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Microwave-induced auditory responses in guinea pigs: Relationship of threshold and microwave-pulse duration

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Auditory brainstem-evoked electrical responses of guinea pigs were used to determine microwave energy thresholds for perception of pulsed radiations. A klystron was used to generate 918-MHz microwaves at pulse widths between 10 and 500 μs; the microwaves were fed into a circular waveguide that partly enclosed a guinea pig's head. At pulse widths less than 30 μs, thresholds were related to the density of absorbed energy (and to the density of incident energy). The minimal absorbed energy density per pulse is 5 mJ kg^{-1}. As the width of the pulse increased, the threshold energy increased. For pulses longer than 70 μs, thresholds were related to the peak of the incident power density. The maximal power density of incident radiation is 90 mW cm^{-2} in the circular waveguide. The dependence of the evoked response on the width of the microwave pulse is in excellent agreement with predictions of thermal-expansion theory. These results provide more evidence that the microwave auditory effect is caused by a thermal expansion in the exposed head.

1. INTRODUCTION

Previous experiments in our laboratory showed that the human and feline threshold for hearing pulsed microwaves is related to the energy density per pulse and is independent of the pulse width for pulses that endure less than 30 μs [*Guy et al.*, 1975]. *Frey and Messenger* [1973] reported that acoustic perception of the microwave pulse is primarily dependent upon peak as opposed to averaged power for pulses to 70 μs in duration. *Foster and Finch* [1974] measured sound pressure of the microwave-generated acoustic transient in 0.15-M KCl solution and found that the pressure is directly proportional to the peak power for longer pulses and depends upon total energy for shorter pulses. Their experimental finding is consistent with predictions of the thermal-expansion theory [*White,* 1963; *Foster and Finch,* 1974; *Chou,* 1975].

To clarify some quantitative relationships between the pulse width and the threshold of hearing, we have performed additional experiments on guinea pigs by use of a new klystron that generates pulses from 1 μs to infinity in duration. Microwave-induced brainstem-evoked electrophysiological responses (BERs) in guinea pigs have been shown to be highly similar to those induced by acoustic pulses [*Chou et al.*, 1975b]. In the same report, we showed that wide-band acoustic noise depressed the microwave-induced BERs. After destruction of the cochlea, the BERs disappeared. All of these results indicate that the microwave-induced BERs are auditory responses. Because of the easy recording procedure, we have chosen to use the brainstem response for the study of auditory perception of microwave pulses in guinea pigs. In this paper, we report the thresholds of BERs determined for pulses of 918-MHz microwaves that ranged in width from 10 to 500 μs.

2. METHODS

2.1. *Waveguide-exposure system.*

The previously described circular waveguide system [*Chou et al.,* 1975b] was modified (Figure 1) so that microwaves could be fed into the system through a ~ 7.94-cm (3.125-in) coaxial waveguide. The TE_{11} mode is the only mode that can propagate in the waveguide at the operating frequency of 918 MHz. After an animal's head is inserted into the waveguide, where it is supported by a Styrofoam rest, it is parallel to the electrical field of the TE_{11} mode; the VSWR can be reduced to a minimal value of 1.02 by adjusting a sliding short and by varying the depth of insertion of a guinea pig's head (Figure 2). The mesh waveguide is less expensive and of lower mass than the solid-brass waveguide. The mesh screen also provides ventilation for the animal and easy viewing of the animal during an experiment. Since the metal-mesh waveguide is highly conductive, the loss in the waveguide is minimal. There is no radiation leakage through the mesh because of the long wavelength of the 918-MHz fields compared with the size of the mesh (~ 0.64 cm).

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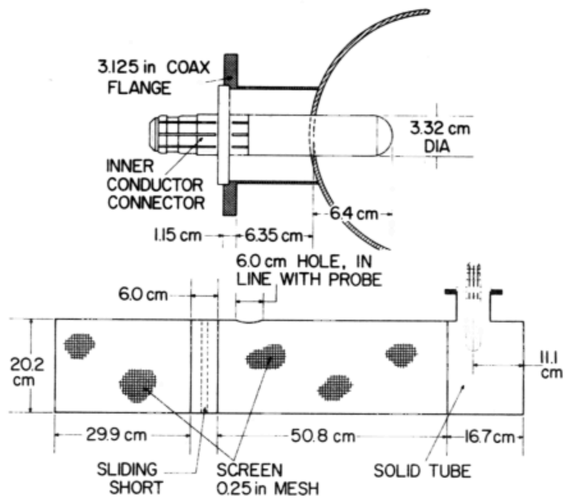

Fig. 1. Details of the circular waveguide for efficient coupling of energy into an animal's head.

