MICROWAVE-INDUCED ACOUSTIC EFFECTS IN MAMMALIAN AUDITORY SYSTEMS AND PHYSICAL MATERIALS*

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INTRODUCTION

One of the most widely observed and accepted biologic effects of low average power electromagnetic (em) energy is the auditory sensation evoked in man exposed to pulsed microwaves.[1-6] The effect appears as an audible clicking or buzzing sensation that originates from within and near the back of the head and that corresponds in frequency to the recurrence rate of the microwave pulses. The effect is of great interest, because it can be elicited by average incident power levels far below those believed to be of thermal significance. The mechanism of the effect, however, has remained obscure. Sommer and Von Gierke[7] have suggested that radiation pressure may be sufficiently high to couple acoustic energy to the inner ear by bone conduction. Frey[8] has discounted this hypothesis, however, and does not believe the interaction is due to transduction of em to acoustic energy. His belief is based on his failure to observe cochlear microphonic potentials associated with the pulsed microwave stimulation of the auditory systems of cats and guinea pigs and on the low levels of incident power at the threshold for perception by the human subject. Frey and Messenger[4] have observed that the loudness of the sensation was proportional to the peak power, whereas Guy and colleagues[5] have observed that the threshold of the sensation is proportional to energy per pulse. It is important that the origin and threshold of the microwave interaction be identified and understood to assess potential hazards of pulsed microwave power. The present ANSI safety standard[9] does not restrict the peak power density as long as the power density, as averaged over any 6-min period, does not exceed 1 mW hr/cm^2, or 3.6 J/cm^2. This value is five orders of magnitude greater than the threshold level for producing an audible sensation by a single short pulse.

The work reported here was formulated to apply a bioengineering approach for establishing the threshold of the effect in man and animals as a function of pulse power or energy, pulse shape, and carrier frequency; the locus of action of the effect, that is, whether it is initiated at a central or at a peripheral site; and whether the stimulation is due to direct action of the em fields on the nervous system or to transduced acoustic energy acting on the auditory system.

The studies involved the following procedures: establishment of incident field and modulation characteristics at the threshold for auditory sensation in humans; com-

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parison of activity evoked in four successive levels of the auditory nervous system in the cat due to incident acoustic and microwave pulses; assessment of the deactivation of the cochlea, the known first stage of transduction for acoustic stimuli on the potentials evoked by both forms of pulsed energy; establishment and quantitation of the transduction of microwave pulse energy to acoustic energy in microwave-absorbing materials by optical interferometry; and demonstration that the microwave auditory phenomenon is consistent with and can be explained by the direct conversion of em energy to acoustic energy in the tissues.

Determination of Thresholds of Microwave-Evoked Responses in Humans

Two of the coinvestigators served as subjects to determine the incident power levels and pulse widths needed to evoke the auditory sensation. An Applied Microwave Laboratory (AML) model PH 40 K signal source, capable of providing up to 10 kW peak power with pulses 0.5–32 μsec wide, was used to feed a 2450-MHz S-band 32 × 26-cm aperture horn by means of an RG8 coaxial cable. The incident power to the horn and reflected power was monitored by a Hewlett-Packard 477 bolometer and 430C power meter combination connected to a Microlab FXR 30-dB bidirectional coupler inserted between the coaxial cable and the horn. The pulse width and recurrence rate were controlled by an external pulse generator and monitored on an oscilloscope. The subject sat with the back of his head directly in front of the horn 15–30 cm from the aperture. Placement of the subject's head in the near-zone field of the horn was necessary to obtain the full dynamic range of pulse widths and power levels required for eliciting an auditory response. The "effective" average power density at the location of the exposed surface of the subject's head was measured with a Narda 8100 power monitor at high pulse rates and low peak power levels as a function of incident power to the horn, without the presence of the subject. The values for higher powers and lower pulse rates were obtained by linear extrapolation from the monitored incident power to the horn. Sections of Emerson & Cuming, Inc. Eccosorb CH490 absorber material were placed around the vicinity of the subject to eliminate reflections. The radiator, absorbing material, and exposed subject were situated in a shielded room completely isolated from the power-generating equipment and operating personnel to eliminate disturbing noises. Cable connectors to the horn and bidirectional couplers were made through bulkhead connections on the wall of the shielded room. A switch was controlled by the subject to signal the operator of the transmitter when an auditory sensation could be heard. Prior to the tests, standard audiograms of the subjects were taken, as shown in Figure 1. The hearing threshold of the first subject was normal, whereas a pronounced notch at 3500 Hz was noted for both ears of the second subject. Similar results were obtained for both air and bone conduction. The background noise of the exposure chamber was measured at 45 dB, 0.0002 dyn/cm^2, with a General Radio 1551-A sound level meter. Each subject was exposed to a range of microwave pulse widths, which varied from 1 to 32 μsec. The pulses were presented as a train of three 100 msec apart every second to maintain an average power density well below 1 mW/cm^2. The output of the generator was set at the threshold at which the pulses could be heard by the subject, as indicated by a light activated by him. Table 1 lists the measured incident peak and average power densities and the energy density per pulse for subject 1 without ear plugs. It was found that regardless of the peak power and pulse width, the threshold was related to an energy density of 40 μJ/cm^2 per pulse, or a peak energy absorption density of 16 mJ/kg, as calculated from a

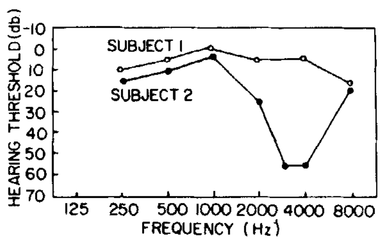

FIGURE 1. Audiograms of human subjects used for determining thresholds of audibility to pulsed microwaves.

spherical model discussed by Johnson and Guy.[11] The results for subject 2 were similar, except that the threshold energy level was approximately 135 $\mu J/cm^2$, or 5 dB higher. When subject 1 used ear plugs, the threshold level declined to 28 $\mu J/cm^2$. Each individual pulse could be heard as a distinct and separate click, and short pulse trains could be heard as chirps, of which the tone corresponded to the pulse recurrence rate. When the pulse generator was keyed manually, transmitted digital codes could be accurately interpreted by the subject. The threshold for two pulses within several hundred microseconds apart was the same as one pulse with the same total energy as the pulse combination. Though the relationship of hearing sensation threshold seems to be at variance with that of peak power and loudness observed by Frey and Messenger,[4] the results appear to be consistent when pulse widths are taken into account, as discussed later.

TABLE 1
THRESHOLD ENERGY OF MICROWAVE-EVOKED AUDITORY RESPONSES IN HUMANS*
(2450 MHz, 3 pps, background noise 45 dB)

Peak Incident Power Density (W/cm^2)	Average Incident Power Density ($\mu W/cm^2$)	Pulse Width (μsec)	Incident Energy Density per Pulse ($\mu J/cm^2$)	Peak Absorbed Energy Density per Pulse† (mJ/kg)
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‡	14
2.15	129	20	43	17
1.8	135	25	45§	18
1.25	120	32	40	16

*Thresholds for subject 1 in FIGURE 1.

†Based on absorption in equivalent spherical model of head as discussed in Johnson and Guy.[11]

‡28 with earplugs.

§135 for subject 2 in FIGURE 1.

Determination of Characteristics and Thresholds of Evoked Auditory System Responses in the Cat by Acoustic and Microwave Pulses

A series of cats, which weighed 2.0–3.4 kg, were surgically prepared for recording potentials from various levels in the auditory nervous system while they were exposed to short pulses of both acoustic and microwave energy. Separate groups of cats were used for recording from the medial geniculate nucleus and the round window of the cochlea to compare differences and to determine the threshold of evoked potentials to acoustic and microwave stimuli. Recordings were made from the VPL† of one animal to assess the cross system central nervous system responses to applied tactile, acoustic, and microwave stimuli. Finally, the effect of cochlear disablement on the interaction of the microwave stimuli with the auditory nervous system was assessed. The experiments are described as follows.

