displacement generated by thermal expansion may be more than three orders of magnitude greater than those generated by the other mechanisms [11], [12]. Consequently, the thermal expansion mechanism has become the most generally accepted transduction mechanism.

This paper presents a theoretical study of the acoustic signal generated in the heads of humans and laboratory animals irradiated with rectangular pulses of microwave energy. Assuming the auditory sensation results from acoustic waves generated in the tissues of the head by rapid thermal expansion of the tissues upon microwave absorption, the amplitude and frequency of the auditory signal are derived for a homogeneous spherical model of the head under constrained-surface conditions. The results for stress-free surfaces have been given previously [13], [14]. Closer agreement between theory and experiment, however, is achieved by extending the theoretical formulation to include constrained-surface boundary conditions.

Absorbed Microwave Distribution

The absorption of microwave radiation in mammalian cranial structures has been theoretically studied using spherical models exposed to plane-wave microwave radiation [15]–[17]. The absorption patterns have also been examined experimentally using homogeneous spherical brain phantoms [18], [19]. It was found that absorption peaks occur [for certain frequencies (i.e., 500–3000 MHz)] inside spherical heads, ranging in size from a small laboratory animal to an adult human. Moreover, standing-wave-like oscillations are seen along any axis and reach maxima near the center of the spherical head model.

For mathematical simplicity, we assume the absorption pattern is spherically symmetric inside the head and approximate it by the function [14]

$$W = I_0[\sin(N\pi r/a)/(N\pi r/a)] \tag{1}$$

where I_0 is the peak energy absorption per unit volume, r is the radial variable, a is the radius of the spherical head, and N denotes the number of oscillations in the absorption pattern. Fig. 1 shows the proposed absorbed energy approximation for $N = 6$. This example is particularly well-suited to the cases of a cat exposed to 2450-MHz microwaves and a human exposed to 918-MHz microwaves.

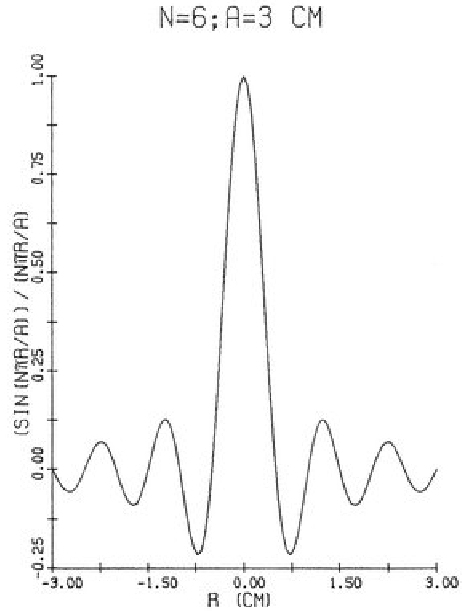

Fig. 1. Spatial distribution of absorbed microwave energy.

Induced Temperature Rise

The temperature change induced by absorbed microwave energy is given by the heat-conduction equation. Taking advantage of the spherical symmetry, the heat-conduction equation may be expressed as a function of r alone [20] such that

$$(1/r^2)[\partial r^2(\partial v/\partial r)/\partial r] - (1/\kappa)(\partial v/\partial t) = -W/K \tag{2}$$

where v is the temperature rise and K and κ are, respectively, the thermal conductivity and diffusivity of brain matter. Assuming heat conduction to be negligible, we may set the spatial derivatives equal to zero [14]. The expression for v then becomes

$$(1/\kappa)(dv/dt) = W/K. \tag{3}$$

We integrate (3) setting the constant of integration (the initial temperature) equal to zero to get the desired temperature distribution. Thus

$$v = (I_0/\rho c_h)[\sin(N\pi r/a)/(N\pi r/a)]t \tag{4}$$

where ρ and c_h are the density and specific heat of brain matter, respectively, and $\rho c_h = K/\kappa$.

Since the stress-wave development time is short compared with temperature equilibrium time in most materials, we assume for a rectangular pulse of microwave energy (t_0 = pulsewidth), immediately after power is removed, that the temperature stays constant at

$$v = (I_0/\rho c_h)[\sin(N\pi r/a)/(N\pi r/a)]t_0. \tag{5}$$

Thermoelastic Sound Generation

Considering the spherical head with homogeneous brain matter as a linear, isotropic elastic medium without viscous damping, and taking advantage of the spherical symmetry, we may express the thermoelastic equation of motion as follows [14], [21], [22]:

$$(\partial^2 u/\partial r^2) + (2/r)(\partial u/\partial r) - (2/r^2)u - (1/c_1^2)(\partial^2 u/\partial t^2) = [\beta/(\lambda + 2\mu)](\partial v/\partial r) \tag{6}$$

where u is the displacement, $c_1 = [(\lambda + 2\mu)/\rho]^{1/2}$ is the velocity of propagation of bulk acoustic wave, $\beta = \alpha(3\lambda + 2\mu)$, α is the linear coefficient of thermal expansion, and λ and μ are Lame's constants. It is clear that under the present circumstances the curl of u is zero since u is a function of the radial variable only. Because μ is very small compared to λ (see Table I), we will neglect shear stress in the following development. The right-hand side of (6) is the driving function for the thermoelastic displacement and we may express it as

$$[\beta/(\lambda + 2\mu)](\partial v/\partial r) = u_0 F_r(r) F_t(t) \tag{7}$$