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The Microwave Auditory Phenomenon

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Abstract—**When human subjects are exposed to rectangular pulses of microwave radiation, an audible sound occurs which appears to originate from within or behind the head. It has been shown that electrophysiological auditory activity may be elicited by exposing the brains of laboratory animals to rectangular pulses of microwave energy. These results suggest that a microwave auditory phenomenon is evoked by a mechanism similar to that responsible for conventional sound reception and that the primary site of interaction resides peripheral to the cochlea. A comparison of the pressure amplitudes, such as those produced in a homogeneous planar layer of brain matter that is irradiated by a microwave pulse, indicates that the peak pressure due to thermal expansion is much greater than either radiation pressure or electrostriction. Theoretical analyses for a spherical brain based on the thermoelastic mechanism of interaction were found to agree with experimentally observed characteristics and indicate also that the induced sound frequency is only a function of the size and acoustic property of the brain. A few suggestions have been made for future research aimed at furthering our knowledge on microwave auditory effect and its health implications.**

I. Introduction

In RECENT YEARS many investigators have studied the auditory effects produced in humans and in animals by appropriately modulated microwave energy [1]-[10]. It has been found that when human subjects are exposed to pulsed microwave radiation, an audible sound occurs which appears to originate from within or near the head. The sound has been described as a click, buzz, or chirp, depending on such factors as pulsewidth and repetition rate. It has also been shown electrophysiologically that auditory activity may be evoked by irradiating the head of laboratory animals with rectangular pulses of microwave energy. Responses elicited in cats by conventional acoustic stimuli and by pulsed microwaves were similar and both disappeared following disablement of the cochlea and following death. Cochlear microphonics have been recorded from the round window of cats and guinea pigs during irradiation by pulse-modulated 918-MHz microwaves. These results indicated that microwave-induced auditory sensation is mediated by a mechanism of hearing similar to that responsible for conventional sound perception and that the primary site of interaction lies distal to the cochlea. A peripheral response to microwave pulses should involve mechanical displacement of the tissues of the head with resultant dynamic effects on the cochlea.

The exposure of solid materials, as well as liquids and gases, to pulse-modulated microwave sources, and the resulting development of acoustic or elastic waves have been described, to some extent, in the literature [5], [11]-[15]. A comparison of the calculated pressure amplitude produced in a semi-infinite layer of homogeneous brain material that is irradiated by a microwave pulse indicates that the peak pressure due to thermoelastic expansion is much greater than either radiation pressure or electrostriction [1], [5].

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A theoretical model based on the thermoelastic mechanism of interaction developed for spherical heads that are irradiated by pulsed microwave energy indicates that the frequency of the auditory signal is a function of the size and acoustic property of the brain tissues in the head [16]–[19]. In addition, it has been found that the experimentally observed characteristics agree with theoretical predictions in regard to pulsewidth and frequency of impinging microwaves, pattern of absorbed microwave energy, frequency of vibration, and threshold of sensation [10].

This paper summarizes the experimental evidence that has been generated on the subject and pays special attention to physical mechanisms for the conversion of microwaves to auditory signals. It also concentrates on the correlation between experimental observations and theoretical predictions based on thermoelastic pressure production in a homogeneous spherical model of the head. It contains a few suggestions for future research aimed at furthering our understanding of microwave interaction with the auditory systems of animals and humans and briefly comments on the probability that microwave auditory phenomenon might become a potential health problem.

II. Experimental Evidence

Human Perception

Short rectangular pulses of microwave radiation that impinge on the head of human subjects produce audible sounds. This was demonstrated by placing the subject's head directly in front of a horn antenna in a shielded room lined with microwave absorbing materials (Fig. 1). The subject was isolated from microwave generating equipment and the experimenter. In order to minimize disturbing noises, the subject used a light switch to signal the experimenter when an auditory sensation was perceived [1]. It was found that 1- to 32-μs wide 2450-MHz microwave pulses could be heard as distinct clicks originating from within or immediately behind the head. The peak power density varied from 1 W/cm² to 40 W/cm² with an average incident power density of 0.1 mW/cm² at the threshold of sensation (Table I). Short pulse trains could be heard as chirps with the tone corresponding to the pulse repetition frequency. The average power required to elicit a response in a subject with sensori-neural conduction impairment near 3.5 kHz was approximately four times that required for a subject with normal hearing [4], [5].