Method of Preparation and Exposure

The basic exposure and recording apparatus is illustrated in the block diagram shown in FIGURE 2. The cats were anesthetized intravenously with α-chloralose (55 mg/kg) dissolved in Ringer's solution (20 cc), and 0.2 mg of atropine sulfate was administered intramuscularly after induction of anesthesia. Cats were paralyzed with Flaxedil® (20 mg) and placed on artificial ventilation. The body temperature of the cats was held constant at 38°C by a heating pad connected to a rectal temperature control unit. A pair of wood, instead of metal, ear bars was used to hold the cat in a stereotaxic instrument to minimize the field distortion around the cat's head. For the same purpose, all metal pieces for fixing the inferior orbit and the upper jaw were replaced by wood fixtures. Following exposure of the dorsal surface of the skull by conventional methods of skin incision and reflection of the underlying muscle, a burr hole was made in the parietal bone. Before insertion of the electrode, each cat was fitted with a piezoelectric crystal transducer for providing acoustic stimuli by bone conduction. The device consisted of the two parts shown in FIGURE 3. A ring of Rexolite® plastic 18 mm in diameter and 3 mm thick was fitted to the dorsal surface of the frontal bone just anterior to the coronal suture and was held rigidly in place by 2-56 nylon screws and dental acrylic cement. The ring bore internal threads to receive the crystal, which thereby allowed easy and rapid removal of the tranducer during microwave stimulation to prevent field enhancement at the point of contact. The electrode was directed toward the medial geniculate nucleus by the standard Horsley Clark's method. The electrode consisted of a Ringer's solution-filled glass pipette with a tip diameter of 80–100 μm. The electrode and accompanying ground connection were coupled via high-resistance (1000 Ω/cm) carbon-loaded plastic conductors (transparent to microwaves) through a low-pass microwave filter to a high-impedance input physiologic signal-processing amplifier, oscilloscope, computer of average transients, and an x-y plotter. The microwave filter was designed to provide more than 150 dB attenuation of the coupled microwave currents with less than 20 pF of shunt capacitance presented to the amplifier input. The responses elicited by acoustic stimulation provided by clicks from a loudspeaker were continuously monitored as the electrode was advanced vertically. Proper placement of the electrode tip was assumed when a proper latency period was observed for the evoked responses. The electrode placement was verified in some of the animals by histologic examination of the brain tissue.

†Ventralis posterior lateralis of the thalamus.

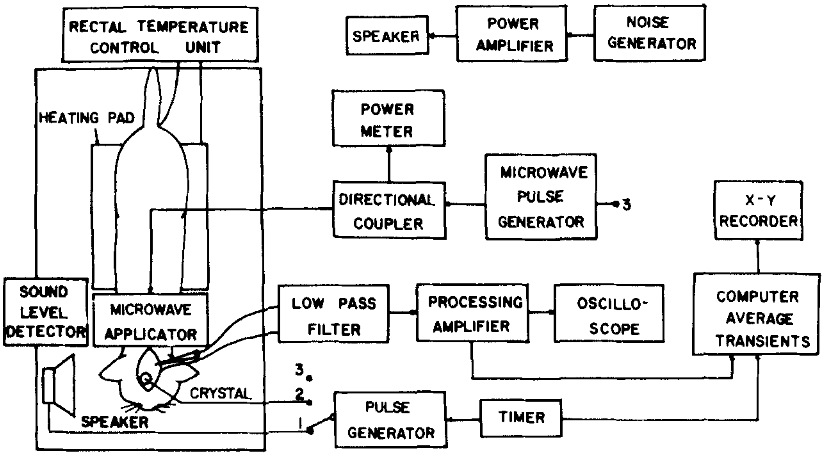

FIGURE 2. Block diagram of equipment used to assess the microwave-evoked auditory effects in the cat.

Air-conducted acoustic pulses were presented to the animal by exciting the loudspeaker placed 17 cm to the right of the centerline of the cat's head, and bone-conducted acoustic pulses were introduced by exciting the skull-mounted piezoelectric transducer with pulses 1–30 μsec in duration at a pulse repetition rate of 1 pps from a Hewlett-Packard model 214A pulse generator.

Microwave pulses of 918 or 2450 MHz power were provided by horn or aperture sources located 8 cm away from the occipital pole of the cat and were fed by the AML PH 40 K signal source. A Narda 8100 power monitor was employed to

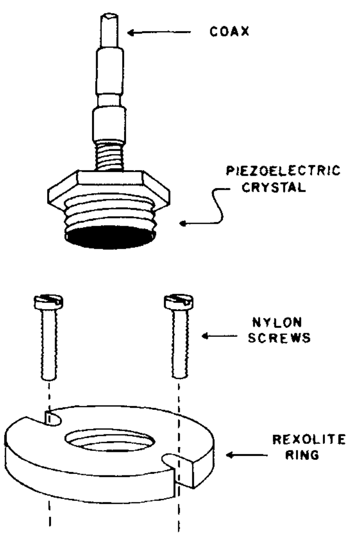

FIGURE 3. Crystal transducer for providing bone-conducted acoustic stimuli to the cat.

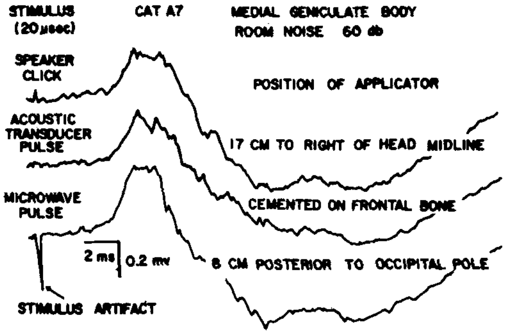

FIGURE 4. Evoked responses recorded from medial geniculate nucleus of the cat.

measure the average incident power density to the cat's head and the bidirectional coupler, bolometer, and power meter were used to measure incident power to the applicators in the same manner as for the human subjects. X-band 8.5–10 GHz microwave pulses were provided by modulating a Litton Industries L3063 magnetron with the 6-kV pulse modulator output of the above AML PH 40 K generator. An X-band standard-gain horn connected to a directional coupler and wave guide feed was used to illuminate the animal for this case. Incident power density was calculated from the known horn gain and the incident wave guide power, as measured with the bolometer through a wave guide to coaxial transducer attached to the directional coupler. A General Radio 1390-B noise generator, Hewlett-Packard 467A power amplifier, and speaker were utilized to provide a 50-Hz to 15-kHz background noise level up to 90 dB, as measured with the General Radio sound meter.

Experimental Results

FIGURE 4 illustrates typical evoked responses recorded from the medial geniculate nucleus due to acoustic and 2450-MHz microwave pulsed stimulation. The response recordings were made on the x-y recorder based on 40 averages taken with

TABLE 2
THRESHOLD ENERGY OF MICROWAVE-EVOKED AUDITORY RESPONSES IN CATS
(2450 MHz, 1 pps, background noise 64 dB)

Peak Incident Power Density (W/cm^2)	Average Incident Power Density ($\mu W/cm^2$)	Pulse Width (μsec)	Incident Energy Density per Pulse ($\mu J/cm^2$)	Peak Absorbed Energy Density per Pulse (mJ/kg)
35.6	17.8	0.5	17.8	10.1
17.8	17.8	1	17.8	10.1
10.0	20.3	2	20.3	11.6
5.0	20.3	4	20.3	11.6
4.0	20.3	5	20.3	11.6
2.2	21.6	10	21.6	12.3
1.9	28.0	15	28.0	15.9
1.7	33.0	20	33.0	18.8
0.6	15.2	25	15.2	8.7
1.5	47.0	32	47.0	26.7

