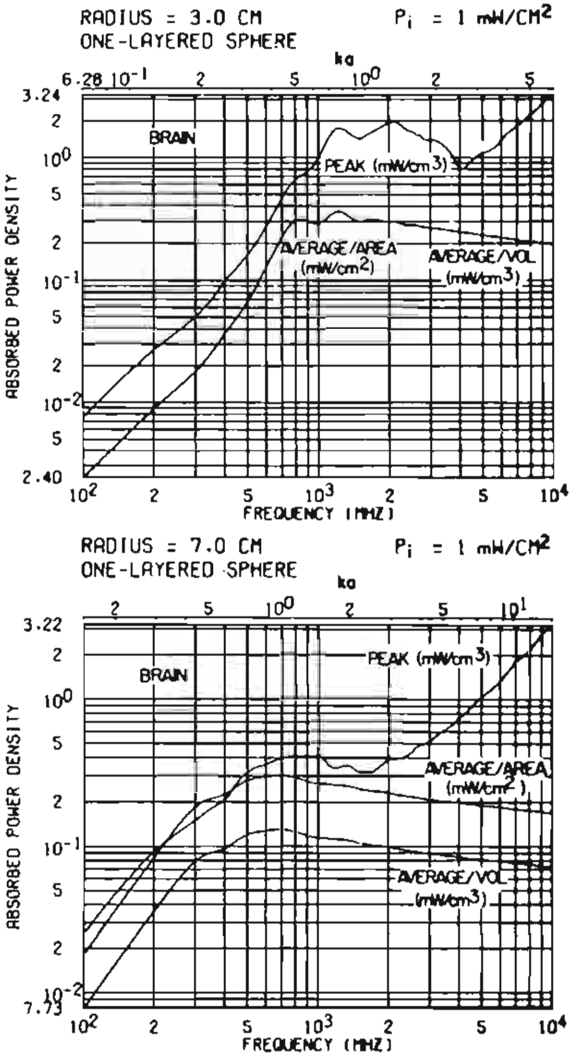


Figure 66. Typical absorption characteristics for homogeneous spherical models of the head exposed to 1 mW/cm² microwave power density as a function of sphere size and microwave frequency. (From Johnson and Guy: Nonionizing electromagnetic wave effects. Courtesy of *Proc IEEE, 60*:692-718, 1972.)

Johnson and Guy, 1972; Lin et al., 1973; Lin, 1976a; Ho et al., 1975; Weil, 1975). The peak absorbed power density, the average absorbed power density per unit volume, and the average absorbed power density per unit surface area for spheres of brain material exposed to an incident power density of one mW/cm² are shown in Figure 66 as a function of sphere size and microwave frequency. It can be seen that the absorbed power varies widely with sphere sizes and frequencies. In general, the absorption initially increases rapidly with an increase of radius and is then followed by some resonant behavior. The peaks of these resonant oscillations are related to the maxima, or hot spots, in the distribution of absorbed energy inside the head model, as shown in Figures 67 and 68. For ($2\pi a/\lambda_o < 0.4$), where a is the sphere radius and λ_o is the wavelength in vacuum, there are no hot spots occurring inside the sphere. Hot spots do occur, however, in spheres with radii between 2 and 8 cm at 918 MHz and between 0.9 and 5 cm at 2450 MHz. It is significant to note that sizes for human and a majority of laboratory animal heads all fall within these ranges. For spheres whose radii exceed the size ranges mentioned above, the maximum absorption appears at the exposed surface of the sphere, and the penetration depth at the surface becomes a dominating factor. The planar model discussed in Chapter 5 may be applied to obtain a theoretical estimation of the absorbed energy in this case.

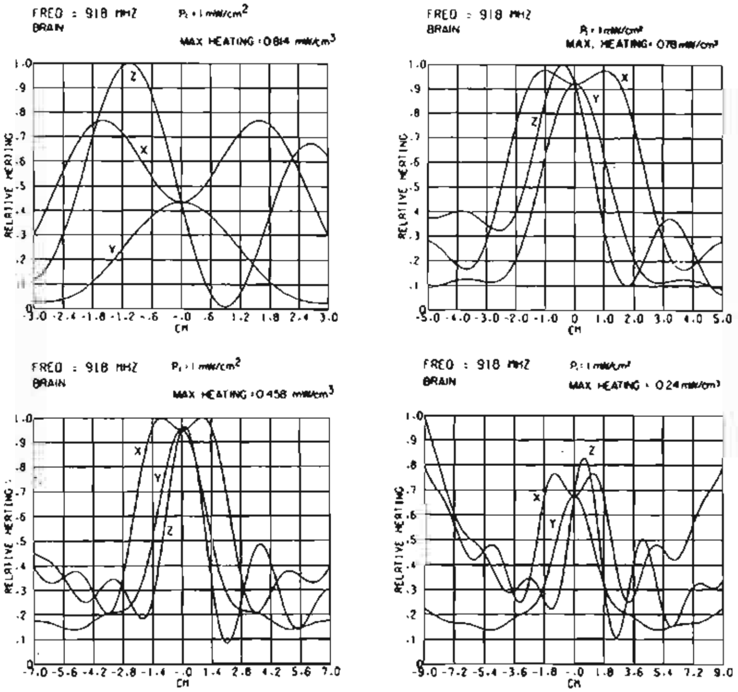


Figure 67. Microwave absorption pattern along the three rectangular coordinate axes of spherical models of the head exposed to 918 MHz plane wave. (From Lin et al.: Microwave selective brain heating. Courtesy of *J Microwave Power*, 8:275-286, 1973.)

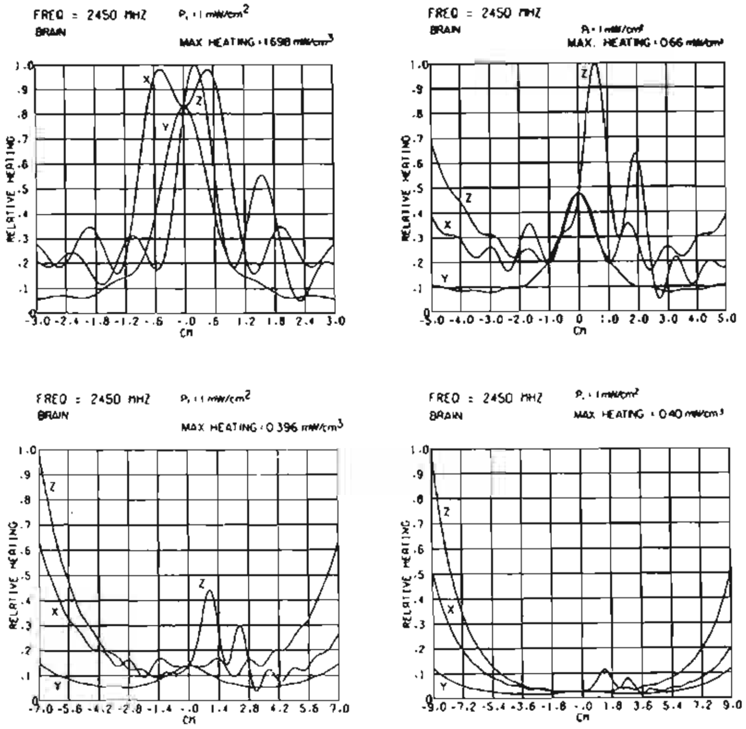


Figure 68. Microwave absorption pattern along the three rectangular coordinate axes of spherical models of the head exposed to 2450 MHz plane wave. (From Lin et al.: Microwave selective brain heating. Courtesy of *J Microwave Power*, 8:275-286, 1973.)

The frequency dependence of microwave absorption is illustrated in the lower graphs in Figure 66 for the head of a small animal, such as a cat or rhesus monkey, and a human head-size sphere. In addition to the resonant behavior described previously, the peak absorption at the surface is seen to increase with increasing frequency for frequencies beyond the last resonant peak. At these frequencies, the constant incident power is absorbed in a decreasingly smaller volume as a result of shortened penetration depth. It is interesting to note that the highest peak absorption for a human head-size sphere (a = 7 cm) occurs around 1000 MHz. This is close to the carrier frequency reported to be optimal for hearing induced by pulse-modulated microwaves.

The absorbed energy distributions inside the spherical head models are shown in Figure 67 and 68. In each of these figures, the patterns are normalized to the maximum along any one of the three rectangular coordinate axes. The prints on top of each figure indicate the maximum absorption to which the curves are normalized. These figures illustrate some interesting points. Not only may the peak absorption differ according to head size and microwave frequency, the distribution of absorbed energy may also vary. Note, for example, that at 918 MHz peak absorption occurs near the center of the head for 5, 7, and 9 cm spheres and approximately 1.2 cm off the center for a 3 cm radius sphere. At 2450 MHz, however, the peak absorption is at the center for 3 and 5 cm spheres, whereas for 7 and 9 cm spheres peaks occur at the proximal portion (the exposed surface of the sphere).

It is seen that in many cases the absorbed energy along the three coordinate axes exhibits standing-wave-like oscillations along the outer portion of the spherical head and reaches a maximum near the center. Although the detailed absorption along the three axes is not the same, we will assume a spherically symmetric absorption pattern and approximate the absorbed energy distribution inside the head by the spherically symmetric function*

$$W = W_o \frac{\sin(N\pi r/a)}{(N\pi r/a)} \qquad (6.3)$$

where W_o is the peak rate of absorbed energy per unit volume, r is the radial variable, and a is the radius of the spherical head. The parameter N specifies the number of oscillations in the approximated spatial dependence of the absorbed energy. Figure 69 shows the approximated energy absorption pattern for N = 3 and is particularly suited for a 2 cm head exposed to 2450 MHz or a 5 cm head exposed to 918 MHz radiation. For some frequencies and

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The results will be the same if $W = W_o \frac{\sin N\pi r/a}{N\pi r/a} + W_1$ is assumed for the pattern of absorbed energy distribution, since W_1 is small compared with W_o. W_1 is a constant included to account for the uniform component.

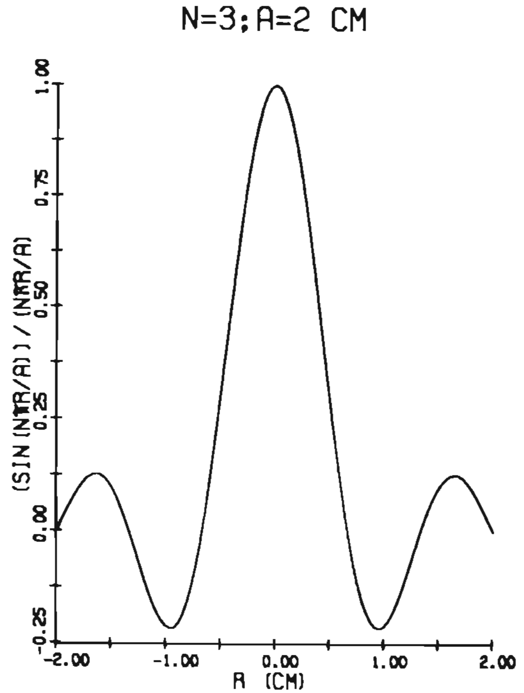

Figure 69. Approximate distribution of absorbed microwaves for N = 3.

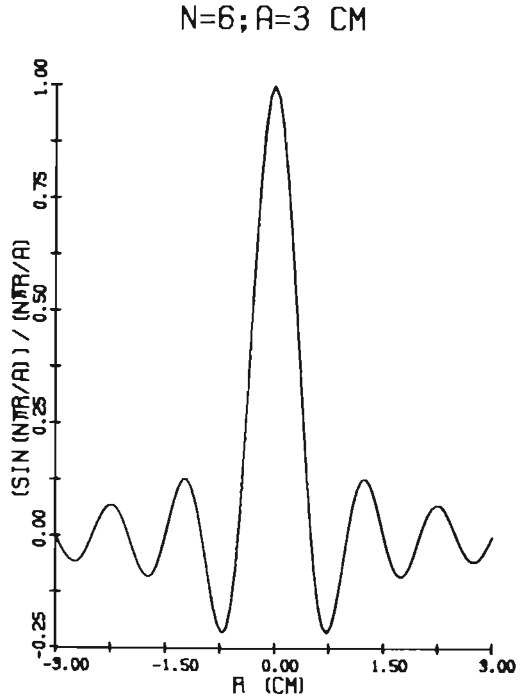

Figure 70. Approximate distribution of absorbed microwaves for N = 6.

sphere sizes, the integer N may be changed to account for the difference in absorption patterns. For instance, $N = 6$ may be chosen to approximate the absorption pattern inside a 3 or 7 cm radius spherical head exposed to 2450 or 918 MHz radiations (Fig. 70). For other frequencies and sphere sizes, a different function will be required to describe the absorbed energy distribution.

TEMPERATURE RISE

We take advantage of the symmetry of the absorbed energy pattern by expressing the heat conduction equation as a function of r alone (Carslow and Jaeger, 1959). That is,

$$\frac{1}{r^2}\frac{\partial}{\partial r} r^2 \frac{\partial v}{\partial r} - \frac{1}{\kappa}\frac{\partial v}{\partial t} = \frac{-W}{K} \qquad (6.4)$$

where v is temperature; κ and K are the thermal diffusivity and conductivity of brain matter, respectively; and W is the heat production rate, which is the same as the absorbed microwave energy pattern and is assumed for the moment to be constant over time.

Because microwave absorption occurs in a very short time interval, there will be little chance for heat conduction to take place. We may therefore neglect the spatial derivatives in equation (6.4) such that

$$\frac{1}{\kappa}\frac{dv}{dt} = \frac{W}{K} \qquad (6.5)$$

Equation (6.5) may be integrated, directly, to give the change in temperature by setting the initial temperatures equal to zero. Thus,

$$v(r,t) = \frac{W_o}{\rho c_h}\frac{\sin(N\pi r/a)}{(N\pi r/a)}\, t \qquad (6.6)$$

where ρ and c_h are the density and specific heat of brain matter, respectively, and $\rho c_h = K/\kappa$.