Using a slightly different arrangement, human subjects were found to perceive buzzing or popping sensations when exposed to 200- to 3000-MHz microwave pulses at average incident power densities of 0.4 to 2 mW/cm² and peak power densities on the order of 300 mW/cm². The pulse repetition frequencies ranged from 200 to 400 Hz. The sensation occurred instantaneously regardless of the subject's orientation in the microwave field. Furthermore, it had a direct correlation with the subject's ability to perceive acoustic energy above approximately 5 kHz by bone conduction [2], [21], [22]. Subjects with an inordinate amount of hearing loss at frequencies above 8 kHz also had difficulty perceiving microwave-induced sound [9].

These studies demonstrate that human beings perceive an auditory sensation when the head is exposed to rectangular pulse-modulated microwave with peak incident power densities on the order of 300 mW/cm², and average power densities as low as 0.1 mW/cm². The frequencies of these microwaves ranged from 200 to 3000 MHz, while the pulsewidth varied from 1 to 100 μs. The microwave-induced sound appeared as an audible click, buzz or chirp depending on such factors as pulsewidth and pulse repetition frequency of the impinging radiation, and usually is perceived as originating from within or near the back of the head.

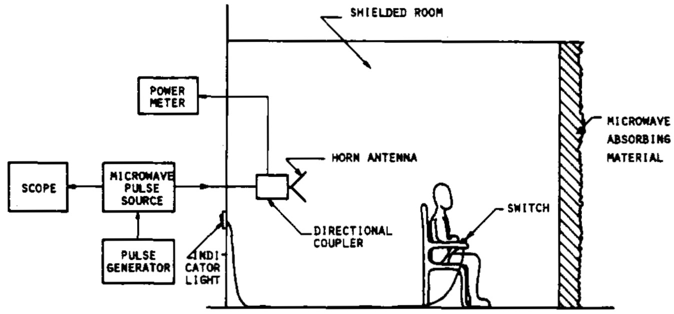

Fig. 1. Experimental arrangement for investigating microwave auditory phenomenon in human subjects [1].

TABLE I
THRESHOLD FOR MICROWAVE-INDUCED AUDITORY EFFECT IN HUMAN SUBJECTS (45 dB BACKGROUND NOISE, 2450 MHz)

Pulsewidth (μs)	Peak power (W/cm²)	Peak SAR* (W/g)	Average power (μW/cm²)	Reference
1	40	16	120	[5]
2	20	8	120	[5]
4	10	4	120	[5]
5	8	3.2	120	[5]
5	2.5	1.0	25	[9]
10	4	1.6	120	[5]
10	1.3	0.5	26	[9]
15	2.33	0.93	105	[5]
15	5	2.0	150	[9]
20	2.15	0.86	129	[5]
32	1.25	0.5	120	[5]

*Peak SAR (specific absorption rate) is based on absorption in equivalent spherical model of the head [30].

Animal Response

Considerable effort has been devoted to acquiring confirmatory data in lower animals. The first part of this section will review the behavioral basis for microwave-induced auditory phenomenon in mammals. The second part of this section will summarize the electrophysiological observations that document microwave auditory effects.

That microwave pulses are acoustically perceptible and can serve as a discriminative auditory cue in behavioral situations is supported by the works of several investigators. Food-deprived laboratory rats were trained to make a specific response to obtain food only during presentation of an audible cue (3-μs wide 7.5-kHz acoustic pulse, 10 pps). After the behavior was conditioned to acoustic stimulus, 918-MHz microwave pulses (from a square aperture antenna at an average incident power density of 15 mW/cm², 10-μs pulsewidth, 10 pps) were surreptitiously substituted for the acoustic stimulus. These animals showed continued ability to perform correctly on the discriminative task when presented with either the acoustic or microwave cue [23]. This is consistent with the finding that rats displayed avoidance behavior to a pulsed microwave field (2880-MHz 2.3-μs pulsewidth at an average incident power density of 10 mW/cm², 100 pps) as well as a sonic field of a 37.5-kHz acoustic tone [24].

