Review Article

HEARING OF MICROWAVE PULSES BY HUMANS AND ANIMALS: EFFECTS, MECHANISM, AND THRESHOLDS

James C. Lin*† and Zhangwei Wang†

Abstract—**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 commonly responds to airborne or bone-conducted 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 microwave radiation. Experimental and theoretical studies have shown 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 pathways 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. Aside from tissue heating, microwave auditory effect is the most widely accepted biological effect of microwave radiation with a known mechanism of interaction: the thermoelastic theory. The phenomenon, mechanism, power requirement, pressure amplitude, and auditory thresholds of microwave hearing are discussed in this paper. A specific emphasis is placed on human exposures to wireless communication fields and magnetic resonance imaging (MRI) coils.**
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Key words: magnetic resonance imaging; imaging; diagnostic imaging; microwaves

INTRODUCTION

THE MICROWAVE auditory phenomenon or microwave hearing effect pertains to the hearing of short-pulse, modulated microwave energy at high peak power by humans and laboratory animals (Frey 1961, 1962; Guy et al. 1975a, b; Lin 1978, 1980, 2004). The effect 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 (Guy et al. 1975a, b; Lin 1978). It has been shown to occur at a specific absorption rate (SAR) threshold of 1.6 kW kg^{-1} for a single 10-μs-wide pulse of 2,450 MHz microwave energy. 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 an audible tune, with a pitch corresponding to the pulse repetition rate (Lin 1978).

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 commonly responds to acoustic or sound pressure waves in the audible frequency range (0–20 kHz). 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.

The phenomenon, mechanism, and thresholds of microwave hearing are reviewed and discussed in this paper. Initially, the microwave auditory effect had been interpreted to imply a direct microwave interaction with the neurophysiological system (Frey 1961, 1962, 1971; Frey and Messenger 1973; Frey et al. 1975). Available experimental and theoretical studies have shown that the microwave auditory phenomenon does not arise from an interaction of microwave pulses directly with nerves along the auditory neurophysiological pathways 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

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normal hearing. Thus, aside from tissue heating, microwave auditory effect is the most widely accepted biological effect of microwave radiation with a known mechanism of interaction: the thermoelastic theory of the microwave-induced acoustic pressure waves in the head.

EXPERIMENTAL RESULTS

Human perception

Human perception of pulse-modulated microwave energy transmitted through air has been demonstrated at radiofrequencies (RFs) and microwave frequencies ranging from 200 to 3,000 MHz, with pulse width varying from 1 to 1,000 μs. The sensation occurred instantaneously and head orientation in the microwave field did not influence the loudness of perceived sound (Frey 1962; Guy et al. 1975a, b; Lin 1978, 1980, 1990). While an ideal, noise-free laboratory environment is not a requirement for perception, the microwave energy required in some cases decreased by more than six dB when earplugs were used. As mentioned, 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 an audible tune, with a pitch corresponding to the pulse repetition rate.

Several investigators have reported thresholds of perception as a function of microwave parameters. Table 1 shows the measured microwave power thresholds for auditory perception in human subjects with normal hearing. It is interesting to note the subjects' report of microwave-induced sound originating from inside the head. Auditory perception was reported under conditions with up to 90 dB of ambient acoustic noise. However, there was an apparent increase in the peak incident power needed for perception.

Animal study

Small electrodes implanted in nuclei along the auditory neural pathway may be used to record electrical potentials that arise in response to acoustic-pulse stimulation. If the electrical potentials evoked by a microwave pulse exhibited characteristics akin to those elicited by conventional acoustic pulses, this would support the argument that pulsed microwaves can be heard. Furthermore, if microwave-evoked potentials were recorded from each of these loci along the auditory neural pathway, 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 (Lin 1978, 1980, 1990).

The classical components of the action potential from the auditory branch of the eighth cranial nerve and the round window of the cochlea were shown to be present in both microwave and acoustic pulse cases (Taylor and Ashleman 1974). This suggested that the initial site of interaction of pulse-modulated microwaves with the auditory system is peripheral to the inner ear. A site of interaction at or outside the cochlea should involve propagation of acoustic pressure waves from tissues in the head, with resultant sound pressure effects in the cochlear fluids, hair cells, and central nervous system: auditory activities that have been well described for the acoustic case. In fact, the cochlear microphonic response—a signature of mechanical displacements in the cochlear hair cells—has been reported in cats and guinea pigs exposed to microwave pulses (Chou et al. 1975, 1976).