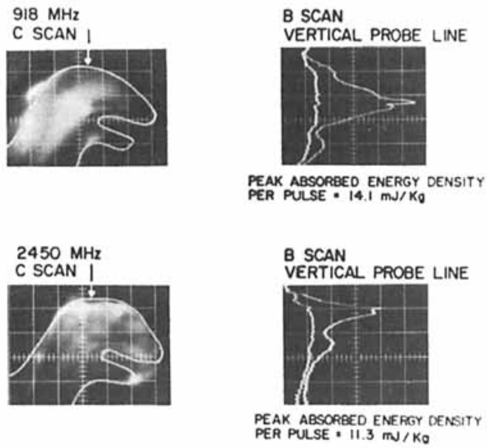

FIGURE 5. Thermograms that show absorbed energy density patterns (per pulse) in cat heads exposed to 918- and 2450-MHz 20-μsec 20-μJ/cm² incident pulses.

a Technical Measurements Corporation computer of average transients CAT 400 C. The threshold of the 2450-MHz microwave pulse evoked response as a function of pulse width is shown in TABLE 2. The thresholds for the responses elicited with microwave pulses 0.5–10 μsec in duration appear to be related to the incident energy density per pulse at a level about half of that which produced audible sensations for the human exposure. The required threshold energy per pulse seems to increase with pulse width for 10–32-μsec duration pulses, with the exception of the 25-μsec case. The peak absorbed energy density per pulse in the cat's head was measured by thermographic methods described by Guy[10] and Johnson and Guy.[11] FIGURE 5 depicts the thermograms obtained of the internal absorbed energy density distribution per 20 μJ/cm² of incident energy density for the sacrificed cat head exposed to 2450- and 918-MHz radiation. The peak absorbed energy densities, which correspond to the thresholds of evoked responses, are also tabulated in TABLES 2 and 3, based on the thermographic data. The incident energy density per pulse that corresponds to

TABLE 3

THRESHOLD ENERGY OF MICROWAVE-EVOKED AUDITORY RESPONSES IN CATS
(918 MHz, 1 pps, background noise 64 dB)

Peak Incident Power Density (W/cm²)	Average Incident Power Density (μW/cm²)	Pulse Width (μsec)	Incident Energy Density per Pulse (μJ/cm²)	Peak Absorbed Energy Density per Pulse (mJ/kg)
5.80	17.4	3	17.4	12.3
3.88	19.4	5	19.4	13.8
2.26	22.6	10	22.6	16.0
1.37	20.6	15	20.6	14.6
1.17	20.6	20	20.6	16.6
0.97	24.3	25	24.3	17.2
0.80	28.3	32	28.3	20.0

the threshold for elicited responses recorded from the medial geniculate body due to 918-MHz radiation, as summarized in TABLE 3, differs very little from that for 2450 MHz. FIGURE 6 shows the relative thresholds averaged over three to five cats for both acoustic and microwave stimuli as a function of background noise. The thresholds for the microwave stimuli varied from 6 to 33 $\mu J/cm^2$ over the group of cats. As the noise level was increased, there was only a negligible increase in the threshold for the microwave stimuli, a moderate increase in the threshold for the piezoelectric bone conduction source, and a large increase in the threshold for the loudspeaker stimuli. An evoked response from the medial geniculate body of the cat

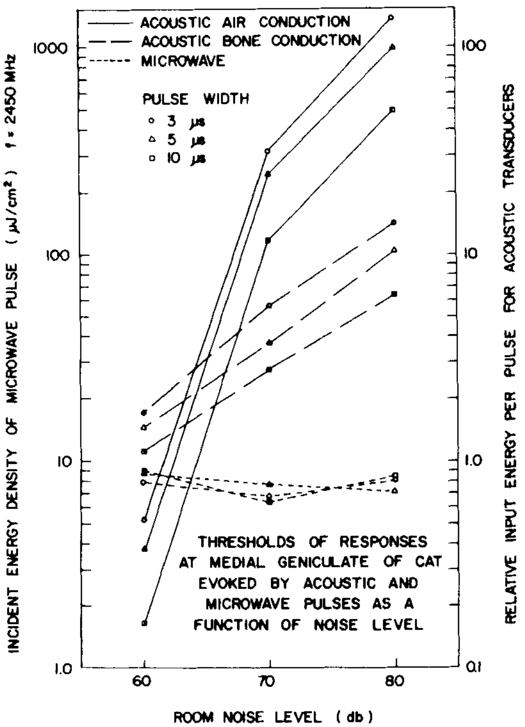

FIGURE 6. Thresholds of evoked medial geniculate responses (averaged for three to five cats) as a function of background noise.

was also obtained for two animals with X-band pulses at frequencies between 8.67 and 9.16 GHz. TABLE 4 shows that the required energy per pulse to elicit the responses was significantly higher than that required for the other frequencies. For this case, the X-band horn had to be placed within a few centimeters from the exposed brain surface of the animal (through the 1.0 cm diameter electrode access hole in the skull). No response could be elicited for an animal in which the electrode access port through the skull was limited to the diameter slightly larger than the hole. When the skull was bared, there still was no response evoked in the above animal. When the hole in the skull was enlarged, however, a response was obtained.

TABLE 4
THRESHOLD ENERGY OF MICROWAVE-EVOKED AUDITORY RESPONSES IN CATS*
(X-BAND, 1 pps, background noise 64 dB)

	Approximate Values
Peak incident power (W/cm^2)	14.8–38.8
Average incident power ($\mu W/cm^2$)	472–1240
Pulse width (μsec)	32
Energy density per pulse ($\mu J/cm^2$)	472–1240

*Application of power directly to top of exposed skull required to elicit responses.

Round Window of the Cochlea

In another series of animals, an electrode, fashioned from high-resistance carbon lead material, was applied to the round window of the cochlea and was used to record activity in response to both acoustic loudspeaker clicks and 2450-MHz microwave pulses.

Before the cats were placed in the stereotaxic instrument, the lateral and ventral surfaces of the auditory bulla were exposed by reflection and removal of the overlying soft tissue. The lateral wall of the bulla was perforated with a drill, and the drill hole was expanded with a small rongeur until the round window of the cochlea could be clearly visualized. A carbon lead was cemented to the round window and connected through a low-pass microwave filter for further signal processing. The remaining surgical procedure was similar to that performed for the medial geniculate nucleus experiments, which included attachment of the piezoelectric crystal transducer. Both acoustic stimuli and microwave pulses elicited activity at the round window, as shown in FIGURE 7. The first trace of the Figure illustrates the composite cochlear microphonic and N_1 and N_2 auditory nerve response evoked by a loudspeaker pulse from the first animal. The cochlear microphonic was quite strong in amplitude, following the decaying oscillatory response shape of the loudspeaker (measured by optical interferometry) as discussed later. When the auditory system of the same animal was stimulated by microwave pulses, a microwave artifact pulse and a clear N_1 and N_2 auditory nerve response was elicited, but there was no evi-

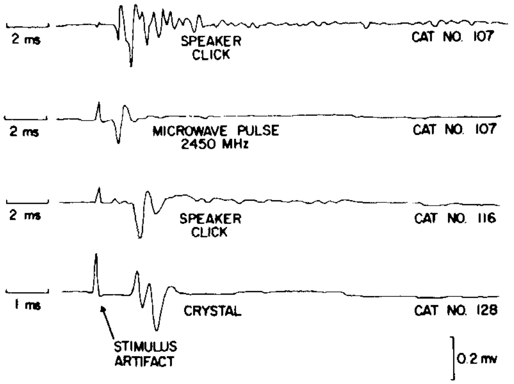

FIGURE 7. Responses in the round window of the cat cochlea due to acoustic and microwave stimuli.

dence of a cochlear microphonic, as seen from the second trace in FIGURE 7. Frey[8] has discounted the role of the cochlea in microwave acoustic effects, partly on the basis of not observing a microphonic in either cats or guinea pigs. We have found, however, in some animals, that the cochlear microphonic is considerably reduced (third trace in FIGURE 7) or not present at all (fourth trace in FIGURE 7) when the auditory system of the animal is stimulated by an acoustic pulse. Furthermore, Wever[12] has pointed out numerous factors that would prevent the observance of a cochlear potential, especially when the stimulus intensity is low. He cites work, for example, in which auditory thresholds in cats, as determined by behavioral levels, were established as being 40 dB below the stimulus level, the first effective level in producing cochlear microphonic potentials of sufficient magnitude to be identified with the conventional oscilloscope display. Thus, considering the fact that the microwave pulse generator is capable of only providing a 10–17-dB increase in pulse energy over that which corresponds to the threshold of elicited responses, the absence of a microwave-evoked cochlear microphonic does not rule out theories

