HUMAN AUDITORY PERCEPTION OF PULSED RADIOFREQUENCY ENERGY

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ABSTRACT

Human auditory perception of pulses of radiofrequency (RF) energy is a well-established phenomenon that is dependent upon the energy in a single pulse and not on average power density. RF-induced sounds can be characterized as the perception of subtle sounds because, in general, a quiet environment is required for the sounds to be heard. The sound is similar to other common sounds such as a click, buzz, hiss, knock or chirp. Effective radiofrequencies range from 216 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. The fundamental frequency of RF-induced sounds is independent of the radiofrequency but dependent upon head dimensions. The detection of RF-induced sounds is similar to acoustic sound detection once the cochlea is stimulated; however, the site of conversion of RF energy to acoustic energy is peripheral to the cochlea. The thermoelastic expansion theory explains 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 only a 5×10^{-6} ^{o}C temperature rise in tissue at the threshold level due to absorption of the energy in the RF pulse. The experimental weigh-of-evidence excludes direct stimulation of the central nervous system by RF pulses. The perception of RF-induced sounds near the threshold exposure level is considered to be a biological effect without an accompanying health effect. This conclusion is supported by a comparison of pressures induced in the body by RF pulses and by clinical ultrasound procedures.

Key Words: RF hearing, microwave, thermoelastic

INTRODUCTION

In their review article on the radiofrequency (RF) hearing phenomenon, Chou et al. (1982) wrote:

> "The earliest report we have found on the auditory perception of pulsed microwaves appeared in 1956 as an advertisement of the Airborne Instruments Laboratory in Vol. 44 of the *Proceedings of the IRE.* The advertisement described observations made in 1947 on the hearing of sounds that occurred at the repetition rate of a radar while the listener stood close to a horn antenna. When the observers first told their coworkers in the Laboratory of their hearing experiences, they encountered skepticism and rather pointed questions about their mental health."

The skepticism surrounding early reports of RF hearing, such as the one quoted above, was based on our understanding of human hearing. The ear was known to be exquisitely sensitive to pressure waves and, at that time, 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 this phenomenon by Frey (1961) did not appear until many years after the development of radar in the early 1940's. Frey described the perception of transient buzzing sounds by human subjects exposed to RF radiation from a rotating radar antenna. 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 small piece of metal screen (5 x 5 cm) over this area completely stopped the sound (Frey, 1962). The subjects in Frey (1961) reported an increase in the RF 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 sound was described as being in the area of the ear on the side opposite to the one that was irradiated. All subjects experienced a buzzing sensation 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 by two of the study investigators in 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 from Russian scientists described the perception of pulsed RF signals as polytonal sounds and tinnitus (Tyazhelov et al., 1979; Khizhnyak et al., 1980).

These studies show that human perception of pulsed RF radiation, resulting in sounds that vary with modulation of the signal, is a well-established phenomenon. The following sections describe the effective radiation 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. Additional information is available in reviews by Chou et al. (1982); Elder (1984); Lin (1978, 1989, 1990, 2001); Postow and Swicord (1996) and Stewart (2000).

EFFECTIVE RF RADIATION PARAMETERS

A summary of RF radiation 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 216 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 lowest effective frequency reported in the literature, the average power density threshold was 4 mW/cm^2 and the peak power density was 670 mW/cm^2 (Frey, 1963). The lowest threshold value expressed in units of average incident power density is 0.001 mW/cm^2 (Cain and Rissmann, 1978). This low value was due to the slow PRR of only 0.5/s (Table 1) because, for a given peak power, average power density depends on the pulse repetition rate. 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 radiation 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 10^{-6} ^{o}C.

A review of the table 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 the 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 laboratory and outdoor environments masked the perception 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 40 to 28 μJ/cm^2. The threshold for a subject with a hearing deficit was much higher, approximately 135 μJ/cm^2.