Moreover, evoked 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. Indeed, auditory-evoked potentials have been recorded from the vertex of the head and from the central auditory nervous system of rats and cats (Lin 1990, 2004). 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 (Fig. 1). Clearly, microwave and acoustic pulses triggered the same neural pathways through the central auditory nervous system. Furthermore, this conclusion was augmented by observations made in systematic studies of loci involved, through production of lesions in ipsilateral auditory nuclei and bilateral ablation of the cochlea, the known first stage

Table 1. Thresholds of microwave-induced auditory sensation in adult humans with normal hearing.

Frequency (MHz)	Pulse width (μs)	Peak power density (kW m^{-2})	Ambient noise level (dB)	Authors (Name Year)
425–1,310	1–100	2.57–2.75	70–90	Frey 1962
1,245	10–70	0.8–6.0	—	Frey and Messenger 1973
2,450	1–32	0.64	45	Guy et al. 1975a, b
3,000	1–100	50	90	Frey 1962
3,000	15–20	2.25–25	—	Cain and Rissman 1978

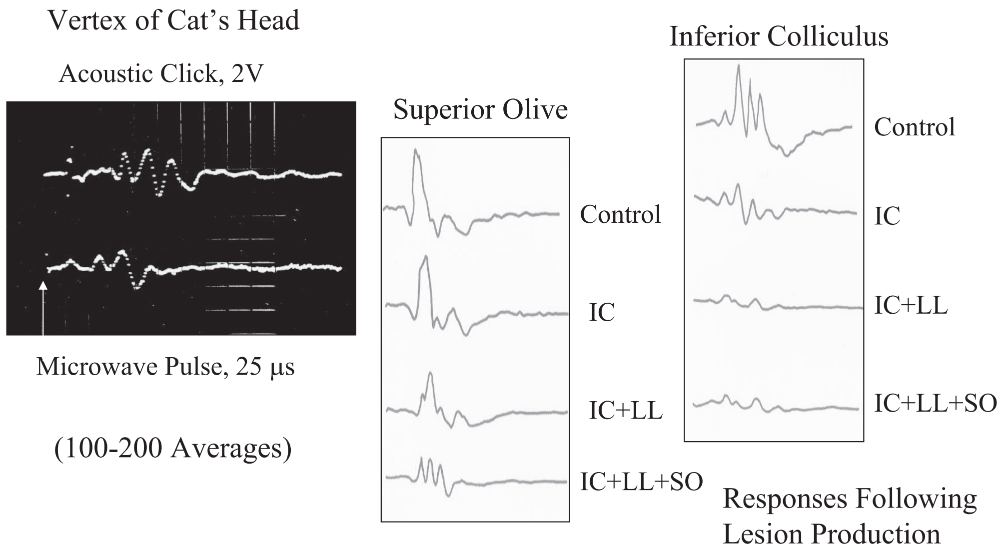

Fig. 1. Microwave and acoustic pulse evoked auditory neural electrical activities recorded from the primary auditory cortex, inferior colliculus (IC) nucleus, lateral lemniscus (LL) nucleus, and the superior olivary (SO) nucleus.

of transduction for acoustic energy into nerve impulses (Chou and Galambos 1979). Also, successive lesion production in the inferior colliculus, lateral lemniscus, and superior olivary nuclei had resulted in a drastic reduction of the recorded auditory responses (Lin et al. 1978, 1979, 1982). 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 results indicated that the initial site of interaction of pulse-modulated microwaves with the auditory system was distal to the cochlea of the inner ear, which does not include any direct neural involvement in the primary interaction.

THERMOELASTIC MECHANISM OF INTERACTION

The data summarized above indicated a peripheral site of initial interaction of pulse-modulated microwave radiation with the auditory system. A peripheral site of initial interaction would involve absorption of microwave pulses by tissues in the head and propagation of sound pressure waves to the cochleas. This scenario suggests that the microwave auditory effect must be mediated by a physical transduction mechanism, and it must include mechanical displacement of tissues in the head. Among the several physical transduction mechanisms suggested that involve mechanical displacement, the thermoelastic expansion had emerged as the most effective mechanism (Foster and Finch 1974; Lin 1976c, 1977a, b, c, 1978, 2005).