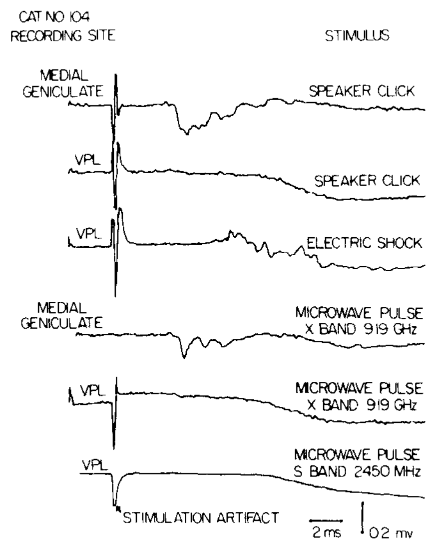

FIGURE 8. Cross-modal central nervous system responses to acoustic and microwave stimuli.

based on em to acoustic energy transduction. The capability of the evoked auditory effect in producing potentials at central nervous system sites other than auditory is illustrated in FIGURE 8. The first trace depicts the normal response recorded at the medial geniculate body as a result of acoustic stimuli. The second trace shows the cross-modal acoustically evoked response as recorded from the VPL, whereas the third trace represents the normal response in the VPL due to an electric shock applied to the tactile receptors at the right forepaw of the animal. The last three traces demonstrate that the microwave stimuli will also produce the same cross-modal responses. Thus, it is clear that evoked potentials due to microwave stimuli could be recorded at central nervous system sites other than those that correspond to the auditory nervous system. This finding leaves open the possibility that elicited potentials recorded from any location in the central nervous system could be misinterpreted as indicating a direct microwave interaction with the particular system where the recording is made.

Effect of Cochlear Disablement on the Interaction of Microwaves with the Auditory System

Nine cats were surgically prepared for recording potentials in three brain sites evoked by acoustic and microwave stimuli. Loci in which potentials were observed were the eighth cranial nerve, the medial geniculate nucleus, and the primary auditory cortex. The effect of cochlear disablement on these potentials was evaluated.

The subjects, which weighed from 2.0 to 3.4 kg, were assigned to three groups of three. The surgical preparation and details of the experiment have been reported previously by Taylor and Ashleman.[6] In the first group, a Ringer's solution-filled glass 100 μm diameter tip electrode was placed within the eighth cranial nerve, where it emerged from the internal auditory meatus. The exposure apparatus and instrumentation were similar to that shown in FIGURE 2, except that the animal's head was positioned in a holder constructed of dielectric material. The second group of animals was prepared in a manner similar to that used for the medial geniculate nucleus studies, discussed above, except that the electrode was cemented in place with dental acrylic material and the animals were removed from the stereotaxic instrument and placed in a dielectric head holder.

In the remaining group of animals, a Teflon®-covered high-resistance carbon conductor similar to that used for the round window cochlea experiments, discussed in the above section, was located by direct observation upon the anterior ectosylvian gyrus of the primary auditory cortex.

In all of the above cases, the cats were placed on a heating pad controlled by a rectal temperature monitor, and each animal was fitted with the piezoelectric crystal transducer, as described previously. Also, the acoustic bulla was surgically exposed in each animal. After surgery, each animal was allowed to stabilize, as evidenced by the uniformity of the waveform and latency of acoustically evoked responses. The crystal voltage was set to a level that appeared to be maximal in eliciting activity, and random samples of the activity were obtained. The crystal was then removed, the microwave pulse energy was set to a maximal level for evoking responses, and the wave forms were recorded.

When it was established for each case that responses were obtained with both acoustic and microwave stimuli, the cochlea was disabled by careful perforation of the round window with a microdissecting knife and aspiration of perilymph. Both cochlea were destroyed in the experiments that involved the medial geniculate nucleus and auditory cortex, sites assumed to have some bilateral representation. Cochlear destruction resulted in total loss of all evoked potentials, even with full available peak power used for both the acoustic and microwave stimuli and with increasing number of signals averaged on the computer of average transients. The data strongly support the contention that the microwave auditory effect is exerted on the animal in the same manner as that due to conventional acoustic stimuli. These results suggest closer examination of Frey and Messenger's[4] contention that the auditory effect cannot be a result of transduction of em to acoustic energy. The following section describes a study aimed toward gaining some insight into this possible mode of interaction.

QUANTITATION OF ELECTROMAGNETIC FIELD TO ACOUSTIC ENERGY TRANSDUCTION IN LOSSY DIELECTRIC MATERIALS

Frey's[3] argument that the auditory effect cannot be a result of em field forces on biologic materials was based in part on an analysis by Sommer and Von Gierke.[7] The latter authors directly compared radiation pressure to that required for free sound field-bone conduction threshold at 1000 cycles. Frey's threshold values for microwave-induced auditory effects appeared far too low to be consistent with the radiation pressure theory. Also, the comparison was incorrectly made between microwave pulses and a 1000-Hz acoustic tone rather than acoustic pulses. Finally, because the microwave energy is capable of penetrating deep into the tissue, volume forces, stresses, and pressures can be set up in many ways due to the sharp field gradients in the complex dielectric medium.

The threshold for audibility of narrow 20–500-μsec airborne acoustic pulses at recurrence frequencies much less than 100 pps has been determined by Flanagan[13] to be proportional to the energy per pulse or to the product of the pulse duration and the square of the pressure. Based on Flanagan's data, corrected for transducer characteristics, the threshold pressure corresponds to 1.26×10^{-2} dyn/cm^2 for a 20-μsec pulse. There is some uncertainty as to what the bone conduction threshold would be for pulses. According to Zwislocki,[14] the difference between air and bone conduction thresholds for continuous wave sound varies from 40 dB at 10 kHz to 60 dB at 1 kHz. Because the pulse frequency spectrum certainly spans this frequency range, we would expect the range of the bone conduction threshold to fall within 1.26–12.6 dyn/cm^2 for a free-field 20-μsec pulse. Based on the acoustic transmission coefficient of 2 from air to soft tissue, the pressure in the tissue would be in the range of 2.5–25 dyn/cm^2. The maximum radiation pressure that a 20-μsec 40-μJ/cm^2 microwave pulse would exert on a highly conducting surface would be 1.33×10^{-3} dyn/cm^2, which value is too low to explain the effect by a surface pressure. A surface pressure relationship is also imcompatible with Flanagan's[13] results and with our observations with respect to dependence of the hearing threshold on pulse energy. The acoustic pulse energy is proportional to the product of pulse width and square of the pressure, whereas the em pulse energy is directly proportional to the product of the induced pressure and pulse width. Frey and Messenger,[4] conversely, found for pulse widths greater than 50 μsec that loudness of microwave-evoked auditory sensation was proportional to the peak power of the applied pulse when the pulse energy was kept constant by decreasing the width, T, as the peak power was increased. Their data show, however, for the narrow 1–30-μsec pulse width range we are concerned with, that loudness did not vary. The decrease in loudness for wider pulses noted by these workers is not unusual, however, because the significant portion of the frequency spectrum of the pulse decreases markedly in width compared to the human auditory band pass. The possible consequences of this fact can be determined by noting the output of a pulsed band-pass filter with a transmission response equivalent to the human bone conduction hearing response. Though such a model may not truly represent a pulse response as it interacts with the auditory system, it does provide some qualitative insight as to possible effects of changing pulse width. If we define $H(f)$ as the normalized inverse of the bone conduction threshold curve given in part by Zwislocki,[14] and in part by Corso,[15] and convolve it with the spectrum of a pulse with width T and amplitude $1/T$

$$X(f) = \frac{\sin \pi f T}{\pi f T} e^{-j\pi f T}, \tag{1}$$

we may obtain the representative spectra shown in FIGURE 9 for the coupled constant energy microwave pulses of various widths. There is very little difference in the spectra for pulse widths up to 30–50 μsec, but as the width is increased beyond this point, the spectrum shape changes with a marked decrease in amplitude.

