Auditory perception of radio-frequency electromagnetic fields

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Absorption of pulsed microwave energy can produce an auditory sensation in human beings with normal hearing. The phenomenon manifests itself as a clicking, buzzing, or hissing sound depending on the modulatory characteristics of the microwaves. While the energy absorbed (~ 10 μJ/g) and the resulting increment of temperature ($\sim 10^{-6}$ °C) per pulse at the threshold of perception are small, most investigators of the phenomenon believe that it is caused by thermoelastic expansion. That is, one hears sound because a miniscule wave of pressure is set up within the head and is detected at the cochlea when the absorbed microwave pulse is converted to thermal energy. In this paper, we review literature that describes psychological, behavioral, and physiological observations as well as physical measurements pertinent to the microwave-hearing phenomenon.

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INTRODUCTION

Pulsed microwaves have been heard as sound by radar operators since radar was invented during World War II. Because the auditory system normally responds only to sound (pressure) waves within the range of audio frequencies, it was difficult to explain how radar operators could hear radar pulses, since the stimulus is an electromagnetic wave and the frequency of the waves ranges upward from hundreds of megahertz.

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. Later, Frey (1961, 1962, 1963) authored a series of papers in which he described the hearing phenomenon. Frey (1961) initiated research by selecting a number of persons who had sensed the phenomenon. He interviewed them and exposed them under controlled conditions to microwave pulses. The sensations perceived by the subjects were reported as buzzing or knocking sounds, depending on the pulse characteristics. Perception was not associated with detection by fillings in the teeth or by an electrophonic effect (Flottorp, 1976).

The mechanism of "radio-frequency" (rf) hearing remained obscure for more than a decade. Frey (1962, 1971) suggested that direct stimulation of the nervous tissue might be responsible. During the last decade, numerous studies using psychological, physiological, behavioral, physical, and theoretical approaches have revealed what most investigators now believe is the mechanism of rf hearing: thermoelastic expansion, first proposed by Foster and Finch (1974).

The radio frequencies are broadly defined as the frequencies extending from 30 Hz to 3000 GHz and the microwave frequencies are between 300 MHz–300 GHz (Reference Data for Radio Engineers, 1972). Because of the conduction and dielectric losses in tissues, radio-frequency electromagnetic fields propagate differently in biological media than in free space. Reflection, scattering, and absorption occur in the body. The absorption of electromagnetic energy in tissues depends on many factors, such as the dielectric properties and geometry and size, and orientation of the tissue, as well as frequency, source geometry of the applied electromagnetic field (Johnson and Guy, 1972). At very low-frequency range (<1 MHz), a human-size biological object absorbs very little radio-frequency energy; however, the absorption can be appreciable at the resonant frequency near 70–80 MHz (where the long dimension of the body is approximately 0.4 wavelengths) (Durney *et al.*, 1978). For a human head, the resonant frequency is near 600 MHz. At frequencies above 10 GHz and toward optical frequency range, the energy absorption occurs more at a superficial level. Although there is a universal agreement on the thermal effects of the high-level (>100 mW/cm^2) radio-frequency electromagnetic radiation, there is considerable debate on the biological effects of low-level (<1 mW/cm^2) electromagnetic radiation. The phenomenon of hearing the pulsed microwaves was considered to be a nonthermal effect because of the low-threshold energy level. More recent data have provided ample evidence that the effect is still thermal in nature.

In 1963, White demonstrated that a thermoelastic pressure wave was generated in water exposed to pulsed

9-GHz microwave fields. The microwave energy was absorbed by water and converted into thermal energy, which caused the water to expand in accord with its thermoelastic properties. Thermal expansion in the surface-heated (i.e., nonuniformly heated) volume produced a wave of pressure. Gournay (1966) analyzed theoretically the conversion of a single pulse of electromagnetic energy to acoustic energy in liquids. Foster and Finch (1974) further measured microwave-induced acoustic transients in a saline solution, using a hydrophone. The amplitude of a thermoelastically launched pressure wave was shown to be in close agreement with that predicted by the analytical equations of thermoelastic expansion (White 1963; Gournay 1966). When tested in distilled water, the pressure wave inverted below 4°C and vanished at 4°C in agreement with the temperature dependence of the thermoelastic properties of water.

Although the literature on rf hearing is well read by investigators of biological effects of electromagnetic fields, it has been published principally in engineering journals and as proceedings of symposia. It is our purpose in this paper to review and summarize the research more or less chronologically on rf hearing, including that of psychological studies of human subjects, of physiological and behavioral observations on animals, and of physical measurements on materials. Theoretical studies have been well covered in numerous publications, including the text by Lin (1978).

I. PSYCHOLOGICAL STUDIES

In 1947, several members of the engineering staff of the Airborne Instruments Laboratory heard sounds at the repetition rate of a large ground-based radar when they were standing close to the radar's horn antenna (Airborne Instruments Laboratory, 1956). The radar was operating at 1.3 GHz and generated 2-μs pulses at 600 pulses per second (pps). The audible response was obtained to distances of 5 or 6 ft from the horn. Power densities of fields at the locations of rf hearing were not specified. The staff found that the most sensitive area on the head for auditory perception was the temporal area. Subsequent work on rf hearing by the same group did not resume until shortly before 1956. The observers found that the sounds seemed to have mostly high-frequency components and not very many fundamentals. They also found that two persons with a hearing deficiency in the region of 5 kHz had a much poorer response than did persons with normal hearing. Because of concern for potential biological hazards of intense microwave irradiation (especially as a cause of cataracts), the work was discontinued.

In 1961, Frey published a technical note on the auditory-system response to rf energy. He used two transmitters, one operating at 1.31 and one at 2.98 GHz. The transmitters operated, respectively, at 224 pps, 6-μs pulse width, and 400 pps, 1-μs pulse width. The subjects, who wore earplugs and were located 100 ft from the transmitting antenna, perceived a buzzing sound when exposed to the beam of either transmitter. The sound was perceived as located a short distance behind their heads. The thresholds of average power density of fields at the head were determined to be 0.4 and 2 mW/cm^2, respectively, for the two transmitters.

Since average power is dependent on the pulse-repetition rate, and since the auditory system is responsive to individual pulses, the energy density per incident pulse is a more reliable quantity than the average power in predicting the threshold of rf hearing. We calculated that Frey's threshold energy densities were 1.6 and 5 μJ/cm^2 for the respective carrier frequencies. The quantity of energy imparted to the head is doubtless responsible, in part, for rf hearing. The quantity of energy coupled to the head varies with the carrier frequency of the electromagnetic field, with the orientation of the subject and the polarization of the fields, with the size and shape of the head, with the pulse duration, and with the exposure conditions. To compare threshold values of rf hearing from different laboratories, it is necessary to specify the energy absorbed per unit mass (J/g), which is designated *specific absorption* (SA) by the National Council on Radiation Protection and Measurements (1981). Unfortunately, SA data are not available in all earlier and in some recent reports.

In Frey's study, a subject with otosclerosis who had a 50-dB loss in air-conduction hearing but who had normal bone-conduction hearing could hear rf sound. Three subjects who could not hear rf sound had audiographically confirmed hearing losses above 5 kHz, which were similar to those reported earlier by the staff of the Airborne Instruments Laboratory. In a sound-matching experiment, Frey reported that it was difficult for subjects to match the rf sound to audio-frequency sine waves. The subjects perceived the best match of the rf-induced sound with high-frequency noise (above 5 kHz).