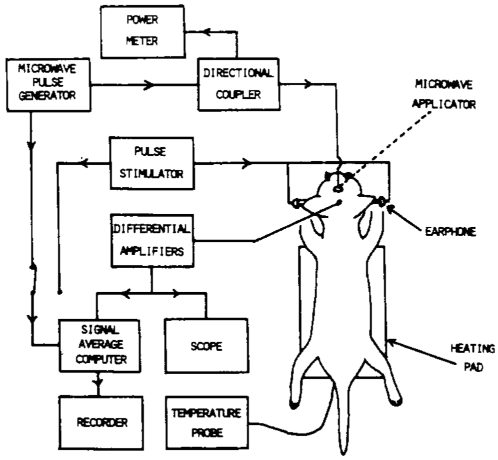

Fig. 2. Arrangement of equipment used to test microwave auditory effects in laboratory animals.

Clearly, microwave pulses interact with the auditory system and are perceived by laboratory rats in the same manner as conventional acoustic pulses. It should be noted, however, that these behavioral studies rely on inference rather than direct measure of the anatomical or physiological entities that are involved in a microwave pulse interaction with the auditory system. They should therefore be complemented by direct observations in identifying the anatomical or physiological substrates. Such observations, which would contribute toward definition of the characteristics, mechanisms, and site of transduction of this phenomenon, have indeed been made through direct neurophysiological investigations.

There are numerous areas along the auditory pathway where microelectrodes may be implanted to record electrical potentials arising in response to acoustic pulse stimulation. If the electrical potentials elicited by microwave pulses exhibit characteristics akin to those evoked by conventional acoustic pulses, it then would vigorously support the behavioral findings that pulsed microwaves are acoustically perceptible. If microwave-evoked potentials are recorded from each of those loci, this would then further support the contention that microwave auditory phenomenon is mediated at the periphery, as is the sensation of conventional acoustic stimulus.

Microwave-evoked neural electrical activities have been recorded from five levels of the central auditory system, i.e. primary auditory cortex, medial geniculate nucleus, inferior colliculus nucleus, lateral lemniscus nucleus, and superior olivary nucleus. Microwave energy was applied to the head using horn antennas, aperture radiators, and direct contact applicators operating between 900 and 3000 MHz. Rectangular pulses with pulsewidths of 1 to 32 μs were presented at repetition rates of 1 to 100/s and at peak incident power densities on the order of 1 W/cm^2. A typical experimental arrangement is illustrated in Fig. 2 which shows the anatomical placement and configuration of microwave, acoustic, and signal conditioning equipment.

Recordings from electrodes placed on the primary auditory cortex of anesthetized cats [6] and guinea pigs [25] following surgical removal of overlying soft tissue and bony structures showed remarkable similarity between microwave pulse and acoustic pulse evoked signals (Fig. 3). The acoustic stimuli were rectangular pulses 10 μs in duration. Essentially identical activities also were recorded from the medial geniculate nucleus [4]-[6], [10], [26], from the inferior colliculus nucleus [9], [20], [26], from the lateral lemniscus nucleus

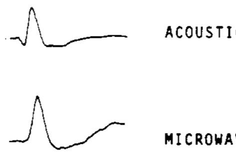

Fig. 3. Primary auditory cortex response in the cat to acoustic and microwave pulses [6].

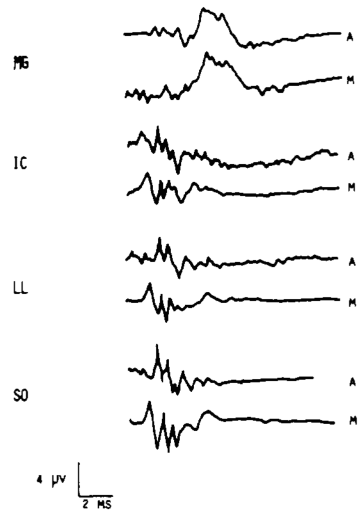

Fig. 4. Acoustic and microwave pulse-evoked responses from auditory nuclei in the cat. MG—medial geniculate body; IC—inferior colliculus; LL—lateral lemniscus: SO—superior olive.

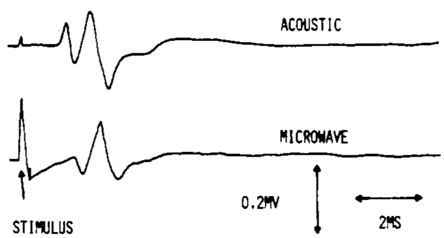

Fig. 5. Auditory nerve response from a cat exposed to acoustic and microwave pulses [6].