2.2. *Exposure parameters.*

The power source was a klystron that generated microwaves at a maximum power of 10 kW; pulse width could be varied from 1 μs to infinity in the range of carrier frequencies from 720 to 1000 MHz. Only 918-MHz energy was used since the waveguide system was designed for minimal reflections at this frequency. The microwaves were fed into the waveguide via coaxial waveguide through a shielded room. The microwaves were generated as rectangular pulses of 10 to 500 μs duration; the rise time was less than 1 μs.

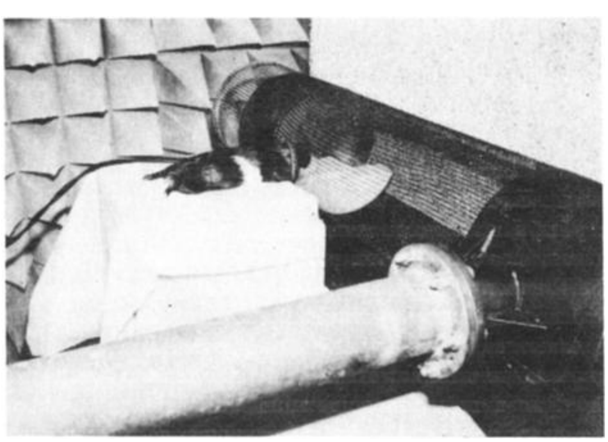

Fig. 2. Circular waveguide showing the ~ 7.94-cm coaxial feed and a guinea pig subject.

An animal's head was inserted into the exposure system, which was tuned for minimal reflected power at a low input (1 W) of CW energy. The tuning procedure usually required less than 30 seconds. After optimal positioning of the head, the exposure system and the animal were enclosed in a shielded, electrically and acoustically anechoic chamber.

2.3. *Recording of brainstem-evoked responses.*

Two carbon-loaded Teflon electrodes (4 S m^{-1}) were attached to the skin of the guinea pig's head at the vertex (top of the head) and at either the right or the left mastoid process. The head of the guinea pig was then placed in the waveguide. The two carbon leads were connected to a Tektronix Model-3A9 differential amplifier. The amplification and the frequency response of the amplifier were set at 2×10^5 and 100-3000 Hz, respectively. The output of the amplifier was fed to a signal-averaging computer (TMC CAT 400C). Finally, evoked potentials that represented the average of 400 summations were traced in ink by an X-Y recorder.

A loudspeaker was located 15 cm from the head of the guinea pig. Sound levels of acoustic pulses were adjusted from 0 to 80 dB with respect to the threshold level of hearing. Acoustic stimulation was used to verify the hearing ability of the animals. The threshold of input power for a detectable BER was determined for each pulse width. A pulse-repetition rate of 30 s^{-1} was chosen since a higher rate resulted in reduced amplitude of the BER.

2.4. *Dosimetry.*

Because the VSWR was very low (1.02) and because thermographic data have previously shown that absorption of microwaves is largely confined to the head [*Chou et al.,* 1975b], the leakage around the neck of the guinea pig was less than 0.1% of the input energy [*Chou et al.,* 1975a]. The averaged density of absorbed energy was calculated by dividing the total energy of the microwave pulse by the mass of the head.

3. RESULTS

Comparisons of the BER as induced by acoustic and by microwave pulses of differing pulse widths are shown in Figure 3. Except for the longer latency of the acoustic BER, due to the slower propagation of sound, the waveforms of acoustically and microwave-induced BERs are highly similar. The latencies of the microwave-induced BERs are about the same despite large differences (190 μs) in pulse width, which indicates that the evoked response is time-locked to the onset of the microwave pulse. This datum is also consistent with previous findings on the chochlear microphonic [*Chou et al.,* 1975a] on a more expanded time scale.

