Bioelectromagnetics Supplement 6:S162–S173 (2003)

Auditory Response to Pulsed Radiofrequency Energy

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The human auditory response to pulses of radiofrequency (RF) energy, commonly called RF hearing, is a well established phenomenon. RF induced sounds can be characterized as low intensity sounds because, in general, a quiet environment is required for the auditory response. The sound is similar to other common sounds such as a click, buzz, hiss, knock, or chirp. Effective radiofrequencies range from 2.4 to 10 000 MHz, but an individual's ability to hear RF induced sounds is dependent upon high frequency acoustic hearing in the kHz range above about 5 kHz. The site of conversion of RF energy to acoustic energy is within or peripheral to the cochlea, and once the cochlea is stimulated, the detection of RF induced sounds in humans and RF induced auditory responses in animals is similar to acoustic sound detection. The fundamental frequency of RF induced sounds is independent of the frequency of the radiowaves but dependent upon head dimensions. The auditory response has been shown to be dependent upon the energy in a single pulse and not on average power density. The weight of evidence of the results of human, animal, and modeling studies supports the thermoelastic expansion theory as the explanation for the RF hearing phenomenon. RF induced sounds involve the perception via bone conduction of thermally generated sound transients, that is, audible sounds are produced by rapid thermal expansion resulting from a calculated temperature rise of only 5×10^{-6} °C in tissue at the threshold level due to absorption of the energy in the RF pulse. The hearing of RF induced sounds at exposure levels many orders of magnitude greater than the hearing threshold is considered to be a biological effect without an accompanying health effect. This conclusion is supported by a comparison of pressure induced in the body by RF pulses to pressure associated with hazardous acoustic energy and clinical ultrasound procedures. Bioelectromagnetics Supplement 6:S162–S173, 2003.

Key words: RF hearing; microwave; thermoelastic; auditory response

INTRODUCTION

An informational advertisement describing observations made in 1947 on the hearing of sounds that occurred at the repetition rate of a radar while the listener stood close to the antenna included the comment that people encountered skepticism and rather pointed questions about their mental health when they first told their coworkers of their hearing experiences [Airborne Instruments Laboratory, 1956]. The skepticism surrounding early reports of radiofrequency (RF) hearing was based on knowledge of the mechanism of human hearing. The ear was known to be exquisitely sensitive to pressure waves but to have no sensitivity to electromagnetic waves at microwave frequencies (300 MHz–300 GHz).

The skepticism helps to explain why the first systematic study of RF hearing by Frey [1961] did not appear until many years after the observation of this effect in the 1940s. Frey's report described the hearing of transient buzzing sounds by human subjects exposed to RF energy from a radar. The apparent location of the sound, which was described as a short distance behind the head, was the same regardless of the body's orientation to the radar [Frey, 1961]. In later reports [Frey, 1962, 1963], RF hearing was described as a ''buzz, clicking, hiss, or knocking'' sound. Table 1 contains descriptions of these and other sounds reported by human beings exposed to pulsed RF fields. When a metal shield of aluminum flyscreen was placed between the subject and the radar, no RF sounds were heard [Frey and Messenger, 1973]. The sensitive area for detecting RF sounds was described as a region over the temporal lobe of the brain, because the placement of a

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Received for review 3 September 2002; Final revision received 21 May 2003

DOI 10.1002/bem.10163

TABLE 1. Auditory Effects in Human Beings Exposed to Pulsed RF Energy

			Exposure conditions							
Effect	Comment	Number of subjects	Frequency (MHz)	Pulse repetition rate (s^{-1})	Pulse width (µs)	Peak power density (mW/cm^2)	Average power density (mW/cm^2)	Energy density per pulse (µJ/cm^2)	Noise level (dB)	Reference
RF hearing: heard repetition rate of radar as “high frequency components”		Not given	1300	600	2	(Peak power ~0.5 MW)				Airborne Instruments Laboratory [1956]
RF hearing: “distinct” clicks	Threshold values	8	3000	0.5	5	2500	0.006	12.5	45 (+plastic foam earmuffs)	Rissmann and Cain [1975]; Cain and Rissmann [1978]
					10	225–2000	0.001–0.01	2.3–20.0		
					15	300–1000	0.002–0.007	4.5–15.0		
RF hearing: buzz heard at PRR>100; individual pulses heard at PRR<100		3	3000	<100–1000	1–2	2500–50000	5	40		Constant [1967]
			6500	<100–1000	1–2	2500–50000	5			
No auditory response			3000	<100–1000	0.5	10000–100000	5			
			6500	<100–1000	0.5	10000–100000	5			
No auditory response			9500	<100–1000	0.5–2	2500–100000	5			
RF hearing: “buzzing sound”	Threshold values	8	1310	244	6	267	0.4		70–80 (+earplugs)	Frey [1961]
		7	2982	400	1	5000	2			
RF hearing: “buzz, clicking, hiss, or knocking”	Threshold values	Not given	216			670	4.0		70–90 (+ear stopples)	Frey [1962, 1963]
			425	27	125	263	1.0			
			425	27	250	271	1.9			
			425	27	500	229	3.2			
			425	27	1000	254	7.1			
No auditory response			8900	400	2.5	25000	25		70–90 (+ear stopples)	Frey [1962]
RF hearing: matched RF sound to 4.8 kHz acoustic sounds	Subjects were trained musicians	3	1200		12.5–50		<0.5			Frey and Eichert [1985]
RF hearing: “buzzing sound”		4	1245	50	10	370	0.19			Frey and Messenger [1973]
			1245	50	70	90	0.32			
RF hearing: “clicks, chirps”	Threshold values	2	2450	3	1–32	1250–40000	0.1	40[a]	45 (±earplugs)	Guy et al. [1975]
RF hearing: buzz	Threshold values (not at 10 GHz)	Not given	1310	244	6	(12 V/cm)	0.3			Ingalls [1967]
			2982	400	1	(18 V/cm)	0.18			
			10000							
RF hearing: “tinnitus”		Not given		100–20000	10–160					Khizhnyak et al. [1979, 1980]
RF hearing: chirps or clicks of high pitch at short pulses (<50 µs); for >100 µs pulses, creaky or gnashing clacks of lower pitch	Threshold values (head exposure to MRI coils)	6	2.4–170	1.2	3–5000	<9000		<9	(+plastic foam ear muffs)	Röschmann [1991]
RF hearing: polytonal sound		18	800	1000–1200	10–30	>500			40 (+ear stopples)	Tyazhelov et al. [1979]