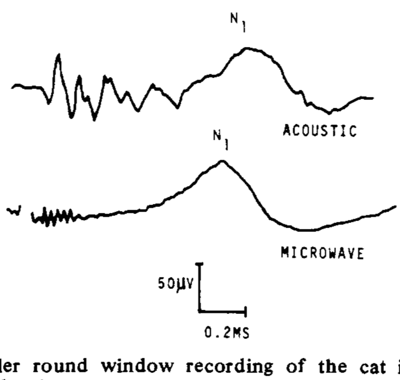

Fig. 6. Cochler round window recording of the cat in response to acoustic and microwave pulse stimulation. Note cochlear microphonics preceedings N_1 responses [7].

[10], [26], and the superior olivary nucleus of cats [10], [26] in response to both microwave and acoustic pulse stimulation (Fig. 4).

By modifying the surgical procedures used to record electrical activities from the central auditory elements, compound action potentials were recorded from the auditory branch of the eighth cranial nerve (Fig. 5) and from the cochlear round window (Fig. 6) of cats [6]. As can be seen from Fig. 6, the

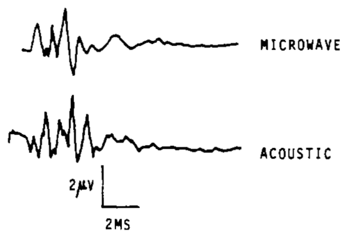

Fig. 7. Acoustic and microwave pulse evoked brainstem potentials from vertex of the cat.

classical N_1 and N_2 components of the auditory nerve action potential are present in both the microwave and acoustic cases. Furthermore, brainstem potentials were evoked by microwave pulses from guinea pigs [25] and from cats [10], [26] and their characteristics were comparable to those evoked by conventional acoustic pulses (Fig. 7). Many single auditory neurons in the cat also demonstrated a response to microwave pulses that was similar to the response to acoustic pulses [27], [28].

These electrophysiological activities recorded from central and peripheral portions of the auditory system imply that microwave and acoustic pulses affect the auditory system in the same manner and suggest a similar mode of interaction operating in both the microwave and the acoustic cases. This interpretation has been augmented by the observations made in systematic studies of auditory loci through production of lesion in ipsilateral auditory nuclei and bilateral ablation of the cochlea, the known first stage of transduction for sonic energy. Successive lesion production in the inferior colliculus nucleus, lateral lemniscus nucleus and superior olivary nucleus resulted in a drastic reduction of response amplitudes recorded from these nuclei [26], [27]. The effect of cochlear disablement was abolishment of all potentials recorded from three levels of the auditory nervous system (primary auditory cortex, medial geniculate nucleus, eighth nerve) evoked by both microwave and acoustic energy [6]. These data indicate that the site of initial interaction of pulse-modulated microwave energy with the auditory system is distal to the cochlea.

A peripheral interaction should involve displacement of the tissues in the head with resultant dynamic effect in the cochlear fluids and nervous system consequences that have been well described for the sonic case. However, cochlear microphonics, the signature of mechanical distortion of cochlear hair cells, had for a long time eluded investigators. This had led to the speculation that microwave pulses, in contrast to conventional acoustic pulses, might not act on any receptor prior to the inner ear apparatus.

The existence of cochlear microphonics has been elegantly demonstrated in cats and guinea pigs [7], [8] using cylindrical waveguides that efficiently couple impinging microwave energy into the head of the experimental animals. Fig. 8 illustrates the evoked potentials recorded from the round window of a guinea pig. The cochlear microphonic preceded the well-defined N_1 and N_2 auditory nerve responses and immediately followed the microwave pulse artifact. Following death of the animal, whether by anoxia or by drug overdose, microwave evoked nerve responses disappeared before the cochlear microphonic. Thus microwave auditory phenomenon is accompanied by mechanical disturbance of hair cells, and is mediated by an electromechanical interaction that is initiated distal to the cochlea. Moreover, psychophysical studies have shown that the ability of a human subject to perceive micro-

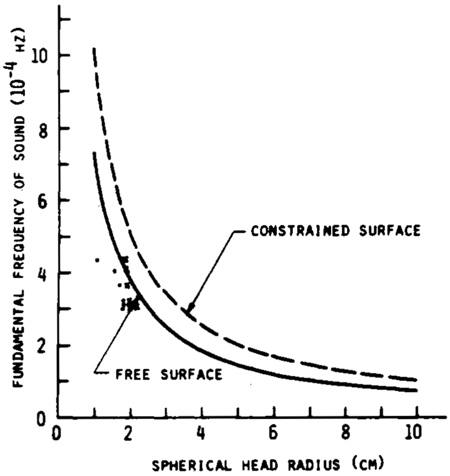

Fig. 8. Comparison of computed fundamental sound frequency and measured cochlear microphonic frequencies [20].

wave pulses is closely related to the ability to perceive acoustic signals through bone conduction.