Taking a cue from some earlier publications describing the conversion of laser energy to acoustic energy by surface heating of fluids, an experiment had shown that microwave pulses in water produced acoustic pressure transients with peak amplitude, which were within the auditory frequency range of 200 Hz to 20 kHz (Foster and Finch 1974). After examining the pressures generated by electrostriction force, radiation pressure, and thermoelastic stress in brain tissue, it was found that the thermoelastic pressures are one to three orders of magnitude greater than the other mechanisms (Lin 1976a, b).

A series of detailed mathematical analyses were conducted in which the electromagnetic and thermoelastic formulations were developed for spherical head models of animals and humans (Lin 1976c, 1977a, b, c). The analyses showed that the minuscule, but rapid ($\sim\mu$s) rise in temperature ($\sim 10^{-6}$ °C), as a result of the absorption of pulse microwave energy, creates a thermoelastic expansion of tissue matter, which then launches an acoustic wave of pressure that travels to the cochlea, is detected by the hair cells, and relayed to the central auditory system. The cascade of events is illustrated in Fig. 2. Specifically, the thermoelastic theory of auditory perception of pulsed microwave radiation predicted the frequency, pressure, and displacement associated with the acoustic waves generated in the head as functions of head size and tissue property, and the characteristics of impinging and absorbed microwave energies. Table 2 lists the computed peak amplitude of thermoelastic pressure waves in mPa for spherical model animal and human heads exposed to 10 μs plane wave pulses at 1 kW g^{-1}.

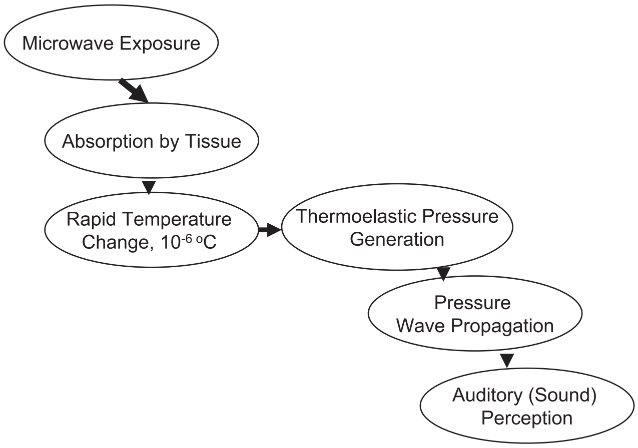

Fig. 2. The cascade of events illustrating the thermoelastic theory of auditory perception of pulse microwaves.

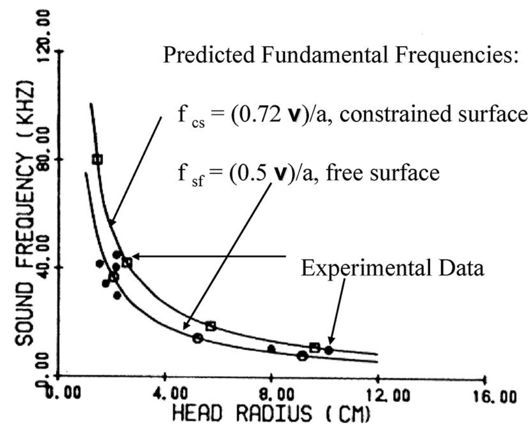

Fig. 3. Thermoelastic theory predicted and experimental measured audible range of frequencies as functions of the subject's head size.

The diameters of 2, 6, 10, and 14 cm are representative of the sizes of a rat, cat, human infant, and adult human female. The SAR of 1 kW kg^{-1} is very high—corresponding to about 5 to 20 kW m^{-2} of incident power density for the specific frequencies listed and gives rise to peak pressure that varied from approximately 350 to 1,000 mPa. The limits of current RF exposure guidelines allow up to 100 kW m^{-2}. The threshold pressure is 20 mPa for human auditory perception at the cochlea (Corso 1963; Lin 1978).