In biological materials, the stress-wave development times are short compared with temperature equilibrium times. The temperature decay is therefore a slowly varying function of time and becomes significant only for times greater than milliseconds. We may thus assume for a rectangular pulse of microwave energy (t_o = pulse width) that, immediately after power is removed, the temperature stays constant at

$$v(r,t) = \frac{W_o}{\rho c_h}\frac{\sin(N\pi r/a)}{(N\pi r/a)}\, t_o \qquad (6.7)$$

THERMOELASTIC EQUATION OF MOTION

Considering the spherical head with homogeneous brain matter as an isotropic, linear, elastic medium without viscous damping, and taking advantage of the spherical symmetry, we may express the thermoelastic equation of motion in spherical coordinates when $\lambda >> \mu$ as follows (Love, 1927; Sokolnikoff, 1956):

$$\frac{\partial^2 u}{\partial r^2} + \frac{2}{r}\frac{\partial u}{\partial r} - \frac{2}{r^2}u - \frac{1}{c^2}\frac{\partial^2 u}{\partial t^2} = \frac{\gamma}{\lambda+2\mu}\frac{\partial v}{\partial r} \qquad (6.8)$$

where u is the displacement of brain matter, $c = [(\lambda+2\mu)/\rho]^{1/2}$ is the velocity of bulk acoustic wave propagation, $\gamma = \beta(3\lambda+2\mu)$, β is the coefficient of linear thermal expansion, and λ and μ are Lamé's constants. It should be noted that the curl of u equals zero since u is in the radial direction only. The right-hand side of equation (6.8) is the change in temperature which gives rise to the displacement. We may express it as

$$\frac{\gamma}{\lambda+2\mu}\frac{\partial v}{\partial r} = u_o F_r(r) F_t(t) \qquad (6.9)$$

such that

$$u_o = \frac{W_o}{\rho c_h}\frac{\gamma}{\lambda+2\mu} \qquad (6.10)$$

and

$$F_r(r) = \frac{d}{dr}\frac{\sin(N\pi r/a)}{(N\pi r/a)} \qquad (6.11)$$

From equations (6.6) and (6.7), we have

$$F_t(t) = \begin{cases} t, & 0 \le t \le t_o \\ t_o & t \ge t_o \end{cases} \qquad (6.12)$$

If the surface of the sphere is stress-free, the boundary condition at r = a is given by

$$(\lambda+2\mu)\frac{\partial u}{\partial r}(a,t) + 2\lambda\frac{u}{r}(a,t) = \gamma v(a,t) = 0 \qquad (6.13)$$

If the surface of the sphere is rigidly constrained, the boundary condition at the surface requires the displacement

$$u(a,t) = 0 \qquad (6.14)$$

The initial conditions for both cases are

$$u(r,0) = \frac{\partial u(r,0)}{\partial t} = 0 \qquad (6.15)$$

Our approach in the following derivations is first to obtain a solution for the case of $F_t(t) = 1$, and then to extend the solution to a rectangular pulse using Duhamel's principle (Lin, 1977a,b).

SOUND WAVE GENERATION IN A STRESS-FREE SPHERE

Solution for F_t (t) = 1

We first write the displacement u(r,t) in the form of a linear combination

$$u(r,t) = u_s(r) + u_t(r,t) \tag{6.16}$$

Substituting equation (6.16) into equation (6.8) and then using $F_t(t) = 1$, the equation of motion becomes two differential equations: a stationary one and a time-varying one. Thus,

$$\frac{d^2u_s(r)}{dr^2} + \frac{2}{r}\frac{du_s(r)}{dr} - \frac{2}{r^2}u_s(r) = u_\circ F_r(r) \tag{6.17}$$

and

$$\frac{\partial^2 u_t(r,t)}{\partial r^2} + \frac{2}{r}\frac{\partial u_t(r,t)}{\partial r} - \frac{2}{r^2}u_t(r,t) = \frac{1}{c^2}\frac{\partial^2 u_t(r,t)}{\partial t^2} \tag{6.18}$$

The corresponding boundary conditions at r = a for a stress-free surface are

$$(\lambda+2\mu)\, du_s/dr + 2\lambda\, u_s/r = 0 \tag{6.19}$$

and

$$(\lambda+2\mu)\, \partial u_t/\partial r + 2\lambda\, u_t/r = 0 \tag{6.20}$$

A solution to the second order ordinary differential equation (6.17) may be obtained by writing

$$u_s(r) = u_p(r) + Dr \tag{6.21}$$

where u_p is a particular solution of (6.17) and is obtained by integrating (6.17) from 0 to r. Thus,

$$u_p(r) = u_\circ\left(\frac{a}{N\pi}\right) j_1\left(\frac{N\pi r}{a}\right) \tag{6.22}$$

where j_1 is the first order spherical Bessel function of the first kind. The coefficient D is evaluated by applying the boundary condition given in (6.19) and it is

$$D = \pm\, u_\circ \left(\frac{1}{N\pi}\right)^2 \frac{4\mu}{3\lambda+2\mu} \cdot \quad N = \begin{cases} 1,3,5,\ldots \\ 2,4,6,\ldots \end{cases} \tag{6.23}$$

The solution to (6.17) is therefore given by

$$u_s(r) = u_\circ\left(\frac{1}{N\pi}\right) \left[a\, j_1\left(\frac{N\pi r}{a}\right) \pm \frac{4\mu}{3\lambda+2\mu}\frac{r}{N\pi}\right], \quad N = \begin{cases} 1,3,5,\ldots \\ 2,4,6,\ldots \end{cases} \tag{6.24}$$

Next we let

$$u_t(r,t) = R(r)\, T(t) \tag{6.25}$$

and use the method of separation of variables to solve equation (6.18) for the time-varying component. Inserting equation (6.25) into equation (6.18) yields

$$\frac{d^2R}{dr^2} + \frac{2}{r}\frac{dR}{dr} + [k^2 - (2/r^2)]\, R = 0 \tag{6.26}$$

$$\frac{d^2T}{dt^2} + k^2c^2T = 0 \tag{6.27}$$

where k is the yet undetermined constant of separation, equation (6.26) is Bessel's equation and its solution is (Stratton, 1941)

$$R(r) = B_1 j_1(kr) + B_2 y_1(kr) \tag{6.28}$$

where $j_1(kr)$ and $y_1(kr)$ are the first order spherical Bessel functions of the first and second kind, respectively. Since R(r) is finite at r = 0, B_2 must be zero. Combining equation (6.28) and the boundary condition of equation (6.20), we obtain a transcendental equation for k, the constant of separation,

$$\tan(ka) = (ka)/[1 - (\lambda + 2\mu)\,(ka)^2/(4\mu)] \tag{6.29}$$

The solution of this equation is an infinite sequence of eigenvalues, k_m; each corresponds to a characteristic mode of vibration of the spherical head. Using the values for brain matter given in Table XI, it can be shown that $k_m a = m\pi$, m = 1,2,3 . . . to within an accuracy of 10^{-7}. Moreover, since equation (6.27) is harmonic in time, a general solution for $u_t(r,t)$ is

$$u_t(r,t) = \sum_{m=1}^{\infty} A_m j_1(k_m r) \cos \omega_m t \tag{6.30}$$

where

$$\omega_m = k_m c = m\pi c/a, \qquad m = 1,2,3,\ldots \tag{6.31}$$

and ω_m is the angular frequency of vibration of the sphere. Note that the frequency of vibration $f_m = \omega_m/2\pi$ is independent of the absorbed energy pattern. It is a function only of the spherical head size and of the acoustic properties of the medium, which supports negligible shear stress.

To evaluate the constants A_m, we need the initial condition given in equation (6.15). Thus,

$$A_m = -u_0 \left\{\frac{a}{N\pi} \int_0^a r^2 j_1(k_m r) j_1\left(\frac{N\pi r}{a}\right) dr \pm \frac{4\mu}{3\lambda+2\mu} \left(\frac{1}{N\pi}\right)^2 \int_0^a r^3 j_1(k_m r)\, dr\right\} / \left\{\int_0^a r^2 [j_1(k_m r)]^2 dr\right\}, \quad N = \begin{cases} 1,3,5,\ldots \\ 2,4,6,\ldots \end{cases} \tag{6.32}$$

The integrals in the above equation may be evaluated with the help of Jahnke and Emde (1945) to give

$$\int_0^a r^2 j_1(k_m r) j_1\left(\frac{N\pi r}{a}\right) dr = \mp \frac{ka}{N\pi} j_0(k_m a) \left[\frac{a^3}{(k_m a)^2 - (N\pi)^2}\right], \quad N = \begin{cases} 1,3,5,\ldots \\ 2,4,6,\ldots \end{cases} \tag{6.33}$$

$$\int_0^a r^3 j_1(k_m r)\, dr = \frac{a^3}{k_m} j_2(k_m a) \tag{6.34}$$

$$\int_0^a r^2 [j_1(k_m r)]^2 dr = \frac{a^3}{2} \{[j_1(k_m a)]^2 - j_0(k_m a) j_2(k_m a)\} \tag{6.35}$$

where $j_2(k_m a)$ is the second order spherical Bessel function of the first kind. Using these relations, (6.32) becomes

$$A_m = \mp u_0 a \left(\frac{1}{N\pi}\right)^2 \left\{\frac{2}{[j_1(k_m a)]^2 - j_0(k_m a) j_2(k_m a)}\right\} \left\{\frac{4\mu}{3\lambda+2\mu} \left(\frac{1}{k_m a}\right) j_2(k_m a) - k_m a\, j_0(k_m a) \frac{1}{(k_m a)^2 - (N\pi)^2}\right\}, \quad N = \begin{cases} 1,3,5,\ldots \\ 2,4,6,\ldots \end{cases} \tag{6.36}$$

For $k_m a = m\pi = N$, equation (6.36) simplifies to

$$A_m = -u_0 a \left(\frac{1}{N\pi}\right) \left[1 + \frac{24\mu}{3\lambda+2\mu} \left(\frac{1}{N\pi}\right)^2\right] \tag{6.37}$$

The displacement of the sphere in response to $F_t(t) = 1$ is now given by introducing equation (6.36) in equation (6.30) and then combining it with equations (6.24) and (6.16). We then have

$$u(r,t) = u_0 Q + \sum_{m=1}^{\infty} A_m j_1(k_m r) \cos \omega_m t \tag{6.38}$$

$$Q = \frac{a}{N\pi} j_1\left(\frac{N\pi r}{a}\right) \pm \frac{4\mu}{3\lambda+2\mu} \frac{r}{N^2\pi^2}, \quad N = \begin{cases} 1,3,5,\ldots \\ 2,4,6,\ldots \end{cases} \tag{6.39}$$

The radial stress or pressure in terms of displacement (Love, 1927; Sokolnikoff, 1956) is

$$P_r(r,t) = (\lambda+2\mu) \frac{\partial u}{\partial r} + 2\lambda \frac{u}{r} - \gamma v \tag{6.40}$$

We therefore have, by substituting equations (6.6), (6.7), and (6.38) into the above relation,

$$P_r(r,t) = 4\mu\, u_0 S + \sum_{m=1}^{\infty} A_m k_m M_m \cos \omega_m t \tag{6.41}$$

where

$$S = \pm \left(\frac{1}{N\pi}\right)^2 - j_1\left(\frac{N\pi r}{a}\right) / \left(\frac{N\pi r}{a}\right), \quad N = \begin{cases} 1,3,5,\ldots \\ 2,4,6,\ldots \end{cases} \tag{6.42}$$

$$M_m = [(\lambda+2\mu) j_0(k_m r) - 4\mu j_1(k_m r)/(k_m r)] \tag{6.43}$$

Solution for Rectangular Pulse

We can now obtain the displacement and pressure for a rectangular pulse of microwave energy by applying Duhamel's principle (Churchill, 1958) to the solutions expressed by equations (6.38) and (6.41). That is,

$$u(r,t) = \frac{\partial}{\partial t} \int_0^t F_t(t-t') u'(r,t')\, dt' \tag{6.44}$$

where $u'(r,t)$ is the solution given by equation (6.38) for the case of $F_t(t) = 1$. An equivalent expression can, of course, be written for the pressure. Therefore, by substituting equations (6.12) and (6.38) into equation (6.44), we have for the displacement

$$u(r,t) = u_0 Q t + \sum_{m=1}^{\infty} A_m j_1(k_m r) \frac{\sin \omega_m t}{\omega_m}, \quad 0 \le t \le t_0 \tag{6.45}$$

$$u(r,t) = u_0 Q t_0 + \sum_{m=1}^{\infty} A_m j_1(k_m r) \left[\frac{\sin \omega_m t}{\omega_m} - \frac{\sin \omega_m (t-t_0)}{\omega_m}\right], \quad t \ge t_0 \tag{6.46}$$

Similarly, we have for the pressure

$$P_r(r,t) = 4\mu\, u_0 S t + \sum_{m=1}^{\infty} A_m k_m M_m \frac{\sin \omega_m t}{\omega_m}, \quad 0 \le t \le t_0 \tag{6.47}$$

$$P_r(r,t) = 4\mu\, u_0 S t_0 + \sum_{m=1}^{\infty} A_m k_m M_m \left[\frac{\sin \omega_m t}{\omega_m} - \frac{\sin \omega_m (t-t_0)}{\omega_m}\right], \quad t \ge t_0 \tag{6.48}$$

where k_m, A_m, Q, S, and M_m are as given in equations (6.31), (6.36), (6.39), (6.42), and (6.43). Equations (6.45) to (6.48) represent the general solution for the displacement and pressure in a spherical head exposed to rectangular-pulse-modulated microwave radiation as a function of the microwave, thermal, elastic, and geometric parameters of the model in the absence of shear stress.