In subsequent papers, Frey (1962, 1963) reported an extended study of human subjects exposed to 216-, 425-, and 8900-MHz fields at various pulse widths. Depending on the parameters of pulsing, i.e., pulse width and repetition rate, the rf sound was perceived as a buzzing, ticking, hissing, or knocking sound that originated within or immediately behind the head. At 425 MHz, a pulse varying in width from 125 to 1000 μs was used. The threshold peak of power at that frequency was between 229–271 mW/cm^2. When the 8.9-GHz transmitter was used, no sound was perceived even at a peak of power density of 25 W/cm^2. From these data, Frey concluded that the threshold of rf hearing depends on the peak of power density, and that the penetration of rf energy into the head at various frequencies is a strongly controlling variable. Four possible intracranial sites or structures for the origin of rf hearing were discussed by Frey. The first involved the tympanic membrane and the oval window acting together as a capacitor. Frey ruled out this possibility since rotation of heads in the field did not change the loudness of the rf sound. The cochlea was mentioned, but there were no conclusive data to support it. Direct interaction of pulsed fields with cerebral neurons was also considered by Frey, who found that the most likely area for the detection of rf sounds was a region over the temporal lobe of the brain; rf sound disappeared when this area was shielded from

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the radiation, consistent with the results of the Airborne Instruments Laboratory. The final possibility considered by Frey was multiple detectors, which were not specified in the paper.

Frey's experiments were conducted in noisy environments (70–90 dB). For example, one was performed next to the New York State Thruway (Frey, 1963). Frey stated, "The numbers given for exposure parameters are conservative; they should not be considered precise, since the transmitters were never located in ideal laboratory environments" (1962). Ten years later, Frey and Messenger (1973) described new experimental studies of human perception of electromagnetic energy. The experiments were conducted in an rf anechoic chamber with a microwave source that operated at 1.25 GHz at a pulse-repetition rate of 50 pps. Four auditors were trained to perform loudness-magnitude estimations. Using the first rf sound as a reference, the subject had to assign an arbitrary number between 0 and 200 to the relative loudness of the second rf sound. Two warm-up trials were given before each session. For the same energy density of the incident field (6.3 $\mu J/cm^2$), the loudness declined for pulses of increasing width above 30 μs. For 10- to 30-μs pulses, the loudness appeared to be the same. Frey and Messenger interpreted the loudness to be a function of the peak of power density rather than a function of average power. They also concluded that a band of optimal pulse widths existed. They thought the 10-μs pulse was below the optimal width for loudness and presented an additional data point for 40-μs pulses, thinking these were within the optimal band, since loudness was greater. However, it should be noted that the energy density of the 40-μs pulse was 25.2 $\mu J/cm^2$—four times larger than that of any other data point. As discussed later, based on the hypothesis of thermoelastic expansion, pulses of 10 to 30 μs in width of the same energy density per pulse should produce the same magnitude of auditory response.

It is difficult for us to interpret Frey and Messenger's data. They indicated that "the precise data will require many more studies for definition because of the sensitivity of judgments of sensory magnitude to details of experimental procedure." In one additional test, Frey and Messenger varied the pulse-repetition rate while holding the pulse width constant. The subjects reported hearing sounds of definite pitch and timbre, but had difficulty judging loudness.

Sommer and von Gierke (1964) studied the hearing of alternating electrostatic fields of audio frequency in humans. Their threshold data indicate that the stimulation might be mechanical excitation by electrostatic force. They extended their calculation on radiation pressure to high-frequency electromagnetic waves and hypothesized that the hearing of modulated rf fields reported by Frey is due to radiation pressure. Frey (1971) disputed the hypothesis discussed by Sommer and von Gierke and pointed out mistakes in their calculations. However, Sommer and von Gierke (1964) did speculate that the stimulation of the cochlea through electromechanical forces by air or bone conduction was the most probable mechanism for the rf hearing and much more probable than direct neural stimulation.

In 1967, Ingalls reported results of an experiment in which he used the same type of transmitters used by Frey. The results were essentially the same as Frey's (1961–1963) except that Ingalls reported that the rf sound was perceived to be above or at the very top of the head. When an observer placed his fingers in his ears to reduce ambient noise, the microwave source seemed to move to the top of the head. In searching for the mechanism, Ingalls indicated that it was very difficult to conduct electrophysiological experiments during microwave exposure because of electromagnetic interference with measuring instruments. He also disputed the radiation-pressure hypothesis of Sommer and von Gierke because of the low amplitude of the radiation pressure, the location of rf-sensitive area not being in the region of the ear, the high-frequency nature of the rf sound, and the independence of head orientation in the rf field. Ingalls favored the hypothesis of direct involvement of the nervous system but acknowledged the need for more work in determining mechanisms.

Experiments on the hearing of rf sound by human beings were also conducted by Guy et al. (1975). In these studies, the microwave source was a 2450-MHz pulse generator capable of producing 10-kW peak power pulses of 0.5 to 32 μs in width. The threshold energy per pulse to produce an auditory response at various pulse widths was determined for two observers. Table I gives the results for an observer with normal hearing as confirmed by audiograms. The results show that regardless of the peak power and pulse width, the threshold was related to an energy density of 40 $\mu J/cm^2$ per pulse, or a peak of specific absorption (SA) of 16 $\mu J/g$ per pulse, as calculated on the basis of a spherical model (Johnson and Guy, 1972). A peak elevation of temperature in the head of 5×10^{-6}°C was calculated to occur with each threshold pulse. As indicated in the footnote to Table I, when earplugs were placed in the auditor, the threshold energy density declined from 35 to 28 $\mu J/cm^2$, and the threshold energy level of the second subject, who had a 55-dB hearing loss near 3500 Hz, was about 135 $\mu J/cm^2$. At a very low repetition rate (3 pps), each individual pulse could be heard as a distinct click, and short trains of pulses could be heard as tonal chirps that corresponded to the pulse-recurrence rate. The threshold for a single pulse was the same as that for two pulses several hundreds of microseconds apart that deposited the same total quantity of energy.

Cain and Rissmann (1978) determined the threshold of energy for 5- to 15-μs pulses delivered to each of eight observers by a 3-GHz field pulsed at 0.5 pps. Five of the subjects heard the clicks, with the same characteristics as reported by Frey (1961) and by Guy et al. (1975). The energy-density thresholds varied from 3.4 to 17.5 $\mu J/cm^2$ depending on the particular subject. In most cases, the threshold was independent of pulse width, in agreement with the data of Guy et al. (1975). The three subjects who were unable to hear the pulses had hearing losses above 8 kHz.

Tyazhelov et al. (1979) have also performed psychological tests of human auditors, exposed to 800-MHz

TABLE I. Threshold energy of microwave-evoked auditory responses in human subjects (2450 MHz, 3 pps, background noise 45 dB) [adapted from Guy et al. (1975)].

Peak of power density (W/cm^2)	Average power density (μW/cm^2)	Pulse width (μs)	Energy density per pulse (μJ/cm^2)	SA per pulse (μJ/g)
40	120	1	40	16
20	120	2	40	16
13.3	120	3	40	16
10	120	4	40	16
8	120	5	40	16
4	120	10	40	16
2.33	105	15	35[a]	14
2.15	129	20	43	17
1.8	135	25	45[b]	18
1.25	120	32	40	16

[a] 28 with earplugs.
[b] 135 for subject 2.

pulse-modulated microwaves. The pulses were 5 to 150 μs in duration and the repetition rates were 50 to 20 000 pps. The thresholds of two subjects (one with a high-frequency auditory limit, HFAL, of 14 kHz, the other with a HFAL of 17 kHz) are shown in Fig. 1. As the pulse-repetition rate was increased from 1000 to 12 000 pps, but at the same peak of power, the rf sound changed in polytonal character. At a given energy level, the loudness fell sharply as the repetition rate increased from 6000 to 8000 pps and then the loudness increased and appeared to reach a maximum at 10 to 11 kHz. Some subjects could not distinguish 5000-pps sound from that at 10 000 pps. Other subjects perceived the pitch associated with 5000 pps as *higher* than that associated with 10 000 pps. Subjects with a HFAL below 10 kHz could not hear rf pulses associated with 10- to 30-μs pulses.