[a] Calculated peak absorbed energy density per pulse is 16 mJ/kg.

small piece of metal screen (5 × 5 cm) over this area completely stopped the sound [Frey, 1962]. The subjects in Frey [1961] reported an increase in the RF induced sound level when earplugs were used to reduce the ambient noise level, an observation confirmed by others [Guy et al., 1975].

The "sound was something like that of a bee buzzing on a window, but with, perhaps, more high frequencies" according to Ingalls [1967] who used two radars like those described in Frey [1961]. The sound seemed to come from about a meter or two above the head. In another report [Constant, 1967], the RF induced sound was described as being in the area of the ear on the side opposite to the antenna. All subjects heard a buzzing sound at a pulse repetition rate (PRR) greater than 100/s, whereas individual pulses were heard at a PRR below 100/s. Cain and Rissmann [1978] reported that human subjects heard distinct clicks either inside the head or behind the head when exposed to pulsed fields. Individual pulses were heard as distinct and separate clicks, and short pulse trains as chirps with the tone pitch corresponding to the PRR [Guy et al., 1975]. The RF induced sound appeared to originate from within or near the back of the head. This report also included the note that transmitted digital codes could be accurately interpreted by the subject when the pulse generator was keyed manually. Two reports described RF induced sounds as polytonal sounds and "tinnitus" [Tyazhelov et al., 1979; Khizhnyak et al., 1980]. RF induced sounds in volunteers exposed to head coils used in magnetic resonance imaging (MRI) were described as chirps or clicks of high pitch for short pulses (<50 μs) and as creaky or gnashing clacks of lower pitch for longer pulses (>100 μs) [Röschmann, 1991].

The above studies show that human perception of pulsed RF energy, resulting in sounds that vary with modulation of the signal, is a well established phenomenon. The following sections describe the effective exposure parameters including thresholds for RF hearing, the dependence of RF hearing on acoustic hearing, the mechanism responsible for human perception of pulsed RF fields, and a discussion of the significance of the effect. Reviews on this subject include those by Lin [1978, 1980, 1981, 1989, 1990, 2001]; Chou et al. [1982]; Elder [1984]; Frey [1988]; Postow and Swicord [1996]; and Stewart [2000].

EFFECTIVE RF EXPOSURE PARAMETERS

A summary of RF exposure parameters used in human studies is shown in Table 1. The parameters include frequency, PRR, pulse width, peak power density, average power density, and energy density/pulse. Threshold values for RF hearing have been reported in several studies and these are shown in the table also.

RF hearing has been reported at frequencies ranging from 2.4 to 10 000 MHz (see Table 1). Although Ingalls [1967] mentioned 10 000 MHz as an effective frequency, other investigators found that lower frequencies (8900 and 9500 MHz) at very high exposure levels did not induce RF sounds. For example, the frequency of 8900 MHz was not effective at an average power density of 25 mW/cm^2 and peak power density of 25 000 mW/cm^2 [Frey, 1962]. At 216 MHz, the average power density threshold was 4 mW/cm^2 and the peak power density was 670 mW/cm^2 [Frey, 1963]. At the lowest effective frequencies (2.4–170 MHz) reported in the literature, the peak power density thresholds were up to 9000 mW/cm^2 [Röschmann, 1991]. The lowest threshold value expressed in units of average incident power density is 0.001 mW/cm^2 [Cain and Rissmann, 1978]; this value was due to the low PRR of only 0.5/s (Table 1) because, for a given peak power, average power density depends on the PRR. The hearing phenomenon, however, has been shown to depend on the energy in a single pulse and not on average power density. Guy et al. [1975] found that the threshold for RF hearing of pulsed 2450 MHz fields was related to an energy density of 40 μJ/cm^2 per pulse, or energy absorption per pulse of 16 μJ/g, regardless of the peak power of the pulse or the pulse width (less than 32 μs); calculations showed that each pulse at this energy density would increase tissue temperature by about 5×10^{-6} °C.