Since u_o and A_m are directly proportional to W_o, both the displacement and the pressure are proportional to the peak absorbed power density. It is easy to see that the displacement and radial stress also depend linearly on the peak incident power density.

At the center of the sphere, r = 0, both equations (6.45) and (6.46) reduce to zero and there is no displacement at the center of the model. On the other hand, at the surface (r = a), equation (6.42) becomes naught. The radial stress is given by the summation of the harmonic time functions alone.

Computed Frequency of Sound

The fundamental frequency of sound generated inside the spherical head, according to equation (6.31), is given by

$$f_1 = c/2a \qquad (6.49)$$

where a is radius of the sphere and c is the velocity of sound propagation in brain matter (see Table IX). A plot of the fundamental frequency of sound as a function of head radius is shown in Figure 71. The frequency exceeds 80 kHz at a radius of 1 cm and decreases rapidly to a value of 25 kHz at a = 3 cm. For larger head sizes, between 7 and 10 cm, it gradually decreases to about 7.3 to 10.4 kHz (Lin, 1976c).

The radius of a guinea pig's head is between 1.5 and 2.5 cm; Figure 71 therefore predicts a fundamental sound frequency between 29 and 48 kHz. This is slightly lower than the cochlear microphonic oscillations recorded from the round window of guinea pigs (Chou et al., 1975). Similar comparisons for cats show that the computed fundamental frequency for this stress-free model is usually smaller than the measured results. However, it should be noted that much better agreement is obtained when the theoretical formulation is extended to constrained surfaces in the following section.

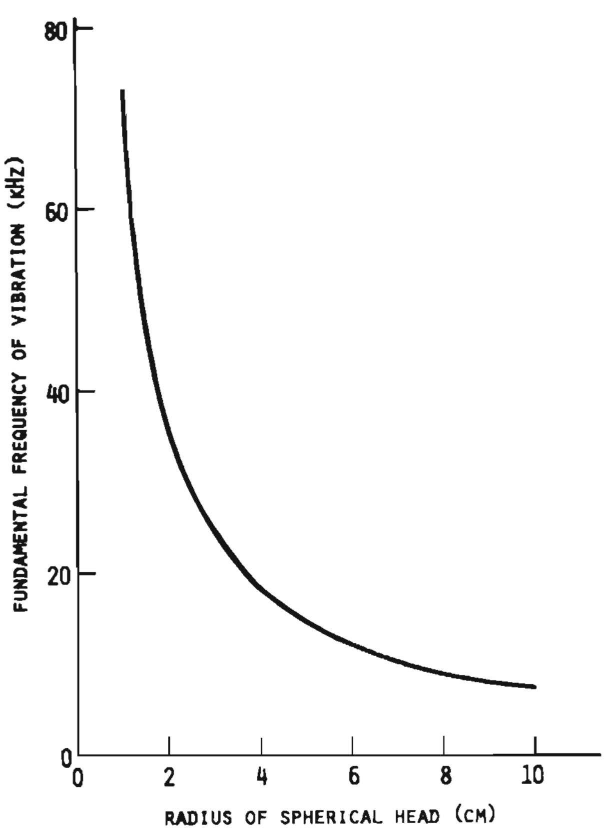

Figure 71. The fundamental frequencies of sound generated inside surface-stress-free spherical head as a function of head radii.

Computed Displacement and Pressure

Using the physical parameters for brain matter given in Tables IX to XII, we can estimate the amplitude of the acoustic signals generated in the heads of animals and humans irradiated with rectangular pulses of microwave energy. Results of many displacement and pressure computations are available (Lin, 1976c, 1977a,c).

Figures 72 and 73 show the computed displacement of brain matter in a 3 cm and a 7 cm radius spherical head exposed to

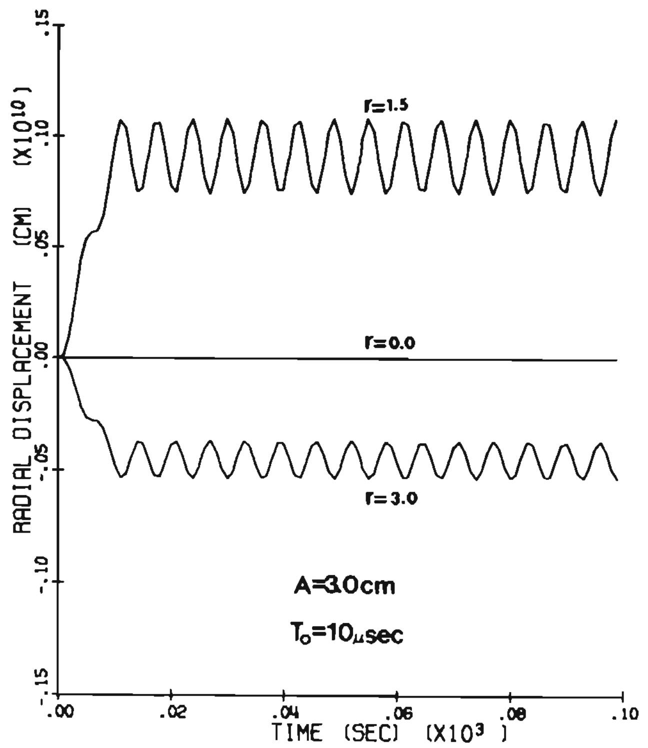

Figure 72. Radial displacement as a function of time for a 3 cm radius spherical head exposed to 2450 MHz plane wave. The peak absorption is 1000 mW/cm^3.

pulsed 2450 MHz and 918 MHz microwave radiation, respectively. The pulse width is 10 μsec and the peak rate of microwave absorption is 1000 mW/cm^3. As expected, the displacement at the center of the sphere is zero. At other locations, the displacement increases almost linearly as a function of time until $t = t_o$, the pulse width; it then starts to oscillate around that value. In both cases shown, the maximum displacements are on the order of 10^{-13} meters. The displacements stay constant after a transient buildup because of the lossless assumption for the elastic media. The apparent higher frequency of oscillation seems to stem from the contribution of higher order modes.

The sound pressures in the spherical head models are shown in

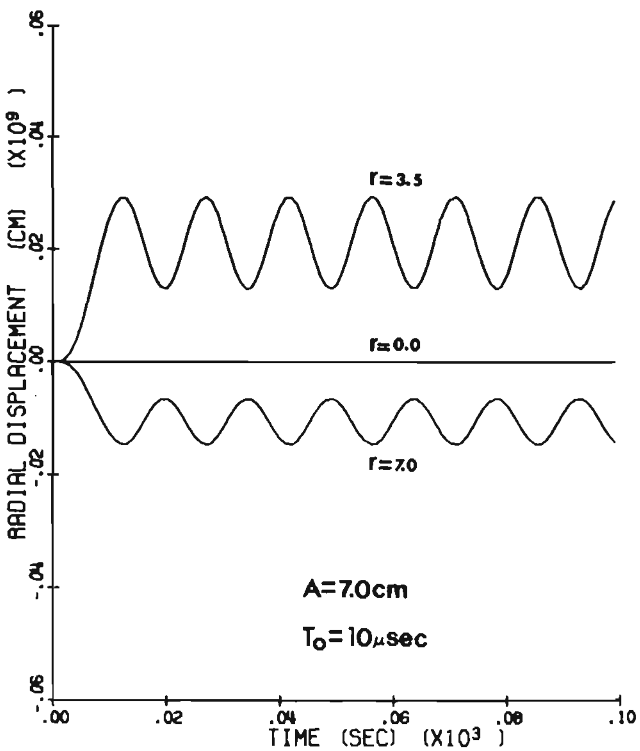

Figure 73. Radial displacement as a function of time for a 7 cm radius spherical head exposed to 918 MHz plane wave. The peak absorption is 1000 mW/cm^3.

Figures 74 and 75 for the displacements shown in Figures 72 and 73. It is interesting to note that the sound pressure begins with zero amplitude and then grows to an intermediate value. With a sudden rise of amplitude the main body of the pressure wave arrives, oscillating at a constant pressure level in the absence of elastic loss.

Table XIV and XV show, for a peak absorption of 1000 mW/cm^3, that the pressures generated at the center of the sphere are 70 to 90 db above 0.0002 dyne/cm^2. At this rate of energy absorption, the rate of temperature rise at the center of both spheres is 0.258°C/sec in the absence of heat conduction. The temperature rise in 10 μsec is, therefore, approximately 2.6×10^{-6}°C.

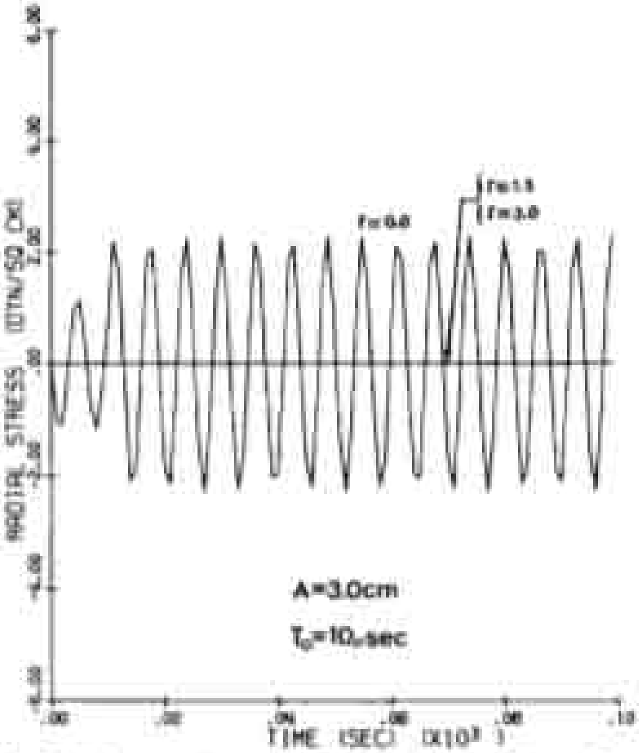

Figure 74. Radial stress (sound pressure) generated in a 3 cm radius spherical head exposed to 2450 MHz plane wave. The peak absorption is 1000 mW/cm³.

TABLE XIV

SOUND PRESSURE IN A CAT-SIZED (a = 3 cm)
SPHERICAL HEAD EXPOSED TO 2450 MHz RADIATION

Pulse Width (μs)	*Incident Power* (mW/cm²)	*Absorbed Power* (mW/cm³)	*Pressure* (dyne/cm²)	*db* re 0.0002 dyne/cm²
0.1	589	1000	0.12	55.6
0.5	589	1000	0.59	69.4
1.0	589	1000	1.15	75.2
5.0	589	1000	1.40	76.9
10.0	589	1000	2.30	81.2
20.0	589	1000	1.35	76.6
30.0	589	1000	1.50	77.5
40.0	589	1000	2.20	80.8
50.0	589	1000	1.20	75.6

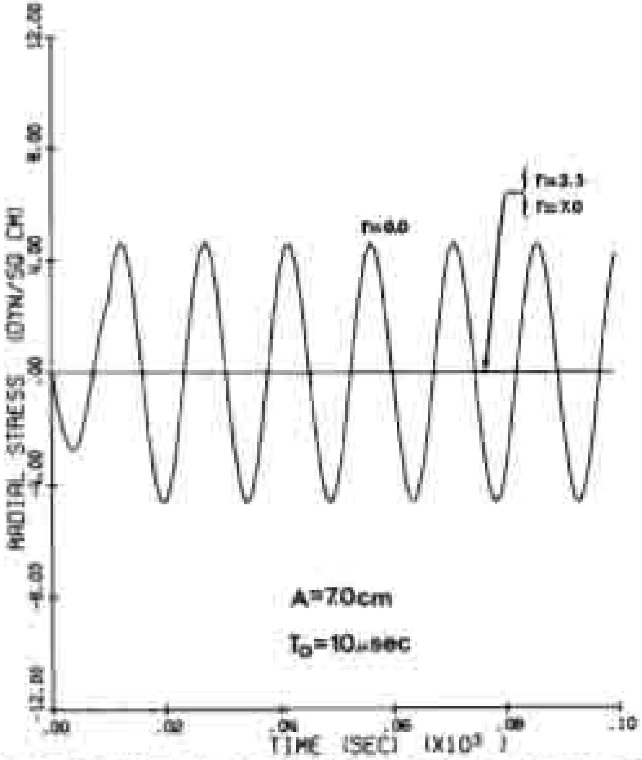

Figure 75. Radial stress (sound pressure) generated in a 7 cm radius spherical head exposed to 918 MHz plane wave. The peak absorption is 1000 mW/cm³.

TABLE XV

SOUND PRESSURE IN A MAN-SIZED (a = 7 cm)
SPHERICAL HEAD EXPOSED TO 918 MHz RADIATION

Pulse Width (μs)	*Incident Power* (mW/cm²)	*Absorbed Power* (mW/cm³)	*Pressure* (dyne/cm²)	*db* re 0.0002 dyne/cm²
0.1	2183	1000	0.12	55.5
0.5	2183	1000	0.60	69.5
1.0	2183	1000	1.19	75.5
5.0	2183	1000	4.90	87.8
10.0	2183	1000	4.70	87.4
20.0	2183	1000	5.10	88.1
30.0	2183	1000	2.80	82.9
40.0	2183	1000	4.10	86.2
50.0	2183	1000	5.40	88.6

Figures 76 and 77 illustrate the results of pressure computations for the above spherical head models irradiated with rectangular pulses from 0.1 to 100 μsec while keeping the peak incident (or absorbed) power density constant. Pulse-modulated, microwave-induced sound pressure amplitudes clearly depend on the pulse width of the impinging radiation. Moreover, there is apparently a minimum pulse width for efficient sound pressure generation which varies according to the sphere size and the frequency of the impinging microwaves. In general, sound pressure first rises rapidly to a maximum and then alternates around a constant average amplitude.