In addition to the expected dependence of sound pressure on the strength of microwave pulses, it prescribed the dependence of induced sound pressure (or loudness of perceived sound) on pulse width, and the dependence of induced sound frequency on head size. For example, the thermoelastic theory predicted a fundamental sound frequency that varies inversely with head radius: the smaller the radius, the higher the frequency. For rat-sized heads, it predicted acoustic frequencies of 25 to 35 kHz in the ultrasonic range, which rats can easily hear. For the size of human heads, the theory predicted frequencies between 7 and 15 kHz, which are clearly within the audible range of humans (Fig. 3).

Table 2. Calculated peak amplitude of thermoelastic pressure waves in mPa for spherical model animal and human heads exposed to 10 μs plane wave pulses at 1 kW kg^{-1}. Data from Lin (1977a, b) and Watanabe et al. (2000) for anatomic human head and 20 μs pulses. The threshold pressure is 20 mPa for perception at the cochlea.

Diameter (cm)	Frequency (MHz)	Peak power (kW m^{-2})	Peak pressure (mPa)
4	2,450	4.45	408
6	2,459	5.89	369
10	918	12.8	961
14	918	21.8	682
Human	915	31.3	238

BIOPHYSICAL MEASUREMENTS

Several sets of experimental measurements have been conducted using a hydrophone transducer (3 mm in diameter), implanted in the brains of cats, rats, and guinea pigs, and in brain-equivalent spherical head models to provide biophysical confirmation of the predicted thermoelastic pressure and frequency. The results, given in Fig. 3, show frequencies of sound pressure as expected from that predicted by the thermoelastic transduction theory (Olsen and Lin 1981, 1983; Su and Lin 1987). Moreover, a speed of thermoelastic pressure wave propagation of 1,523 m s^{-1} was measured in the brain of cats exposed to pulsed microwaves (Lin et al. 1988).

A rather surprising prediction was revealed by the thermoelastic theory—a sound pressure or loudness that initially increases with pulse width and, after reaching a peak value, with further increases in pulse width, it starts to oscillate toward a lower pressure (Lin 1977a, b, c, 1978). While some indirect experimental evidence had come from the measured amplitudes of evoked auditory responses of animal subjects (Lin 1980), a direct measure of the sound pressure or loudness, which had confirmed the prediction, came from a study conducted in Moscow (Lin 1981, 1990, 2004). The Tyazhelov et al. (1979) study investigated the variation of loudness perception with pulse width on human subjects exposed to microwave pulses. The experimental data were presented as the subjects' sensitivity to microwave-induced auditory sound—the inverse of perceived sound loudness or pressure. The results showed remarkably similar loudness or pressure characteristics (Fig. 4), as predicted by the thermoelastic theory, furnishing direct evidence in support of the theory.

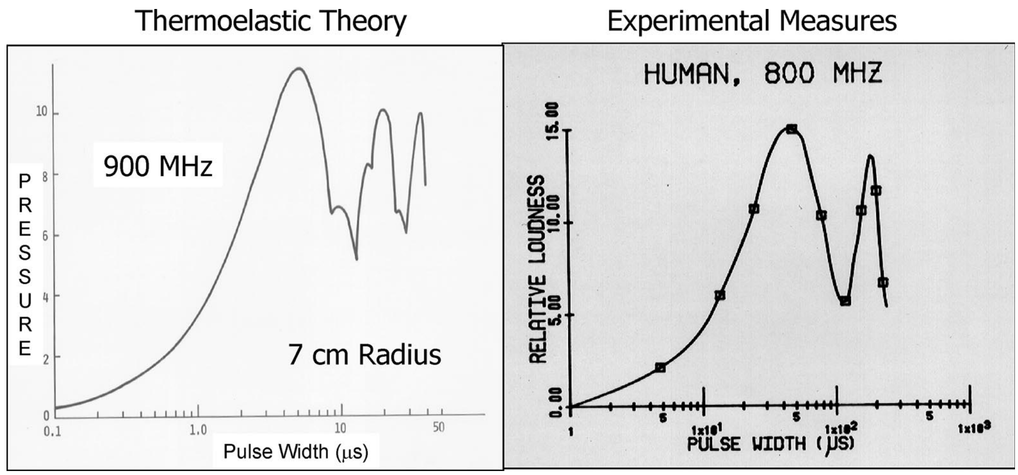

Fig. 4. A comparison of sound pressure and perceived loudness as functions of pulse width in human subjects (note different scales) exposed to microwave pulses: sound pressure predicted by theory (Lin 1976–1978) and measured variation of loudness perception—inverse of subject's sensitivity (Tyazhelov et al. 1979).