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 perceiving the RF 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 sound at approximately the same power density that induced threshold perception in subjects with normal hearing. In a later study, humans were shown to match 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 to 8000 Hz and for bone conduction to 4000 Hz, Cain and Rissmann (1978) measured the hearing ability of eight subjects over the frequency range of 1 to 20 kHz. They found that although there was no apparent correlation between the ability to perceive 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 sounds under conditions in which the other subjects could perceive RF sounds. The studies by Frey (1961), Frey and Eichert (1985) and Cain and Rissmann (1978) show RF hearing to depend on high-frequency hearing in the range of about 5 to 8 kHz and bone-conduction hearing at lower acoustic frequencies. Calculated values of fundamental frequencies of RF sound in the human head based on animal data or models are somewhat similar, e.g., 7-10 kHz (Chou et al., 1977), 13 kHz (Lin 1977) and 7-9 kHz (Watanabe et al., 2000); the results of these three studies are described in more detail below.

SIMILARITY OF AUDITORY RESPONSE TO MICROWAVE AND CONVENTIONAL ACOUSTIC STIMULI

The auditory pathway by which acoustic waves detected by the ear become interpreted as sound in the brain is known in some detail 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.

In 1962, Frey 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 theory 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. In 1975, Chou et al. 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. The demonstration that RF sounds are perceived by the normal auditory system via the cochlea provided evidence against the proposal that RF pulses directly simulated the central 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 peripheral to the cochlea.

In cats with an undamaged cochlea, 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) reached the same conclusion based on the similar response of single auditory neurons in the cat to pulsed 915-MHz fields and acoustic clicks. The detection of these electric potentials in auditory neurons was expected based on the results of studies that demonstrated subjective auditory perception (Frey, 1962), auditory evoked potentials (Taylor and Ashleman, 1974), and cochlear microphonics (Chou et al., 1975).

It is known that acoustic stimuli can cause evoked potentials, called “cross-modal” responses, in central nervous system sites outside the auditory pathway. Similar “cross-modal” responses due to the auditory response to RF pulses were recorded by Guy et al. (1975). This finding indicated 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- to 15,000-Hz bandwidth) increased from 60 to 80 dB, there was only a negligible increase in the threshold for microwave stimuli, a moderate increase in the threshold for a piezoelectric bone-conduction source, 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 interacted with the high-frequency portion of the auditory system.

Additional support for the dependence of RF hearing on high-frequency 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, 1977). 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 RF radiation. The calculations of Lin 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 frequency 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. These calculations provide further evidence that a necessary condition for auditory perception by adult humans is the ability to hear sound waves at frequencies above about 5 kHz (Frey, 1961; Rissmann and Cain, 1975).

The results of Lin (1977) appear to be 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.

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) the fundamental frequencies in the head are on the order of several hundred kilohertz, well above the maximum acoustic frequency of 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 peripheral to the cochlea, the fundamental frequency of RF sound is independent of the radiofrequency 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 sounds, one must be exposed to pulses of RF energy in the MHz range and be capable of hearing acoustic waves in the kHz range.

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 to a physiological 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, resulting from only a 5×10^{-6} °C temperature rise in the physiological solution, due to absorption of the energy in the RF pulse. This conclusion led to their proposal that thermoelastic expansion is the mechanism for RF hearing. This mechanism is consistent with the following results.

1) RF pulses that would elicit sounds perceived by a human produced acoustic transients 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 thermoelastic properties of water.

3) The thermoelastic theory predicts that the maximal pressure in the medium is

4) 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} ^{o}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.

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 hearing sensation in the 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. The threshold dependence on pulse width reported by Chou and Guy (1979) is in agreement with the predictions of the thermoelastic mechanism. They showed 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.