Examination of the numerical results given in Table XIV indicates that the incident power density required to produce the threshold sound pressure of 120 db (Corso, 1963) necessary for perception through bone conduction is about 14,500 $\mathrm{mW/cm^2}$. This is approximately 6.5 times greater than the 2200 $\mathrm{mW/cm^2}$ incident power reported by Guy et al. (1973, 1975). The sound pressure generated in a surface-stress-free spherical head model is therefore smaller than known results. However, we should emphasize this happens only if the surface of the sphere is stress free. The agreement between theory and measurement is much better if the boundary of the sphere is assumed to be rigidly constrained, as we shall see in the following discussions.

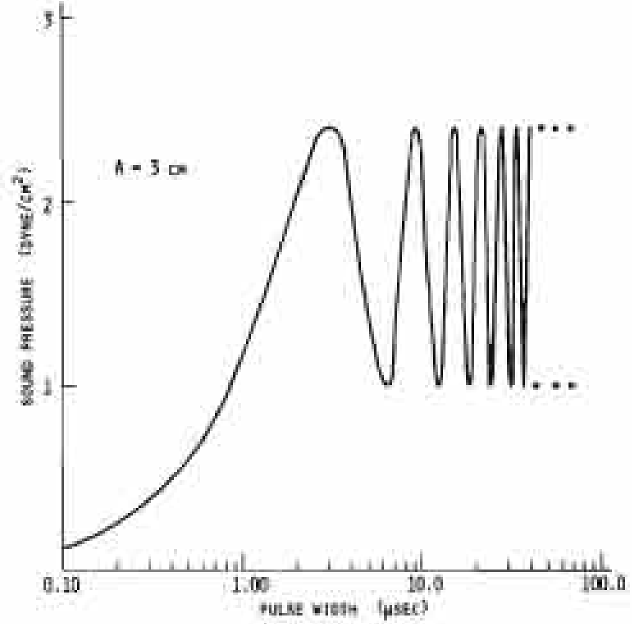

Figure 76. Sound pressure amplitude generated in a 3 cm radius spherical head exposed to 2450 MHz plane wave as a function of pulse width. The peak rate of absorbed energy density is 1000 $\mathrm{mW/cm^3}$.

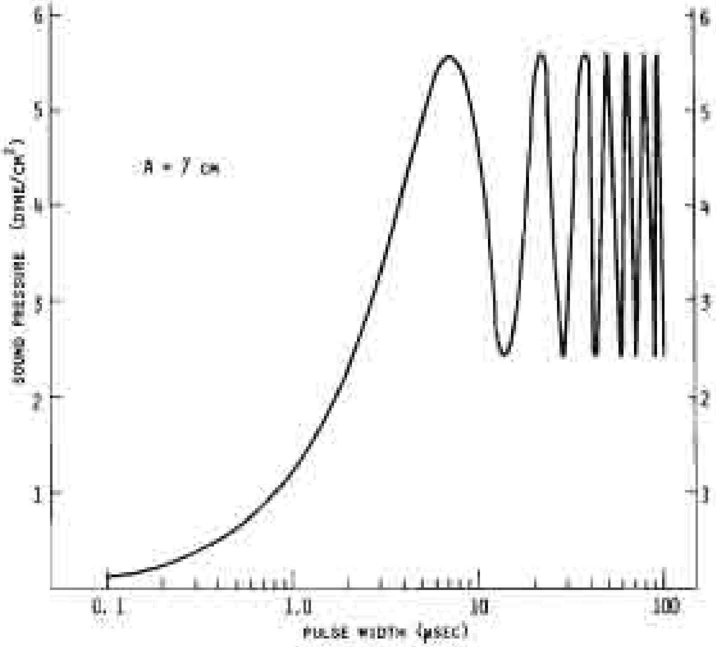

Figure 77. Sound pressure amplitude generated in a 7 cm radius spherical head exposed to 918 MHz plane wave as a function of pulse width. The peak rate of absorbed energy density is 1000 $\mathrm{mW/cm^3}$.

SOUND WAVE GENERATION IN A SPHERE WITH CONSTRAINED BOUNDARY

Theoretical Analysis

If the surface of the sphere is rigidly constrained, the boundary condition at the surface requires that the displacement

$$u(a,t) = 0 \tag{6.14}$$

Following the procedures set forth in the previous section, we may first obtain a solution for $F_1(t) = 1$ by expressing the displacement $u(r,t)$ as a summation. That is

$$u(r,t) = u_s(r) + u_t(r,t) \tag{6.50}$$

where $u_s(r)$ is found using the boundary condition $u_s(a) = 0$ to be

$$u_s(r) = (\frac{u_0}{N\pi})\left[a\, j_1(\frac{N\pi r}{a}) \mp \frac{r}{N\pi}\right], \quad N = \begin{cases} 1,3,5,\ldots \\ 2,4,6,\ldots \end{cases} \tag{6.51}$$

and where the time-varying component is given by

$$u_t(r,t) = \sum_{m=1}^{\infty} A_m j_1(k_m r) \cos \omega_m t \tag{6.52}$$

where k_m is the positive zeroes of

$$j_1(ka) = 0 \tag{6.53}$$

and

$$\omega_m = k_m c \tag{6.54}$$

The solution of equation (6.53) is an infinite sequence of eigenvalues, k_m. Since $f_m = \omega_m/2\pi$ represents the frequency of vibration of the spherical head model, there are therefore an infinite number of modes of vibration of the spherical head irradiated with appropriate pulse modulated microwave energy. The values of $k_m a$ for m = 1 to 11 are listed in Table XVI. The fundamental frequency of sound generated inside a spherical head with constrained boundary without shear stress is given by

TABLE XVI

ZEROES OF $j_1(ka) = 0$

m	$k_m a$
1	4.493411
2	7.725252
3	10.904122
4	14.066194
5	17.220755
6	20.371303
7	23.519453
8	26.666054
9	29.811598
10	32.956389
11	36.100622

$$f_1 = k_1 c/(2\pi) = 4.49\, c/(2\pi a) \tag{6.55}$$

It can be seen that the fundamental frequency under constrained surface condition is significantly higher than that given by the stress-free case. As before, the frequency of the acoustic wave generated is a function of the acoustic property (velocity of propagation) and size of the sphere.

To determine the coefficient A_m in equation (6.52), we may insert equations (6.51) and (6.52) into equation (6.50) and make use of the initial condition of equation (6.15). Because the function $j_1(k_m r)$ is orthogonal, we get, after integration over r from 0 to a,

$$A_m = \pm 2u_0 a\, (\frac{1}{N\pi})^2 \frac{(\frac{2}{k_m a})\, j_2(k_m a) \pm k_m a\, j_0(k_m a) \frac{1}{(k_m a)^2 - (N\pi)^2}}{[j_1(k_m a)]^2 - j_0(k_m a) j_2(k_m a)} \tag{6.56}$$

$$N = \begin{cases} 1,3,5,\ldots \\ 2,4,6,\ldots \end{cases}$$

The displacement of brain matter inside the spherical model is therefore given by

$$u(r,t) = u_0 D + \sum_{m=1}^{\infty} A_m j_1(k_m r) \cos \omega_m t, \tag{6.57}$$

where

$$D = \frac{1}{N\pi}\left[a\, j_1(\frac{N\pi r}{a}) \mp (\frac{r}{N\pi})\right], \quad N = \begin{cases} 1,3,5,\ldots \\ 2,4,6,\ldots \end{cases} \tag{6.58}$$

and A_m is given by equation (6.56). The pressure $p_r(r,t)$ is obtained from the displacement using

$$p_r(r,t) = (\lambda + 2\mu) \frac{\partial u}{\partial r} + 2\lambda \frac{u}{r} - \gamma v \tag{6.59}$$

and is given by

$$p_r(r,t) = u_0 P_0 + \sum_{m=1}^{\infty} A_m k_m P_m \cos \omega_m t, \tag{6.60}$$

where

$$P_0 = \frac{-4\mu a}{N\pi r}\, j_1(\frac{N\pi r}{a}) \mp (3\lambda + 2\mu)(\frac{1}{N\pi})^2, \quad N = \begin{cases} 1,3,5,\ldots \\ 2,4,6,\ldots \end{cases} \tag{6.61}$$

$$P_m = (\lambda + 2\mu)\, j_0(k_m r) - \frac{4\mu}{k_m r}\, j_1(k_m r) \tag{6.62}$$

The solutions expressed by equations (6.57) and (6.60) apply to the case of $F_1(t) = 1$. This solution may be extended to the case of a rectangular pulse using Duhamel's principle according to equation (6.44). Therefore, by letting $u'(r,t)$ be equal to equation (6.57), we have for the displacement of the spherical head in response to a rectangular pulse of microwave energy with pulse width t_o, in the absence of shear stress,

$$u(r,t) = u_o D t + \sum_{m=1}^{\infty} A_m j_1(k_m r) \frac{\sin \omega_m t}{\omega_m} \qquad 0 < t < t_o \tag{6.63}$$

$$u(r,t) = u_o D t_o + \sum_{m=1}^{\infty} A_m j_1(k_m r) \left[\frac{\sin \omega_m t}{\omega_m} - \frac{\sin \omega_m (t-t_o)}{\omega_m}\right], \ t > t_o \tag{6.64}$$

In a similar manner, we have for the pressure

$$p_r(r,t) = u_o P_o t + \sum_{m=1}^{\infty} A_m k_m P_m \frac{\sin \omega_m t}{\omega_m}, \ 0 < t < t_o \tag{6.65}$$

$$p_r(r,t) = u_o P_o t_o + \sum_{m=1}^{\infty} A_m k_m P_m t_o \sin \omega_m (t-t_o), \quad t \geq t_o \tag{6.66}$$

Equations (6.63) through (6.66) represent the displacement and sound pressure generated in the spherical head model with constrained surfaces exposed to rectangular-pulse-modulated microwave radiation. Since u_o is related to peak absorbed power density W_o, the sound pressure generated is also proportional to peak power density.

The dependence of sound pressure on pulse width is more complicated in general. For short pulses ($\omega_m t_o << 1$), however, equation (6.66) simplifies to

$$p_r(r,t) = u_o P_o t_o + \sum_{m=1}^{\infty} A_m k_m P_m \left[\frac{\sin \omega_m t}{\omega_m} - \frac{\sin \omega_m (t-t_o)}{\omega_m}\right], \ t > t_o \tag{6.67}$$

We see that for short pulses, the pressure generated in the head model is also proportional to the product of power density and pulse width or energy density per pulse. From Table XVI and equation (6.54), it is seen that the maximum pulse width for which equation (6.67) is applicable is approximately one μsec for a = 7 cm and 0.5 μsec for a = 3 cm.

Computed Frequency of Sound

The fundamental frequency of sound generated in a spherical head with constrained-boundary is given by equation (6.55). As mentioned before, the frequency is completely independent of the microwave absorption pattern; it is only a function of the size of the spherical head and the acoustic properties of the tissue involved. This indicates that the frequency of sound perceived by a subject irradiated by rectangular pulses of microwave energy will be the same regardless of the frequency of the impinging radiation.

The fundamental frequency is plotted as a function of spherical head radius in Figure 78. It is readily observed that the frequency in various subjects differs according to their equivalent

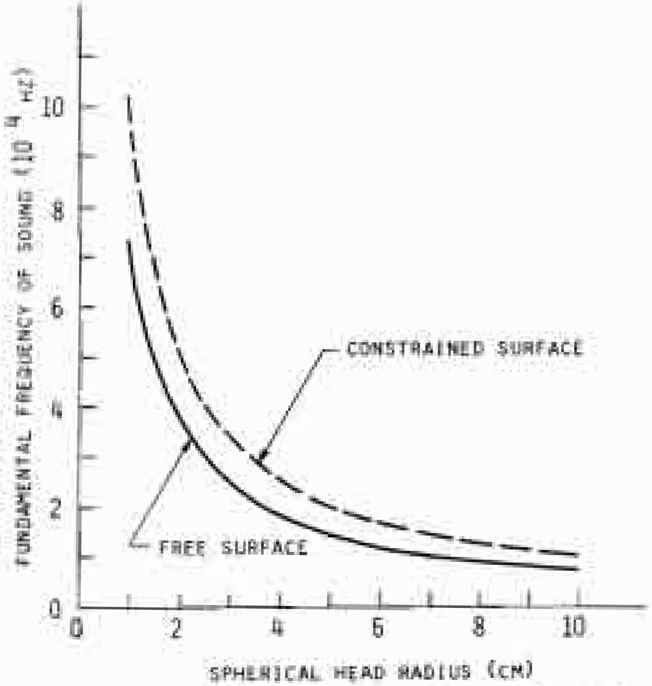

Figure 78. Fundamental frequency of sound generated inside spherical models of the head.

spherical head sizes, i.e. the smaller the head size, the higher the frequency. For example, the average head radius for guinea pigs is about 1.5 to 2.5 cm; Figure 78 yields a range of 40 to 70 kHz for the corresponding fundamental sound frequency. The average head radius for cats is approximately 2.5 to 3.5 cm; the corresponding fundamental sound frequency is between 30 to 40 kHz. It is significant to note that these frequencies are very close to the 50 kHz cochlear microphonics reported for guinea pigs (Chou et al., 1975) and 38 kHz oscillations reported for cats (Chou et al., 1976). Human head sizes are known to vary from 7 to 10 cm for adults. From Figure 78, we see that the estimated fundamental sound frequency ranges from 10 to 15 kHz. This is certainly not in violation of the known facts of auditory physiology nor is it in conflict with the observation that a necessary condition for auditory perception of microwaves is the ability to perceive auditory signals above 5 or 8 kHz (Frey, 1961; Rissmann and Cain, 1975).