If we go one step further and calculate the assumed coupled acoustic energy (proportional to the square of pressure or square of the peak em pulse power) as a

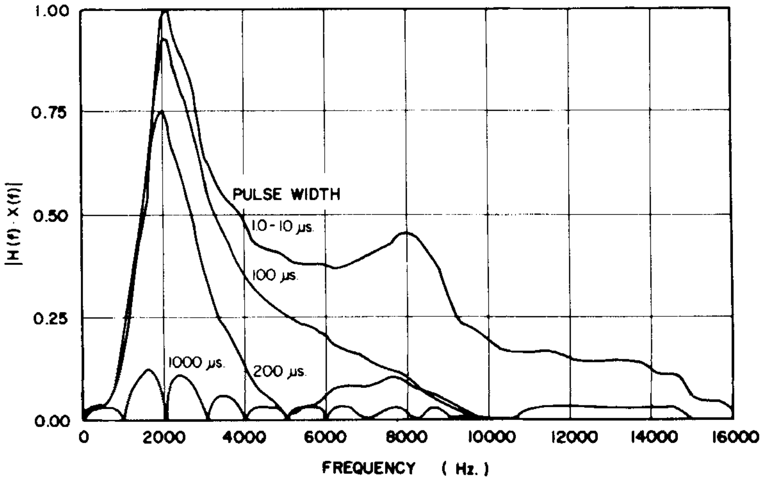

FIGURE 9. Output spectrum of pulsed band-pass filter with transmission characteristics that correspond to human bone conduction hearing response.

function of pulse width by squaring and integrating the spectra over the frequency domain, we obtain the upper curve in FIGURE 10. It is interesting to note that the plotted function decreases for pulse widths greater than 30 μsec, which corresponds to the variable loudness region observed by Frey and Messenger.[4] The lower curves in FIGURE 10 were plotted for the band-pass characteristics for the human subjects

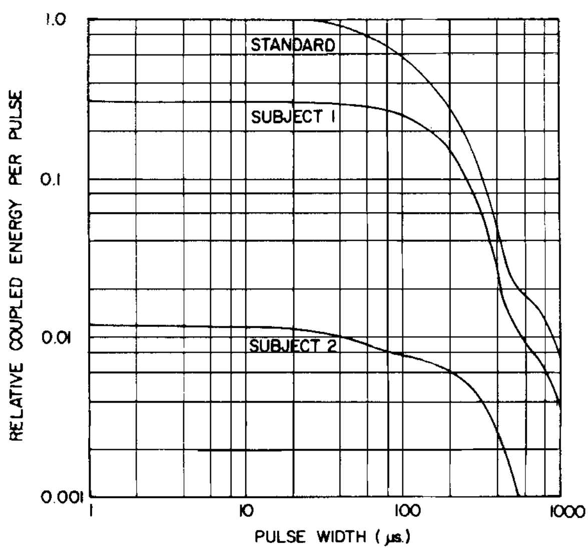

FIGURE 10. Relative transmitted energy per pulse of band-pass filter with characteristics of human bone conduction hearing response.

used in the auditory experiments already discussed. The subjects' audiograms are given in FIGURE 1. It is also interesting to note the 14-dB decrement between the curves in FIGURE 10 for the human subjects in light of the 10-dB (equivalent converted acoustic energy) difference in microwave-induced hearing threshold and the report by Frey[16] that subjects with loss of hearing above 5 kHz could not detect the microwave pulses.

Although the above observations do not support the radiation surface pressure hypothesis, they do not rule out other em to acoustic energy transduction processes. At the frequencies where the auditory effect is most pronounced, the em energy that penetrates and is absorbed deep in the tissues of the head can generate volumetric forces by various modes of interaction. Two types of pressures, much greater than radiation pressure, can be produced in tissues exposed to microwave pulses. These include electrostrictive and thermal expansion forces proportional to the square of the electric field in the material. Although the electrostrictive forces are unknown for biologic materials exposed to microwave frequencies, a rough estimate of the possible magnitudes may be obtained from the following equation given by Stratton[17] for an electrostatic field applied to a noncompressible dielectric fluid:

$$p = \frac{1}{6}\epsilon_0 E^2(\kappa + 2)(\kappa - 1), \quad (2)$$

where E represents the electric field, p is the pressure increase over it where $E = 0$, ϵ_0 denotes permittivity of free space, and κ is the dielectric constant of the liquid.

Although the thermal expansion forces are also unknown for biologic material, a theoretic and experimental analysis of the conversion of visible electromagnetic radiation from a Q-switched ruby laser to acoustic energy by thermal expansion due to absorbed energy in various liquids was made by Gournay.[18] It was shown that the pressures vastly exceeded radiation pressure. Foster and Finch[19] extended Gournay's analysis to the case of physiologic Ringer's solution exposed to microwave pulses and showed theoretically and experimentally that pressure changes far in excess of radiation pressures could produce significant acoustic energy in the exposed medium. It is very significant to note that the audible sounds could be produced by rapid thermal expansion associated with only a 5×10^{-6}°C temperature rise in the medium due to the absorbed em energy. The maximum pressure, p, induced in a semiinfinite absorbing liquid medium due to an incident microwave em pulse normal to the surface was derived by Gournay[18] as

$$p = \frac{3C\beta I_0}{2JS}(1 - e^{-\alpha CT})\ddagger \quad (3)$$

for a free surface and

$$p = \frac{3C\beta I_0}{JS}(1 - e^{-\alpha CT/2}) \quad (4)$$

for a constrained surface, where C is the elastic wave velocity, β represents the linear coefficient of thermal expansion, S denotes the specific heat, α equals the absorption coefficient for the medium, J is the mechanical equivalent of heat, I_0 is the em power intensity at the surface, and T represents the pulse width. Gournay's analysis also demonstrated that the maximum conversion efficiency (energy of

‡ Equations include corrections for errors that appear in the original reference.

propagated elastic wave divided by energy of transmitted em wave) for the energy transduction was

$$N = \frac{9C\beta^2 I_0}{2\rho S^2 J^2} F(\alpha CT), \tag{5}$$

where

$$F(\alpha CT) = (1 - e^{-\alpha CT} - \alpha CT e^{-\alpha CT})/\alpha CT \tag{6}$$

for a free surface and

$$F(\alpha CT) = (\alpha CT e^{-\alpha CT} + 3e^{-\alpha CT} + 2\alpha CT - 3)/\alpha CT \tag{7}$$

for a constrained surface, where ρ equals the density of the medium. The maximum value of $F(\alpha CT)$ is 0.3 at $\alpha CT = 2.0$ for the free surface and 2.0 at $\alpha CT > 10$ for the constrained surface.

Though the above analysis is based on an exposed semiinfinite medium with an absorption coefficient of α, we would expect acoustic pressures within the same order of magnitude to be induced in more complex media exposed to microwave pulses. If we assume a peak absorbed power density in the brain of 0.4 W/kg per 1 mW/cm^2 incident power density, based on a theoretical analysis by Johnson and Guy,[11] and also assume that Equations 3 or 4 may be applied to this case, the calculated acoustic pressure in the brain of approximately 2.2–3.0 dyn/cm^2 due to an incident 20-μsec 40-$\mu J/cm^2$ em pulse would be close to the computed internal threshold pressures. The estimated electrostrictive force of 1.4×10^{-2} dyn/cm^2 from Equation 2 would be far below the threshold of hearing range and much lower in amplitude than that due to the rapid thermal expansion conversion process.

It is of interest to note for the constrained surface where $\alpha CT < 5$ (which corresponds to pulse widths less than 30 μsec for Ringer's solution exposed to 2450-MHz microwaves) that $F(\alpha CT)$ is approximately equal to $\alpha CT/2$, which implies that the propagated elastic wave energy is proportional to the square of the incident electromagnetic wave energy. This finding is consistent with our experimental observations that the hearing threshold is constant with pulse energy for pulses less than 32 μsec and also with Frey's observations that loudness increased with peak power for pulse widths greater than 50 μsec.