Tyazhelov et al.'s (1979) data on thresholds of hearing as a function of pulse width are difficult for us to interpret. The loudness increased with pulse widths from 5 to 50 μs, diminished with further widening of the pulses from 70 to 100 μs, and then increased again with pulse widths greater than 120 μs. The reported use of 150-μs pulses at 8000 pps raises some questions, since a repetition rate of 8000 pps would limit the maximum width of pulses to 125 μs, corresponding to a cw field. When the pulse widths varied between 5 and 150 μs, sounds of lower and higher pitch were reported during exposures to 50- to 100-μs pulses. When pulse widths were near 100 μs, the subjects perceived a downward shift in pitch and the sound appeared to arise from a point behind the head. When the pulse width was less than 50 μs, the subjects always heard a high-pitched sound.

During the audio- and rf-sound matching experiments, a beat-frequency could also be heard by the observers of Tyazhelov et al. (1979). By adjusting the phase of the audio sound in opposition to that of the rf-induced sound a loss of sensation of the rf sound occurred. This cancellation could also be obtained by presenting audio sound at harmonic frequencies of the microwave pulse-repetition rate. The auditor's head was also exposed while partially or fully immersed in sea water, to change the acoustic resonant boundary conditions. Under these exposure conditions, the characteristics of all acoustic sensations remained the same for exposure pulses less than 50-μs wide but the loudness decreased proportional to the depth of immersion. This observation led Tyazhelov et al. (1979) to question the thermoelastic expansion hypothesis since the perceived sound quality was not altered by water immersion. We feel, however, that the results support the thermoelastic expansion model very well, since the skull can be considered as a constrained boundary that is not affected by water immersion. Tyazhelov et al. (1979) accept the hypothesis of thermoelastic expansion for microwave pulses of high peak power and short width (i.e., <50 μs) but question the applicability of the hypothesis to some of their observations that involve near-threshold pulses of low-power, long-duration, and high-repetition rate.

In summary, there is uniform agreement that human beings with normal high-frequency hearing can perceive an auditory sensation when exposed to microwave pulses of sufficient energy content. The rf sound may be perceived as clicks, buzzes, or hisses depending on the modulation characteristics of the microwaves. The perceived sound, at least for pulses ≤50 μs, seems to originate at the central, posterior aspect of the head. The threshold energy density per pulse for the auditory sen-
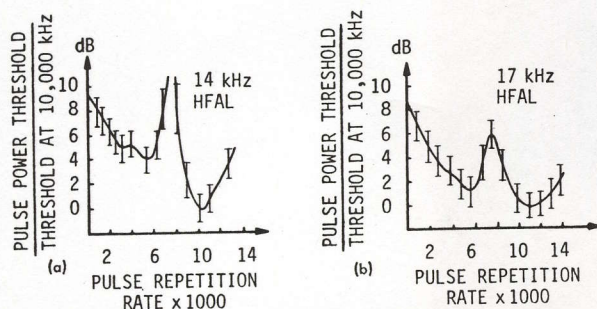

FIG. 1. Threshold of rf hearing as a function of pulse repetition rate for two human subjects. (a) High-frequency auditory limit (HFAL) of subject is 14 kHz, (b) HFAL is 17 kHz [from Tyazhelov et al. (1979)].

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sation is very low ($2-40$ $\mu J/cm^2$). The maximal rise in temperature of the exposed tissue is on the order of 10^{-5} to 10^{-6} °C for exposure of an individual pulse at the threshold of energy density.

II. PHYSIOLOGICAL RECORDINGS

Elucidation of the mechanism for the microwave-induced auditory responses has been attempted by the use of electrophysiological recordings in controlled experiments with laboratory animals. Data have been obtained from cochlear potentials recorded at the round window, from single-unit responses recorded at the eighth nerve, from evoked potentials recorded at various locations of the auditory pathway (eighth nerve to auditory cortex), and from surface potentials picked up by scalp electrodes.

A. Cochlear potentials

Frey (1967) used a coaxial metal electrode in the first attempts to record evoked responses from various nuclei of the brainstem. He found no cochlear microphonic responses to the rf pulses. The cochlear microphonic (CM) is the first of the series of physiological potentials initiated by soundwaves. An electrical analog of the sound of this potential results from cochlear hair-cell activation (Honrubia et al., 1973; Karlan et al., 1972). After presentation of pulsed acoustic stimuli, the CM is followed by auditory nerve responses (N_1 and N_2). Frey's observation that there were microwave-induced auditory neural responses in guinea pigs and cats, but no CM, led him to propose the hypothesis of direct neural stimulation as an explanation for the hearing of microwaves (Frey, 1971).

Guy et al. (1975) similarly failed to record microwave-induced CM from cats fitted with carbon-loaded Teflon electrodes (conductivity of 1 S/m, which approximates that of tissues) at the round window. The use of low-conductivity electrodes is necessary to prevent field intensifications caused by highly conducting objects in contact with neural tissues (Chou and Guy, 1979a). The experiments yielded only auditory-nerve responses to rf stimulation. Guy et al. (1975) concluded that the absence of detectable CM resulted from insufficient application of rf energy. They were able to demonstrate, however, that bilateral destruction of the cochlea abolished all microwave-evoked potentials that previously had been recorded at higher levels in the auditory pathway. Evidence was thereby obtained which indicates that the cochlea is necessary for rf hearing.

Foster and Finch (1974) had demonstrated that pulsed microwaves can induce acoustic transients in water, in consequence of its thermoelastic properties. If such an acoustic transient can also be generated in the head, and if it is potent enough to be detected by the cochlea, then it should generate a CM. In relation to the absence of a detectable CM, as reported by Guy et al. (1975), other factors besides the low quantity of incident energy were found to be possible inhibitors of measurement. These are the limited frequency response of recording instruments and the presence of large microwave artifacts that can obscure the CM. To increase the possibility of

visualizing the CM, Chou et al. (1975) repeated the experiment of Guy et al., in a 918-MHz circular waveguide to couple the microwave energy more efficiently into the animal's head.

The exposure system isolated from the recording system was located in a rf shielded room to reduce microwave artifact. The upper frequency response of the recording instrument extended to 80 kHz. With this exposure-and-recording system, a microwave-induced CM (Fig. 2) was clearly detectible at the round window of the guinea pigs (Chou et al., 1975, 1976a). The CM is the electrical event that immediately follows the microwave-stimulus artifact. A time expansion of this signal, shown in the upper trace of Fig. 2, revealed that the CM is a damped oscillation of approximately 50 kHz that was 50 μV in initial amplitude and 200 μs in duration. Figure 3 provides a comparison of the CM evoked by microwave pulses of 10, 5, and 1 μs at the same peak of power density. The successive oscillations of CM occur at the same latency which indicates that the response is time locked to the onset and not to the offset of the microwave pulse. If the animal is euthanized, either by anoxia or by overdose of phenobarbital sodium, the N_1 and N_2 responses disappear before the CM, a phenomenon that also occurs with acoustic stimulation (von Bekesy, 1951, 1952).

When the guinea pigs were pulsed by a laser or were stimulated by a piezoelectric crystal in contact with the skull, similar CMs were recorded (Chou et al., 1976a). For example, Fig. 4 shows the response that resulted from acoustic stimulation by a piezoelectric transducer (Chou et al., 1976a). A 50-kHz oscillation followed the onset of the applied voltage at a delay near 20 μs. A variation from 10 μs to 100 ms in the width of the electrical pulse that excited the transducer did not cause any change in the latency of the CM, which indicates that the signal is time locked to the onset of the stimulus as it is with the microwave-induced CM. It is clear that this 50-kHz signal is the true CM since its polarity was inverted when the polarity of the applied voltage was reversed [Fig. 4(c)].