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 widths greater than about 30 μs. 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. These observations on human perception of long pulses are consistent with the results of electrophysiological responses in cats, that is, long pulses of 250 to 300 μs led to a decrease in sensitivity of high-frequency auditory responses (Lebovitz and Seaman 1977). 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 a subsequent paper, Tyazhelov and colleagues suggested that the thermoelastic theory accounted for the low frequency, but not the high frequency, RF sounds (Khizhnyak et al., 1980); however, no other reports have been found that support their proposed model for high frequency RF sounds.

Other 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 the RF-induced auditory sensation in laboratory animals (Table 2). In cats exposed to pulses of 918- and 2450-MHz radiation, 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 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. (1975b) 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.

In guinea pigs, the threshold dependence on pulse width was found to be in agreement with the predictions of the thermoelastic expansion mechanism; that is, the threshold was related to the incident energy per pulse for short pulse widths (<30 μs) and was related to the peak power for longer pulses. At the shortest pulse width (10 μs), the threshold was about 6 μJ/g (Chou and Guy, 1979).

Chou et al. (1985) documented the dose response relationship of the auditory brainstem-evoked response (BER) in rats exposed to pulses of 2450 MHz fields in circularly polarized waveguides. The results were consistent with the thermal expansion theory because the same BER response was evoked when the incident energy density or absorbed energy density per pulse was the same, regardless of pulse width.

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 (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 paper by Chou et al. (1980) demonstrated that the holographic technique used by Frey and Coren (1979) did not have the sensitivity to detect 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 radiation. 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 pulsed radiation. These autoradiographic results confirmed the finding that RF hearing does not involve the middle ear (Frey, 1961; Chou and Galambos, 1979). Unexpectedly, Wilson et al. (1980) found similar patterns of radioactive tracer uptake in the auditory system of rats exposed to continuous wave radiation and to pulsed radiation. These results with a continuous wave field, however, have not been independently replicated and there are no known reports of continuous wave signals causing RF-induced sound in humans or experimental animals.

In summary, evidence from both human and laboratory animal studies indicates that thermoelastic expansion is the mechanism that explains the RF hearing phenomenon. The evidence includes measurements of acoustic transients in water, physiological (KCl) solution, 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 (Foster and Finch,1974; Frey and Messenger, 1973; 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 (Lin 1978; Chou et al., 1977) that correlate well with the perception of high frequency sounds in the kHz range.

SIGNIFICANCE OF RF HEARING

The potential for human exposure to pulsed fields that could induce RF hearing raises two questions in 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 radiation at intensities at and above the threshold for hearing?

The perception 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] 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 hearing can be characterized as the perception of subtle sounds because, in general, a quiet environment is required for the sounds to be heard. It was noted in this review 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 our knowledge of the effective exposure conditions is sufficient to develop measures to eliminate RF sounds determined to be annoying. One solution is to move farther away from the source. 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 a few feet from 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 90-50,000 mW/cm^2 (see Table 1). This information on distance and effective exposure levels indicates that anyone

[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 developed by the IEEE CES SCC28/SC4 Revision Working Group.)

reporting RF hearing would be relatively close to a pulsed source operating in the 216 –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 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. 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. This threshold value is more than 42,000X lower than ultrasound-induced pressure (7700 Pa, spatial peak temporal average) during medical diagnosis, which includes exposure of the fetus; the factor would be much greater if the comparison was to the higher spatial peak temporal power of the ultrasound pulses. Another comparison shows that the pressure at the RF hearing threshold is 1,000,000X lower than the pressures at the surface of the brain that produce changes in the EEG and moderate brain damage (1.5×10^5 Pa 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 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 (see Guy et al., 1975; Gandhi and Riazi, 1986). The comparison with ultrasound pressures suggests that RF-induced pressures would have to be several orders of magnitude greater than the pressure at the hearing threshold to cause adverse effects.

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 ^{o}C resulting in petit or grand mal seizures lasting for one minute after exposure, followed by a four-to-five-minute unconscious state. The brain temperature returned to normal within five minutes after exposure and the animals began moving when the brain temperature returned to within 1 ^{o}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 one 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 100,000X higher than the thresholds for auditory responses in rats (5-180 mJ/kg) and humans (16 mJ/kg) (Guy et al., 1975).