A comparison of the RF auditory thresholds reported in the literature to the thresholds observed in human subjects exposed to fields from MRI coils showed good agreement over a wide range of frequencies (2.4–3000 MHz) [see Fig. 7 in Röschmann, 1991]. Another comparison in this report showed that electrophysiological measurements in cats yielded thresholds quite similar to results from RF hearing tests of humans.

A review of Table 1 reveals that many of the threshold values were determined in a very quiet environment or subjects used earplugs or earmuffs to decrease the ambient noise level. As mentioned in Introduction, earplugs were used by the subjects in Frey's first report in 1961. Thus, investigators were generally aware that a quiet environment was required because, in many cases, the normal noise levels in outdoor, laboratory, and MRI environments masked the hearing of RF sounds. In Guy et al. [1975], for example, the threshold value cited above was obtained in a very quiet environment having a background noise level of only 45 dB. When earplugs were used, the threshold level for one subject decreased from 35 to 28 μJ/cm^2.

The threshold for a subject with a hearing deficit was much higher, approximately 135 $\mu J/cm^2$ (no earplug).

DEPENDENCE OF RF HEARING ON ACOUSTIC HEARING

The advertisement from Airborne Instruments Laboratory [1956] stated that two persons with hearing loss above 5 kHz did not perceive RF sounds as well as did observers with normal hearing up to 15 kHz. Later studies provided more information on the relationship between acoustic and RF hearing. Frey [1961] reported that a necessary condition for hearing the RF induced sound was the ability to hear audiofrequencies above approximately 5 kHz, although not necessarily by air conduction. This conclusion was based on results with subjects with normal or defective hearing. One subject with normal air conduction hearing below 5 kHz failed to hear the microwave pulses; the person was subsequently found to have a substantial loss in bone conduction hearing. Another subject with good bone conduction hearing but with poor air conduction hearing perceived the RF induced sound at approximately the same power density that induced threshold perception in subjects with normal hearing. In a later study, human subjects matched sounds caused by repetitive exposure to a pair of RF pulses in the MHz range to acoustic frequencies near 4.8 kHz [Frey and Eichert, 1985].

In addition to determining standard audiograms that measure hearing thresholds for air conduction at acoustic frequencies of 250–8000 Hz and for bone conduction to 4000 Hz, Cain and Rissmann [1978] measured the hearing ability of eight subjects up to 20 kHz. They found that although there was no apparent correlation between the ability to hear pulsed RF fields at 3000 MHz and hearing ability as measured by standard audiograms, there was a strong correlation between the RF hearing threshold and thresholds to air conducted acoustic signals above 8 kHz. For example, three of the subjects who had normal hearing below 4 kHz, but a hearing deficit at frequencies above 8 kHz, could not hear RF induced sounds. The studies by Frey [1961], Cain and Rissmann [1978], and Frey and Eichert [1985] show RF hearing to depend on high frequency hearing in the range of about 5–8 kHz and bone conduction hearing at lower acoustic frequencies. Calculated values of fundamental frequencies of RF induced sound in the human head based on animal data or models are somewhat similar, e.g., 7–10 kHz [Chou et al., 1977], 8 and 13 kHz [Lin, 1977a,b], and 7–9 kHz [Watanabe et al., 2000]; the results of these studies are described in more detail below.

SIMILARITY OF AUDITORY RESPONSE TO RF ENERGY AND CONVENTIONAL ACOUSTIC STIMULI

The auditory pathway by which acoustic waves detected by the ear become interpreted as sound in the brain is well known and several studies have been done to determine if the electrophysiological response of the auditory pathway to RF pulses is similar to the response to acoustic stimuli. The first stage of sound transduction is mechanical distortion of cochlear hair cells that result in cochlear microphonics, electrical potentials that mimic the sonic waveforms of acoustic stimuli. Subsequent to the detection of sound by the cochlea, electric potentials associated with the detection of sound may be recorded by electrodes placed in neurons at various locations along the auditory pathway.

Frey [1962] proposed that RF hearing might be a result of direct cortical or neural stimulation but the results of later studies described in this review showed that Frey's hypothesis was incorrect. His proposal was based, in part, on his failure to demonstrate that RF pulses stimulate the cochlea, that is, cochlear microphonics were not recorded at power densities much higher than those required to elicit auditory nerve responses [Frey, 1967]. Guy et al. [1975] also failed to measure cochlear microphonics but determined that the failure was due to insufficient absorption of RF energy. Chou et al. [1975] reported their success in overcoming the technical problems that had prevented investigators from recording cochlear microphonics from RF exposed animals. The results showed that pulses of RF energy activated the cochlea because cochlear microphonics were recorded that were similar to those evoked by acoustic stimuli [Chou et al., 1975, 1976]. The demonstration in animals that RF induced auditory responses are perceived by the normal auditory system via the cochlea provided evidence against the proposal that RF pulses directly stimulate the nervous system.

Taylor and Ashleman [1974] and Guy et al. [1975] showed the importance of the cochlea by finding that destruction of the cochlea abolished RF evoked potentials recorded at higher levels in the auditory pathway. These results indicated that the locus of the initial interaction of pulse-modulated microwave energy with the auditory system is within or peripheral to the cochlea.