It should be noted that the frequencies predicted by the constrained-surface formulation are about 70 percent higher than those calculated earlier based on stress-free boundary conditions (see Fig. 78). Since the head is neither entirely stress free nor rigidly constrained, it is possible that the actual fundamental sound frequency falls somewhere between those predicted by the two approaches.

Computed Pressure and Displacement

Figure 79 is a plot of pressure in a 3 cm radius spherical head irradiated with 2450 MHz radiation as a function of time for a 10 μsec pulse. The curves are evaluated at $r = 0$, 1.5, and 3.0 cm. It is seen that the pressure is the highest in the center of the spherical head. After a transient buildup, which lasted for the duration of the pulse-width, the pressure oscillates at a constant level because of the lossless assumption for the elastic medium. It is also important to note that the high frequency oscillation is modulated by a low-frequency envelope whose frequency is the same as the fundamental frequency of sound given in Figure 78 for a spherical head with $a = 3$ cm. The pressure generated at the center of the

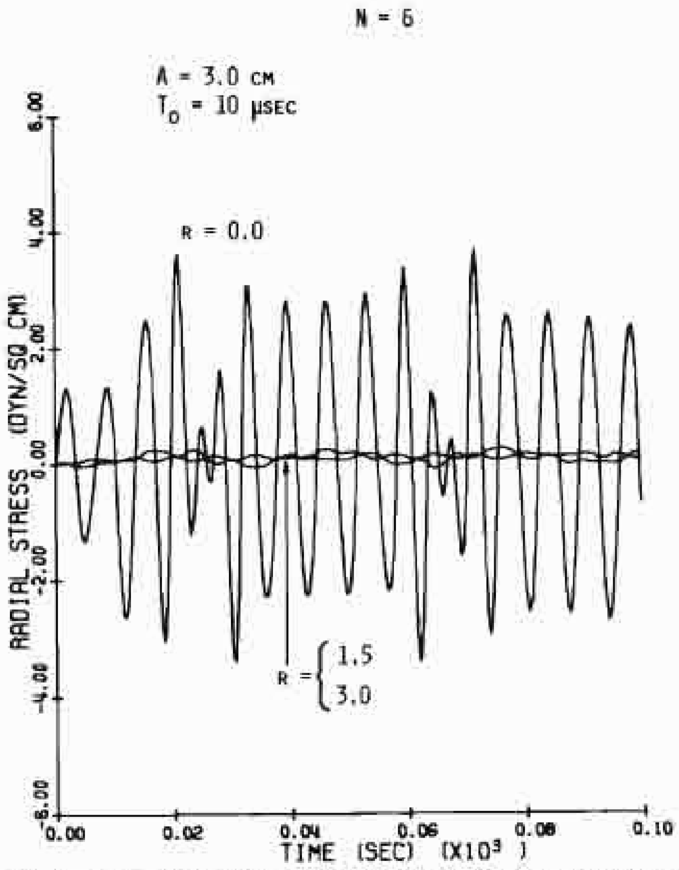

Figure 79. Sound pressure in a 3 cm radius spherical head exposed to 2450 MHz microwave energy. The rate of absorbed energy density is 1000 mw/cm^3.

spherical head is 3.69 dyne/cm^2 for a peak absorption of 1000 mW/cm^3, which corresponds to 589 mW/cm^2 of incident power (Lin et al., 1973). This pressure is considerably higher than that obtained from the surface stress-free model.

There are two sets of experimental data that are particularly suitable for comparison with the results described above. In one case the threshold incident power density was reported to be 2200 mW/cm^2 (Guy et al., 1973, 1975). For the other, the threshold was said to be about 1300 mW/cm^2 (Rissmann and Cain, 1975). The corresponding pressure amplitude is therefore between 8.1 and 14 dyne/cm^2, i.e. 92 to 97 db relative to 0.0002 dyne/cm^2. Assuming that perception by bone conduction for cats is the same as for humans, the minimum audible sound pressure at 40 kHz is about 120 db according to Corso (1963). Thus, the theoretically predicted threshold incident power density is very close to the measured value.

The computed pressure as a function of pulse width is shown in Figures 80 and 81 for a 3 cm radius sphere exposed to 2450 MHz radiation and for a 7 cm radius sphere exposed to 918 MHz radiation, respectively. The curves are evaluated at an absorbed microwave energy density rate of 1000 mW/cm^3. We see that the microwave-induced pressure peaks around 2 μsec for the first case and peaks around 5 μsec for the second case. We may, therefore, consider these values as the optimum pulse widths required for efficient conversion of pulsed microwave to acoustic energy. This is qualitatively similar to the free-surface formulation, although the detailed dependence on pulse width differs somewhat for the two approaches.

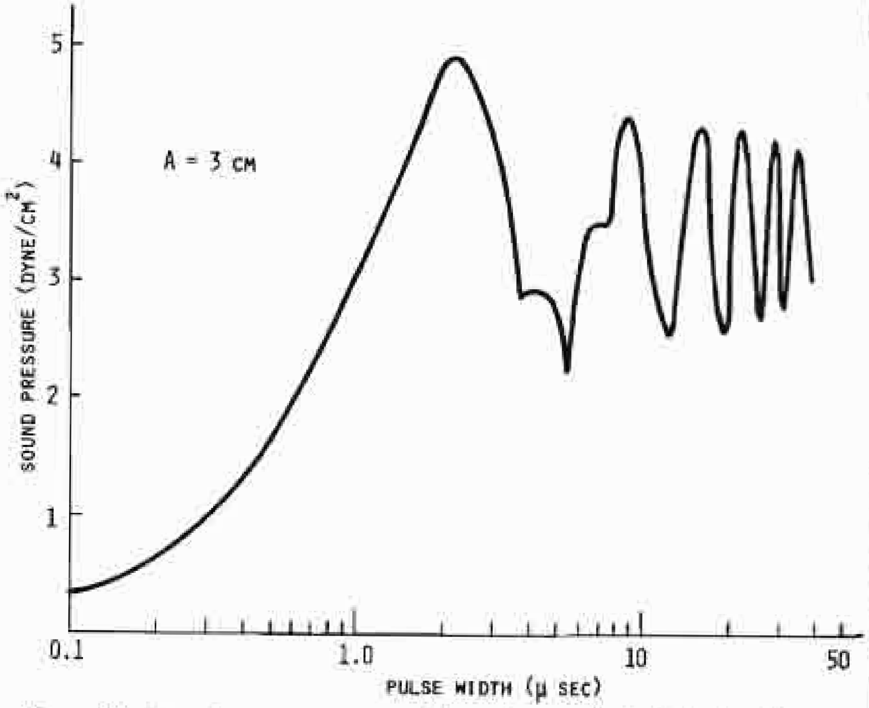

Figure 80. Sound pressure generated in a 3 cm spherical head with constrained surface as a function of pulse width of impinging microwave pulses. Peak absorption is 1000 mW/cm^3.

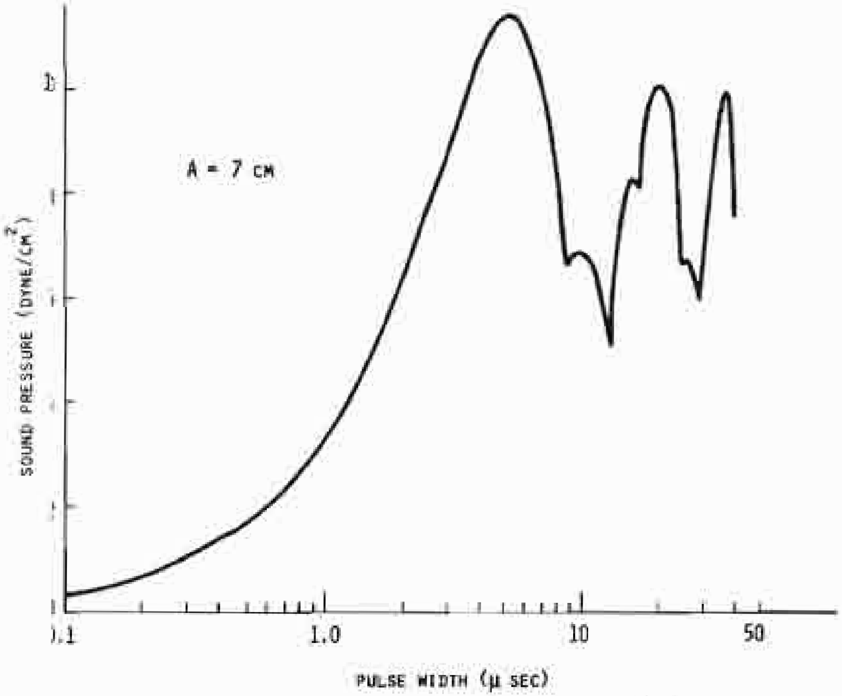

Figure 81. Sound pressure generated inside a 7 cm spherical head with constrained boundary as a function of pulse width of impinging microwave pulses. Peak absorption is 1000 mW/cm^3.

The displacement in the spherical model of the cat's head is shown in Figure 82. As expected, the displacement is zero at both the center and the surface of the sphere. For the case shown, the maximum displacement is around 10^{-13} meters. The frequency of mechanical oscillation compares exactly with that predicted in Figure 78.

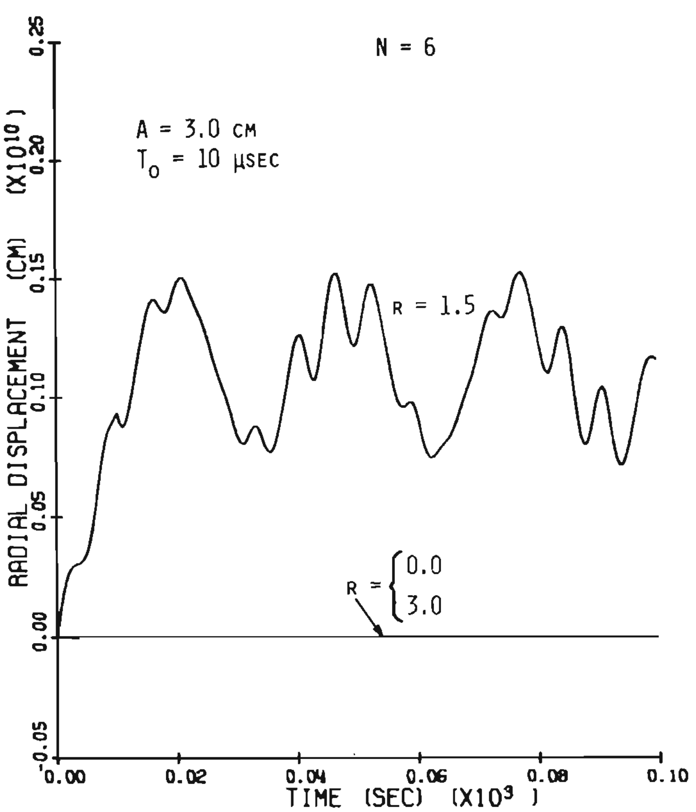

Figure 82. Displacement in a 3 cm radius spherical head exposed to 2450 MHz radiation. Peak absorption is 1000 mW/cm^3.

Computations of pressure and displacement have also been performed for a 7 cm radius sphere simulating an adult human head exposed to 918 MHz radiation (see Figs. 83 and 84). For this case, the pressure at the center is 6.82 dyne/cm^2 for a peak absorption of 1000 mW/cm^3 and an incident power density of 2183 mW/cm^2. Although specific measurements have not been made for humans exposed to 918 MHz radiation, Frey and Messenger (1973) have conducted a series of measurements at 1245 MHz for humans and have reported the threshold peak incident power density to be around 80 mW/cm^2. Assuming that the absorption characteristics at 918 and 1245 MHz are similar, the computed pressure of 0.25 dynes/cm^2 is 62 db *re* 0.0002 dyne/cm^2. The minimum audible sound pressure for bone conduction is about 60 db at frequencies between 6 and 14 kHz (Corso, 1963; Zwislocki, 1957). Clearly, there is agreement between theory and measurement. Extensive computations have also been done for other sphere sizes (Lin, 1977b,c); the general features are similar to those illustrated above.

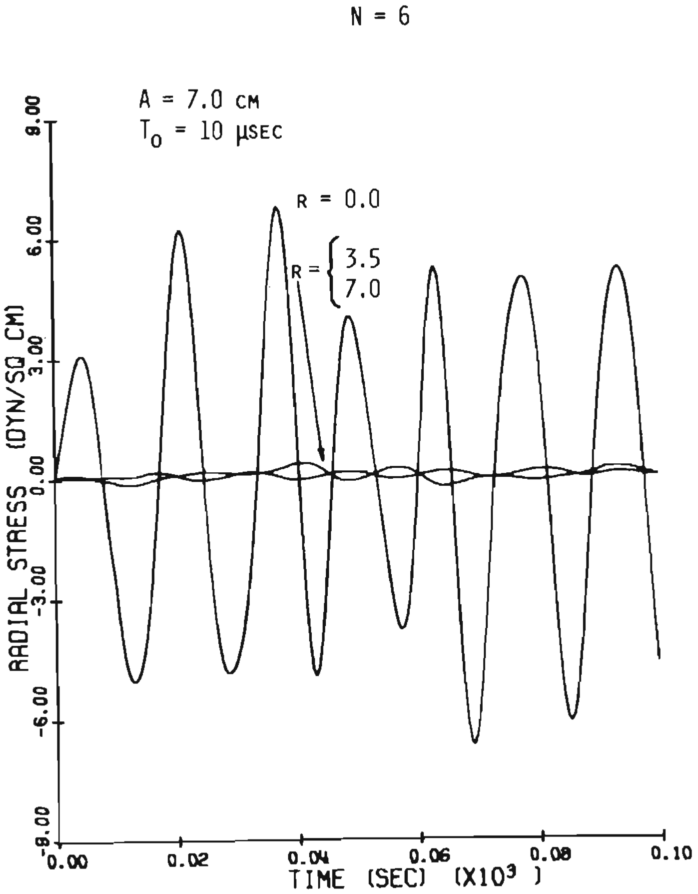

Figure 83. Sound pressure in a 7 cm radius spherical head exposed to 918 MHz radiation. Peak absorption is 1000 mW/cm^3.

