TABLE I
ELASTIC AND THERMAL PROPERTIES OF BRAIN MATTER

Specific heat, c_h	0.88 cal/gm-°C
density, ρ	1.05 gm/cm^3
coefficient of thermal expansion, α	4.1×10^{-5}/°C
Lame's constant, λ	2.24×10^{10} dyn/cm^2
Lame's constant, μ	10.52×10^3 dyn/cm^2
Bulk velocity of propagation, c_1	1.460×10^5 cm/sec

microwaves at 918 MHz. The oscillations promptly followed onset of radiation, preceded the nerve responses, and disappeared after death. It is therefore reasonable to conclude that the microwave-induced auditory effect is a cochlear response to acoustic signals that are generated, presumably in the head, by pulsed microwaves.

When human subjects are exposed to pulsed microwave radiation, an audible sound occurs which appears to originate from within or immediately behind the head. The microwave-generated sound has been described as clicking, buzzing, or chirping depending on such factors as pulsewidth and repetition rate [2], [4], [5], [7], [8]. The effect is of great significance since the average incident power densities required to elicit the response are considerably lower than those found for other microwave biological effects and the threshold average power densities are many orders of magnitude smaller than the current safety standard of 10 mW/cm^2 [9].

Although the effect is widely accepted as a genuine biologic effect occurring at low average power densities, there exists some controversy regarding the mechanism by which pulsed microwave energy is converted to sound [1], [4], [7], [10]–[13]. This paper analyzes the acoustic wave generated in the heads of animals and man exposed to pulsed microwave radiation as a result of rapid thermal expansion.

We assume that the auditory effect arises from the minuscule but rapid rise of temperature in the brain as a result of absorption of microwave energy. The rise of temperature occurring in a very short time is believed to create thermal expansion of the brain matter which then launches the acoustic wave of pressure that is detected by the cochlea [13].

We consider the head to be perfectly spherical and consisting only of brain matter. The impinging radiation is assumed to be a plane wave of pulsed microwave energy. Our approach is first to obtain the absorbed microwave energy inside the head. The accompanying temperature rise is then derived, and finally the inhomogeneous thermoelastic motion equation is solved for the acoustic wave generated in the head.

The relevant physical parameters of brain matter are listed in Table I. All except one are typical values obtained from the literature [14]–[16]. For the coefficient of thermal expansion, which does not seem to have been measured in the past, we assume a value equal to 60 percent of the corresponding value for water. These values will be useful for quantitative estimations of the frequency and threshold of pulsed microwave-induced hearing.

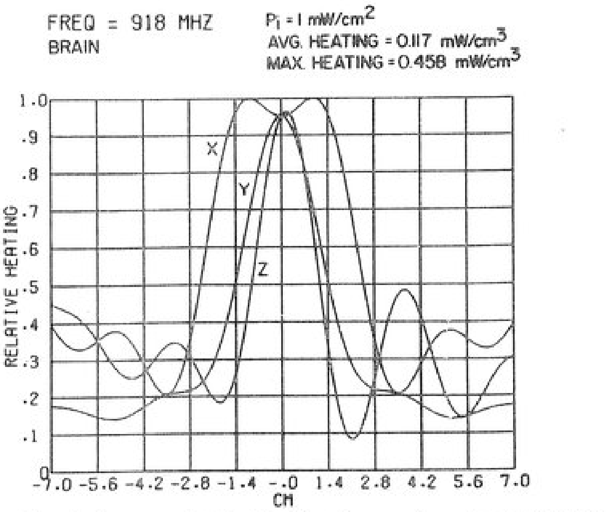

Fig. 1. Absorbed energy distribution in a 7-cm-radius spherical model of the head exposed to 918-MHz plane wave. The incident power density is 1 mW/cm^2 [20].

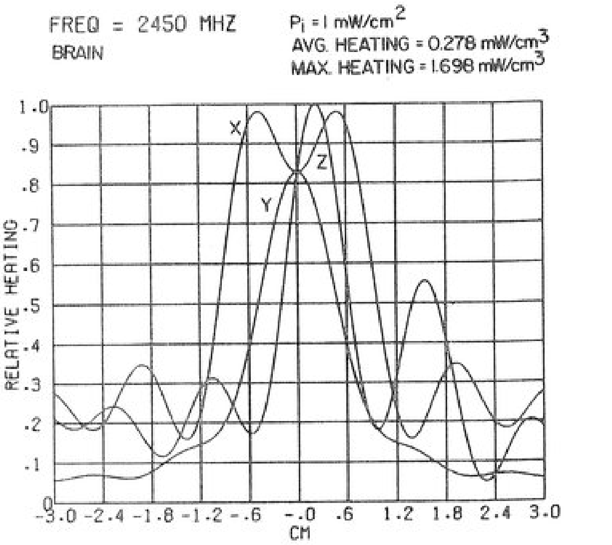

Fig. 2. Absorbed energy distribution in a 3-cm-radius spherical model of the head exposed to 2450-MHz plane wave. The incident power density is 1 mW/cm^2 [20].

II. THEORETICAL FORMULATION

A. Microwave Absorption

Let us consider a homogeneous spherical model of the head exposed to a plane wave of pulsed microwave energy. The absorbed microwave energy $I(r,t)$ at any point inside the head is given by

$$I(r,t) = \tfrac{1}{2}\sigma|\bar{E}|^2 \quad (1)$$

where σ is the electrical conductivity of brain matter. The induced electric field $\bar{E}$ is given by

$$\bar{E} = E_0 e^{-i\omega t} \sum_{j=1}^{\infty} i^j \frac{2j+1}{j(j+1)} [a_j \bar{M}_{01j} - i b_j \bar{N}_{e1j}] \quad (2)$$

where E_0 is the incident electric field strength, $\omega = 2\pi f$, f is frequency, a_j and b_j are magnetic and electric oscilla-