III. Mechanism of Interaction

Several transduction mechanisms have been suggested involving mechanical displacement of the cranium for microwave induced auditory sensation [1], [5], [14], [15]. A comparison of the most likely candidates revealed that thermoelastic expansion is the most effective mechanism since pressure generated by thermoelastic stress in brain tissues may be one thousand times greater than the other possible mechanisms. A detailed analysis of the acoustic signals generated in the heads of animals and humans exposed to plane wave microwave pulses has been developed by considering a spherical head consisting only of brain matter [1], [16]-[19]. It suggested that the minuscule ($\sim 10^{-6}$ °C/s) but rapid rise (~ 10 µs) of temperature in the brain as a result of microwave energy absorption creates thermoelastic expansion of the brain matter which then launches an acoustic wave of pressure that is detected by the hair cells in the cochlea via bone conduction.

It was shown that there are an infinite number of resonant frequency, each corresponding to a mode of vibration of the spherical brain. The frequency of vibration was found to be independent of microwave absorption pattern; it was only a function of radius and acoustic properties of the spherical brain. Specifically, the fundamental frequencies of vibration are given by

$$f_c = 0.72\, v/a \qquad \text{constrained surface} \tag{1}$$

$$f_s = 0.50\, v/a \qquad \text{stress-free surface} \tag{2}$$

where v is the velocity of acoustic wave propagation and a is the radius of the spherical brain. These results suggested that the frequency of sound perceived by a subject exposed to microwave pulses are the same regardless of the frequency of the impinging microwaves. This has been corroborated by the observation that the same frequency and cochlear microphonics were induced by 918- and 2450-MHz microwaves [8], and the evoked auditory responses have similar time characters as the location of a direct contact microwave applicator is moved around the head of a cat [10], [26].

Fig. 8 shows a comparison of computed fundamental sound frequency and measured cochlear microphonic frequency [7],

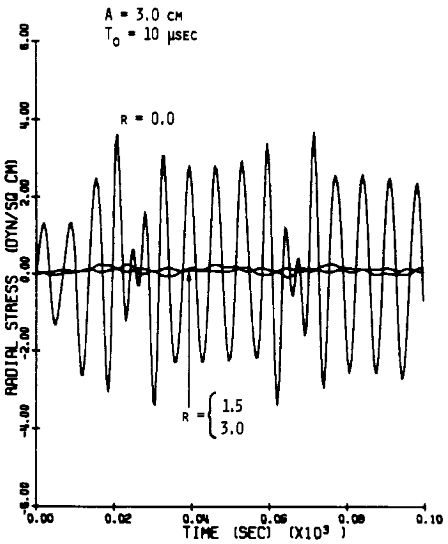

Fig. 9. Computed acoustic pressure in a spherical model of a cat-size (3-cm radius) brain exposed to 2450-MHz radiation at a SAR of 1 W/g [18].

[8], [20]. It is seen that the measured data, although limited, follow closely the predicted sound frequencies in cats and guinea pigs. The computed frequency of sound in the human brain ranged from 7 to 18 kHz for different radii. Although direct experimental data are not available, pertinent results have indicated the ability to hear short microwave pulses were correlated with human hearing at higher frequencies [1], [2], [9], [17], [18].

The computed sound pressure level threshold required for human subjects to just perceive a microwave pulse-generated sound is about 62-dB relative to 0.0002 dyne/cm^2 [18]. The minimum audible sound pressure for bone conduction is about 60 dB at frequencies between 6 and 14 kHz [31], [32]. Clearly, there is agreement between theory and measurement. Moreover, assuming that perception by bone conduction for cats is the same as for humans, the minimum audible sound pressure at 30 kHz is about 120 dB. It was found that at threshold peak incident power densities, the computed peak pressure amplitude was about 100 dB [18]. Thus the predicted threshold incident power density is close to the measured value. Fig. 9 shows the acoustic pressure in a cat-size spherical brain exposed to 2450-MHz radiation as a function of time for a 10-μs pulse [18]. The pressure is greatest in the center of the brain because the absorbed energy is greatest at this point.