In solid, more compressible materials, such as bone, electrostrictive and thermal expansion forces could be much larger. The fact that the interaction of microwave pulses with nonliquid lossy dielectric materials can produce sufficient volumetric forces and displacement in the material to be audible to nearby observers has recently been observed by Sharp and coworkers.[20] Audible sounds were elicited from microwave anechoic-absorbing material by peak pulse energies that corresponded to those that produced the auditory sensation to exposed humans.

We found in our laboratory that the air-conducted sounds could be evoked from microwave-absorbing materials of either porous or solid composition. Audible air-conducted sounds could be obtained neither from lossy liquids or gels exposed to the microwave pulses nor from good conductors (silver-painted plastic disks) or dielectrics (plastics with low dielectric constant). Weak audible sounds could be heard from exposed samples of low loss but high dielectric constant material. The prerequisite for audibility seems to be an electrical conductivity and/or dielectric constant within the range of human tissues such that the absorbed or stored em energy is distributed over a large volume of the illuminated material. With only surface absorption, such as with silver-coated samples, there was no detectable interaction. This result is consistent with Frey's observations, and ours, that the lowest thresholds of interaction occur at frequencies where absorption in the head occurs over a large volume.

To study the interaction with solid materials more quantitatively, a Michelson interferometer was assembled, as shown in FIGURE 11. A helium-neon laser beam was split so that one beam reflected from a small mirror attached to a dielectric test sample would form an interference pattern with a second beam reflected from a fixed mirror illuminating a pinhole in a plate. A fiberoptics guide was connected to an oscilloscope, a wave form averager, and an x-y plotter. The sample dielectric was illuminated with pulsed microwaves by the same 918-MHz power source and power measuring equipment used for the human and animal experiments. The sample interferometer and exposure apparatus were electrically isolated from the photomultiplier and associated electronics by a shielded room.

Shifts in the fringes of the interference pattern due to vertically polarized microwave field-induced displacements of the test object and mirror were sensed by the photomultiplier through the fiber-optics pathway, which extended through the wall of the shielded room. The system was calibrated to measure displacement as a function of the brightness of a fringe line over the pinhole by noting the full dynamic range of the oscilloscope voltage excursion (proportional to brightness) when the mirror was displaced one-half light wavelength or more. The sensitivity of the system was enhanced by repetitive averaging of the triggered responses of the sample. The dielectric samples tested for acoustic transduction properties were 5 cm diameter solid cylinders from 0.5 to 4.0 cm long. Four different types of materials were tested; three consisted of Laminac® 4110 polyester plastic loaded with varying amounts of acetylene black to produce electrical conductivities close to human tissue, as shown in TABLE 5, and the fourth was a sample of Eccosorb ANW-77 microwave absorber. The electrical properties of the disk were measured by standard transmission line techniques. The interferometer was also employed to deter-

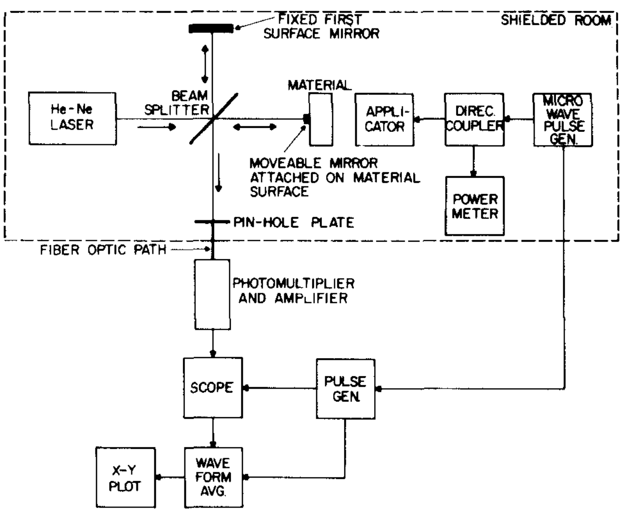

FIGURE 11. Michelson interferometer for measuring displacements in dielectric material illuminated by microwave pulses.

TABLE 5
COMPOSITION AND ELECTRIC PROPERTIES OF DIELECTRIC DISKS

Frequency (MHz)	Material*: Acetylene Black Content† (%)	Material*: Laminac 4110‡ (%)	Dielectric Constant ϵ'	Conductivity σ(mho/m)
918	1	99	6.41	0.266
918	2.5	97.5	14.12	1.817
918	5	95	20.00	3.316
2450	1	99	5.25	0.370
2450	2.5	97.5	10.47	2.126
2450	5	95	16.45	3.734

*A small amount of catalyst was added.
†Product of Shawinigan Products Corp.
‡Product of American Cyanamid Co.

mine the displacement wave form of the piezoelectric crystal and the loudspeaker used in the animal experiments.

To relate the internal fields in the samples to the acoustic responses of the sample, the internal energy density absorption and electric field patterns were measured in the disks by the thermographic technique described by Guy[10] and Johnson and Guy.[11] A high-power cw 918-MHz source was used to obtain the thermograms depicted in FIGURE 12, and the results were extrapolated linearly to determine the absorbed energy density and maximum internal root mean square electric field due to the vertically polarized incident 20-μsec 1.07-mJ/cm^2 pulse. The patterns for the 0.5–4-cm disks with the highest dielectric constant and electrical conductivity are illustrated at the left of the Figure, and those for a 4-cm thick sample with varying dielectric properties are provided at the right of the Figure. The "C" scan thermograms on the left of the Figure show the absorbed energy patterns (intensity proportional to brightness) at the exposed surface of the disks. Immediately to the right are horizontal profile "B" scans with vertical deflection proportional to absorbed energy density. The group of thermograms at the right of the Figure show the patterns for a longitudinal midsection scan of the disks. The maximum root mean square field strengths and absorbed energy densities are indicated in the Figure and may be used as references to determine values elsewhere.

FIGURE 13 illustrates displacement recordings made with the interferometer. The first wave form is that of the piezoelectric crystal excited with a 20-μsec 40-V pulse, the second is that of the loudspeaker excited with a 20-μsec 0.16 V pulse, the third is the typical response of a lossy dielectric disk exposed to a microwave pulse, and the last is the response of a 5-cm diameter 3-cm long cylinder cut from a slab of spongy Eccosorb ANW-77 absorber. The latter was interesting, since the displacement per unit of incident energy was greater than that for any of the other dielectric materials tested, probably due to its lower density and greater compressibility. The slight delay between the application of the pulse and first sign of displacement is also of interest. The displacement wave forms provided both maximum displacement and frequency of oscillation information useful for making estimates of internal pressures. In all cases, the acoustic responses of the disks to the incident microwave pulses were audible to nearby observers.