Small but significant changes in the otoacoustic emissions from the cochlea may serve as an indicator of outer hair cell subclinical or clinical pathology. A recently published paper found no functional changes in otoacoutic emissions of RF-exposed rats at average SARs in the head of 0.2 (950 MHz) and 1 W/kg (936 and 950 MHz) (Marino et al., 2000). Although the field was not pulsed and RF sounds would not occur, this report is important because it addresses potentially functional effects in the auditory system of exposed animals.

CONCLUSIONS

Human perception of pulses of RF radiation is a well-established phenomenon that is not an adverse effect. RF-induced sounds are similar to other common sounds such as a click, buzz, hiss, knock or chirp. Furthermore, the phenomenon can be characterized as the perception of subtle sounds because, in general, a quiet environment is required for the sounds to be heard.

The detection of RF-induced auditory sensations is similar to acoustic sound detection once the cochlea is stimulated; however, the site of conversion from RF to acoustic energy is peripheral to the cochlea. To hear the sounds, individuals must be capable of hearing high-frequency acoustic waves in the kHz range and the exposure to pulsed RF fields must be in the MHz range. The effective radiofrequencies reported in the literature range from 216 to 10,000 MHz.

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 $\mu J/g$.

The thermoelastic expansion theory explains the phenomenon, that is, audible sounds are produced by rapid thermal expansion, resulting from only a 5×10^{-6} ^{o}C temperature rise in tissue due to absorption of the energy in the RF pulse. The experimental weight-of-evidence does not support direct stimulation of the central nervous system by RF pulses. No published reports support the suggestion by Tyazhelov et al. (1979) that the theory does not explain all characteristics of RF hearing.

A comparison with routine 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 hearing threshold would be unlikely to cause significant biological effects.

REFERENCES

Airborne Instruments Laboratory. 1956. An Observation on the Detection by the Ear of Microwave Signals. Proceedings of the IRE 44:2A.

Cain, CA, Rissmann, WJ. 1978. Mammalian Auditory Responses to 3.0 GHz Microwave Pulses. IEEE Trans. Biomed. Eng., BME-25:288-293.

Chou, CK, Galambos, R, Guy, AW, Lovely, RH. 1975. Cochlear Microphonics Generated by Microwave Pulses. J. Microwave Power, 10:361-367.

Chou, CK, Guy, AW, Galambos, R. 1976. Microwave-Induced Auditory Response: Cochlear Microphonics. In: Biological Effects of Electromagnetic Waves, Vol. 1, C.C. Johnson and M.L. Shore, eds. HEW Publication (FDA) 77-8010, Rockville, Maryland. pp 89-103.

Chou, CK, Guy, AW, Galambos, R. 1977. Characteristics of Microwave-Induced Cochlear Microphonics. Radio Sci., 12(6):221-227.

Chou, CK, Guy, AW. 1979. Microwave-Induced Auditory Responses in Guinea Pigs: Relationship of Threshold and Microwave-Pulse Duration. Radio Sci., 14(6S):193-197.

Chou, CK, Galambos, R. 1979. Middle-Ear Structures Contribute Little to Auditory Perception of Microwaves. J. Microwave Power, 14:321-326.

Chou, CK, Guy, AW, Foster, KR Galambos, R, Justesen, DR. 1980. Holographic Assessment of Microwave Hearing. Science, 209:1143-1144.

Chou, CK, Guy, AW, Galambos, R. 1982 Auditory Perception of Radio-Frequency Electromagnetic Fields. J. Acoust. Soc. Am., 71(6):1321-1334.

Chou, CK, Yee, KC, Guy, AW. 1985. Auditory Response in Rats Exposed to 2,450 MHz Electromagnetic Fields in a Circularly Polarized Waveguide. Bioelectromagnetics, 6:323-326.