The influence of pulsewidth on the acoustic pressure amplitude inside the brain, and therefore on the threshold of auditory perception is shown in Fig. 10. The continuous curve is the calculated peak pressure in a 3-cm radius brain sphere simulating the head of a cat exposed to 2450-MHz radiation using the expressions [18]

$$P = U_0 G t + \frac{1}{v} \sum_{m=1}^{\infty} A_m H_m \sin \omega_m t, \qquad 0 < t < t_0 \tag{3}$$

$$P = U_0 G t_0 + \frac{1}{v} \sum_{m=1}^{\infty} A_m H_m \left[\sin \omega_m t - \sin \omega_m (t - t_0)\right], \qquad t > t_0 \tag{4}$$

where t_0 is microwave pulsewidth, ω_m is resonant frequency

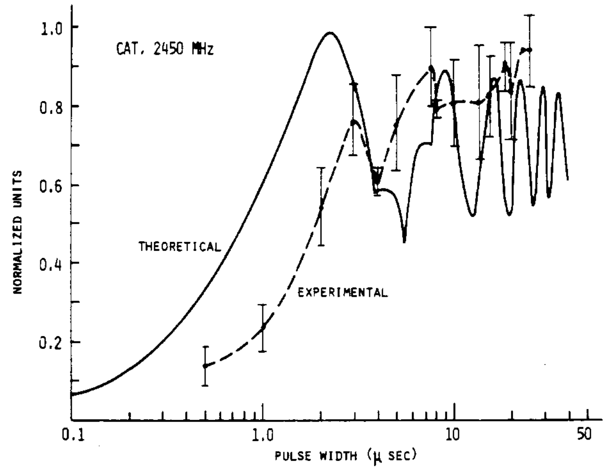

Fig. 10. The influence of pulsewidth on microwave induced sound in the cat [20].

of the spherical brain, v is velocity of acoustic wave propagation, and A_m, H_m, U_0, and G are constants related to the thermoelastic properties of brain tissue and peak specific absorption rate (SAR) [1], [18]. The broken line shows the variation of microwave-induced auditory brainstem response in cats with the width of impinging microwave pulses [20] while holding constant the peak power and repetition rate. Even though the fit is not exact, the correlation is unmistakable. Predicted sound pressure and measured potentials both show that increasing the pulsewidth increases the amplitudes to a plateau with subsequent oscillation. An equivalent observation was that increasing the pulsewidth decreases the SAR required to elicit a threshold auditory brainstem response [33]. The nonmonotonic dependence of the response on microwave pulsewidth has also been demonstrated in some single auditory neurons in the cat [27], [28]. It is similar to the effect of pulsewidth on the cochlear microphonic and auditory nerve responses of cats exposed to pulses of ultrasonic radiation [34], as well as responses of primary auditory fibers to acoustic pulses [35]. Thus there exists an impressive array of evidence that rigorously substantiates the thermoelastic mechanism of microwave-induced auditory effect.

IV. Health Risk

The studies concerning microwave hearing phenomenon have emphasized demonstration of auditory responses and delineation of interactive mechanisms. This attention is warranted inasmuch as the effect is very different from that associated with responses to continuous wave radiation. So much so, that it implied the possibility of significant neurophysiologic interaction. The results summarized above document collectively that the auditory systems of animals and humans respond to pulsed microwaves. They indicate that there is little likelihood of microwave hearing phenomenon arising from direct interaction of microwave pulses with the cochlear nerve or neurons at higher structures along the auditory pathway. Rather, the pulsed microwave energy initiates a thermoelastic wave of pressure in brain tissue that activates the inner ear receptors via bone conduction. Indeed, studies of the phenomenon's characteristics have now reached the point where it is possible to specify with some precision the relationship between microwave parameters such as peak power, pulsewidth and repetition frequency and perceived pitch and loudness. However, several highly pertinent questions remain.

Does the microwave auditory phenomenon pose a health risk to an individual? Under what conditions does microwave exposure become a hazard?

The problem of differentiating effect from hazard is enormous due to lack of information. While we now have some reasonable approximations concerning safe versus hazardous exposure to continuous wave radiation, a meaningful consensus regarding pulsed microwave exposure has not yet been achieved.

The problem can be approached, in principle, from the equivalency of microwave and acoustic pulse-evoked responses and from the perspective of sound exposure on humans. The known effects of sound exposure can be divided into two types: 1) auditory effects—effects of sound exposure on hearing; 2) nonauditory effects—the general physiological and psychological reactions [36], [37]. Unfortunately, there is very little data regarding the effect on hearing of exposure to microwave pulses. It is not known what relationship exists between the sound exposure in air and microwave-induced hearing.