TABLE 6 summarizes the measured power absorption and acoustic characteristics of the exposed disk samples. The measured dielectric properties and sample

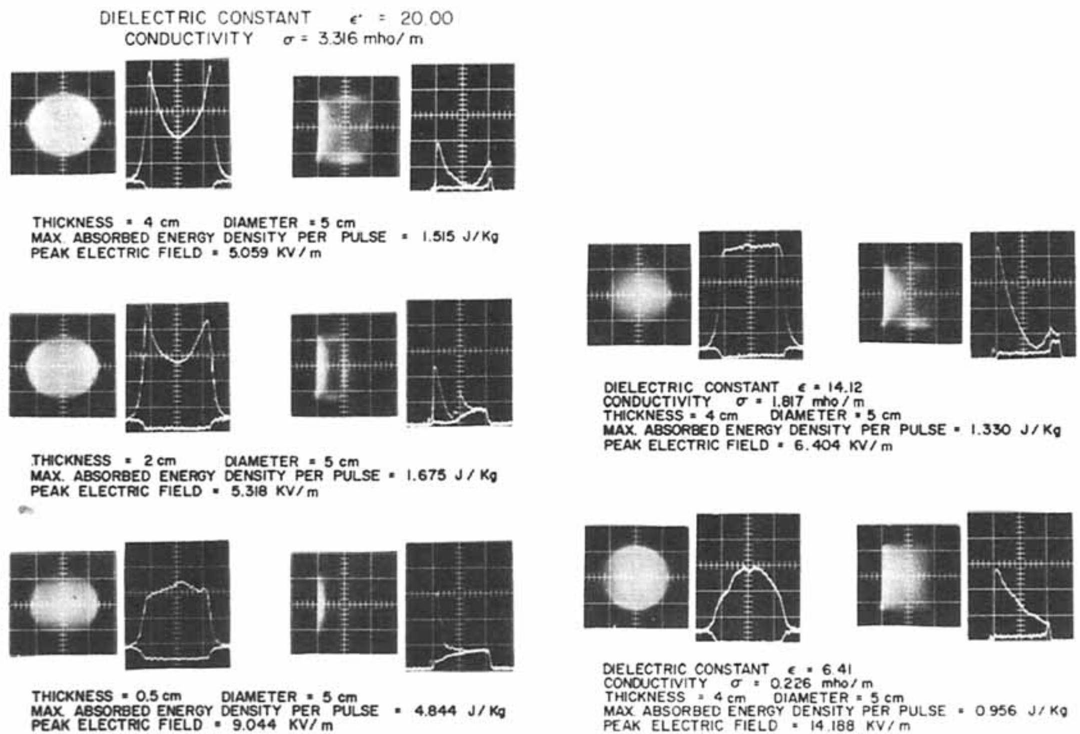

FIGURE 12. Thermograms that show absorbed energy density patterns (per pulse) in dielectric cylinders exposed to 918-MHz 20-μsec 1.07-mJ/cm² incident microwave pulses.

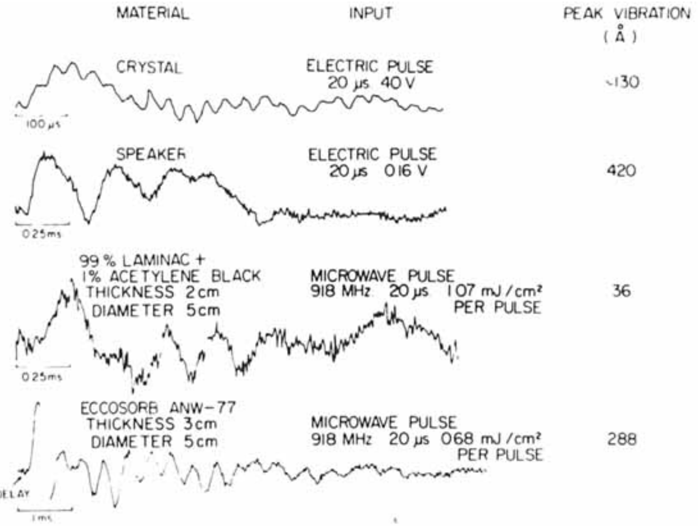

FIGURE 13. Displacement wave forms for pulsed acoustic transducers and for lossy dielectrics illuminated with microwave pulses.

thicknesses are given in the first three columns. The respective measured peak absorbed energy densities per pulse, the maximum root mean square electric field strengths, and the maximum measured displacements of the flat surface of the disks are tabulated in the next three columns. A rough estimate of the internal peak pressure vibration, p, in the disk was determined for each case from

$$p = \frac{2\pi\delta\rho v}{T_0}, \tag{8}$$

where δ represents the measured displacement, $\rho = 1.12 \times 10^3$ kg/m³ is the measured density, $v = 2400$ m/sec denotes measured velocity of sound propagation, and T_0 was the period of vibration of the disks.

To appreciate the significance of the calculated pressures, it is useful to compare them to pressures derived from Equation 3 for the semiinfinite medium (free surface) by use of the same internal measured field strengths and dielectric properties. The mechanical properties of the nonloaded polyester plastic were used. These calculated pressures are tabulated in the last column of TABLE 6. It is clear that the pressures listed in the last two columns of the Table exceed the calculated radiation pressure of 3.6×10^{-2} dyn/cm² by many orders of magnitude. It is also obvious that the induced oscillatory pressures in the exposed sample disks are far above those predicted for a fluid with the dielectric properties of brain matter. The disk oscillations produce sounds similar to the microwave-evoked "clicks" sensed in the human auditory system. The large difference in pressures between those calculated for liquids and the solid disk are certainly consistent with our failing to detect any displacement in liquid or gel materials. Foster and Finch's[19] measurement with a more sensitive hydrophone did detect the acoustic disturbances in the liquids, however. The actual hearing sensation is probably mediated by high-recurrence-rate multiple reflections of the acoustic disturbances within the head or portions of the skull. This

TABLE 6

COUPLED EM ENERGY* AND ACOUSTIC PROPERTIES OF EXPOSED DIELECTRIC DISKS

Dielectric Property		Sample Thickness (cm)	Maximum Absorbed Energy Density per Pulse (J/kg)	Peak Electric Field (kV/m)	Measured Displacement (Å)	Calculated Pressure† for Disk (dyn/cm^2)	Pressure for Semiinfinite Dielectric Medium‡ (dyn/cm^2)
ϵ'	σ(mho/m)						
6.41	0.266	4	0.96	14.19	28	993	2397
		2	1.02	14.66	36	2553	2559
		0.5	2.24	21.73	47	4546	5619
14.12	1.817	4	1.33	6.40	36	1277	1263
		2	1.72	7.29	38	2696	1638
		0.5	7.00	14.69	48	4643	6651
20.00	3.316	4	1.52	5.06	48	1703	1053
		2	1.68	5.32	66	4682	1164
		0.5	4.84	9.04	74	7157	3360

*918 MHz, 20 μsec, 1.07 mJ/cm^2 incident microwave pulses.

†Based on Equation 8.

‡Magnitude of estimated field-induced pressure in semiinfinite dielectric medium based on Equation 3.

is evidenced by the fact that the band-limited 50-Hz to 15-kHz noise did not affect the threshold of evoked potentials in the cat to the microwave stimuli as it did for the acoustic stimuli. It is known that cats perceive higher frequencies through both air and bone conduction. In humans, sound perception by bone conduction as high as 95 kHz has been reported by Corso.[15]

Conclusions

It has been shown that the threshold for microwave pulse-evoked auditory sensations or responses in both humans and cats is related to the incident energy per pulse, with values of approximately 20 $\mu J/cm^2$ for cats to 40 $\mu J/cm^2$ for humans for pulses less than 30 μsec wide. These values correspond to an estimated peak absorbed power density of 10–16 mJ/kg as measured in the cat head and approximately 16 mJ/kg as estimated for a human head. This energy density is capable of increasing the tissue temperature by only 5×10^{-6}° C. As background noise (50 Hz to 15 kHz bandwidth) was increased, the threshold for evoked responses in the medial geniculate nucleus of the cat remained stable for pulsed microwave stimuli but increased for acoustic stimuli. This finding would tend to indicate that the microwaves may be interacting more with the high-frequency portion of the auditory system. Except for the absence of the cochlear microphonic round window, all evoked potentials due to microwave stimulation were similar to those due to stimulation by acoustic clicks from a loudspeaker (air conduction) and a piezoelectric transducer (bone conduction) attached to the skull. It was shown, however, that the cochlear microphonic was not necessarily present for all types and magnitudes of acoustic stimuli. Because cochlear destruction resulted in total loss of all evoked potentials due to microwave and acoustic stimuli, there is strong support for the contention that the microwave auditory effect is exerted on the animal in the same manner as are conventional acoustic stimuli. Radiation and electrostrictive pressures were eliminated as a probable cause of the evoked response, because they are both too low in magnitude and inconsistent with the known threshold behavior for acoustic pulses. The most likely mechanism of electromagnetic field interaction appears to be conversion of em energy to acoustic energy due to thermal expansion. The thermal expansion forces appear to be the most likely interaction mechanism based on their relatively high predicted and measured values in liquid and solid materials exposed to microwave pulses. This hypothesis is further reinforced by the fact that the behavior of the measured threshold characteristics with pulse width agree with those predicted by the thermal expansion theory. It has been shown with a Michelson interferometer that displacements and forces induced in lossy dielectric disk samples by incident microwave pulses are many orders of magnitude above the threshold values for hearing. The interaction with the absorbing material was sufficiently strong that it was audible to nearby observers.

