we start with the observation that $\boldsymbol{h}_d$ is a gradient:

$$\boldsymbol{h}_d = \nabla \phi_d. \tag{B2}$$

Then from the divergence theorem

$$\int_\Omega (\boldsymbol{m} + \boldsymbol{h}) \cdot \boldsymbol{h}_d \, dV = \int_{S_\Omega} \phi_d(\boldsymbol{m} + \boldsymbol{h}) \cdot d\boldsymbol{S} - \int_\Omega \phi_d \nabla \cdot (\boldsymbol{m} + \boldsymbol{h}) \, dV. \tag{B3}$$

The first integral on the right-hand side is zero because the RF magnetic induction $(\boldsymbol{m} + \boldsymbol{h})$ must be parallel to the coupling conductors, which define the surface S_Ω. The second integral is zero because $\nabla \cdot (\boldsymbol{m} + \boldsymbol{h}) = 0$.

A similar argument demonstrates that

$$\int_\Omega \boldsymbol{h}_e \cdot \boldsymbol{h}_d \, dV = 0. \tag{B4}$$

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Further Studies on the Microwave Auditory Effect

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Abstract—**Auditory signals generated in humans and animals who are irradiated with short rectangular pulses of microwave energy have been studied. Assuming that the effect arises from sound waves generated in the tissues of the head by rapid thermal expansion caused by microwave absorption, and using a technique described previously, the governing equations are solved for a homogeneous spherical model of the head under constrained-surface conditions. The results indicate that the frequency of the auditory signal is a function of the size and acoustic property of the head only. While the amplitude and frequency of the microwave-induced sound are higher than those predicted by the stress-free boundary condition formulation, they are compatible with the experimental results reported to date.**

Introduction

IN RECENT YEARS many investigators have studied the auditory sensations produced in man by appropriately modulated microwave energy [1]–[5]. Other investigators [3], [5]–[7] have shown that electrophysiologic auditory activity may be evoked by irradiating the brains of laboratory animals with rectangular pulses of microwave energy. Responses elicited in cats both by conventional acoustic stimuli and by pulsed microwaves were similar and they disappeared following disablement of the cochlea and following death. More recently, cochlear microphonics have been recorded from the round window of cats and guinea pigs during irradiation by pulse-modulated 918-MHz microwaves. These results suggested that microwave-induced auditory sensation is transduced by a mechanism similar to that responsible for conventional sound perception and that the primary site of interaction resides somewhere peripheral to the cochlea. A peripheral response to microwave pulses should involve mechanical displacement of the tissues of the head with resultant dynamic effects on the cochlea.

Several physical mechanisms have been suggested to account for the conversion of microwaves to acoustic energies; these include radiation pressure, electrostriction, and thermal expansion [3], [8]–[10]. A comparison of these three mechanisms for planar geometries revealed that the forces of

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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.

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

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

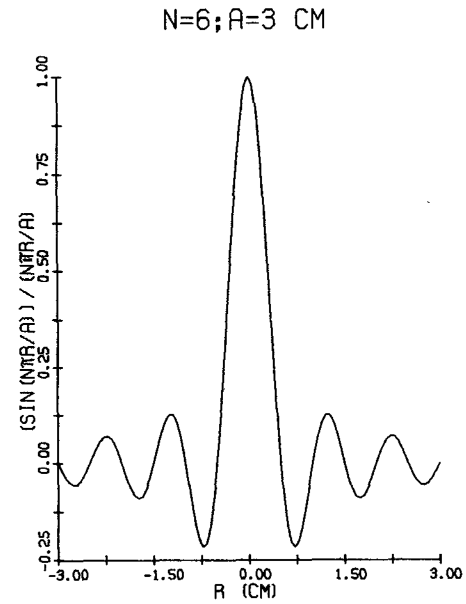

Fig. 1. Spatial distribution of absorbed microwave energy.

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

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

TABLE I
THERMOELASTIC PROPERTIES OF BRAIN MATTER [14]

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

such that

$$u_0 = (I_0/\rho c_h)[\beta/(\lambda + 2\mu)] \tag{8}$$

and

$$F_r(r) = (d/dr)[\sin (N\pi r/a)/(N\pi r/a)] \tag{9}$$

also

$$F(t) = \begin{cases} t, & 0 < t < t_0 \\ t_0, & t > t_0. \end{cases} \tag{10}$$

For a constrained surface, the boundary condition at the surface of the sphere is expressed by

$$u(a,t) = 0. \tag{11}$$

The initial conditions are

$$u(r,0) = \partial u(r,0)/\partial t = 0. \tag{12}$$

Following a technique used previously [14], we will first solve (6) for the case of $F_t(t) = 1$ and then extend the solution to a rectangular pulse using Duhamel's principle.