The nonauditory effects of sound exposure are quite subtle compared with the responses of the hearing apparatus. The reactions are in many aspects similar to general stress responses that can be elicited by such stimuli as pain and motion stress. Some of the bodily functions reported to be adversely affected by excessive sound exposure include respiration, digestion, and circulation [37], [38], [39]. However, the most widely reported nonauditory effect of sound exposure is annoyance. In fact, criteria for limiting community noise are often based on the presence of annoyance reactions among exposed population groups [38]-[40].

Although annoyance reaction has not been explicitly evaluated in humans, studies have shown that laboratory rats find pulsed microwave exposure sufficiently aversive such that they are motivated to actively avoid the exposure [24], [41]. It has been shown that the avoidance behavior elicited by microwave-induced sound [24], that presumably annoyed the animals, much as acoustic impulses are annoying to humans. In fact, it can be shown that for the microwave parameters used, i.e., 2.3-μs wide 2880-MHz microwave pulses at 45 W/cm^2, peak power density, microwave-induced peak sound pressure level inside the rat's brain is about 120 dB—a value that is well within the hearing range.

V. Conclusions

It is a foregone conclusion that auditory sensations are evoked when the heads of laboratory animals and human subjects are exposed to pulsed microwave radiation. On the strength of the experimental results summarized here, the thermoelastic theory is adequate for describing microwave-induced sound frequency, threshold of sensation, the influence of pulsewidth and frequency of the impinging microwave radiation. While the precise location in the head microwave pulses are transformed into the acoustically perceived wave of pressure is at present not identifiable, it is clear that the primary site of interaction resided distal to the cochlea.

The question of whether and under what conditions the microwave auditory phenomenon poses a health risk to an exposed individual could be approached from the equivalency of microwave and acoustic pulse-evoked responses and from the perspective of known effects of sound exposure on humans. However, neither the physiological nor the behavioral data are sufficient at the present time to permit a complete analysis of this problem. The kind of studies that would be useful are behavioral investigations of pulsed microwave exposed animals including the effects on performance, and morphological examinations of the hearing apparatus of exposed animal subjects. Finally, it seems appropriate to indicate that a number of interesting and beneficial applications of microwave auditory phenomenon have been introduced in recent years [1]. The potential applications, however, are sufficiently novel that they do not at the present lend to full elaboration.

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Advances in Microwave-Induced Neuroendocrine Effects: The Concept of Stress

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Abstract—**Recent evidence indicates that neuroendocrine effects are induced by microwave exposure with a threshold intensity required for the onset of the response. The level of that threshold is dependent upon intensity and duration of exposure. The threshold can vary with the given endocrine parameter studied. The level of that threshold is yet unclear due to conflicting reports of effect in chronic or repeatedly exposed populations of man or experimental animals. The response of the endocrine systems appears to be a nonspecific stress reaction in the case of adrenocortical and growth hormone changes, but it is apparently a metabolically specific response to increased energy input in the case of pituitary-thyroid changes.**

Introduction

NUMEROUS biological effects of microwaves have been reported in the literature and have been the subject of several reviews. The validity as well as the actual significance of many of these reported microwave bioeffects have elicited controversies regarding the setting of exposure standards. The suggestion of direct action by low-level microwave exposure on the central nervous and the endocrine systems apart from the well-established heating effect of microwaves has raised uncertainties in the characterization of the general effects of exposure to microwave energy.

At all levels of mammalian biological organization adverse environment elicits a complex array of nervous, endocrine, neurohumoral, and motor reactions to adjust body fluid balance, energy metabolism, and behavior to the needs concomitant with survival in a changed environment. The neuroendocrine system, a complex of hormone secreting glands, and the central nervous system function as a chemical regulatory system in mammals to control and regulate metabolism and growth and to protect the body from endogenous and exogenous alterations in homeostasis.

Neuroendocrine function is of considerable importance in the response of an organism to microwave exposure. However, the information available at the present time is not sufficient to clarify microwave-induced neuroendocrine effects, due in part to insufficient documentation of some of the available data. Since other reviews [1]-[4] have provided a general survey of this subject area, we will not attempt to reiterate what has been covered in those treatises. The objective of this presentation is to evaluate recent progress in the area of

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