A CM at 38 kHz was recorded from cats in contrast to the 50-kHz CM recorded from guinea pigs. This gave rise to the possibility that the frequency of the CM is related either to the volume or to the mass of the head (Chou et al., 1976b). The possibility was explored in guinea pigs and cats of different body mass (Chou et al.,
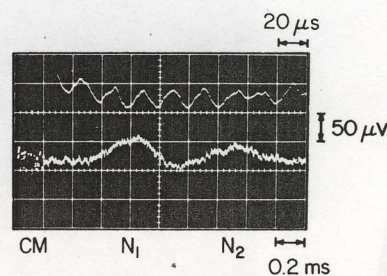
FIG. 2. Round-window response evoked by 918-MHz, 10-μs pulsed microwaves. Average specific absorption per pulse is 1.33 mJ/g. Upper trace is an expansion of the initial 200 μs of the lower trace [from Chou et al. (1976a)].
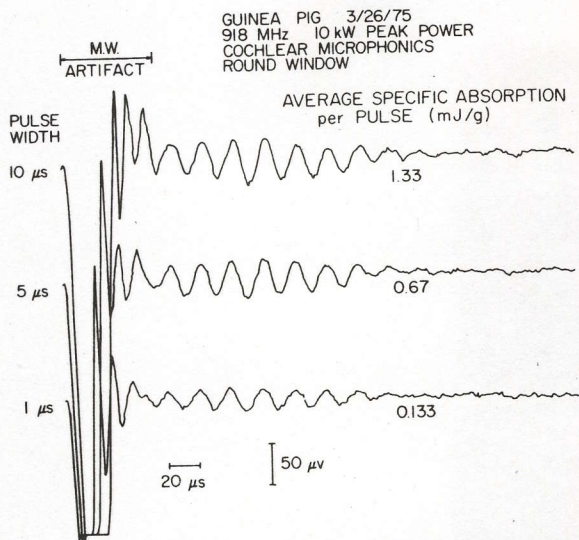
FIG. 3. Average cochlear microphonic responses evoked by 918-MHz microwave pulses, 10, 5, and 1 μs pulse width at the same peak power 10 kW [from Chou *et al.* (1975)].

FIG. 5. Microwave-induced CM in guinea pigs and cats, pulsed microwaves 918 MHz, 10 μs width [from Chou *et al.* (1977)].

1977) with the results illustrated in Fig. 5. Tables II and III list the data in detail. Both 918- and 2450-MHz pulses produced CMs of the same frequency and duration. The parameters of the CM (except for amplitude) are not influenced by the orientation of the body's long axis relative to the electric field or by pulses of microwaves less than 30-μs wide. Physical parameters of the animal (including body mass, head mass, skull mass, skull dimensions, skull thickness, brain cavity dimension, brain volume, bulla dimensions, cerebellum-cavity dimensions, and cerebellum volume) were plotted versus the frequency of the CM in both guinea pigs and
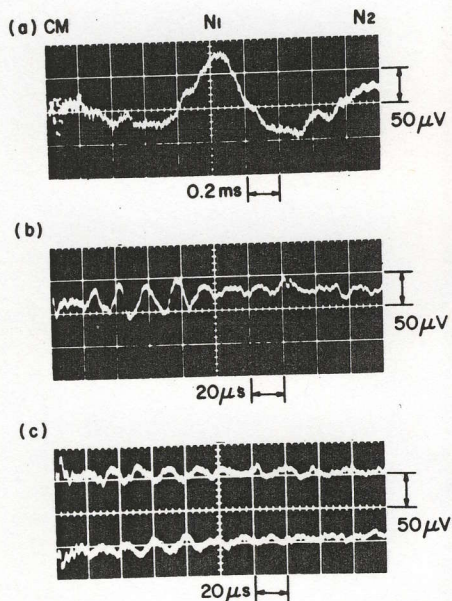
cats. The longest dimension in the brain cavity shows a consistent relation to frequency of the CM both in cats and guinea pigs; i.e., the greater the length of the brain cavity, the lower the frequency of the microwave-induced CM. All other plots did not reveal a consistent covariation of frequency with the CM of cats. Foster and Finch (1974) showed that a reflected pressure wave was present in a lucite tank filled with KCl solution when exposed to pulsed microwaves. The time between pressure waves corresponded to the propagation time of acoustic waves in the solution. We postulate that the thermoelastic waves generated in the head propagate within the brain cavity. Based on this hypothesis and the data from guinea pigs and cats, the predicted frequency of the microwave-induced CM in man would be between 7 and 10 kHz, which is consistent with the inability of hearing rf sound in human subjects with hearing loss above 5 kHz, to hear rf sound.

Frey and Coren (1979) claimed that the reported recordings of CMs (Chou *et al.*, 1975, 1976a, b, 1977) might only be artifacts of vibration of either the carbon-loaded Teflon electrodes or the foam material used to support the head of the test animal. This possibility is ruled out, however, since similar CMs were recorded as responses to laser and piezoelectric stimulation. Also, CMs of different character were recorded from animals of differing cranial dimensions, which indicates that the response was generated in the animal and not in the electrode. Further, the foam used to support the heads was a lossless Styrofoam incapable of emitting rf-induced sound. Finally, and most conclusively, any acoustic stimuli generated outside of the head of the animal produce physiological responses with a much longer latency than those initiated by microwave pulses.

In summary, pulsed microwaves produce CMs that are similar to those elicited by other stimuli (laser pulse and piezoelectric crystal vibrations). The fact that the frequency of the CM is related to the long dimension of the brain's cavity indicates that the CM potential is a response to the microwave pulse, which is generated within the animal and not by an outside source. The results

FIG. 4. (a) Round window response evoked by a bone-conducted stimulus generated from a piezoelectric crystal transducer (10-μs, 60-V electric pulse), (b) expansion of the initial 200 μs of the above trace, (c) record of the CM polarity of the electric pulses (10 μs, 30 V) delivered to the transducer is reversed [from Chou *et al.* (1976a)].
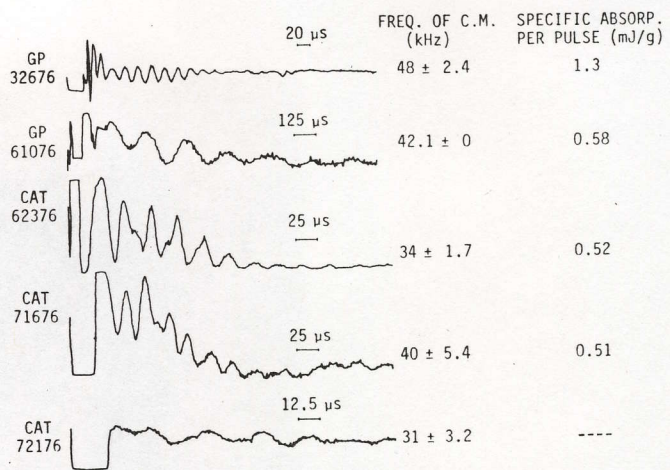
TABLE II. Characteristics of microwave-induced cochlear microphonics in guinea pigs [from Chou et al. (1977)].

Animal number	Body mass (kg)	Frequency ±SD (kHz)	No. of oscillations	$t_{1/e}$ (μs)	Exposure apparatus	Specific absorption per pulse (mJ/g)
GP 30675	~0.4	~50	8	...	Cylindrical cavity	...
GP 32575	~0.4	50 ±0	11	...	Cylindrical waveguide	1.4
GP 32675	~0.45	48 ±2.4	12	31.6	Cylindrical waveguide	1.3
GP 32875	~0.45	50 ±0	5	...	Cylindrical waveguide	1.3
GP 61076	1.10	42.1 ±0	8	36.3	Cylindrical waveguide	0.7
GP 61476	1.07	46.1 ±2.5	10	55	Cylindrical waveguide	0.8
GP 61576	1.13	39.2 ±4	6	49	Cylindrical waveguide	0.6

TABLE III. Characteristics of microwave-induced cochlear microphonics in cats [from Chou et al. (1977)].