Solution for $F_t(t) = 1$

We first write the displacement u as

$$u(r,t) = u_s(r) + u_t(r,t) \tag{13}$$

and substitute (13) into (6) to obtain

$$(d^2u_s/dr^2) + (2/r)(du_s/dr) - (2/r^2)u_s = u_0 F_r(r) \tag{14}$$

and

$$(\partial^2 u_t/\partial r^2) + (2/r)(\partial u_t/\partial r) - (2/r^2)u_t = (1/c_1^2)(\partial^2 u_t/\partial t^2). \tag{15}$$

The corresponding boundary conditions are

$$u_s(a) = 0 \tag{16}$$

and

$$u_t(a,t) = 0. \tag{17}$$

To facilitate the solution of (14), we let

$$u_s = u_p + Br \tag{18}$$

where u_p is a particular solution of (14) and is obtained by integrating (14) from 0 to r. Thus

$$u_p = u_0(a/N\pi)j_1(N\pi r/a) \tag{19}$$

where j_1 is the spherical Bessel function of the first kind. The coefficient B is evaluated by applying the boundary condition given in (16). The solution to (14) is therefore

$$u_s = (u_0/N\pi)[aj_1(N\pi r/a) \mp (r/N\pi)], \quad N = \begin{cases} 1, 3, 5, \cdots \\ 2, 4, 6, \cdots. \end{cases} \tag{20}$$

Next we let

$$u_t = R(r)T(t) \tag{21}$$

and solve (15) using the method of separation of variables. Substituting (21) into (15) we have

$$(d^2R/dr^2) + (2/r)(dR/dr) + (k^2 - 2/r^2)R = 0 \tag{22}$$

and

$$(d^2T/dt^2) + k^2c_1^2 T = 0 \tag{23}$$

where k is the yet undetermined constant of separation. The solution of (22) is a set of spherical Bessel functions j_1 and y_1 or

$$R = B_1 j_1(kr) + B_2 y_1(kr). \tag{24}$$

Since R is finite at $r = 0$, B_2 must be zero. Substituting (24) into the boundary condition of (17) we get an equation for the separation constant k. Thus

$$j_1(ka) = 0. \tag{25}$$

We may denote the zeros of j_1 by $k_m a$, $m = 1, 2, 3, \cdots$. The solution to (23) is clearly harmonic in time. We may write the general solution to (15) as

$$u_t = \sum_{m=1}^{\infty} A_m j_1(k_m r) \cos \omega_m t \tag{26}$$

where A_m is yet to be determined and $\omega_m = k_m c_1$ or

$$f_m = k_m c_1/2\pi. \tag{27}$$

Since f_m represents the frequency of vibration of the spherical head, there are, therefore, an infinite number of modes of vibration of the spherical head irradiated with appropriate pulse-modulated microwave energy.

To evaluate A_m, we need the initial condition $u(r,0) = 0$ and the orthogonality relations given in [14]. Thus

$$A_m = \pm 2u_0 a(1/N\pi)^2 \cdot \frac{(1/k_m a)j_2(k_m a) \pm k_m a j_0(k_m a)/[(k_m a)^2 - (N\pi)^2]}{[j_1(k_m a)]^2 - j_0(k_m a)j_2(k_m a)}, \quad N = \begin{cases} 1, 3, 5, \cdots \\ 2, 4, 6, \cdots. \end{cases} \tag{28}$$

By substituting (20) and (26) into (13), we have

$$u = u_0 D + \sum_{m=1}^{\infty} A_m j_1(k_m r) \cos \omega_m t \tag{29}$$

where

$$D = (1/N\pi)[aj_1(N\pi r/a) \mp (r/N\pi)], \quad N = \begin{cases} 1, 3, 5, \cdots \\ 2, 4, 6, \cdots. \end{cases} \tag{30}$$