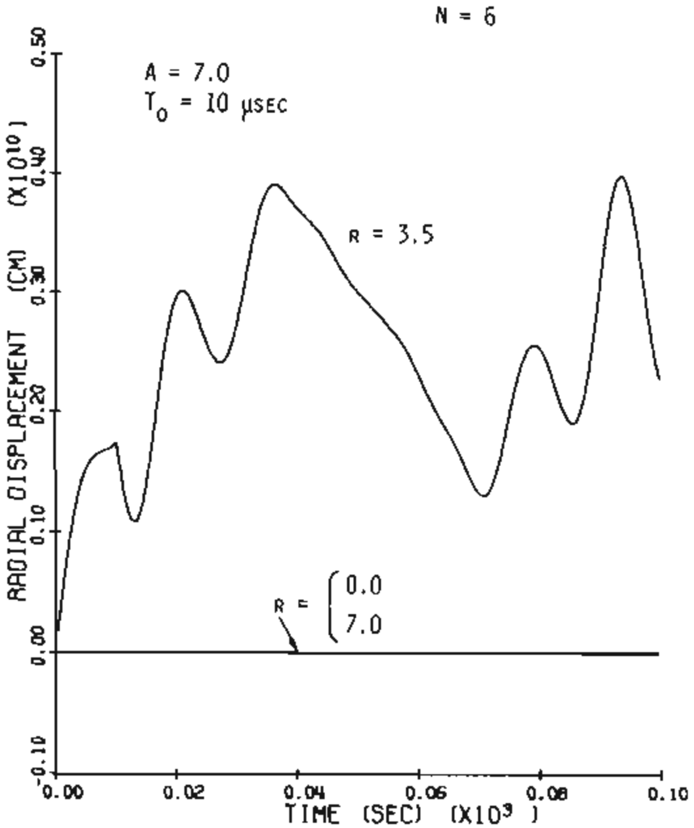

Figure 84. Displacement in a 7 cm radius spherical head exposed to 918 MHz microwave energy.

A SUMMARY

We have presented a model for sound wave generation in spheres simulating heads of laboratory animals and human beings by assuming a spherically symmetric microwave absorption pattern. The impinging microwaves are taken to be plane wave rectangular pulses. The problem has been formulated in terms of thermoelastic theory in which the absorbed microwave energy represents the volume heat source. The thermoelastic equation of motion without shear stress is solved for the sound wave under

TABLE XVII

PEAK PRESSURE AND DISPLACEMENT IN SPHERICAL HEAD MODELS IRRADIATED WITH 10 μsec RECTANGULAR MICROWAVE PULSES AT A PEAK ABSORPTION RATE OF 1000 mW/cm^3

Sphere Radius (cm)	Microwave Frequency (MHz)	Species	Pressure (dyne/cm^2)	Displacement (10^{-11} cm)	Incident Power (mW/cm^2)
2	2450	guinea pig	4.08	2.16	445
3	2450	cat	3.69	1.51	589
5	918	human infant	9.61	9.34	1282
7	918	human adult	6.82	3.97	2183

both stress-free and constrained-surface conditions using boundary value technique and Duhamel's principle.

The results indicate that the frequency of the auditory signals generated is independent of both the frequency of the incident microwave and the absorbed energy distribution; it is only a function of head size and the tissue acoustic property (velocity of acoustic wave propagation). In particular, the frequency varies inversely with sphere radius: the higher the frequency, the smaller the radius. It should be noted that the fundamental frequency predicted by the constrained-surface formulation is about 70 percent higher than that computed from the stress-free expression and it is extremely close to the experimental data reported to date (see Fig. 78).

Extensive numerical computations have shown that, although the resultant waveforms are qualitatively similar, pressures that are computed based on the constrained-surface formulation are consistently higher than those calculated using the stress-free expression. Moreover, agreement between theory and experiment is excellent for the constrained-boundary formulation.

Table XVII is a summary of peak pressure and displacement in four animals irradiated with 10 μsec wide pulses at the same absorbed energy level. The incident power density and frequency differ according to the species involved. Although the pulse width and peak absorption are the same in each case, the pressure and displacement differ somewhat. The results shown in Figures 76, 77, 80, and 81 indicate that there is a minimum or optimum pulse width for the efficient conversion of microwaves to acoustic energy, as has been suggested on experimental grounds (see Chapter 3, section on "Experimental Human Exposures," and Chapter 4, section on "'Threshold' Determination"). Finally, the general agreement between theoretical calculations and reported experimental measurements of sound frequency and threshold parameters clearly demonstrates the applicability of the model to microwave-induced hearing in mammals.

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Chapter 7

Applied Aspects

PRECEDING CHAPTERS have emphasized the interaction of pulse-modulated microwave energy with the auditory systems of humans and animals. In this chapter, we will discuss briefly where and how this effect can be used in health care and scientific investigations and in developing applicable safety standards that guard the general population against possible injury. We will also discuss some other biological effects of pulse-modulated microwave radiation.

POTENTIAL APPLICATIONS

A number of interesting applications for microwave-induced auditory effects in life science and medicine have been suggested in recent years. A few of these are briefly described in the following paragraphs. It should be noted that pulsed microwave energy in the form of diathermy has been used in physical medicine to treat musculoskeletal diseases for many years (Ginsberg, 1961; Lehmann, 1971). Short bursts (1 to 2 sec or less) of high power microwave energy is also used for rapid *in vivo* inactivation of brain enzymes (Stavinoha, 1973) prior to analysis for cyclic nucleotides. The technique is based on the principle that cyclic nucleotides are relatively heat-stable substances (Sutherland and Roll, 1960), while the enzymes that both produce and degrade cyclic nucleotides are heat labile and denature irreversibly at temperatures around 85°C.

Medical Uses

Potential medical applications of microwave-induced auditory effects include the assessment of hearing loss, specialized speech communication, and perhaps aid for individuals with impaired hearing in the form of hearing aids.

Bone conduction is important in distinguishing between types of deafness. A difference between air and bone conduction thresholds usually describes impairment of the conductive mechanisms of hearing. On the other hand, when bone-conducted responses follow air-conducted responses, the presence of sensorineural hearing loss is indicated.

In testing an ear's hearing ability through bone conduction, a vibrating device such as a tuning fork is often placed on the skull. The tuning fork is then struck with sufficient intensity to produce a desired sound level. Since rectangular-pulse-modulated microwave radiation is capable of generating an auditory signal with known frequency, it is possible to use an impinging microwave pulse to achieve an estimate of sensorineural impairment, whether or not the external and middle ear apparati are functioning properly. This method has several advantages over more conventional techniques because it does not require placing a device on the subject and it is noncontact. The disadvantage of this approach is the smaller number of sound frequencies available for presentation. Since additional techniques can sometimes improve the diagnostic process, pulse-modulated microwaves may prove to be useful as an adjunct in the auditory evaluation of patients.

A related potential clinical application is the use of pulse-modulated microwave radiation as a stimulus for sensory evoked potentials. When an acoustic click is presented to a human subject, a characteristic sequence of evoked potentials occurs in the electroencephalogram recorded using scalp electrodes (Picton et al. 1974). The averaged responses show a series of early waves occurring in the first 8 msec after a stimulus represents activation of the cochlea and the auditory brain-stem nuclei. The intermediate latency components occurring between 8 and 50 msec after the stimuli arise from both cerebral sources and extracranial muscle reflex potentials. The late components occurring 50 and 300 msec after the stimuli are recorded most prominently over frontocentral scalp regions and most likely represent widespread activation of frontal cortex. These scalp-recorded, average evoked potentials in response to an acoustic click are highly consistent from one subject to the next and reflect brain activity from cochlea to the auditory cortex. They are therefore of particular importance in the objective evaluation of hearing and in the assessment of neurological disorders.

Figure 85 shows the first 10 msec of a normal auditory evoked response recorded using electrodes placed over the vertex and the mastoid. At least seven distinct wave components are seen representing activation of the brain stem nuclei of a human subject.

Rapin (1967) has detected residual hearing in a number of multiply-handicapped infants using auditory evoked potentials and has prescribed effective hearing aids for these patients who might have been assumed completely deaf were it not for the evoked potential methodology. Also, Sohmer et al. (1974) have shown that in the presence of tumors which exert pressure on or near the junction of the auditory nerve and the brain stem (acoustic neurinoma and petrous bone meningioma), only the earliest components were recorded. On the other hand, in the presence of brain stem lesions some of the later waves were absent.

A third medical application, which is too new for full evaluation, is the potential use of pulse-modulated microwaves for speech communication. During the course of documenting microwave-induced auditory effects, Guy et al. (1973, 1975) noted that short trains of rectangular microwave pulses could be heard as chirps with tones corresponding to the pulse repetition frequen-

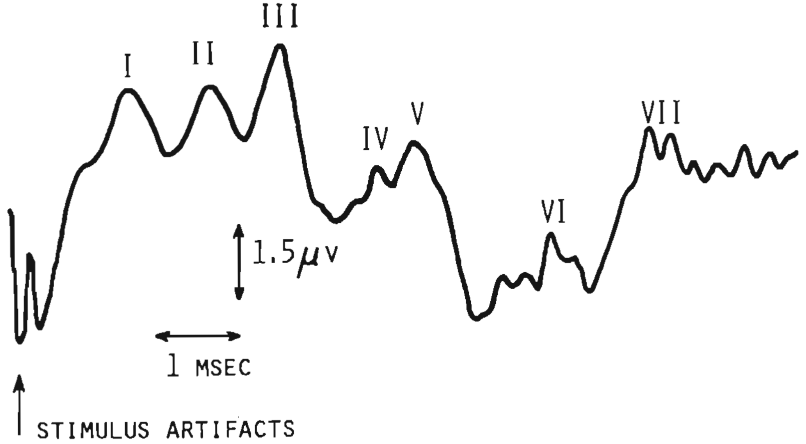

Figure 85. Normal brain stem auditory evoked response. Average of responses to 1500 clicks each having a duration of 100 μsec. Recording electrodes are located on the vertex and the mastoid. (Courtesy of Dr. G. Lynn, Wayne State University.)

cies, as mentioned in Chapter 3. It was also found that when the pulse generator was keyed manually–such that each closing and opening of a push-button switch resulted in emitting a short rectangular pulse of microwave energy–transmitted digital codes could be received and accurately interpreted by the irradiated subject.

Direct communication of speech via appropriate modulation of microwave energy has been demonstrated by Sharp and Grove (see Justesen, 1975). They tape recorded each of the single-syllable words for digits between one and ten. The speech waveforms of each word were then converted to digital signals in such a fashion that each time an analog speech wave crossed the zero reference in the negative direction, a short pulse of microwave energy was emitted from the transmitter. By radiating themselves with the "speech modulated" microwave energy, Sharp and Grove reported they were able to hear, identify, and distinguish the words tested. Communication of more complex words and sentences was not attempted because the average power density required to transmit these messages would exceed the current 10 mW/cm² guide for safe exposure. The capability of communicating directly with humans by pulsed microwaves is obviously not limited to the field of therapeutic medicine. However, as Justesen indicated, the question of how much microwave radiation exposure an individual can safely tolerate will probably forestall applications in the immediate future.

Research Uses

There are at least two experimental situations in which the microwave auditory effect offers a unique potential as a research tool. First is in the area of microwave auditory stimulation in behavioral investigations. It is clear from the material treated in Chapter 3 that appropriate pulse-modulated microwaves can control or disrupt the behavior of experimental animals in terms of induced auditory stimulation, as does conventional acoustic energy. Microwave auditory stimulation therefore appears to be a useful research tool for specialized psychophysical experimentation on the auditory system.

The cochlear nuclei, inferior colliculus, medial geniculate body, and primary auditory cortex have all been shown to be tonotopically organized, i.e. at sufficiently weak stimulus intensities, only one frequency ("best frequency") excites the neuron (Rose et al. 1959, 1963; Katsuki et al. 1958; Hind, 1960). For example, the primary auditory cortex consists of a central region surrounded by three sections of neural tissues. The majority of the cortical neurons in the central region show sharp frequency responses following a tonal stimulation from threshold intensity to about 60 db above threshold. Moreover, Tunturi (1952) showed, by using tonal stimulation and strychnine-soaked filter paper applied to the dog's auditory cortex, that at threshold intensity different frequencies gave rise to different points of maximal electrical activity on the auditory cortex (see Fig. 86). Since microwave-induced

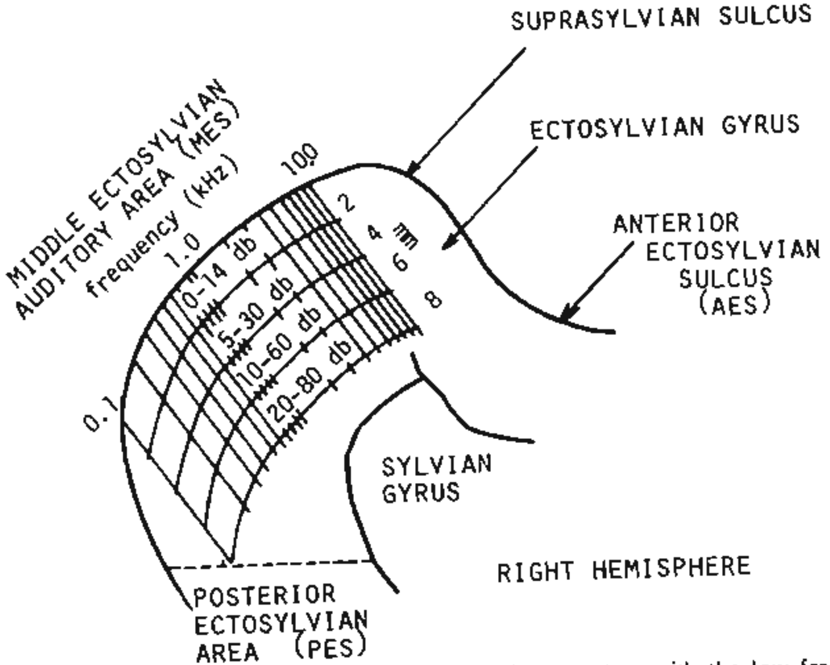

Figure 86. Tonal localization in the dog's auditory cortex, with the low frequencies represented posteriorly and high frequencies anteriorly. An intensity distribution (db) is found in the mediolateral direction. (Adapted from Tunturi: A difference in the representation of auditory signals. *Am J Physiol, 168:*712-727, 1952.)

auditory signals occur instantaneously at average power densities well below those reported to produce biological damage, and the acoustic frequencies are in the ten's of kilohertz range, these signals can be a unique stimulus for mapping the tonal locations of the primary auditory cortex in response to ultrasonic frequencies. In addition to bilateral stimulus presentation, independent of the subject's orientation with respect to the microwave field, this approach eliminates such problems as attenuation and distortion of ultrasonic pulses through air and through bony structures of the cranium. The points of maximal electrical activity may be recorded using either strychnine spikes or microelectrode techniques.