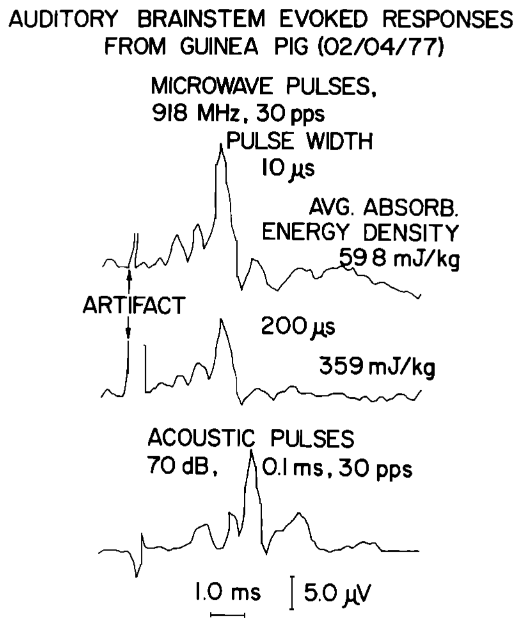

Fig. 3. Auditory brainstem-evoked responses produced by microwave and acoustic stimuli.

The thresholds of the microwave-induced BER were determined for each pulse width (Table 1). The power density of incident radiation was calculated by dividing the input power by the cross-sectional area of the circular waveguide. The averaged density of absorbed energy per pulse was calculated by multiplying the peak of power density of incident radiation by the pulse width, and then dividing the product by the mass of the animal's head. Because of the efficient coupling of energy in the waveguide, the thresholds of incident radiation or of energy density are about ten times lower than those measured in a free field [*Guy et al.*, 1975]. However, the averaged density of absorbed energy per pulse is about the same as that measured in the free field [*Guy et al.*, 1975].

Figure 4 illustrates the relationship between pulse width and the threshold of peak-power density. The peak of power density decreases as the pulse width increases to 30 μs. Above 30 μs, the threshold of peak power increases and then reaches a constant value for pulses longer than 70 μs. If plotted in terms of averaged density of absorbed energy (Figure 5), the threshold increases monotonically for pulses longer than 30 μs.

4. DISCUSSION

We have shown that the absorbed-energy threshold of microwave hearing in guinea pigs is the same for microwave pulses shorter than 30 μs; however, the threshold increases for longer pulses (Figure 5). For pulses longer than 70 μs, the threshold is determined by peak power (Figure 4).

In agreement with *Gournay's* [1966] equations for determining pressure from thermal expansion in a semi-infinite medium, the maximal pressure in the medium is proportional to the total energy of the pulse for shorter pulses and is proportional to the peak power for longer pulses [see also *Chou*, 1975]. *Foster and Finch* [1974] measured acoustic transients in KCl solution for microwave pulses to 25 μs and found the predicted relationship.

Frey and Messenger [1973] have shown that a given

TABLE 1. Threshold of microwave hearing of guinea pig at various pulse widths.

(Pulsed 918-MHz Microwaves, 30 pps, in Circular Waveguide)

PULSE WIDTH (μs)	PEAK INCIDENT POWER DENSITY* (mW/cm^2)	AVG. INCIDENT POWER DENSITY* ($\mu W/cm^2$)	INCIDENT ENERGY DENSITY PER PULSE* ($\mu J/cm^2$)	AVG. ABSORBED ENERGY DENSITY PER PULSE (mJ/kg)
10	156.0	46.8	1.56	5.99
20	78.0	46.8	1.56	5.99
30	62.4	56.2	1.87	7.19
50	78.0	117.0	3.90	14.97
70	93.6	196.6	6.55	25.15
100	93.6	280.8	9.36	35.93
150	87.3	392.8	13.10	50.30
200	93.6	561.6	18.72	71.86
300	87.3	785.7	26.19	100.60
400	93.6	1123.2	37.44	143.71
500	93.6	1404.0	46.80	179.64

*The energy density of incident radiation is calculated by dividing the total input power or energy by the cross-sectional area of the waveguide. Due to the efficient energy coupling in the waveguide, the threshold power or energy of incident radiation is about ten times lower than those in free space. The averaged density of absorbed energy is comparable to that in free space.