Constant, PC, Jr. 1967. Hearing EM Waves. Digest of the Seventh International Conference on Medical and Biological Engineering, B. Jacobson, ed. Department of Medical Engineering, Karolinska Institute, Stockholm, Sweden. P. 349.

Elder, JA 1984. Special Senses. In: Biological Effect of Radiofrequency Radiation, Elder, J.A., Cahill, D.R., editors. U.S. Environmental Protection Agency (EPA-600/8-83-026F), 1984, pp 5-64 – 5-78. (Available as Report No. PB 85-120-848 from National Technical Information Service, Springfield, VA.)

Foster, KR, Finch, ED. 1974. Microwave Hearing: Evidence for Thermoacoustic Auditory Stimulation by Pulsed Microwaves. Science, 185:256-258.

Frey, AH. 1961. Auditory System Response to Radio Frequency Energy. Aerospace Med., 32:1140-1142.

Frey, AH. 1962. Auditory System Response to Radio Frequency Energy. Aerospace Med., 32:1140-1142.

Frey, AH. 1963. Some Effects on Human Subjects of Ultra-High-Frequency Radiation. Am. J. Med. Electron. 2:28-31.

Frey, AH. 1967. Brain Stem Evoked Responses Associated with Low-Intensity Pulsed UHF Energy. J. Appl. Physiol., 23:984-988.

Frey, AH, Eichert, ES. 1985. Psychophysical Analysis of Microwave Sound Perception. J. Bioelectricity 4:1-14.

Frey, AH, Messenger, R. 1973. Human Perception of Illumination with Pulsed Ultrahigh-Frequency Electromagnetic Energy. Science, 181:356-358.

Frey, AW and Coren, E. 1979. Holographic Assessment of Hypothesized Microwave Hearing Mechanism. Science 206:232-234.

Gandhi, OP, Riazi, A. 1986. Absorption of Millimeter Waves by Human Beings and Its Biological Implications. IEEE Transactions on Microwave Theory and Techniques MTT-34: 228-235.

Gournay, LS. 1966. Conversion of Electromagnetic to Acoustic Energy by Surface Heating. J. Acous. Soc. Amer. 40:1322-1330.

Guy, AW, Chou, CK. 1982. Effects of High-Intensity Microwave Pulse Exposure of Rat Brain. Radio Science 17(5S):169S-178S.

Guy, AW, Chou, CK, Lin JC, Christensen D. 1975. Microwave-Induced Acoustic Effects in Mammalian Auditory Systems and Physical Materials. Ann. N.Y. Acad. Sci. 247:194-215.

Ingalls, CE. 1967. Sensation of Hearing in Electromagnetic Fields. NY State J. Medicine 67:2992-2997.

Khizhnyak, EP, Shorokhov VV, Tyazhelov, VV. 1980. Two Types pf Microwave Auditory Sensation and Their Possible Mechanism. In: Proceedings of the URSI Symposium, Ondes Electromagnetiques et Biologie (Electromagnetic Waves and Biology), A. Berteaud and B. Servantie, editors, Jouy en Josas, pp. 101-103.

Lebovitz, RM, Seaman, RL. 1977a. Microwave Hearing: The Response of Single Auditory Neurons in the Cat to Pulsed Microwave Radiation. Radio Sci., 12(6S) 229-236.

Lebovitz, RM, Seaman RL. 1977b. Single Auditory Unit Responses to Weak, Pulsed Microwave Radiation. Brain Research 126:370-375.

Lin, JC. 1977. Theoretical Calculation of Frequencies and Thresholds of Microwave-Induced Auditory Signals. Radio Sci. 12(6S):237-242.

Lin, JC. 1978. Microwave Auditory Effects and Applications. Charles C. Thomas, Springfield, Illinois, 221 pages.