MAXIMUM PERMISSIBLE EXPOSURE

Recommendations for permissible exposure levels for the population have been developed by the American National Standard Institute (ANSI C95.1-1974). The levels are set to prevent possible thermal biological injury to the individual from exposure to microwave radiation. The thermal effects were considered to be the most harmful and have therefore been used as the basis for establishing the permissible exposure levels.

For normal environmental conditions, an individual should not be exposed to power densities greater than 10 mW/cm^2 for continuous-wave (cw) radiation. This is exclusive of deliberate medical exposure. For modulated fields, the average energy density over any 0.1 hour period should not exceed 1 mWHr/cm^2. Values for other exposure conditions can be found in the above mentioned standards. These recommendations pertain to both whole body and partial body exposure.

It is known that anatomic details and microwave frequency and its penetration ability affect the amount of energy absorbed. Hence, the recommended values are related in a complicated manner to the power levels at which injuries have been observed to occur. It should be understood that recommended levels are maximum values and that every attempt should be made, especially under moderate to severe heat stress, to minimize exposure.

The applicability of the safety guide to situations involving short pulses of microwave energy with low pulse repetition frequency is questionable. For example, the equivalent free-space electric field strength allowed by the safety guide for a 0.1 μsec pulse repeated once every 0.1 hour would exceed the breakdown field strength of air. Clearly, the safety standard needs to be refined to account for field strength and modulation as more knowledge is gained in these areas.

The possibility of using microwave auditory effect as a warning signal against exposure to hazardous levels of microwave energy (radar, for example) has also been discussed briefly (Michaelson, 1975). Although the thresholds for the auditory effect have not yet been adequately determined, we have shown that exposure to pulse-modulated microwaves with average incident power density well below one mW/cm^2 produces distinct hearing sensations (see Chapter 3). Thus, exposure to radar fields whose average power densities exceed 100 mW/cm^2 should yield very noticeable auditory effects. On the other hand, the warning property of the microwave auditory effect may be limited in operational situations because of high ambient acoustic noise and other psychological factors attendant to human response to warning signals in general.

OTHER BIOLOGICAL EFFECTS

Up to this point we have concentrated our discussion on the auditory effect of pulse-modulated microwaves on biological systems. Attention is now directed to considering the general effects of pulsed microwave energy on the physiology and behavior of exposed subjects. We present a brief account of results obtained in five different areas of research. It is possible that some of these reported findings may be related to incidental microwave-induced acoustic stimulation including displacement and pressure.

Cardiac Rhythm

The effects of pulse-modulated microwave radiation on heart rate have been investigated by several researchers; however, there has been no general agreement as to the nature of these effects. Levitina (1964) of the Soviet Union exposed twelve localized areas of the rabbit body, including the frontal and occipital parts of the head from the dorsal and ventral aspects, to a series of short microwave pulses (see Table XVIII for pulse parameters used). He found bradycardia (reduced heart rate) in 60 percent of the

TABLE XVIII
EFFECT OF PULSE-MODULATED MICROWAVES ON HEART RATE

Species	Effect	Frequency MHz	Peak (Average) Power mW/cm^2	Exposure Duration min	Pulse Width μsec	Comments	Investigator
Rabbit	Decrease	3000	(350)	20	1	Localized whole body	Levitina (1964)
Frog	Increase	1425	60	1.0	10	Isolated heart	Frey and Seifert (1968)
Frog	No change	3000	5500	1.0	2-10	Isolated heart	Clapman and Cain (1975)
Frog	No change	1420	60	1.0	10-150	Isolated heart	Clapman and Cain (1975)

animals exposed, while no change was obtained in the control group. He also reported that microwave irradiation of the posterior half of the abdomen and dorsal aspect of the neck after preanesthesia of the skin had no effect on the heart rate. He suggested that the effect was the result of microwaves acting directly on the skin receptors. The question of microwave interference with the recording equipment (which could produce the reported rhythm change via direct current pickup or stimulation of the skin receptors at the point of electrode contact by induced current on the electrode) is not relevant here, since, if induced current stimulation of the skin receptors was involved, one would expect to observe the same rhythm changes regardless of the physiologic state of the exposed area of the body.

Frey and Siefert (1968), using isolated frog hearts and pulse-modulated 1425 MHz radiation synchronized with the p-wave of the electrocardiogram, have shown significant heart rate increase. On the other hand, Clapman and Cain (1975) have found no effect when isolated frog hearts were irradiated using essentially the same protocol. The frequency and power density of the impinging radiation used in these studies are indicated in Table XVIII. It should be noted that related examinations by Liu et al. (1976) also showed a gross insensitivity of frog heart rate to pulse-modulated 1420 MHz and 10,000 MHz microwave energy.

Although these latter studies failed to demonstrate any microwave-induced change in heart rate, they do not necessarily imply that the observations of Levitina and Frey and Seifert were artifactual. The living heart, whether *in vitro* or *in situ,* is a very complex biological system. Subtle differences in experimental protocols could easily lead to significant differences in the observed effects.

Several important differences between Liu et al.'s experiments and those of Frey and Seifert could have contributed to the conflicting results. The hearts in the Frey and Seifert experiments were moistened with a Ringer's solution and were irradiated with 10 μsec pulses from a standard gain horn, whereas Liu et al. immersed the hearts in Ringer's solution and irradiated them using 100 μsec pulses coming from a coaxial microprobe. Since microwave absorption and its distribution inside the heart are closely related to the wavefront of the impinging radiation and the geometry of the object under irradiation, it is entirely possible that the absorbed energy differences associated with these studies produced an effect in one and had no effect in the other. Also, the hearts in the Frey and Seifert study came from decapitated frogs, whereas they came from curarized frogs in the Liu et al. study. Because *d*-tubocurarine is known to produce a variety of mild effects in sympathetic ganglion cells of the frog, among others, it is possible that curarization suppressed what otherwise might have been an unmistakable sensitivity to microwaves (Liu et al., 1976).

On the other hand, Clapman and Cain (1975) reported that the heart rate of an isolated frog heart is extremely sensitive to stimulation by short current pulses applied from 200 to 300 msec after the occurrence of the p-wave. The effect is very similar to that observed by Frey and Seifert in their microwave study. Because metal electrodes were used in the Frey and Seifert study and because metal electrodes are known to enhance energy absorption and to distort its distribution in the tissue surrounding the electrode (see Chapter 4, section on "Brain Stem"), it is therefore difficult to accept their results as convincing evidence for a microwave-induced change in heart rate. It is possible that the undetected increase in absorbed microwave energy combined with microwave-induced currents on the metal electrode contributed to the reported sensitivity to pulse-modulated microwave radiation.

With Levitina's report, as with much Soviet and eastern European literature on the subject of biological effects of microwave radiation, details of pertinent experimental procedures are lacking. This effectively prevented any realistic and meaningful duplication of the experiment to confirm its findings. For example, while the author indicated that twelve localized areas of the rabbit's body were irradiated, he failed to report how and with what applicator the partial body irradiation was accomplished. These variables, both individually and combined, affect the degree and pattern of microwave absorption by the biological object and are of crucial importance in determining the rabbit's response to microwave energy.

Analeptic Effects

A series of studies by McAfee on alterations in animal behavior and neurophysiology under pulsed microwave exposure has indicated an analeptic effect (1961, 1962, 1971). In these studies, the heads of rats were exposed to 20 to 40 mW/cm^2 average power densities of 10,000 MHz radiation at 300, 600, or 1000, pulses per second. The pulse shape was presumably rectangular in character. At approximately five minutes of exposure, a sleeping or anesthetized animal was aroused and the alertness of an awake animal increased; little or no noticeable rectal temperature change was seen at this stage. The rats' blood pressure was unchanged initially and then suddenly decreased with arousal. Respiratory hyperpnea regularly appeared, presumably as the result of a laryngeal spasm that may then produce asphyxiation, convulsion, and death even after microwave radiation was discontinued. The analeptic effect was considered to rise from thermal stimulation of peripheral nerves.

A comparable physiological change was observed in rats following infrared radiation and warm-water thermode stimulation of the afferent peripheral fibers within the microwave exposed subcutaneous tissue. The critical temperature was reported to be around 45°C.

The effect has also been demonstrated in cats, dogs, and rabbits at approximately the same incident power densities that aroused the rat, but without danger of convulsion or death. The pupils of Nembutal®-anesthetized cats dilated widely upon arousal. The animal was able to move its head, open its eyes, and vocalize. Some cats required additional anesthetics after the arousal episode for a surgical level of anesthesia to be maintained. If the lower legs of these animals were exposed under the same conditions, identical responses were observed. Injection of the skin of the head or the leg with a peripheral nerve blocker (Xylocaine®) completely abolished the response.

The effect may be useful in clinical medicine. The above experiments suggest that an individual who is comatosed from an overdose of drug or injury to the cerebrum might be awakened by treatment with pulse-modulated microwave radiation applied to the cutaneous nervous structures of the limbs or branches of the trigeminal or facial nerve until a temperature of 45°C is obtained subcutaneously (McAfee, 1971). There is no danger of burns to the skin or the subcutaneous tissue. The increased temperature of the cutaneous nerve branches that lie within the subcutaneous tissue is reached while the temperature of the surrounding tissue remains relatively unchanged. Both the skin and muscle are well vascularized and are able to dissipate the microwave-generated heat, while heat will accumulate in the poorly vascularized subcutaneous fatty tissue with resulting localized temperature rise, particularly if the microwave energy is pulsed.

Pharmacologic Effects

Prolonged exposure to pulse-modulated microwaves has been shown to alter the sensitivity of laboratory animals to certain drugs. The mortality of albino mice (Charles River CD-1) was strongly exposure-period dependent (Figure 87) between eight and thirty-six days, according to observations made at the end of the exposure period and after intraperitoneal injection of pentetrazol (50 mg/kg) (Servantie et al., 1974). Microwave exposure was seen to delay the appearance of convulsion for animals exposed less than fifteen days. For longer exposure periods, microwaves were found to hasten the onset of convulsion in these mice, particularly after twenty-seven days. The microwave energy used in these experiments was 3000 MHz, with an average incident power density of 5 mW/cm^2 applied at a rate of 500 pulses per second. The pulse width was 1 μsec, and the estimated peak power density was about 5 W/cm^2. The whole-body exposure was conducted in the far field of an anechoic chamber.

Servantie et al. also studied the effect of pulsed microwaves on the doses of curarelike drugs required for complete paralysis in rats anesthetized with Nembutal. Curarelike drugs were injected through a catheter inserted into the jugular vein at the rate of 1 mg/min. The time required for the disappearance of all movement was measured, and the dose in mg/kg of body weight was computed. Table XIX presents the number of animals paralyzed by a subthreshold dose: 6 mg/kg for gallamine, 1.5 mg/kg for suxamethonium. It shows that the animals exposed for ten to fifteen days appeared to be significantly less susceptible to paralyzing drugs than normal rats. They attributed the decreased sensitivity of rats to curarelike drugs to the microwave-induced decrease of binding energy between the drug molecule and the enzyme molecule at the neuromuscular junction.

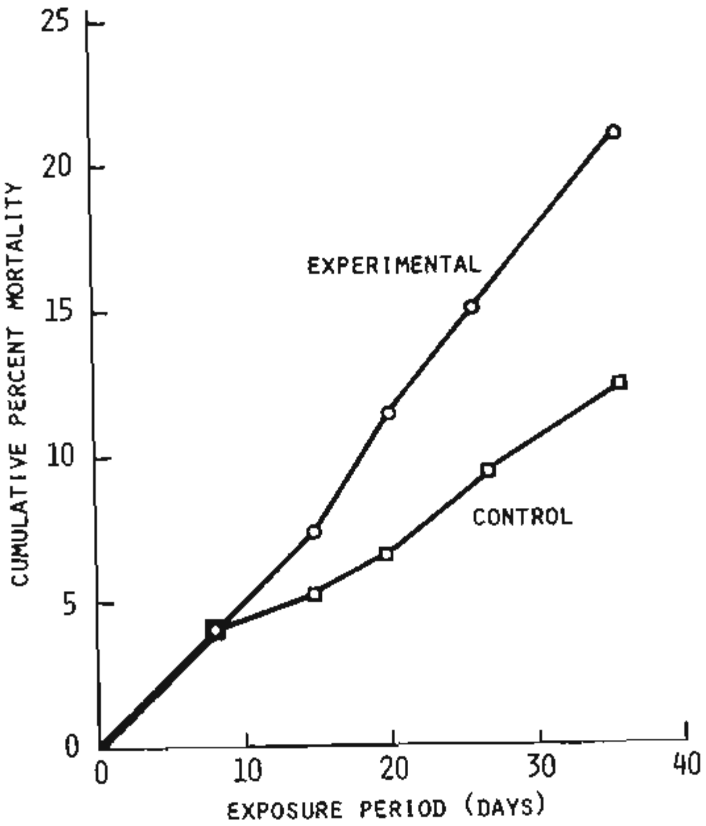

Figure 87. Mortality of mice injected with 50 mg/kg of pentetrazol after prolonged pulse-modulated microwave exposure. (Adapted from Servantie et al.: Pharmacologic effects of a pulsed microwave field. In Czerski, P. et al. (Eds.): *Biologic Effects and Health Hazards of Microwave Radiation*, 1974. Courtesy of Polish Medical Publ, Warsaw.)