Animal number	Body mass (kg)	Frequency ±SD (kHz)	No. of oscilllations	$t_{1/e}$ (μs)	Exposure apparatus	Specific absorption per pulse (mJ/g)
Cat 12076	2.9	~33	3	...	Applicator	...
Cat 52176	3.2	31.7 ±7.9	3	91	Applicator	...
Cat 52576	2.7	31.6 ±4.3	5	...	Applicator	...
Cat 60376	2.6	32.5 ±2.8	5	...	Applicator	...
Cat 60476	2.9	29.6 ±1.3	4	140	Applicator	...
Cat 61676	3.1	30.5 ±5.0	4	96.3	Applicator	...
Cat 61776	0.9	36.0 ±3.3	9	117	Applicator	...
		35.5 ±4.8	10	120	Cylindrical waveguide	0.80
Cat 62376	1.0	35.0 ±2.7	6	97.5	Applicator	...
		34.0 ±1.7	7	107.5	Cylindrical waveguide	0.52
Cat 71676	1.45	40.0 ±5.4	8	100	Cylindrical waveguide	0.51
Cat 71976	1.78	32.2 ±1.7	5	110	Cylindrical waveguide	0.43
Cat 72076	1.92	31.0 ±3.0	8	...	Cylindrical waveguide	0.51
Cat 72176	4.3	31.0 ±3.2	4	137	Applicator	...

provide strong evidence that the terminal event initiating the microwave auditory effect is mechanical in nature.

B. Single-unit responses

Lebovitz and Seaman (1977 a, b) have recorded extracellular potentials from single eighth-nerve fibers of cats during exposure to pulsed 915-MHz microwaves. Post-stimulus time histograms (PSTH) were obtained for responses to pulsed acoustic and to pulsed microwave stimuli. Except for differences in latency, which are adduceable to air conduction, the acoustic PSTHs were remarkably similar to those produced by microwave pulses (Fig. 6). However, because the microwave generator was limited in output power, the maximal SA was only 40 $\mu J/g$ per pulse, which is only 10 dB higher than the threshold level of ~4 $\mu J/g$. The authors suggested that this small dynamic range might be the reason only approximately one-half of the auditory units examined responded to microwave pulses. The latency of the microwave PSTH was between 2–5 ms depending on the characteristic frequency (CF) of the fiber; in general, the lower the CF, the longer the latency.

Lebovitz and Seaman (1977a, b) also occasionally observed that the amplitude of the PSTH changed nonmonotonically when the peak of power density was held constant and the pulse width was increased from 25 to 300 μs. This observation is consistent with results reported by Kiang (1965) on the effect of duration of the acoustic pulse on responses of primary fibers. The strong correlation ($r = 0.99$) found by Lebovitz and Seaman (1977a, b) between the interpeak intervals of the microwave and acoustic PSTHs indicates that both microwave and acoustic pulses excite peripheral receptors mechanically in a similar way. Lebovitz and Seaman's data (1977a, b) are most consistent with physiological activation of the auditory periphery by mechanical means, except that a smaller number of fibers with high CF (2.3–5 kHz) respond to microwave pulses. This exception do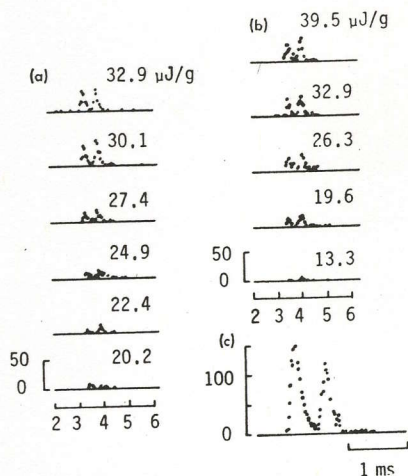es not appear to be consistent with the coch-lear microphonic data obtained from animals and with the introspective observations made by human subjects exposed to pulsed microwaves. This exception is also in disagreement with thermoelastic expansion theory, since the theory predicts the occurrence of a high-frequency response (Lin, 1978). However, it should be noted that Lebovitz and Seaman (1977a, b) used long pulses (250–300 μs) in order to obtain maximum energy per pulse. The results of Tyazhelov et al. (1979) showed that, for long pulses (100 μs) lower pitch rf sound was perceived by humans. Two observers with a high-frequency auditory limit of 10 kHz could not perceive shorter rf pulses, but were able to sense the longer pulses. Therefore the results of single unit recording in cats are consistent with human perceptions when the pulse widths are long.

C. Evoked responses in brainstem nuclei

Evoked responses can be recorded from the scalp by surface electrodes or by electrodes inserted into the brain substance. Frey (1967) was the first to record from the depths of the brain of cats exposed to low-intensity pulsed microwaves. He used coaxial, rf-shielded, metal electrodes and although these could cause severe field intensification at the tip of the electrode (Johnson and Guy, 1972; Tyazhelov et al., 1977), he obtained responses at several brainstem nuclei such as reticular formation, inferior olive, and subthalamus, which are not in the direct auditory pathway.

The auditory brainstem-evoked response (BER), as recorded with surface electrodes, is the electrical event that occurs in auditory-brainstem nuclei within the first 8 ms after onset of an acoustic stimulus. Chou et al. (1976a) recorded BERs from guinea pigs exposed to pulsed, 918-MHz microwaves. Microwave-transparent carbon-loaded Teflon electrodes were attached to the skin at the vertex and the mastoid process. Except for a difference in latency, the microwave-induced BERs were highly similar to those produced by acoustic pulses (see Fig. 7). This means that excitation occurs similarly at the peripheral level and that the same auditory
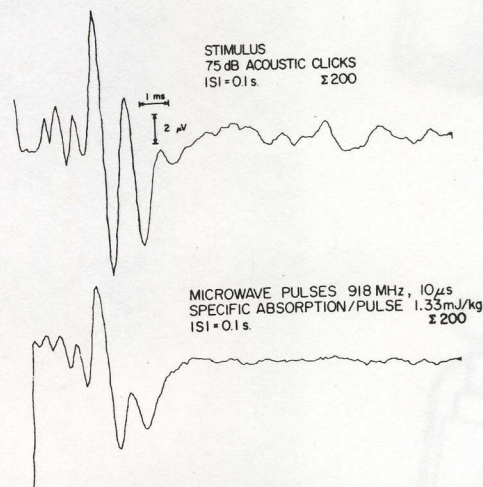
FIG. 6. PSTHs of (a) responses to microwave pulses at fixed duration of 250 μs and decreasing intensity, (b) responses to microwave pulses at same peak power and variable duration from 100–300 μs, (c) responses to acoustic clicks [from Lebovitz and Seaman (1977b)].

FIG. 7. Surface recorded brainstem evoked responses to acoustic and microwave stimulation (intrastimulus interval = ISI) [from Chou et al. (1976a)].

pathway through the central nervous system is activated by both microwave and acoustic stimuli. The two responses are, however, not exactly the same since microwave-induced sounds are much higher in frequency than those produced acoustically.

Cain and Rissmann (1978) recorded responses from both the inferior colliculus and scalps of cats exposed to 3-GHz microwave pulses. The traces of their responses were quite smooth, probably due to the limited frequency response of their recording system. Lin *et al.* (1979) recorded from surface electrodes and from implanted stainless-steel electrodes microwave-induced BERs in cats exposed to a small microwave-contact applicator. They found waveforms comparable to those evoked by acoustic pulses. They also studied the relation between amplitude of the BER and the pulse repetition rate, the pulse width, and the peak power of the microwave pulses.

Since the technique of recording BERs with surface electrodes is elemental, we applied it in two studies to achieve further understanding of microwave auditory effects.

