Health Effects

Hearing Microwaves: The Microwave Auditory Phenomenon

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In common usage, the handset of a wireless telephone is held against the ear. Computational and experimental studies have demonstrated that about 50% of the radiated RF/microwave energy is deposited in tissues on the same side of the head, nearest to the telephone. The deposited energy measured in specific absorption rates (SAR) of RF/microwave energy is nonuniformly distributed inside the head. Depending on the specific model used, the SAR inside the inner ear is about 20-40% of that permissible by existing rules and regulations.

The permissible SAR from exposure to cellular mobile telephone radiation in Europe, Japan, and by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) is 2 W/kg in any 10 g of tissue in the head. The maximum SAR allowed by rules of the U.S. Federal Communication Commission (FCC) and IEEE standard is 1.6 W/kg in 1 g of tissue.

The possible health risk associated with mobile telecommunication devices, used close to the human head and, in particular, effects on the inner ear and hearing of users have been recommended for further investigation by several groups. Recently, a number of projects have been initiated in France, Germany, and Italy to investigate the structures and functions of the middle and inner ear following exposure to wireless communication radiation. Examination of the organic correlation of damage to hearing and any functional otoacoustic effects on the cochlear epithelium in the inner ear of rats exposed to wireless communication radiation is still in the preliminary stage [1]. Thus, the potential effect on the auditory system, as may be revealed through objective evaluation of organic correlates, must await the conclusion of ongoing experiments. However, the phenomenon of microwave-induced auditory sensation in humans and animals is a well-established effect [2].

The microwave auditory phenomenon, or microwave hearing effect, pertains to the hearing of short pulses of modulated microwave radiation at high peak power by humans and laboratory animals. Anecdotal and journalistic reports of the hearing of microwave pulses persisted throughout the 1940s and 1950s. The first scientific report of the phenomenon appeared in 1961 [3]. The effect has been observed for RF exposures across a wide range of frequencies (450-3,000 MHz). It can arise, for example, at an incident energy density threshold of 400 mJ/m^2 for a single 10-μs-wide pulse of 2,450 MHz microwave energy, incident on the head of a human subject, and it has been shown to occur at an SAR threshold of 1.6 kW/kg for a single 10-μs-wide pulse of 2,450 MHz microwave energy, impinging on the head. A single microwave pulse can be perceived as an acoustic click or knocking sound, and a train of microwave pulses to the head can be sensed as

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an audible tune, with a pitch corresponding to the pulse repetition rate (a buzz or chirp). Note that the SAR threshold of 1.6 kW/kg is about 1,000 times higher than that allowable by FCC rules for cellular mobile telephones.

The hearing of microwave pulses is a unique exception to the airborne or bone-conducted sound energy normally encountered in human auditory perception. The hearing apparatus responds to acoustic or sound pressure waves in the audible frequency range, but the hearing of microwave pulses involves electromagnetic waves whose frequency ranges from hundreds of MHz to tens of GHz. Since electromagnetic waves (e.g., light) are seen but not heard, the report of auditory perception of microwave pulses was at once astonishing and intriguing. Moreover, it stood in sharp contrast to the responses associated with continuous wave (CW) microwave radiation. Initially, it had been interpreted to imply direct microwave interaction with the neurophysiological system [3], [4].

We now know that the microwave auditory phenomenon does not arise from an interaction of microwave pulses directly with the auditory nerves or neurons along the auditory neurophysiological pathway of the central nervous system. Instead, the microwave pulse, upon absorption by soft tissues in the head, launches a thermoelastic wave of acoustic pressure that travels by bone conduction to the inner ear. There it activates the cochlear receptors via the same process involved for normal hearing.