In cats with undamaged cochleae, Taylor and Ashleman [1974] measured the electrophysiological response in three successive levels of the cat auditory nervous system (eighth cranial nerve, medial geniculate nucleus, and primary auditory cortex) to both acoustic and pulsed microwave (2450 MHz) stimuli. They found similar responses to microwave stimuli and conventional acoustic stimuli. Lebovitz and Seaman [1977a,b] also found similar responses of single auditory neurons in cats to pulsed 915 MHz fields and acoustic clicks. Guy et al. [1975] and Lin et al. [1978, 1979] showed that electrophysiological responses of the auditory pathway in cats to RF pulses is similar to the response to acoustic stimuli and, by studying the responses after lesions were made in successive parts of the auditory pathway, confirmed that the primary site of transduction of the RF energy was outside or at the cochlea. The detection of electric potentials in auditory neurons in response to RF exposure was expected based on the results of studies that demonstrated subjective auditory perception [Frey, 1962] and cochlear microphonics [Chou et al., 1975]. Seaman [1990] described a model for thresholds of auditory neurons to RF pulses that was consistent with thresholds measured in the cat for 20–200 μs pulses.

It is known that acoustic stimuli can cause evoked potentials in central nervous system sites outside the auditory pathway and such evoked potentials due to the auditory response to RF pulses were recorded by Guy et al. [1975]. These authors explained that electric potentials recorded from any CNS location could be misinterpreted as a direct interaction of RF energy with the particular neural system in which the recording was made, as reported by Frey [1967].

In an experiment in which the thresholds of evoked electrical responses from the medial-geniculate body in the auditory pathway in cats were determined as a function of background noise, Guy et al. [1975] found that as the noise level (50–15 000 Hz bandwidth) increased from 60 to 80 dB, there was only a negligible increase in the threshold for microwave stimuli, and a large increase in the threshold for loudspeaker produced stimuli. The finding that the evoked response to microwave stimuli did not increase in relation to background noise, which included acoustic frequencies to 15 000 Hz, indicated that pulsed RF energy may be interacting more with the high frequency portion of the auditory system (above 15 kHz in cats).

Additional support for the dependence of RF hearing on high frequency acoustic hearing was provided by theoretical analysis of acoustic vibrations induced in the heads of animals and humans based on thermal expansion in spheres exposed to pulses of RF energy [Lin, 1976a, 1977a,b]. The frequency of the induced sound was found to be a function of head size and of acoustic properties of brain tissue; hence, the acoustic pitch perceived by a given subject is the same regardless of the frequency of the incident RF energy. These calculations show that the fundamental frequency predicted by the model varies inversely with the radius of the head, i.e., the larger the radius, the lower the frequency of the perceived RF sound. The estimated fundamental frequencies of vibration in guinea pigs, cats, and adult humans were 45, 38, and 13 kHz, respectively; the frequency for an infant human head was estimated to be about 18 kHz [Lin, 1977b, 1990]. These calculations provide further evidence that a necessary condition for RF induced sounds in humans is the ability to hear acoustic waves at frequencies above about 5 kHz [Frey, 1961; Rissmann and Cain, 1975].

The calculated fundamental frequency (45 kHz) in guinea pigs [Lin, 1977b] is in good agreement with the measurements of Chou et al. [1975], who found cochlear microphonics of 50 kHz in guinea pigs exposed to RF pulses. In a later report, Chou et al. [1977] found the frequency of cochlear microphonics in guinea pigs and cats to correlate well with the longest dimension of the brain cavity and, based on these data, estimated the frequency of the microwave-induced cochlear microphonics in human beings to be between 7 and 10 kHz. As mentioned above, Lin [1977a,b] had calculated frequencies of 8 and 13 kHz. In contrast to these results, one laboratory has reported responses from cochlear nucleus units with characteristic frequencies in the normal range of hearing for the cat that were inconsistent with head resonance having a primary role in RF hearing [Seaman and Lebovitz, 1987].

Gandhi and Riazi [1986] calculated RF hearing thresholds at 30–300 GHz, but there is little if any physiological significance of these calculations to RF hearing because: (a) their calculated fundamental frequencies in the head are of the order of several hundred kilohertz, well above the maximum acoustic frequency of about 20 kHz for human hearing, and (b) there are no reports of human perception of RF pulses at frequencies higher than 10 GHz (see Table 1).

The results of the above studies of evoked electrical potentials in the auditory system, including the demonstration of pulsed RF evoked cochlear microphonics, strongly indicate that the detection of RF induced auditory sensations is similar to that of acoustic sound detection, the site of conversion from RF to acoustic energy is within or peripheral to the cochlea, the fundamental frequency of RF induced sound is independent of the frequency of the incident RF energy but dependent upon the dimensions of the head, and the pulsed RF energy interacts with the high frequency portion of the auditory system. To hear RF induced sounds, a human must be exposed to pulses of RF energy in the MHz range (see Table 1) and be capable of hearing acoustic waves in the kHz range above about 5 kHz.

MECHANISM OF RF HEARING: THERMOELASTIC EXPANSION

One of the first challenges to Frey's proposal of direct neural stimulation [Frey, 1961, 1962] came from

Sommer and von Gierke [1964], who suggested that stimulation of the cochlea through electromechanical field forces by air or bone conduction appeared to be a more likely explanation of the RF hearing phenomenon. Other scientists who helped lay the foundation for identifying the mechanism are White [1963] and Gournay [1966]. White [1963] showed that pressure waves could be detected in water exposed to pulses of RF energy, and his analysis of waves in this system predicted that, as a result of thermal expansion, the resulting temperature gradient would generate stress waves that propagate away from the site of energy absorption. Gournay [1966] extended White's analysis to show that for single long pulses, the induced stress wave is a function of peak power density and, for shorter pulses, the stress wave is a function of the peak power density and pulse width (or energy density per pulse).