A prerequisite for interaction with the material is that the conductivity be sufficiently high and the frequency proper to permit a penetration of energy and loss over an appreciable fraction of the volume when the object is exposed to a microwave pulse. Microwave absorber materials used to reduce reflections and solid materials with the dielectric properties close to human tissues seem to fulfill the above requirements. The fact that the sounds are mediated by pulse energy levels sufficient to raise the tissue temperature only 5×10^{-6}° C points out the extreme care that one must exercise in classifying an effect as thermal or nonthermal based simply on the level of temperature increase.

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DISCUSSION

DR. K. R. FOSTER (*Naval Medical Research Institute, Bethesda, Md.*): I would like to point out that our measurements of actual acoustic pressures in fluid very closely duplicate your theoretic results. For pulse widths of less than 30 μsec, the sound intensity is related only to the energy per pulse. For longer pulses, the sound intensity is related to the peak pulse power. I question the relevance of exhibiting audiograms for patients when you only show the sensitivity up to 6000 Hz, because it's known that bone conduction hearing is generally sensitive to somewhat higher frequencies. Also, other circumstantial data indicate that this microwave hearing effect probably functions at much higher frequencies, for example, from 20 kHz down to 10 dHz. It might be more relevant to show the sensitivity in a higher-frequency hearing range.

Our theory shows that the measurements in a crystal or a dielectric solid may not be relevant to measurements made in a fluid. Specifically, the pulse produces a bimodal sound wave in a fluid. The leading and trailing edges of the pulse produce a large positive and a large negative transient, respectively. And this would be somewhat different than what you might expect to measure in a heated cell, such as would be produced by a laser pulse on a crystal.

DR. GUY: I agree with you. I think the microwave interaction probably occurs along the higher-frequency portion of the auditory system, as evidenced by the fact that the bandwidth of noise, from 50 Hz to 15 kHz, didn't seem to effect the microwave stimuli nearly as much as it did the acoustic stimuli. Additional evidence is that the loudness curve observed by Dr. Frey in patients was much steeper than that which can be predicted by using the band-pass filter concept. If coupling were enhanced in the high-frequency portion of the spectrum, it would produce a sharper change in the drop-off on this curve. The Michelson interferometer wasn't sensitive enough to measure any displacements in liquids. We tested liquids, gels, and other similar materials and could not detect any displacement. But, in the solid materials, it was very, very intense. In fact, observers could hear the sounds coming from all these samples quite well. Some measurements should be made on the solid materials, because I think that one could measure higher induced pressures in solid materials than in liquids.

DR. FOSTER: I think it's also important to qualify what you mean by the term "thermal" as applied to this kind of effect. This is certainly produced by heating, but the microwave hearing and thermal acoustic effects are related to the very rapid heating rate and not to the actual amount of heating in the fluid. The temperature rise per pulse is very small, about 10^{-6} °C. But, whether it occurs in a few microseconds or in 100 μsec is the important parameter, not the actual amount of temperature rise. So, this is a thermal effect in a very special sense of the term.

DR. K. D. STRAUB: I would like to offer an alternative explanation for these effects that may involve both cooling and heating. There is a well-known phenomenon pointed out by the Italian physicist Galietti to possess biologic relevance, namely, the Ludwig-Soret effect, which is the thermally induced electric field set up in ionic liquids. This effect is dependent not on the temperature rise but on the thermal gradient. In biologic materials, in which there is a conductive pathway in fluid and then a barrier, such as the cell membrane, one can obtain rather large thermal gradients, for example, 10^{5} °C/cm, with very small temperature changes. Such a large thermal gradient can produce, by the Ludwig-Soret effect, very large electric field changes in the membrane, large enough to cause depolarization, or movement of calcium from the surface of the membrane. Of course, the same phenomenon occurs in the cooling phase, in which thermal gradients in the opposite direction could give very large electric fields.

DR. FOSTER: We have performed some preliminary experiments with tissues, including blood and muscle. It appears that the magnitude of the thermal acoustic effect is not substantially different in tissue from that in water. This effect is simply transient heating produced by dielectric absorption of the water inside the tissues. I don't think that cooling is too relevant in this case. Thermal conduction is irrelevant in this instance, in the same sense that it is irrelevant to most ordinary acoustic processes. This fluid expands very quickly and emits a pressure wave. The speed at which this wave is propagated is much faster than that at which heat is dissipated through the medium. Cooling occurs over a much longer period of time.

I think that hearing of tones is simply the induction of repeated transients. The ear is somehow able to sense the harmonic content of this transient. This capability is very limited. Dr. Frey pointed out that it is not possible to modulate the hearing effect, that is, produce tones. One can basically only transmit the acoustic transient.

DR. GUY: What was your pressure in dynes per square centimeter for the 40 μJ supplied to your model?

DR. FOSTER: Somewhere between 10 and 20.

DR. J. DURANT (*Temple University, Philadelphia, Pa.*): What was the spectrum of your masking noise? Was it a broad-band mask?

DR. GUY: 50 Hz to about 15 kHz.

DR. DURANT: Some fairly convincing evidence has been presented to argue that the effects would not have an ultimate acoustic-like action in the cochlea, because cochlear microphonics should have reflected any activity created by the radiation, in that it does mimic the displacement of the cochlear partition. If it has an analogous acoustic effect, you would have been able to mask the response, although Dr. Foster's comment about the possible higher spectrum of effect makes this concept a little shakey, because the masking would not have been broad enough. Also, I would expect changes in the evoked eighth nerve potential, but such data present particular problems, in that you may be looking at a higher frequency spectrum than the standard click. The evoked potential is, after all, a statistical distribution of single unit discharges that occur simultaneously, and it will depend upon the displacement characteristics of the cochlear partition. We see a very classic potential wave form in practically any recording, whether a click or a pure tone. Of course, with a burst of tone, the response appears only at the tone onset. It is possible that if the excitation were an unusually high frequency, we might not see the typical AP wave form, but I would not expect the latency to be changed. Your result certainly doesn't look like an evoked potential in the usual sense.

Therefore, might the action be a more direct electric dipolarization of the neurons, from which I would expect much shorter latencies, if any? Also, have you recorded any single unit activity and looked at fiber specificity for this type of response?

DR. GUY: When we aspirated the fluid from the cochlea, all of the responses disappeared. We did not examine single units. Our capability was limited to providing energy levels from 10 to 17 dB higher than the threshold value. Also, with the piezoelectric transducer, we weren't able to produce any cochlear microphonics. We apparently did not have the capability to bring the microwaves up to the level required to produce microphonics.

DR. A. H. FREY: With regard to tonal perception, we have been examining for several years the communication aspects of the microwave hearing effect. We have explored for periodicity pitch phenomena. You can generate perception of tone. You can produce more than just clicks with this phenomenon.

DR. GUY: I agree with you. With pulse trains, we were able to produce pitch sensations that correspond to the frequency of the pulse repetition rate.

DR. J. M. OSEPCHUK (*Raytheon Research Division, Waltham, Mass.*): There is extensive literature on the thermal acoustic effect produced by microwaves, lasers, electron beams, and so forth, mainly reported by Richard M. White in the *Journal of Applied Physics* in the early 1960s. From his experiments, the acoustic effect appears plausible in terms of analyses that seem relevant to this problem.

DR. W. R. ADEY: I think we're moving a little closer to locating the transducing focus. I am surprised that there was no discussion of Dr. Guy's observation that re-moving fluid from the inner ear was associated with disappearance of these responses, because all these physiologic transducing surfaces require carefully arranged macromolecular hydration to remain viable. Possibly, his observation has more importance than this fleeting reference would imply.