Lin, JC. 1989. Pulsed Radiofrequency Field Effects in Biological Tissues. In Electromagnetic interaction with Biological Systems, J.C. Lin, editor, Plenum Press, NY, pp 165-177.

Lin, JC. 1990. Auditory Perception of Pulsed Microwave Radiation. In Biological Effects and Medical Applications of Electromagnetic Energy, O.P. Gandhi, editor, Prentice Hall, Englewood Cliffs, NJ, Chapter 12, pp 275-318.

Lin, JC. 2001. Hearing Microwaves: The Microwave Auditory Phenomenon. IEEE Antennas and Propagation Magazine,43:166-168.

Lin, JC, Su, JL, Wang, Y. 1988. Microwave-Induced Thermoelastic Pressure Wave Propagation in the Cat Brain. Bioelectromagnetics 9:141-147.

Marino, C, Cristalli, G, Galloni, P, Pasqualetti, P, Piscitelli, M, Lovisolo, GA. 2000. Effects of Microwaves (900 MHz) on the Cochlear Receptor: Exposure Systems and Preliminary Results. Radiation and Environmental Biophysics 39:131-136.

Olsen, RG, Hammer WC. 1980. Microwave-Induced Pressure Waves in a Model of Muscle Tissue. Bioelectromagnetics 1:45-54.

Olsen, RG, Lin, JC. 1983. Microwave-Induced Pressure Waves in Mammalian Brains. IEEE Transactions on Biomedical Engineering BME-30:289-294.

Postow, E, Swicord, ML. 1996. Modulated Fields and “Window” Effects. In Handbook of Biological Effects of Electromagnetic Fields, C. Polk and E. Postow, editors, CRC Press, Boca Raton, FL, pp 542-545.

Raslear, TG, Akyel, Y, Bates, F, Belt, M, Lu, ST. 1993. Temporal Bisection in Rats: The Effects of High-Peak-Power Pulsed Microwave Irradiation. Bioelectromagnetics 14:459-478.

Rissmann, WJ, Cain, CA. 1975. Microwave Hearing in Mammals. Proc. Natl. Elec. Cong., 30:239-244.

Seaman, RL, Lebovitz RM. 1989. Thresholds of Cat Cochlear Nucleus Neurons to Microwave Pulses. Bioelectromagnetics 10:147-160.

Sommer, HC, von Gierke, HE. 1964. Hearing Sensations in Electric Fields. Aerospace Med., 35:834-839.

Taylor, EM, Ashleman, BT. 1974. Analysis of Central Nervous System Involvement in the Microwave Auditory Effect. Brain Res. 74:201-208.

Tyazhelov, VV, Tigranian, RE, Khizhniak, EO, Akoev, IG. 1979. Some Peculiarities of Auditory Sensations Evoked by Pulsed Microwave Fields. Radio Sci., 14(6S):259-263.

Watanabe, Y, Tanaka, T, Taki, M, Watanabe, S. 2000. FDTD Analysis of Microwave Hearing Effect. IEEE Transactions on Microwave Theory and Techniques, 49:2126-2132.

Wilson, BS, Zook, JM, Joines, WT, Casseday JH. 1980. Alterations in Activity at Auditory Nuclei of the Rat Induced by Exposure to Microwave Radiation: Autoradiographic Evidence Using [^{14}C]2-Deoxy-D-Glucose. Brain Res., 187:291-306.

White, RM. 1963. Generation of Elastic Waves by Transient Surface Heating. J. Applied Physics, 34:3559-3567.