1. Involvement of middle-ear structure in microwave hearing

The contribution of the bones of the middle ear to auditory perception of microwaves was evaluated with the BER technique (Chou and Galambos, 1979). Guinea pigs were exposed to 918-MHz pulsed microwaves in a circularly polarized waveguide. Amplitudes and latencies of BERs were recorded when the auditory system was stimulated by acoustic pulses and by microwave pulses of various intensity. Blocking of the external ear and damping of the ossicular movement by filling the bulla with mineral oil produced no change in BERs elicited by microwave pulses (Fig. 8). Removal of the ossicles diminished in amplitude the microwave-induced BER slightly as compared with the acoustic BER. This diminution may be due to the small relative motion between the stapes and the cochlea. These results show that the middle ear is not critical for auditory perception of microwaves,
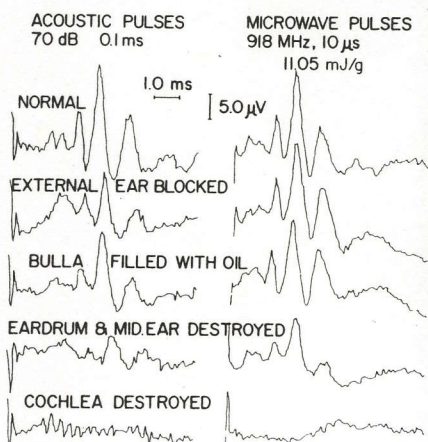
which is consistent with the observation that human beings with loss of conductive hearing can still hear microwaves (Frey, 1961). It was also shown in this study that the effect of middle-ear manipulation on the bone-conducted BER as stimulated by a piezoelectric transducer is similar to that of the microwave-induced BER. These results indicate that the conduction of pressure waves through the calvarium appears to be the acoustic pathway for the perception of pulsed microwaves.

2. Relation between perceptual threshold and microwave-pulse duration

Guy *et al.* (1975) demonstrated that the threshold of human and infrahuman acoustic perception of pulsed microwaves is highly correlated with energy density per pulse and is independent of pulse widths shorter than 30 μs in duration. Frey and Messenger (1973) reported that perception of loudness is primarily dependent upon peak power as opposed to average power for pulses to 70 μs in duration. Foster and Finch (1974) measured the sound pressure of microwave-induced acoustic transients in KCl solution and found that the pressure was directly proportional to the peak power for long pulses and to the quantity of energy for short pulses. This relation is also predicted by the analytic equations of thermoelastic expansion (Gournay, 1966; Guy *et al.*, 1975; Chou, 1975).

To clarify some quantitative relationships between the pulse width and the threshold of microwave hearing, guinea pigs were exposed to 918-MHz microwave pulses of 10- to 500-μs duration (Chou *et al.*, 1979b). The threshold of specific absorption (SA) per pulse and the peak of power density of the microwave-induced BER were obtained for various pulse widths. Figure 9 shows the results, which indicate that microwave hearing is dependent upon the energy content of pulses that are shorter than 30 μs and is dependent upon the peak of power for pulses longer than 50 μs. This relation is consistent with the prediction of thermoelastic expansion.

D. Central nervous system studies

Microwave-induced responses at the medial geniculate body and the auditory cortex were recorded by Taylor and Ashleman (1974) with microelectrodes filled with Ringer solution. The responses disappeared after bilateral destruction of the cochleas. Guy *et al.* (1975) demonstrated microwave-evoked medial-geniculate responses in cats and showed that noise masking (50 Hz–15 kHz) did not affect the threshold. This indicates that microwaves trigger a response in the high-frequency portion of the auditory system. The surface-recorded cortically evoked responses were very similar for both acoustic and microwave stimuli, which indicates that neural transmissions follow the same auditory pathway from the cochlea to cortex (Chou *et al.*, 1976a). All of these results are consistent with the CM and BER data.

Wilson *et al.* (1980) applied an autoradiographic method based on [14C]2-deoxy-D-glucose to map auditory activity in rat brains exposed to pulsed and cw microwaves. After one of the middle ears of a rat was ablated, ac-

FIG. 8. Effects of external and middle-ear maneuvers on the brainstem evoked responses from guinea pig (9/1/76) [from Chou and Galambos (1979)].

BRAINSTEM EVOKED RESPONSE
918 MHz CIRCULAR WAVEGUIDE
GUINEA PIG (02/07/77)

(a)

BRAINSTEM EVOKED RESPONSE
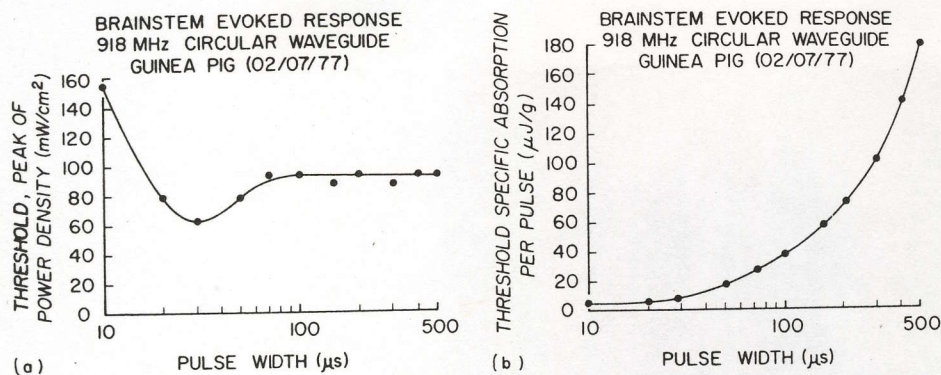918 MHz CIRCULAR WAVEGUIDE
GUINEA PIG (02/07/77)

(b)

FIG. 9. Thresholds of (a) peak of power density, (b) specific absorption per pulse for microwave-induced BER in guinea pigs as a function of pulse width [from Chou *et al*. (1979b)].

tivity due to acoustic stimulation (even very weak background noise) appeared on the contralateral side of the inferior colliculus in contrast with the bilateral symmetry of responses observed when the animal was exposed to pulsed microwaves. This indicates that microwave hearing does not involve the middle ear, a result consistent with the human data of Frey (1961) and with data from the middle-ear study of guinea pigs by Chou and Galambos (1979). Wilson *et al*., also showed that cw microwaves produce bilateral symmetry of the auto-radiographic responses at the inferior colliculus in rats exposed to microwaves at 10 and 2.5 mW/cm². They interpreted that an auditory response occurs due to cw microwave radiation. The authors proposed several possible mechanisms for the effect, including change resulting from small temperature increases, and stimulation of cell membranes in the cochlea. Despite these data, there has never been any hearing sensation reported due to cw microwave exposure.

In summary, electrophysiological recordings from infrahuman mammals have demonstrated similarities and differences between microwave and acoustically evoked responses and have revealed the origin of the effect, the relation between frequency of induced sound and physical dimensions of the head, as well as the relation between hearing threshold and pulse duration. All of these results underscore the mechanical nature of the effect and are consistent with a mechanism of hearing based on thermoelastic expansion.

III. BEHAVIORAL STUDIES

In addition to controlled physiological experiments on animals of several species, behavioral studies involving microwave irradiation have generated data that may be of relevance to the microwave-auditory effect.