The microwave auditory effect is the most widely accepted biological effect of microwave radiation, aside from tissue heating, with a known mechanism of interaction: the thermoelastic theory of the microwave-induced acoustic pressure waves in the head. However, there is little data regarding effects on the inner-ear hearing apparatus or the central nervous tissue from exposure to these microwave pulses. It is clear that threshold microwave auditory response would have an insignificant effect on the hearing apparatus. However, any health effect that may attend exposure over a prolonged period, or exposure to supra-threshold microwave pulses, has not been investigated systematically.

In general, the mechanism of microwave interaction with biological systems is poorly understood. Studies on interaction mechanisms, although difficult, are important to gain a better understanding of the biological phenomenon. They are invaluable in guiding future research, and they can support the development of safe exposure standards. As the thermoelastic theory of microwave auditory effect illustrates, a genuine physical explanation of the effect is not only *descriptive* (capable of describing the biological phenomenon), it is *predictive* and *prescriptive* as well. The predictive attribute provides a theory with parametric relations among its dependent variables that could be further studied, and the prescriptive feature delineates experiments that can be conducted to test its predictions.

The acceptance of the microwave-pulse-induced auditory effect was enhanced by two independent lines of experimental research, discrimination response in behavioral tests and electrophysiological recordings, which have contributed to the definition of the characteristics, mechanism, and transduction of this phenomenon.

The fact that microwave pulses are acoustically perceptible and can serve as a discriminatory, auditory cue in behavioral tests was studied by several investigators. For example, food-deprived laboratory rats were trained to make a nose-poking response to obtain food only during the presentation of an acoustic cue (7.5-kHz acoustic pulse, 3-μs wide, 10 pps). After the behavior was conditioned to the acoustic stimulus, 900-MHz microwave pulses (peak power density of 150 kW/m^2, 10 μs, 10 pps) were surreptitiously substituted for the acoustic stimulus. The animal demonstrated a continued ability to perform correctly (at 85-90% level) on the discriminative task when presented with either the acoustic or the pulsed microwave cues.

Behavioral studies rely on inference, rather than direct measurement of the anatomical or physiological substrates involved in the microwave-pulse interaction with the auditory system. They should, therefore, be complemented by direct observations in identifying the anatomical and/or physiological evidence. Such observations have been made through direct neurophysiological investigations in animals.

On many sites along the auditory neural pathway, small electrodes may be inserted to record electrical potentials that arise in response to acoustic-pulse stimulation. If the electrical potentials elicited by a microwave pulse exhibited characteristics akin to those evoked by conventional acoustic pulses, this would vigorously support the behavioral findings that pulsed microwaves are acoustically perceptible. Furthermore, if microwave-evoked potentials were recorded from each of these loci, this would lend further support to the contention that the microwave auditory phenomenon is mediated at the periphery, as is the sensation of a conventional acoustic stimulus.

Indeed, a large amount of accumulated electrophysiological evidence demonstrates that auditory responses are elicited by microwave pulses and that these responses are similar to those evoked by conventional acoustic pulses. Evoked-potential recordings have been obtained from the vertex of the head, from the inner ear, and from the central auditory nervous system of cats, guinea pigs, and rats.

Specifically, responses recorded from the vertex represent volume-conducted electrical events that occur in the auditory brainstem nuclei within the first 8 ms after the onset of an acoustic stimulus. Comparable brainstem auditory-evoked responses have been recorded from cats, guinea pigs, and rats. Moreover, essentially identical microwave and acoustic pulse-evoked neural electrical activities were recorded from five levels of the central auditory system: the primary auditory cortex, medial genicular nucleus, inferior colliculus nucleus, lateral lemniscus nucleus, and the superior olivary nucleus. Thus, the same pathway through the central auditory nervous system is activated by both microwave and acoustic pulses.

Also, the classical components of the action potential from the auditory branch of the eighth cranial nerve and the round window of the cochlea appeared in both microwave and acoustic pulse cases. These results suggest that the site of initial interaction of a pulse-modulated microwave radiation with the auditory system is at or outside the cochlea of the inner ear.