Table 1. Summary of Human Studies Describing Auditory Effects of Pulsed RF Radiation

Effect	Comment	Number of Subjects	Exposure Conditions: Frequency (MHz)	Pulse Repetition Rate (s^{-1})	Pulse Width (us)	Peak Power Density (mW/cm^2)	Av. 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	1,300	600	2	(peak power ~0.5 MW)				Airborne Instruments Lab (1956)
RF hearing: "distinct" clicks	Threshold Values	8	3,000	0.5	5 10 15	2500 225-2,000 300-1,000	0.006 0.001-0.01 0.002-0.007	12.5 2.3-20.0 4.5-15.0	45 (+plastic foam earmuffs)	Cain and Rissmann (1978); Rissmann and Cain (1975)
RF hearing: buzz heard at PRR>100; individual pulses heard at PRR<100		3	3,000 6,500	<100-1,000 <100-1,000	1-2 1-2	2,500-50,000 2,500-50,000	5 5	40		Constant (1967)
No auditory response			3,000 6,500	<100-1,000 <100-1,000	0.5 0.5	10,000-100,000 10,000-100,000	5 5			
No auditory Response			9,500	<100-1,000	0.5-2	2,500-100,000	5			
RF hearing: "buzz, clicking, hiss, or knocking"	Threshold values	Not given	216 425 425 425 425	- 27 27 27 27	- 125 250 500 1,000	670 263 271 229 254	4.0 1.0 1.9 3.2 7.1		70-90 (+ear stopples)	Frey (1962,1963)
No auditory Response			8,900	400	2.5	25,000	25		70-90 (+ear stopples)	Frey (1962)
RF hearing: Matched RF sound to 4.8 kHz acoustic sounds	Subjects were trained musicians	3	1,200		12.5-50		<0.5			Frey and Eichert (1985)
RF hearing: "buzzing sound"		4	1,245 1,245	50 50	10 70	370 90	0.19 0.32			Frey and Messenger (1973)
RF hearing: "clicks, chirps"	Threshold values	2	2,450	3	1-32	1,250-40,000	0.1	40*	45	Guy *et al.* (1975)
RF hearing: Buzz	Threshold values (not at 10 GHz)	Not given	1,310 2,982 10,000	244 400 -	6 1 -	(12 v/cm) (18 v/cm)	0.3 0.18 -			Ingalls (1967)
RF hearing: "tinitus"		Not given	-	100-20,000	10-160	-	-			Khizhnyak et al. (1980)
RF hearing: polytonal sound		18	800	1,000-1,200	10-30	>500	-	-	40 (+ear stopples)	Tyazhelov *et al.* (1979)

*Calculated peak-absorbed-energy density per pulse is 16 mJ/kg.

Table 2. Summary of Studies Concerning Threshold Values for Auditory-Evoked Potentials in Animals

		Exposure Conditions							
Effect	Species (n)	Frequency (MHz)	Repetition Rate (s^{-1})	Pulse Width (μs)	Peak Power Density (mW/cm^2)	Av. Power Density (mW/cm^2)	Energy Density Per Pulse ($\mu J/cm^2$)	Peak Absorbed Energy y Density Per (μJ/g)	Reference
Response obtained with scalp electrodes	Cat (2) [also dog and chinchill a]	3000	0.5	5 10 15	2,200, 2,800 1,300 580		11, 14 13 8.7		Cain and Rissmann (1978); Rissmann and Cain (1975)
Response obtained from round window with carbon lead	Guinea pig (5)	918	100	1-10	*	*		20	Chou *et al.* 1975)
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)
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 8,670-9,160	1 1 1	3-32 0.5-32 32	800-5,800 600-35,6000 14,800-38,800	0.017-0.028 0.015-0.047 0.472-1.24	17.4-28.3 15.2-47.0 472-1,240	12-3-20.0 8.7-26.7	Guy *et al.* (1975)
Response obtained from individual auditory neurons with glass electrode	Cat (n not given)	915	<10	25-250	-	1.0	-	4-40	Lebovitz and Seaman (1977)
Neuronal action potentials in cochlea	Cat	915		20-700				0.6	Seaman and Lebovitz (1989)

*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 10 times higher than for free-field exposure (See Chou et al. 1975, p. 362).