Foster and Finch [1974] extended Gournay's analysis by conducting experiments in water and KCl solution exposed to RF pulses similar to those that produce sounds in humans. They showed both theoretically and experimentally that pressure changes would result from the absorption of RF pulses which could produce significant acoustic energy in the solution. They concluded that audible sounds were produced by rapid thermal expansion due to absorption of the energy in the RF pulse. These results led to their proposal that thermoelastic expansion is the mechanism for RF hearing. This mechanism is consistent with the following results of their experiment.

1) RF pulses that would elicit sounds in humans produced acoustic transients that were recorded with a hydrophone immersed in a solution (0.15 N KCl) having an electrical conductivity similar to that of tissue. In addition, acoustic transients were detected in blood, muscle, and brain exposed in vitro to pulses of RF energy.
2) The RF induced pressure wave generated in distilled water inverted in phase when the water was cooled below 4 °C, and the response vanished at 4 °C, in agreement with the temperature dependence of the thermal expansion properties of water.
3) The thermoelastic theory predicts that the maximal pressure in the medium is proportional to the total energy of the pulse for short pulses and is proportional to the peak power for long pulses. The relationship between pulse width and the RF generated acoustic transient in the KCl solution was consistent with the theory.

Based on these findings, Foster and Finch concluded that RF induced sounds involve perception, via bone conduction, of the thermally generated sound transients caused by the absorption of energy in RF pulses. The pulse can be sufficiently brief (≤ 50 μs) such that the maximum increase in tissue temperature after each pulse is very small ($<10^{-5}$ °C). The peak power intensity of the pulse, however, must be moderately intense (typically 500 to 5000 mW/cm^2 at the surface of the head). These values are within the range of effective peak power intensities of 90–50 000 mW/cm^2 in the human studies shown in Table 1. Mathematical modeling has shown that the amplitude of a thermoelastically generated acoustic signal is of such magnitude that it completely masks that of other possible mechanisms such as radiation pressure, electrostrictive force, and RF field induced force [Guy et al., 1975; Lin, 1976b; Joines and Wilson, 1981]. These and other results led Guy et al. [1975], Lin [1978], Joines and Wilson [1981], and Röschmann [1991] to conclude that the thermoelastic expansion mechanism is the most likely physical mechanism to explain the RF induced auditory effect in human beings.

A year before the thermoelastic theory was proposed by Foster and Finch [1974], Frey and Messenger [1973] published the results of a human study that are in agreement with the theory. That is, the loudness of the RF induced sounds in human subjects depended upon the incident peak power density for pulse widths >30 μs; for shorter pulses, their data show that loudness is a function of the total energy per pulse. In related work, results from animal experiments showed the predicted threshold dependence on pulse width. Chou and Guy [1979] found that the threshold for RF hearing in guinea pigs, as measured by auditory brainstem evoked electrical responses, is related to the incident energy per pulse for pulse widths <30 μs and is related to the peak power for longer pulses up to 500 μs. Using short pulse widths of 1–10 μs, Chou et al. [1985] observed that the auditory threshold in rats was independent of pulse width. This paper is also important because the results demonstrated that the RF induced auditory response occurred in rats exposed at low field strengths in a circularly polarized waveguide, an exposure system in common use in studies of the biological effects of RF energy.

The results on threshold and loudness may be summarized as follows. The energy in the first 30 μs or so of the pulse determines the threshold and loudness levels regardless of pulse width. For wider pulses (>90 μs), loudness is related to peak power rather than energy because the energy associated with the first 30 μs of the pulse increases directly with peak power. Thus, if sufficient energy is deposited within a 30 μs period, an RF induced sound will result without regard to pulse width. And, for pulses >30 μs, loudness increases with an increase in peak power. Thus, the auditory response undergoes a gradual transition from an energy related effect at pulse widths <30 μs to an effect dependent on peak power at pulse widths >90 μs [Frey and Messenger, 1973; Chou and Guy, 1979].

A psychophysical experiment with 18 subjects examined the adequacy of the thermoelastic hypothesis and the perceptual qualities of RF induced sounds [Tyazhelov et al., 1979]. Audiofrequency signals were presented alternately to or concurrently with microwave pulses (see Table 1) under conditions in which the subject could adjust the amplitude, frequency, and phase of the audio signal. Long pulses (∼100 μs) resulted in a lower pitch of the RF sound and two subjects who had a high frequency auditory limit of 10 kHz could not hear short RF pulses but could hear long pulses. Tyazhelov et al. [1979] concluded that the thermoelastic hypothesis adequately explained some of their findings for RF pulses of high peak power and short width (<50 μs), but they questioned the applicability of the hypothesis to some observations involving near-threshold pulses of low power, long duration, and high repetition rate (see Chou et al. [1982] for a critique of Tyazhelov et al. [1979]). In other papers, Tyazhelov et al. suggested that the thermoelastic theory accounted for the low frequency, but not the high frequency, RF induced sounds [Khizhnyak et al., 1979, 1980]; however, no other reports have been found that support their proposed model for high frequency responses. A more recent report [Röschmann, 1991] on auditory system response of six human subjects, whose head was exposed to RF energy from MRI coils, concluded that the dependence of thresholds on pulse width confirmed theoretical predictions from the thermoelastic expansion theory.