This interpretation is augmented by observations made in systematic studies of loci involved through the production of coagulative lesions in ipsilateral auditory nuclei and bilateral ablation of the cochlea, the known first stage of transduction for acoustic energy into nerve impulses. Successive lesion production in the inferior colliculus, lateral lemniscus, and superior olivary nuclei resulted in a drastic reduction of the recorded response amplitude. The consequence of cochlear disablement was abolishment of all potentials recorded from three levels of the auditory nervous system (the primary auditory cortex, brainstem nucleus, and the eighth nerve), evoked by both microwave and acoustic pulses. These data indicate that the peripheral site of initial interaction of pulse-modulated microwave radiation with the auditory system is, indeed, distal to the cochlea of the inner ear.

A peripheral interaction should involve the displacement of tissues in the head, with resultant dynamic effects in the cochlear fluids, hair cells, and nervous system—consequences that have been well described for the acoustic case. In fact, the cochlear microphone response, a signature of mechanical disturbances in the cochlear hair cells, has been demonstrated in cats and guinea pigs subjected to microwave pulse exposure. These results confirmed that the microwave auditory effect is mediated by a physical transduction mechanism, initiated outside the inner ear, and involves mechanical displacement of biological tissues.

Among the several transduction mechanisms suggested that involve mechanical displacement, thermoelastic expansion has emerged as the most effective mechanism. The pressure waves generated by thermoelastic stress in brain tissue are found to be one to three orders of magnitude greater than any other candidate mechanism. A detailed mathematical analysis has shown that the minuscule (10^{-6} °C) but rapid rise in temperature in the heads of animals and humans as a result of the absorption of pulsed microwave energy creates a thermoelastic expansion of tissue matter that then launches an acoustic wave of pressure that travels to the cochlea and is detected by the hair cells there.

The thermoelastic theory of auditory perception of pulsed microwaves describes the acoustic waves (frequency, pressure, and displacement) generated in the head as functions of head size and characteristics of impinging and absorbed microwave energies. In addition to the expected dependence of sound pressure on the intensity of microwave pulses, it prescribes the dependence of induced sound pressure (perceived loudness) on pulse width, and the dependence of induced sound frequency on head size. For example, the theory predicts a fundamental sound frequency that varies inversely with head radius: the smaller the radius, the higher the frequency. For a rat-size head, it predicts a sound frequency of 25-35 kHz, which a rat could detect. For the size of a human head, the theory predicts frequencies between 7 and 15 kHz, which is within the range audible by humans.

It is significant to note that physical measurements, using a hydrophone (3 mm in diameter) implanted in the brains of cats, rats, guinea pigs, and in brain equivalent spherical head models, showed sound frequencies as predicted by the theory. Moreover, pressure waves propagating at a speed of 1,523 m/s were observed in the brain of cats irradiated with pulsed microwaves.

Experiments performed using human and animal subjects and theoretical predictions have shown the sound pressures that initially increase with pulse width but soon reach a peak, and then oscillate gradually to a lower value with further increases in pulse width. A study of loudness perception variation with pulse width on human subjects in Moscow [5] also lent support to the thermoelastic theory, since they showed similar characteristics. The study had been designed to disprove the thermoelastic theory [6], [7] and yet, in the end, supported it [2].

The thermoelastic theory for hearing microwave pulses was developed on the basis of bulk absorption of pulsed microwave energy in the brain, which was assumed to be spherical, for analytically clarity and simplicity [6], [7]. Recently, a numerical analysis was presented using the finite-difference/time-domain computational formulation, which is capable of detailed anatomic modeling of the brain and head structure [8]. Aside from confirming the characteristics of the induced acoustic waves, such as sound frequency and pressure amplitude—previously obtained using a homogeneous spherical head, the numerical computation graphically illustrates the sequence of pressure wave propagation inside the head, following absorption of pulsed microwave energy. The pressure wave reverberated, and then focused near the center of the head.

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