A. Aversive behaviors

Frey and Feld (1975) conducted a behavioral study in which rats were exposed in a shuttle box for 30 min to pulsed 1.2-GHz microwaves. One-half of the box was shielded from microwaves. The percentage of time a rat spent in the exposed and shielded sides of the shuttle box and the number of crossings between sides were measured. The measurements revealed significant differences in preference for a side by animals exposed to 30-μs pulses at peaks of power densities of 133 mW/cm² (0.4 mW/cm² average, 4 μJ/cm² per pulse) and 300

mW/cm² (0.9 mW/cm² average, 9 μJ/cm² per pulse). When compared with rats of the control group, exposed rats made fewer crossings (7 versus 15 per session) and spent less time (29% versus 57%) in the irradiated side of the box. Preference for the shielded side shifted from about 50% before exposure to about 70% during exposure. The levels of incident energy in this study are near the threshold of hearing if compared with the human data of Frey (1962). However, it should be emphasized that the effect is related to the quantity of absorbed energy. It has been shown theoretically (Durney *et al*., 1978), and experimentally (Gandhi *et al*., 1977), that the applied frequency of 1.2 GHz is near the resonant frequency of the rat, which could result in energy absorption one order of magnitude higher than that in a man exposed to microwaves with body axis parallel to the vector of the electric field.

When a different shuttle box was used in the same study by Frey and Feld (1975), the rats were divided into three groups of six rats each. A pulsed group was exposed to pulse-modulated 1.2-GHz microwaves (0.5-ms pulse had 1-μs rise time and then decayed exponentially to less than 1/3 of the peak amplitude) at a peak of power density of 2.1 mW/cm² (0.2 mW/cm² average, 1 μJ/cm² per pulse). The cw group was exposed to cw waves at 2.4 mW/cm². The third group was sham exposed. The rats showed no particular preference of location in the box during the first two sessions of exposure, but there was a statistically significant shift in preference to the sheltered side during the third and fourth sessions between the pulse (70%) and cw groups (36%) and the pulse and sham (48%) groups, but no reliable difference between the cw and sham groups was noted. Frey and Feld (1975) interpreted the preference of rats for the shielded side as an avoidance of the pulsed microwaves.

Hjeresen *et al*. (1979) felt that the preference data of Frey and Feld (1975) might be related to hearing of the pulsed microwaves. They conducted a study in which rats were exposed in a shuttle box to 2.88-GHz pulsed microwaves (3-μs pulse width, 100 pps, peak of power density 33 W/cm², average power density 9.5 mW/cm², incident energy density 99 μJ/cm² per pulse, whole body average SA per pulse 63 μJ/g). Two groups of rats were exposed alternately for 1-h daily either in the right or left side of the box. The third group was exposed on both sides, and the fourth group was not exposed at all. The percentage of time the rats spent on each side and

the number of crossings between sides were measured for nine sessions (one session per week). In sessions 1 to 5, the rats developed a preference for the unexposed side but this effect also was reduced by alternating the side of exposure. In session 6, when the microwave stimulus was exchanged for a high-frequency (37.5 kHz) acoustic stimulus, the rats showed a preference for the acoustically unstimulated side. In sessions 7–9, the stimulus was changed back to microwave radiation. A significant preference was seen only during session 8. The number of crossings was increased when both sides of the box were exposed either to microwaves or to sonic stimuli. The crossings decreased during the session when one side of the box was exposed. When high-frequency, acoustically "pink" noise was applied at the same time as were microwave pulses during five additional sessions, there was no statistically significant difference between the experimental and control animals. However, in all cases, crossing activity was higher in the exposed animals than in the unexposed controls.

These results indicate that rats can generalize to pulsed sonic stimulation from the pulsed microwave stimulation. The noise-masking results also indicate that the auditory sensation perceived during pulsed microwave exposure is the likely mediator of preference. Besides concluding that auditory perception of pulsed microwaves could be responsible for the side-preference effect, the authors indicated that the increased crossing activity shown by continuously exposed rats may be due to thermal loading or other undefined motivating factors.

B. Discriminative control

Johnson *et al.* (1976) showed that food-deprived rats trained to respond during acoustic stimulation for food reward can also use pulsed microwaves as a discriminative stimulus. The rats were trained to use a nose-poking operant to obtain a reward of food pellets in the presence of acoustic clicks. During the fourth week of training, half-way through a stimulus-off period, the animals were exposed to 918-MHz, 10-μs pulsed microwaves for 30 s at an incident energy density of 150 μJ/cm^2 per pulse at a repetition rate of 10 pps, the same as used for the acoustic pulses. Prior to the 30-s microwave exposure, the rats were grooming or engaged in other nonrelevant behavior. When microwave irradiation was activated, the animals oriented initially just as they did to the acoustic stimulus. Then they hesitantly began to respond and continued hesitantly to respond in the absence of reinforcement until the end of the 30-s microwave exposure. During the remaining time of the stimulus-off period, the rats responded sporadically, in apparent frustration [Fig. 10(a)]. On the following day, the pulsed microwaves were given instead of the acoustic stimulus during the stimulus-on period. The animals showed increasingly less hesitancy to respond for reinforcement. By the end of the day's session, the animals had an 80%–85% response efficiency. On the next day, the rats responded with the same efficiency to either acoustic or microwave stimulation [Fig. 10(b)]. This experiment clearly demonstrates the close similarity of the rats' perceptions of
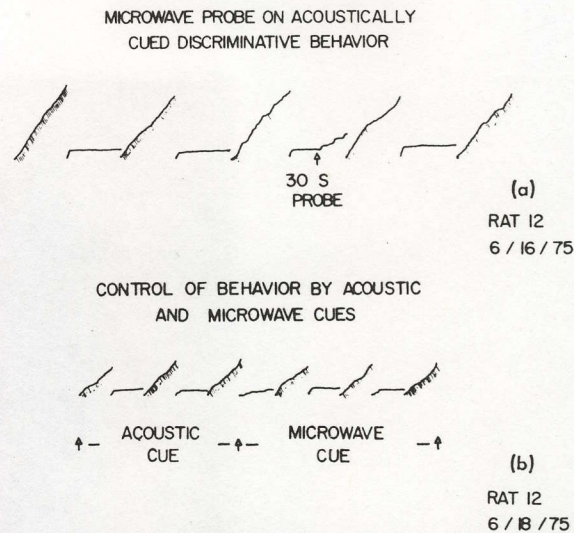

FIG. 10. Cumulative records of nose-poking behavioral response; (a) in response to 30-s microwave probe, rats respond as if acoustic cue had been presented, (b) rats respond equally well during acoustic and microwave stimulation [from Johnson *et al.* (1976)].

pulsed microwaves and of acoustic pulses. In another experiment on anesthetized rats, the threshold of the microwave-induced auditory brain-stem evoked response was demonstrated to be the same, 10 μJ/cm^2, as that below which the nose-poking behavior disappears.

C. Audiogenic seizures

Kitsovskaya (1960) found that audiogenic seizures in rats were suppressed after exposure to 3-GHz pulsed microwaves at 10 mW/cm^2 average power density for 9 min daily across 40 days. The recovery of suppression occurred 19 days after exposure ended. However, this suppression did not happen to animals exposed daily to 10-GHz fields at 10 mW/cm^2 for 90 min over 105 days or to 3 GHz, 1 mW/cm^2 for 90 min over 117 days.

Stverak *et al.* (1974) exposed 24 audiogenically-seizure-prone rats (as compared with 16 controls), starting the second day after birth, for 4 h daily for ten weeks, to 2850-MHz 2.7-μs pulsed microwaves at a repetition rate of 357 pps and an average power density of 30 mW/cm^2. Seventy percent of the exposed rats and 20% of the 16 control rats did not show any seizure during the test. In other words, the pulsed microwave exposure reduced the probability of an audiogenic seizure. The mean intervals between audio stimulus onset and seizure onset were also compared in the exposed and the control rats, but no difference was found.

Both Kitsovskaya (1960) and Stverak *et al.* (1974) experiments showed that the audiogenic seizure response is decreased by the exposure to pulsed microwaves. In Stverak *et al.*'s experiment, the energy density per pulse was 84 μJ/cm^2, which is sufficient to cause hearing sensation in the rats. If the animals were exposed to microwave-induced sound for long periods of time, the adaptation to sonic stimulation explains why the audiogenic seizure sensitivity to audio stimulus is decreased. In addition to hearing sensations, exposure to a field at

average power density of 30 mW/cm² can also cause significant heating of an animal.