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 a homogeneous sphere for analytically clarity and simplicity (Lin 1976c, 1977a, b, c, 1978). A numerical analysis using the finite difference time domain (FDTD) computational algorithm applied to a detailed anatomic modeling of the brain and head structure (Watanabe et al. 2000) had verified the characteristics of microwave pulse-induced acoustic waves such as sound frequency and pressure amplitude—previously obtained using a homogeneous spherical head. Moreover, the numerical computation had provided the values of 2.63 kW m^{-2} and 0.08 kW kg^{-1} for the peak incident power density and peak SAR, respectively, to reach the 20 mPa auditory sound pressure threshold at the cochlea for a 20-ms pulse at 915 MHz.

MRI-INDUCED THERMOELASTIC PRESSURES

Recently, the intensity and power spectra of thermoelastic pressure waves generated by RF pulses from magnetic resonance imaging (MRI) coils have been reported (Lin and Wang 2005; Wang and Lin 2005). The thermoelastic pressure waves from RF/microwave energy absorbed by the head of a human subject inside 1.5 and 7.0 T birdcage MRI coils of conventional design [coil—15 cm in radius, 16 cm in length, 16 rungs (each 1 cm wide); shield—19 cm in radius, 24 cm in length with ideal current sources at midpoint of each end ring] were computed using the FDTD method. The models of human head included brain spheres and anatomic images obtained from the "Visible Human Project" of the U.S. National Library of Medicine. The calculations were based on computational cells of $3 \times 3 \times 3$ mm for the anatomic adult human model and cells of $4 \times 4 \times 4$ mm for the spherical model (18-cm-diameter adult-sized head).

It can be seen from Fig. 5 that initially a negative pressure was noted to begin at zero, then grow to a peak value, and was followed by oscillations, which could rise to even higher peaks after the end of the pulse. The power spectra of the pressure waves showed that the spectral amplitudes for the 200-μs pulses were greater than that of the 100-μs pulses. On the other hand, a fundamental frequency component at about 8 kHz inside the head was observed both for 1.5 and 7 T. This means that the fundamental frequency of the thermoelastic pressure wave was not a function of MRI-field-strength related microwaves, but depended on the dimensions of the head, loading the birdcage MRI coil, as predicted by the thermoelastic theory (Lin 1976c, 1977a, b, c, 1978). Moreover, while the spectral power at 7 T was much higher than that at 1.5 T, similarities in the spectral content indicate that the spectral power peaks correspond to the resonant frequencies of pressure waves inside the head. Table 3 shows similar variations of the pressure wave amplitudes for 100- and 200-μs pulses in the anatomic adult human model. It should be emphasized that the thermoelastic pressures oscillated as a function of time both during and after the pulse and reached a peak shortly after the cessation of the 100- and 200-μs pulse. The MRI-induced, sound-pressure wave depends on head size, pulse width, absorbed power, and MRI field strength or microwave frequency.

The computed currents from a birdcage MRI coil required to induce peak SARs of 4, 8, 10, and 20 W kg^{-1} from 100 and 200 μs pulses at 1.5 T (64 MHz) and 7 T (300 MHz), respectively, in anatomic and homogeneous