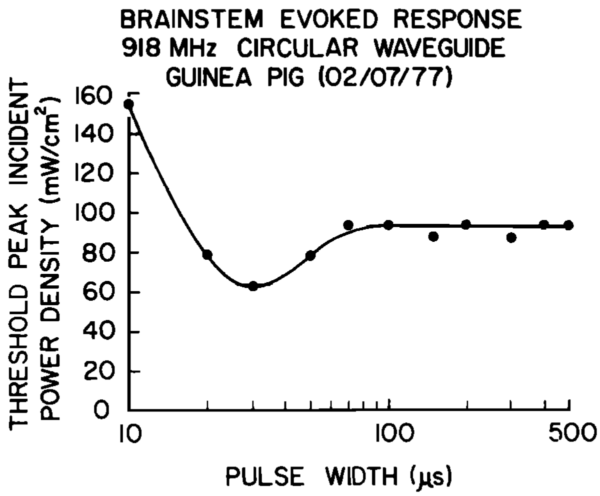

Fig. 4. Thresholds of peak density of incident microwaves for evocation of acoustic responses in guinea pigs as a function of pulse width.

averaged power density of incident radiation (i.e., at a given density of absorbed energy), the loudness of microwave-induced sound is about the same for pulse widths between 10 and 30 μs, and decreases for pulses longer than 50 μs. When the peak power was kept constant, the loudness increased when the pulse width was lengthened from 10 to 30 μs, and then decreased with pulses longer than 30 μs. All of their data are consistent with ours, although they interpreted their data differently.

Lin [1977] has computed pressures from thermal expansion for spherical models of the brain of 3- and 7-cm radius; he assumed a sinc-function pattern of heating.

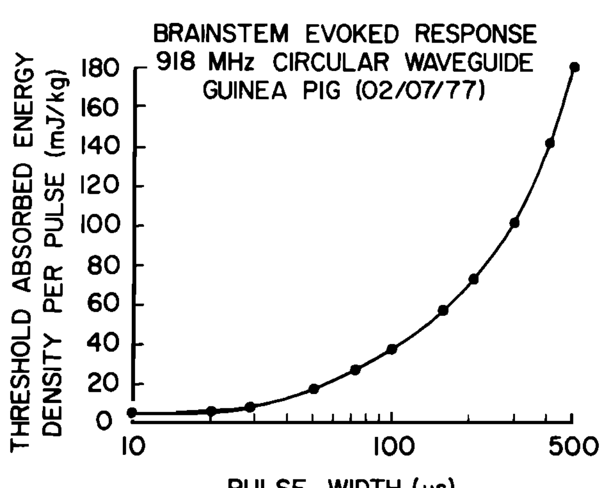

Fig. 5. Thresholds of density of absorbed energy per microwave pulse for evocation of acoustic responses in guinea pigs as a function of pulse width.

Under a free-surface boundary condition and a given peak power of incident radiation, the pressure in the center of the spheres should increase rapidly with increasing pulse width and then oscillate about a constant value. The disagreement between Lin's theoretical calculation and our experimental findings is probably due to the theoretical assumptions upon which the calculations were based.

Our previous studies of cochlear microphonics [*Chou et al.*, 1975b] indicated that microwave hearing is due to a mechanical disturbance of cochlear hair cells. Experiments involving animals of differing body mass showed that the frequency of the cochlear microphonic is related to the dimension of the brain cavity [*Chou et al.*, 1977]. This finding further supports the mechanical nature of the microwave auditory effect. The elegant experiment performed by *Foster and Finch* [1974] showed that the wave of pressure that is generated by a microwave pulse in distilled water is inverted between 0 °C and 4 °C, and reappears above that temperature, in agreement with the temperature-dependent density of water. Theoretical calculations of the pressure of the thermal-expansion wave that is generated in the human head are close to values of the threshold of hearing [*Guy et al.*, 1974; *Chou*, 1975; *Lin*, 1977]. With the additional data presented here, we believe it is highly probable that thermal expansion is the mechanism of microwave hearing.

5. CONCLUSION

Experiments on guinea pigs have shown that the threshold of microwave hearing is related to the incident energy per pulse for pulses shorter than 30 μs and is related to the peak power of incident energy for longer pulses, at least to 500 μs. The threshold dependence on pulse width is consistent with predictions of the thermal-expansion theory. In conjunction with the data on the microwave-induced cochlear microphonic, all of the evidence indicates that microwave hearing is the result of a thermoelastic mechanical disturbance.

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