Theoretical analysis by Lin [1977a] predicted that sound pressure as a function of pulse width initially increased, reached a peak, decreased, then oscillated with maximal values below the peak. Human data in Tyazhelov et al. [1979] and animal data in Chou and Guy [1979] and Lin et al. [1979] are in general agreement with this pattern of response with pulse width. More detailed discussion of the pulse width dependence of perceived sound loudness based on the human data in Tyazhelov et al. [1979] is given in reviews by Lin [1981, 1990].

Results of animal studies, in addition to those already discussed, support and extend our understanding of RF hearing and the thermoelastic mechanism. Several investigators have determined the threshold for RF induced auditory system responses in laboratory animals as shown in Table 2. In cats exposed to RF pulses (918 and 2450 MHz), the threshold was related to the incident energy density per pulse. The cat's threshold energy density per pulse was about one-half of the

TABLE 2. Threshold Values for Auditory System Responses in Animals Exposed to Pulsed RF Energy

		Exposure conditions							
Effect	Species (n)	Frequency (MHz)	Repetition rate (s^{-1})	Pulse width (μs)	Peak power density (mW/cm^2)	Average power density (mW/cm^2)	Energy density per pulse (μJ/cm^2)	Peak absorbed energy density per pulse (μJ/g)	Reference
Response obtained with scalp electrodes	Cat (2) [also dog and chinchilla]	3000	0.5	5 10 15	2200, 2800 1300 580		11, 14 13 8.7		Rissmann and Cain [1975]; Cain and Rissmann [1978]
Response obtained with carbon-loaded Teflon® electrodes	Guinea pig (n not given)	918	30	10–500	62–156	0.02–1.4	1.56–46.8	6–180	Chou and Guy [1979]
Response obtained from round window with carbon lead	Guinea pig (5)	918	100	1–10	[a]	[a]		20	Chou et al. [1975]
Brainstem evoked response	Rat (10)	2450	10	1–10	150–3000		1.5–3	0.9–1.8	Chou et al. [1985]
Electrode implanted in brain stem	Cat (11)	1200–1525	12–130	10	60	0.03			Frey [1967]
Response obtained from medial geniculate with glass electrode	Cat (2)	918 2450 8670–9160	1 1 1	3–32 0.5–32 32	800–5800 600–356000 14800–38800	0.017–0.028 0.015–0.047 0.472–1.24	17.4–28.3 15.2–47.0 472–1240	12.3–20.0 8.7–26.7	Guy et al. [1975]
Response obtained from individual auditory neurons with glass electrode	Cat (7)	915	<10	25–250		≤1.0		4–40	Lebovitz and Seaman [1977a,b]
Neuronal action potentials in cochlea	Cat (18)	915		20–700				0.6	Seaman and Lebovitz [1989]

[a] Direct comparison of power density in the circular waveguide exposure system to free field power density is improper because the efficiency of energy coupling is ten times higher than that for free field exposure [see Chou et al., 1975, p. 362].

human threshold [Guy et al., 1975]. The thresholds in Cain and Rissmann [1978] are in general agreement with the results in Guy et al. [1975], but a lower threshold was reported by Seaman and Lebovitz [1989]. At higher frequencies between 8670 and 9160 MHz, Guy et al. [1975] found that the threshold values of power density and of energy density per pulse were an order of magnitude higher than those at 918 and 2450 MHz (Table 2), but it is noted that no auditory response was obtained at the two higher frequencies unless the brain was exposed by removing part of the skull.

By measuring acoustic pressure waves with a miniature hydrophone transducer implanted in the brains of rats, cats, and guinea pigs exposed to pulses of RF energy, Olsen and Lin [1983] confirmed earlier theoretical predictions of pressure waves in the head. In later work, Lin et al. [1988] observed that the speed of RF induced pressure waves in the cat brain was similar to that of conventional acoustic wave propagation. These results support the thermoelastic expansion theory.

The hypothesis of Foster and Finch [1974] predicts that the RF hearing effect is related to thermoelastically induced mechanical vibrations in the head. Vibrations of this type can be produced by other means, such as by a laser pulse or by a pulsed piezoelectric crystal in contact with the skull which also induced cochlear microphonics in guinea pigs [Chou et al., 1976]. Frey and Coren [1979] used a holographic technique to test whether the skull and the tissues of the head of an animal have the predicted vibrations when exposed to a pulsed RF field. No displacements were recorded, but a subsequent analysis by Chou et al. [1980] demonstrated that the holographic technique used by Frey and Coren [1979] did not have the sensitivity to detect the small displacements related to vibrations from microwave-induced thermoelastic expansion in biological tissues.