TABLE XIX

NUMBER OF MICE PARALYZED BY A SUBTHRESHOLD DOSE OF CURARE-LIKE DRUGS UNDER PULSED MICROWAVE IRRADIATION

	Gallamine (threshold dose = 6 mg/kg)		*Suxamethonium (threshold dose 1.5 mg/kg)*	
Effect	*Control*	*Experimental*	*Control*	*Experimental*
Paralyzed	45	32	21	6
Not paralyzed	19	44	6	18

Baranski and Edelwejn (1974) exposed one-year-old male rabbits to pulse-modulated 3000 MHz microwaves at an average incident power density of 7 mW/cm² for two months and investigated the effect of chronic exposure on the function of the different central nervous system structures, using various central acting drugs injected intravenously following the microwave irradiation period. They observed that chlorpromazine (4 mg/kg) produced similar electroencephalographic (EEG) patterns in both control and irradiated rabbits. Administration of pentetrazol (8 mg/kg) produced a series of high voltage spikes in irradiated animals which were not apparent in the control group. Phenobarbitone administration resulted in a slight facilitating action of the drug on EEG desynchronization in irradiated rabbits. These studies indicate that the ascending portion of the mesencephalic reticular formation is involved in the pulsed microwave interaction with the central nervous system.

Behavioral Effects

Microwave-induced changes in the ongoing behavior of animals trained to respond on multiple reinforcement schedules were reported by Thomas et al. (1975). The rat was initially trained to press a level for food reinforcement on a ratio schedule (FR-20) when a red pilot light above the right level was illuminated with the house light turned off. When a blue pilot light above the left lever was illuminated and the house light turned on, a differential reinforcement of low rate (DRL) provided a food reward after a single response on the left lever that followed a preceding lever press by at least eighteen seconds and not more than twenty-four seconds. The FR and DRL schedules alternated for three-minute periods randomly, with a thirty-second time-out period between the two schedules. The procedure was repeated for sixty daily one-hour sessions. The subjects were then exposed to pulse-modulated microwave radiation at 2860 MHz with a pulse width of 1 μsec and a pulse repetition frequency of 500 Hz. They reported that a thirty minute exposure immediately before the behavior test session at 10 mW/cm² average power density caused a marked increase in the proportion of shorter interresponse times on the DRL schedule and produced an overall decrease in FR response rate.

Hunt et al. (1975) studied three widely divergent forms of behavior: exploratory activity, swimming, and discrimination performance on a vigilance task. Novel rats restrained in a modified Bollman holder were exposed to 2450 MHz microwaves for thirty minutes in a cavity with half-sine wave modulation, whose pulse width was approximately 2.5 msec and repeated at a rate of 120 per second. Immediately after irradiation, the animals were placed in an activity apparatus and allowed to explore freely for one or two hours. They reported that, at an absorbed power density just above 6 mW/g, the irradiated rats exhibited less activity than control rats during most of the test period. In parallel replications, the animals were held undisturbed in a metal cage similar to the home cage for one hour postirradiation before the activity test to insure that the animals were not responding to the transient rise in body temperature produced by microwaves. The investigators were also careful to rule out any incidental stress by repeatedly confining the animals to the holder and sham irradiating them prior to their experimental treatment.

They tested the effect of pulse-modulated microwaves on the highly motivated work performance of rats in a physically demanding task using the same microwave irradiation arrangement. They trained rats to perform a repetitive swim task in a straight alley swim apparatus. They found that the performance of animals tested immediately after microwave irradiation exhibited a moderate reduction in swimming speed rate in the test session, after they had been swimming for a considerable distance with apparently the same proficiency as their sham-irradiated controls. The reductions in swimming speed late in the test probably resulted from a loss of capacity due to microwave-induced fatigue.

Hunt et al. (1975) also trained water-deprived rats to perform accurately on a vigilance task to study the prompt effects of microwaves on the animals' performance on a complex discrimination task. The paradigm involved a light flash signalling availability of a single saccharin-flavored water reinforcement and a brief sound burst indicating that a "time-out" punishment would follow a lever response. One or the other was presented at the start of each five-second interval. Failure to respond in time for the positive light signal, which was presented randomly on the average of forty-five times in the thirty-minute session, constituted an error of omission. Response in the intervals when negative sound burst was presented resulted in a fifteen-second time-out period, and responses in these intervals constituted errors of commission. It was shown that the rats were omitting presentations of positive light signal at the outset of testing after microwave exposure. There was no evidence of change in commission error rate following exposure. Rapid recovery of discrimination responding was evident at the beginning and throughout the test session. Complete recovery was observed by the middle of the test period. The investigators indicated that the performance losses appeared to be directly related to the microwave-induced hyperthermia.

Effect on Brain Permeability

Evidence of permeability changes in the brain tissues of rats following pulsed microwave exposure was presented by Frey et al. (1975). Rats (Sprague-Dawley) were irradiated with 1200 MHz microwaves in five different head positions (Fig. 88) in the far field of an anechoic chamber. The pulse width used was 500 μsec, and the pulse repetition rate was 1000 pps. The peak power density was 2.1 mW/cm², and the average power density was 0.2 mW/cm². Immediately following irradiation, sodium fluorescein dye was injected intravenously into the animals and allowed to circulate in the blood stream for several minutes. The rats were then

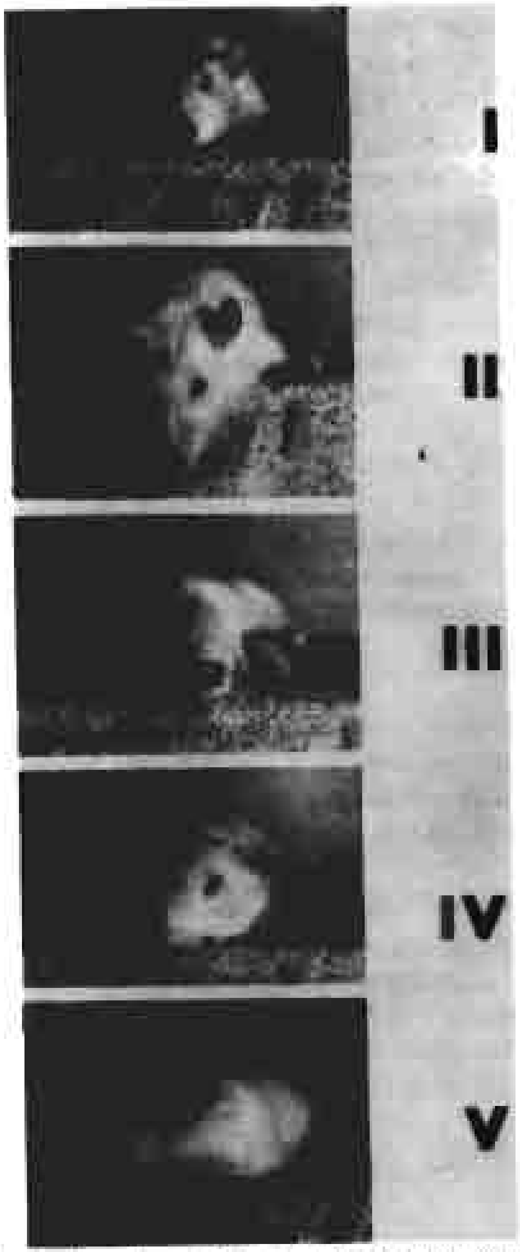

Figure 88. Head orientations of rats used in the brain permeability experiment. (From Frey et al.: Neural function and behavior. Courtesy of *Ann NY Acad Sci* 247:433-439, 1975.)

exsanguinated, the brains were perfused with saline, molded in gelatin, frozen, sectioned, and examined for fluorescence under ultraviolet light. They found fluorescence at the dien-, mes-, and metencephalon of the brain, and it was most conspicuous in the vicinity of the lateral ventricles and near the third ventricle. Animals irradiated in head position V of Figure 88 were least affected. This could possibly be the result of a different energy absorption due to head position.

The blood-brain barrier governs the permeability, or selective exchange of solutes between blood and brain. The molecular criteria governing its permeability have been reasonably well defined during the past decade (Rapoport, 1976). The above experiment indicates that low-level microwave exposure of small animals affects the brain barrier. It appears that pulse-modulated microwave energy is more effective than cw energy. It also suggests that it may be possible to gain temporary opening in the barrier by pulsed-microwave irradiation, which might have useful clinical implications.

A Summary

An effort has been made to show that exposure to pulse-modulated microwave radiation, in addition to the auditory effect discussed in great detail, leads to a large number of biological responses in the irradiated mammal. It is apparent that available data are far from complete enough to allow detailed evaluation. The deficiencies lie not only in the availability of quantitative data on the effects of pulsed microwave radiation on mammalian systems but also in the reporting of details of the experimental protocols. It is therefore important that these observations be independently examined and replicated where a single observation prevails and that the apparent discrepancies be studied and analyzed in detail, taking into consideration all the biochemical, biophysical, and physiological factors inside the body and the external physical variables that may influence the response of the biological system.

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Appendix A

Units and Conversion Factors

THE International System (SI) of Units was adopted by the Eleventh General Conference on Weights and Measures in 1961 in Paris, France, and it was officially adopted for scientific usage in the United States by the National Bureau of Standards

TABLE XX

INTERNATIONAL SYSTEM OF UNITS (SI) OF FREQUENTLY USED QUANTITIES

Quantity	*SI Unit*	*Equivalent Unit*
Mass	kilogram (kg)	1000 g
Time	second (sec)	10^3 msec = 10^6 μsec
Frequency	hertz (Hz)	1.0 cycle/sec
Wavelength	meter (m)	100 cm
Length	meter (m)	100 cm
Velocity	$\frac{\text{meter}}{\text{second}}$ (m/sec)	100 cm/sec
Area	meter^2 (m^2)	10^4 cm^2
Volume	meter^3 (m^3)	10^6 cm^3
Pressure	$\frac{\text{newton}}{\text{meter}^2}$ (N/m^2)	10 dyne/cm^2
Energy	joule (j)	1.0 N m = 1.0 W sec
Power	Watt (W)	1000 mW
Electric field strength	$\frac{\text{volt}}{\text{meter}}$ (V/m)	0.01 V/cm
Surface power density	$\frac{\text{Watt}}{\text{meter}^2}$ (W/m^2)	0.1 mW/cm^2
Volume energy density	$\frac{\text{joule}}{\text{meter}^3}$ (j/m^3)	1.0 W sec/m^3 = 10^{-6} j/cm^3
Absorbed power density (rate of absorbed energy)	$\frac{\text{Watt}}{\text{meter}^3}$ (W/m^3)	10^{-3} mW/cm^3
Electrical conductivity	$\frac{\text{mho}}{\text{meter}}$ mho/m	10 m mho/cm
Temperature	Kelvin degree (°K)	Celsius degree (°C)
Heat	joule (j)	0.2389 cal
Specific heat	$\frac{\text{joule}}{\text{kilogram °K}}$ (j/kg °K)	2.389 × 10^{-4} cal/g °C
Thermal conductivity	$\frac{\text{joule}}{\text{meter-second °K}}$ (j/m-sec °K)	0.2389 cal/m-sec °C

in 1964. It is a modernized version of the metric system. Table XX lists some of the commonly used units in this book. The complete International System involves not only units but also other recommendations. One of these is the prefix used with multiples the submultiples of the SI units (see Table XXI).

TABLE XXI

STANDARD PREFIXES USED WITH SI UNITS

Prefix	*Abbreviation*	*Magnitude*
atto	a	10^{-18}
fento	f	10^{-15}
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
deci	d	10^{-1}
deka	da	10^{1}
hecto	h	10^{2}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}

Appendix B

Publications of Pertinent Conferences and Symposia

Peyton, M. F. (Ed.): *Biological Effects of Microwave Radiation.* New York, Plenum, 1961.

Cleary, S. F. (Ed.): *Biological Effects and Health Implications of Microwave Radiation.* Rockville, Md. U.S. Dept. Health, Education, and Welfare, Dept BRH/DBE 70-2 (PB 193.858), 1969.

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Tyler, P. (Ed.): *Biologic Effects of Nonionizing Radiation.* Annals New York Academy of Sciences, Vol. 247, 1975.

Michaelson, S. M., Miller, M. W., Magin, R., and Carstensen, E. L.: *Fundamental and Applied Aspects of Nonionizing Radiation.* New York, Plenum, 1975.

Johnson, C. C. and Shore, M. L. (Eds.): *Biological Effects of Electromagnetic Waves.* Vol. I and II, HEW Publication (FDA) 77-8010, 1976.

Justesen, D. R. and Guy, A. W. (Eds.): *Biological Effects of Electromagnetic Waves.* Radio Science Special Supplement, Vol. 12/SS-1, 1977.

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