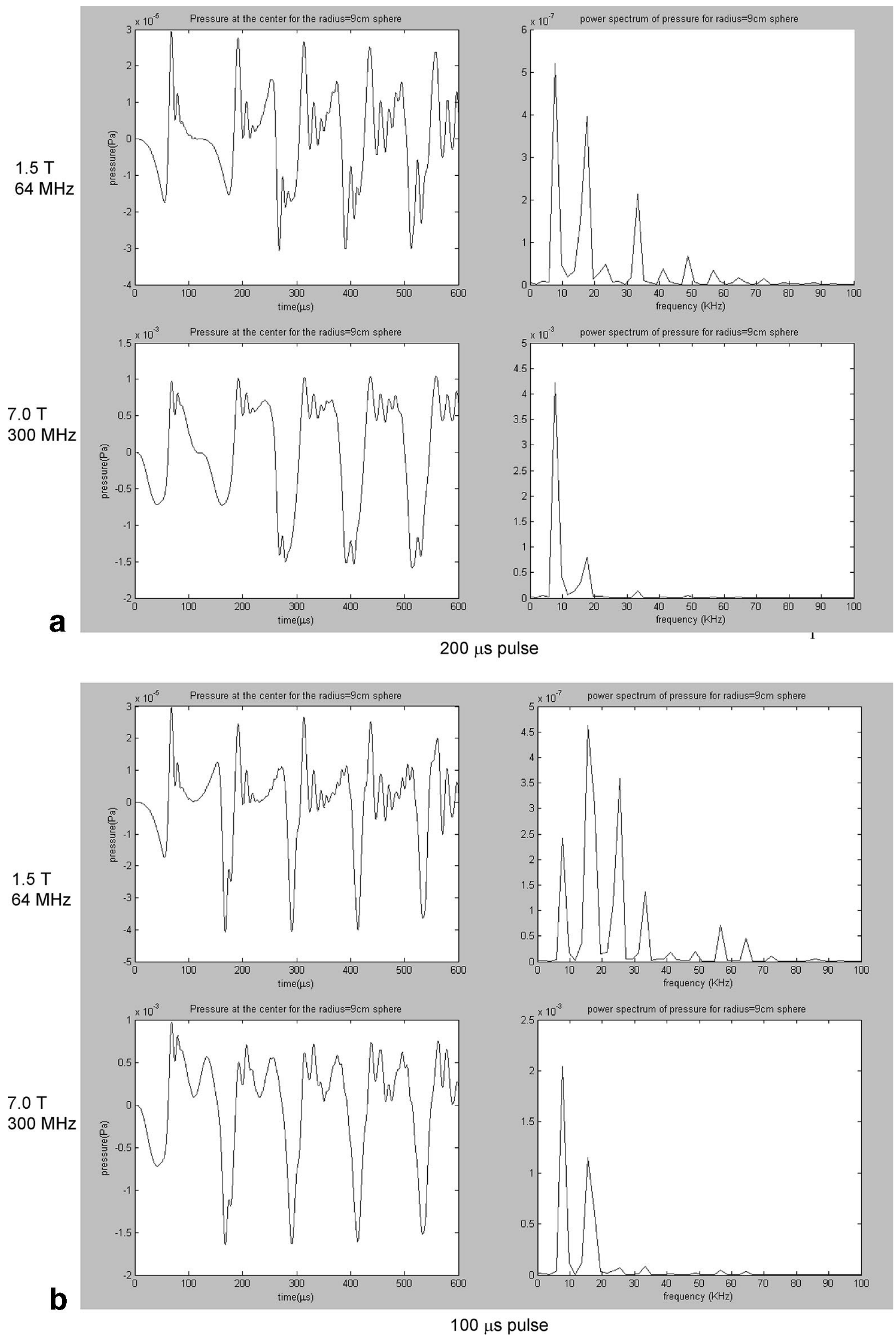

Fig. 5. Computed thermoelastic pressures and power spectra for a spherical model of adult-size head (9-cm radius) inside 1.5 T and 7.0 T MRI imaging coils (a) 200 μs; (b) 100 μs.

Table 3. Calculated peak thermoelastic pressure wave amplitude (mPa) in a human head inside 1.5 and 7.0 T MRI coils for 100 and 200 μs pulses at 100 mA as a function of time.