Wilson et al. [1980] described an autoradiographic technique in which [^{14}C]2-deoxy-D-glucose was used to map auditory activity in the brain of rats exposed to acoustic stimuli and to pulsed and continuous wave fields. With this technique, in vivo determination of metabolic activity, i.e., glucose utilization and associated functional activity in the brain, can be visualized. Prior to exposure to the acoustic stimuli or to microwaves, one middle ear was ablated to block detection of sound waves in one side of the head. The expected bilateral asymmetry of radioactive tracer uptake in the auditory system of rats exposed to acoustic clicks or weak background noise was demonstrated. In contrast, a symmetrical uptake of tracer was found in the brain of animals exposed to RF pulses. These autoradiographic results support the findings that RF hearing does not involve the middle ear in humans [Frey, 1961] and guinea pigs [Chou and Galambos, 1979]. Unexpectedly, Wilson et al. [1980] found increased radioactive tracer uptake in the auditory system of rats exposed to continuous wave fields but, in a later report, this RF effect was attributed to intracochlear heating [Wilson and Joines, 1985]. The results with a continuous wave field have not been independently replicated and there are no known reports of continuous wave signals causing RF induced sound in humans or RF induced auditory responses in experimental animals.

In summary, evidence from human, laboratory animal, and modeling studies supports the thermoelastic expansion theory as the mechanism for the RF hearing phenomenon. The evidence includes measurements of acoustic transients in water, KCl solution having electrical properties similar to that in cells, and tissues [Foster and Finch, 1974] as well as in muscle-simulating materials [Olsen and Hammer, 1980]; the relationship of the threshold value to pulse duration [Frey and Messenger, 1973; Foster and Finch, 1974; Chou and Guy, 1979]; the characteristics of the RF induced cochear microphonics in laboratory animals [Chou et al., 1975, 1977] and calculations of the fundamental frequencies in the human head [Chou et al., 1977; Lin, 1978] that correlate well with the perception of high frequency sounds in the kHz range above about 5 kHz.

SIGNIFICANCE OF RF HEARING

The potential for human exposure to pulsed fields that could induce RF hearing raises two questions with regard to the significance of the effect. One, what is the psychological impact of RF sounds? Two, aside from the perception of sounds, what is the physiological significance of exposure to pulsed RF energy at intensities at and above the threshold for hearing?

The hearing of RF sounds at threshold exposure levels is considered to be a biological effect without a health effect and, therefore, is not an adverse effect[1].

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[1] An adverse effect is a biological effect characterized by a harmful change in health. For example, such changes can include organic disease, impaired mental function, behavioral dysfunction, reduced longevity, and defective or deficient reproduction. Adverse effects do not include: (1) Biological effects without a health effect. (2) Changes in subjective feelings of well being that are a result of anxiety about RF effects or impacts of RF infrastructure that are not related to RF emissions. (3) Indirect effects caused by electromagnetic interference with electronic devices. These indirect effects are covered by other standards. (This definition was adopted by the IEEE ICES SCC28/SC4 Revision Working Group.)

This conclusion is based on the following points. The sounds associated with RF hearing are not unusual but are similar to other common sounds such as a click, buzz, hiss, knock, or chirp (see Table 1). Furthermore, RF induced sounds can be characterized as low intensity sounds because, in general, a quiet environment is required for the sounds to be heard. It is noteworthy that most of the human subjects in the studies listed in Table 1 used earplugs to create conditions sufficiently quiet to hear RF sounds. The apparent location of the sounds, however, may vary from within, behind, or above the head.

Under some exposure situations that may lead to prolonged periods of RF sounds, the sounds might become an annoyance, but current knowledge of the effective exposure conditions (see Table 1) is sufficient to develop measures to eliminate RF sounds determined to be annoying. One solution is to move farther away from the RF antenna. A review of the human studies in Table 1 reveals that most of the studies were done in laboratory settings in which the subjects were close to the RF antenna. In three of the four field studies, the distance of the subjects from the radar ranged from about six feet up to several hundred feet. Such close proximity was needed to achieve the effective, moderately high, peak power intensities ranging from 90 to 50 000 mW/cm^2 (see Table 1). This information on distance and effective exposure levels indicates that anyone reporting RF hearing would be relatively close to a pulsed source operating in the 2.4–10 000 MHz range (Table 1). If it is not possible to increase the distance from the source, remediation measures could include metal shielding and changes in the operating procedure of the RF device.

Aside from the perception of sound, it is important to address the physiological significance of exposure to RF pulses at and above the threshold for hearing. One approach is to compare the magnitude of the pressure of the RF induced acoustic wave in the head to pressures from other sources. The peak power levels and the duration of RF pulses used for MRI of the human head can meet the requirements for RF induced sounds [Röschmann, 1991]. RF transmitter power levels up to 15 kW, if applied to the head with an MRI coil, would cause an RF induced sound pressure about 100 times the threshold for RF hearing. According to Röschmann [1991], a discomfort level of RF evoked transients in the head is avoided if the peak power of RF pulses (>100 μs) applied to the head coils is limited to about 30 kW (6 kW for surface coils); this limit is based on the discomfort threshold [110 dB sound pressure level (SPL)] for external sound stimuli. Hazardous thresholds of external sound stimuli for pain (140 dB SPL) and for damage to the auditory system (150–160 dB SPL) would be several orders of magnitude greater than the 110 dB SPL that is likely to be evoked by 30 kW RF pulses. Röschmann [1991] stated that there was no evidence known for detrimental health effects from RF induced sounds caused by MRI at peak power levels up to 15 kW, a power level available at the time his paper was written.