In summary, the behavioral studies indicate that rats can perceive pulsed microwaves. The behavior of rats based on discriminative control and shuttle-box preference tests demonstrates that they perceive pulsed microwave radiation. The avoidance behavior and the effect of chronic exposure to microwaves on audiogenic seizures can also be attributed to the hearing effect. Since the threshold for hearing pulsed microwaves is very low, it is important to determine whether any observed biological responses in animals exposed to pulse modulated microwaves is due to the hearing of microwaves.

IV. PHYSICAL MEASUREMENTS

White (1963) analyzed the generation of elastic waves in solid and liquid materials exposed to pulsed microwaves. His analysis deals with the nonuniform heating at the surface of an exposed object. The analysis predicts that, as a result of thermal expansion, a temperature gradient produces strains in the exposed medium and leads to the generation of stress waves which propagate away from the heated area. The amplitude of the stress wave depends upon the elastic constraints applied at the heated surface. The amplitude is much higher for a constrained surface than for a stress-free surface. White also showed analytically that the thermoelastic pressure wave is much higher than the radiation pressure. Experimentally, when he exposed water to 9-GHz, 2-μs microwave pulses at peak power density of 2 W/cm² corresponding to a calculated peak temperature rise of 0.001 °C, elastic waves could be detected by a piezoelectric crystal probe (White, 1963). White also observed a difference-frequency beat pattern when he applied two X-band pulsed microwaves operating at frequencies differing by a few kilohertz. The beat disappeared if the two pulses were not coincident, and if the two microwave frequencies differed by so much that the instrument was not sensitive enough to record it. The theoretical analysis of White was on a harmonically varying power density. This analysis was extended later by Gournay (1966) for a single pulse. The relationship of the amplitude and the condition of the surface, as predicted by White, was experimentally proved by von Gutfeld and Melcher (1977) using pulsed lasers. The ratio of constrained versus free surface thermoelastic expansion was shown to be up to 46 dB.

A thermoelastic wave of pressure was first suggested by Foster and Finch (1974) as the underlying mechanism of the microwave auditory effect. They used a sensitive hydrophone to record pressure waves in a 0.15 N-KCl solution exposed to 2450-MHz microwave pulses of 2- to 27-μs width. The recorded pressure was in agreement with theoretical predictions. The latency between the onset of stimulus and the onset of signal was equal to the propagation time of the pressure wave. The reflection of pressure waves from the walls of the solution container was also recorded. Foster and Finch (1974) proved that the pressure wave was due to thermoelastic expansion by exposing distilled water and noting that the pressure wave would reverse polarity as the tempera-

ture of the water fell below 4 °C. The pressure wave vanished in water at a temperature of 4 °C. Acoustic transients were also observed in in vitro biological tissues such as blood, muscle, and brain. Foster and Finch (1974) also showed that the microwave-induced wave of pressure depends on the product of peak power and pulse duration, i.e., on the quantity of energy per pulse, for short pulses, and on peak power for longer pulses, both of which findings are consistent with theoretical predictions (Gournay, 1966).

Olsen and Hammer (1980) also used a hydrophonic transducer to measure the pressure wave in a rectangular block of simulated muscle tissue exposed to 5.655-GHz, 0.5-μs pulses of microwaves. This study was later extended to spherical models that simulated brains of differing sizes (Olsen and Lin, 1981). They also showed that appropriately selected pulse repetition rates cause acoustic resonances that can enhance the microwave-induced pressure by severalfold. The frequency of the wave bouncing back and forth inside the sphere is directly related to the diameter of the spheres, which is consistent with the theoretical prediction of Lin (1978).

Using a holographic technique, Frey and Coren (1979) detected vibrations in carbon-deposited polystyrene foam that was exposed to pulsed microwaves. However, because of their inability to detect any vibration in the heads of irradiated cadavers of guinea pigs and rats, they questioned the validity of the thermoelastic expansion hypothesis. Chou et al. (1980) responded by demonstrating that the sensitivity of Frey and Coren's (1979) holographic technique is orders of magnitude too low to detect displacements related to vibrations from the microwave-induced thermoelastic expansion in biological tissues.

Before the relation between the mechanism of thermoelastic expansion and the microwave-auditory effect was established, Sharp et al. (1974) reported the eliciting of sound from carbon-impregnated polyurethane microwave absorbers and from crumpled aluminum foil exposed to pulsed microwaves. There was little difference in the sound quality when the microwave frequency was varied from 1200 to 2450 MHz.

Guy et al. (1975) quantified the surface displacement of microwave induced acoustic vibration in microwave-absorbing materials of porous and solid composition by means of a helium–neon laser Michelson interferometer. The peak vibrations of a microwave absorber (Eccosorb ANW-77) exposed to a 918-MHz 20-μs pulse at an energy density of 0.68 mJ/cm² was only 288 Å. The strength of the induced wave of pressure, which is several orders of magnitude higher than the radiation pressure and the electrostrictive forces associated with the microwave field, is very close to that predicted by the equations of thermoelastic expansion. Comparisons of such pressures were analyzed theoretically by Lin (1976). Justesen (1975), who could not directly perceive the microwave hearing phenomenon because of bilateral high-frequency hearing loss, could hear air-conducted audio sound originating from a tiny piece of microwave absorber that was held on a toothpick and exposed to the pulsed microwaves.

V. DISCUSSION

The microwave-induced auditory phenomenon is an example of a microwave-biological interaction that has been well quantified and has been widely accepted as a bonafide "weak-field" effect. Although originally the hypothesis of a direct nervous system stimulation was proposed, the evidence is now strongly convincing that the hearing phenomenon is related to a thermoelastically induced mechanical vibration. The same type of vibration can be produced by other means, e.g., by a laser pulse, or by activating a piezoelectric crystal in contact with the skull. The frequency of the response appears to be related to the long physical dimension of the cranium, which indicates that intracranial acoustic resonance plays an important part in shaping the acoustic phenomenon's physical and perceptual characteristics.

The question of site of electromechanical transduction is unanswerable at this time. During exposure of the heads, the conversion of electromagnetic energy to mechanical energy occurs volumetrically in a manner that depends on the pattern of absorption and on a tissue's thermal expansion coefficient. Airborne Instruments Laboratory (1956) and Frey (1962) showed that the most sensitive area was the temporal areas. Ingalls (1967) reported that the sensation of hearing occurred only when the forehead was exposed. Tyazhelov et al. (1979) exposed the back of the subject's head while the head was immersed in water. In animals, Lin et al. (1979) used a small contact microwave applicator on the dorsal or frontal surface of cats' heads to elicit microwave-induced auditory responses. These results indicate that the sensation can be evoked by exposure of the head in any aspect. For details of the sensitivity at specific sites, such as skull, muscle, brain, or cochlea, more research is required for clear answers.

The low threshold of the microwave-hearing phenomenon makes it essential to differentiate the hearing effect from other biological effects observed during pulsed-microwave exposure. For example, the incident field at energy densities used by Servantie et al. (1975) was adequate to evoke auditory responses and so the "synchronization" they report may well have been initiated by what their rats heard. Control experiments with deaf animals will be necessary before a biological effect of pulsed microwaves can properly be ascribed to a nonauditory cause.

VI. CONCLUSION

Microwave hearing is most easily explained by the mechanism of thermoelastic expansion, i.e., absorption of microwave energy produces nonuniform heating of the exposed head; a thermoelastic wave of pressure is then launched, presumably through bone conduction, to the cochlea where it is detected. After auditory-nerve excitation in the high-frequency portion of the cochlea, transmission of the microwave-induced neural response follows the same auditory pathways as do all of the acoustically induced responses through the brainstem and thalamus to the auditory cortex.

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