	100 μs		200 μs	
Time (μs)	64 MHz (1.5 T)	300 MHz (7.0 T)	64 MHz (1.5 T)	300 MHz (7.0 T)
20	0.0065	0.50	0.0065	0.50
40	0.0115	0.84	0.0115	0.84
60	0.0094	0.39	0.0094	0.39
80	0.0143	0.90	0.0143	0.90
100	0.0127	0.78	0.0125	0.77
120	0.0102	0.71	0.0061	0.32
140	0.0138	0.57	0.0117	0.55
160	0.0164	0.86	0.0121	0.94
180	0.0174	1.19	0.0069	0.38
200	0.0243	1.10	0.0153	0.67
220	0.0149	0.72	0.0135	1.18
240	0.0199	0.97	0.0169	1.11

human head models, are shown in Table 4. Also, the computed peak thermoelastic pressure wave amplitudes induced in the head models are provided in the table. As expected, the coil currents and peak pressures all increased as SAR ranged from 4, 8, 10, and 20 W kg^{-1} both for 1.5 and 7.0 T. It is emphasized that the coil current required to induce a given SAR at 1.5 T or 64 MHz is nearly ten times as much as at 7 T or 300 MHz. Note that the peak pressures generated by 100-μs and 200-μs pulses in both the anatomic and homogeneous models all were higher than the threshold pressure of 20 mPa for sound perception by humans at the cochlea for SARs of 4, 8, 10, and 20 W kg^{-1}. Moreover, results in Table 4 indicate that the peak thermoelastic pressure in the brain could be as much as 2 to 4 times the auditory threshold at the FDA guidelines of 4 to 8 W kg^{-1}. At an SAR of 20 W kg^{-1}, the thermoelastic pressure in the brain could be as much as 10 times the auditory threshold. In other words, the sound pressure levels would be about 20 dB above threshold of perception at the cochlea, but below the discomfort threshold. A similar observation was provided by a study on six human volunteers in RF coils for MRI (Roschmann 1991).

CONCLUSION

The microwave auditory phenomenon does not arise from an interaction of microwave pulse 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. Aside from tissue heating, microwave auditory effect is the most widely accepted biological effect of microwave radiation, with a known mechanism of interaction, i.e., the thermoelastic theory. Peak amplitude of thermoelastic pressure waves have been computed for spherical head models approximating the sizes of rats, cats, human infants, and adult human females exposed to 10 μs plane wave pulses at 1 kW kg^{-1}. The corresponding incident power density is about 5 to 20 kW m^{-2} for frequencies between 915 and 2,450 MHz and the induced peak pressures were found to vary from approximately 350 to 1,000 mPa. The threshold pressure is 20 mPa for perception of sound at the cochlea by humans. The limits of current RF exposure guidelines allow up to 100 kW m^{-2}. The thermoelastic pressure waves generated by RF pulses from MRI coils could be 2 to 4 times the auditory threshold at the FDA guidelines of 4 to 8 W kg^{-1}. At an SAR of 20 W kg^{-1}, the thermoelastic pressure in the brain could be as much as 10 times the auditory threshold. The sound pressure levels correspond to about 20 dB above threshold of perception at the cochlea, but below the discomfort threshold. It is noted that the coil current required to induce a given SAR at 1.5 T or 64 MHz is nearly ten times as much as at 7.0 T or 300 MHz.

Table 4. MRI coil currents and thermoelastic pressure wave amplitudes induced in anatomic and homogeneous head models by SARs of 4, 8, 10, and 20 W kg^{-1} from 100 and 200 μs pulses at 1.5 and 7 T. The threshold pressure is 20 mPa for perception at the cochlea.

Human head model	Peak SAR (W kg^{-1})	64 MHz (1.5 T) Coil current (mA)	64 MHz (1.5 T) 100 μs pressure (mPa)	64 MHz (1.5 T) 200 μs pressure (mPa)	300 MHz (7.0 T) Coil current (mA)	300 MHz (7.0 T) 100 μs pressure (mPa)	300 MHz (7.0 T) 200 μs pressure (mPa)
Anatomic	4	4,080	40	28	489	29	28
Anatomic	8	5,770	80	57	692	57	57
Anatomic	10	6,451	100	71	773	71	71
Anatomic	20	9,123	200	142	1,093	142	141
Brain sphere	4	3,290	39	28	452	31	19
Brain sphere	8	4,653	78	56	639	62	38
Brain sphere	10	5,202	97	70	715	77	48
Brain sphere	20	7,359	195	141	1,011	154	90

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