Based on calculated pressures resulting from the absorbed energy of 915 MHz pulses in human head models, Watanabe et al. [2000] found the RF induced pressure at the hearing threshold to be only 0.18 Pa or more than 42 000 times lower than the ultrasound-induced pressure of 7700 Pa at the lower value (2 mW/cm^2) of the range of diagnostic ultrasound exposure. The limit for fetal imaging is 720 mW/cm^2 [FDA, 1997], thus the pressure allowed for medical imaging of the developing human fetus is more than 15×10^6 times greater than the RF hearing threshold. Another comparison with a very different physical force shows that the pressure at the RF hearing threshold is about 1 000 000 times lower than the pressures at the surface of the brain that produce changes in the EEG and moderate brain damage (1.5×10^5 and 3×10^5 Pa, respectively), based on studies of traumatic head injury (see Raslear et al., 1993, p. 476). When compared to pressures exerted by acoustic energy at the hazardous threshold, medical ultrasound exposure and traumatic injury, it is highly unlikely that the RF hearing effect at the threshold level is hazardous with regard to the strength of the pressure waves, the dominant force in comparison to electrostrictive force and radiation pressure [Guy et al., 1975; Lin, 1976b; Gandhi and Riazi, 1986]. Furthermore, this comparison suggests that RF induced pressures would have to be many orders of magnitude greater than the pressure at the hearing threshold to cause adverse effects. This conclusion is supported by the following discussion.

Very high intensity RF pulses will induce adverse effects such as convulsions and a state of unconsciousness (stun effect), as demonstrated by Guy and Chou [1982]. These authors determined the threshold for these effects in rats exposed to a single, high intensity, 915 MHz pulse that caused an elevation in brain temperature of 8 °C, resulting in petit or grand mal seizures lasting for 1 min after exposure, followed by a 4–5 min unconscious state. The brain temperature returned to normal within 5 min after exposure, and the animals began moving when the brain temperature returned to within 1 °C of normal. Limited histopathological examination of four exposed rats revealed significant changes, including neuronal demyelination at one day after exposure, and brain swelling at 1 month after exposure. The threshold for the stun effect was 680 J, regardless of peak power and pulse width, or about

28 kJ/kg, expressed in terms of peak specific absorption. The stun threshold, a clearly adverse effect, is about 100 000× higher than the thresholds for auditory responses in rats (5–180 mJ/kg) and humans (16 mJ/kg) [Guy et al., 1975].

Although the field was not pulsed and RF induced sounds would not occur, a recent report [Marino et al., 2000] is included because it addresses potentially functional effects in the auditory system of exposed animals, i.e., changes in the otoacoustic emissions from the cochlea may serve as an indicator of outer hair cell subclinical or clinical pathology. In this report, no effect was found on otoacoustic emissions of RF exposed rats at average SARs in the head of 0.2 (950 MHz) and 1 W/kg (936 and 950 MHz).

CONCLUSIONS

The human auditory response to pulses of RF energy, commonly called RF hearing, is a well established phenomenon and the RF induced sounds are similar to other common sounds, such as a click, buzz, hiss, knock, or chirp. Furthermore, the RF induced sounds can be characterized as low intensity sounds because, in general, a quiet environment is required for the sounds to be heard.

The site of conversion of RF energy to acoustic energy is within or peripheral to the cochlea, and once the cochlea is stimulated, the detection of RF induced sounds in humans and RF induced auditory responses in animals is similar to acoustic sound detection. To hear the sounds, humans must be capable of hearing high frequency acoustic waves in the kHz range above about 5 kHz and the exposure to pulsed RF fields must be in the MHz range (2.4–10 000 MHz, see Table 1).

The hearing phenomenon depends on the energy in a single pulse and not on average power density. Guy et al. [1975] found that the threshold for RF induced hearing of pulsed 2450 MHz radiation was related to an energy density of 40 $\mu J/cm^2$ per pulse, or energy absorption per pulse of 16 μJ/g.

The weight-of-evidence of the results of human, animal, and modeling studies supports the thermoelastic expansion theory as the explanation for the RF hearing phenomenon. The theory describes how audible sounds are produced by rapid thermal expansion, resulting from a calculated temperature rise of only 5×10^{-6} °C in tissue at the threshold of hearing due to absorption of the energy in the RF pulse. Theory and experimental data from human beings and animals are in general agreement with the dependence on pulse width of perceived sound loudness in humans and auditory induced responses in animals. No published reports support the suggestion by Tyazhelov et al. [1979] that the theory does not explain all characteristics of RF hearing, and the experimental weight of evidence does not support direct stimulation of the central nervous system by RF pulses.

Based on this review, the perception of RF induced sounds by human beings is not considered an adverse effect. A comparison with pressure at the hazardous acoustic threshold and ultrasound pressures during medical diagnosis, including exposure of the fetus, suggests that RF induced pressures more than about five orders of magnitude greater than the pressure at the human hearing threshold would be unlikely to cause adverse biological effects. Based on this comparison, the exposure limit for a single RF pulse of 576 J/kg (spatial peak) in the IEEE C95.1 standard [IEEE, 1999], although 36 000 times greater than the threshold for RF hearing in humans, is below potentially adverse effects levels.

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