The radial stress (pressure) in terms of displacement [14] is

$$\sigma = (\lambda + 2\mu)(\partial u/\partial r) + (2\lambda/r)u - \beta v \tag{31}$$

and so we have, by substituting (29) into (31),

$$\sigma = u_0 G + \sum_{m=1}^{\infty} A_m k_m H_m \cos \omega_m t \tag{32}$$

where

$$G = -(4\mu a/N\pi r)j_1(N\pi r/a) \mp (1/N\pi)^2(3\lambda + 2\mu), \quad N = \begin{cases} 1, 3, 5, \cdots \\ 2, 4, 6, \cdots \end{cases} \tag{33}$$

$$H_m = (\lambda + 2\mu)j_0(k_m r) - (4\mu/k_m r)j_1(k_m r). \tag{34}$$

Solution for a Rectangular Pulse

We are now in the position to apply the above results to obtain the appropriate expressions for the displacement and pressure due to a short rectangular pulse of microwave energy with pulsewidth t_0. As previously mentioned, Duhamel's principle [23] allows us to find the solution u for any $F_t(t)$ once the solution u' for $F_t(t) = 1$ is known. The method is to apply the formula

$$u = (\partial/\partial t) \int_0^t F_t(t - t')u'(r,t')\, dt'. \tag{35}$$

Therefore, by substituting (10) and (29) into (35), we have for the radial displacement

$$u = u_0 Dt + \sum_{m=1}^{\infty} A_m j_1(k_m r)(\sin \omega_m t/\omega_m), \qquad 0 < t < t_0 \tag{36}$$

$$u = u_0 Dt_0 + \sum_{m=1}^{\infty} A_m j_1(k_m r) \cdot [\sin \omega_m t/\omega_m - \sin \omega_m (t - t_0)/\omega_m], \qquad t > t_0. \tag{37}$$

Similarly, we have for the pressure

$$\sigma = u_0 Gt + \sum_{m=1}^{\infty} A_m k_m H_m (\sin \omega_m t/\omega_m), \qquad 0 < t < t_0 \tag{38}$$

$$\sigma = u_0 Gt_0 + \sum_{m=1}^{\infty} A_m k_m H_m [\sin \omega_m t/\omega_m - \sin \omega_m (t - t_0)/\omega_m], \qquad t > t_0 \tag{39}$$

where D, G, and H_m are as given in (30), (33), and (34). Equations (36)–(39) represent the general solution for the radial displacement and pressure in a spherical head model with the constrained boundary exposed to a rectangular pulse of microwave radiation. It is seen that the displacement becomes zero both at the center and at the surface of the spherical head.

Since u_0 and A_m are proportional to I_0, both the displacement and the pressure are proportional to the peak absorption, similar to the stress-free boundary case. The dependence on total pulse energy $I_0 t_0$, however, is not as clear cut.

TABLE II
ZEROS OF THE SPHERICAL BESSEL FUNCTION $j_1(ka) = 0$

m	$k_m a$
1	4.493411
2	7.725252
3	10.904122
4	14.066194
5	17.220755
6	20.371303
7	23.519452
8	26.666054
9	29.811599
10	32.956389
11	36.100622

NUMERICAL RESULTS

We may use the results of the last section to estimate the frequency and amplitude of acoustic signals generated in the heads of animals and humans exposed to rectangular pulses of microwave energy. The useful physical parameters of brain matter are listed in Table I.

Frequency of Sound

The frequency of vibration of the spherical head is derived from (25). As mentioned before, there are an infinite number of resonant frequencies; each corresponding to a mode of vibration of the spherical head. The first 11 zeros of $j_1(k_m a)$ are given in Table II. It is seen that the frequency of vibration is completely independent of the microwave absorption pattern; it is only a function of the size of the spherical head and the acoustic properties of the tissue involved. This indicates that the frequency of sound perceived by a subject irradiated by rectangular pulses of microwave energy will be the same regardless of the frequency of the impinging radiation.

The fundamental frequency as seen from (27) and Table II is

$$f_1 = k_1 c_1/2\pi = 4.49 c_1/(2\pi a). \tag{40}$$

The fundamental frequency is plotted as a function of spherical head radius in Fig. 2. It is readily observed that the frequency in various subjects differs according to their equivalent spherical head sizes, i.e., the smaller the head size, the higher the frequency. For example, the average head radius for guinea pigs is about 1.5–2.5 cm; Fig. 2 yields a range of 40–70 kHz for the corresponding fundamental sound frequency. The average head radius for cats is approximately 2.5–3.5 cm; the corresponding fundamental sound frequency is between 30 and 40 kHz. It is significant to note that these frequencies are very close to the 50-kHz cochlear microphonics reported for guinea pigs [7] and the 38-kHz oscillations reported for cats [24]. Human head sizes are known to vary from 7 to 10 cm for adults. From Fig. 2, we see that the estimated fundamental sound frequency ranges from 10 to 15 kHz. This is certainly not in violation of the

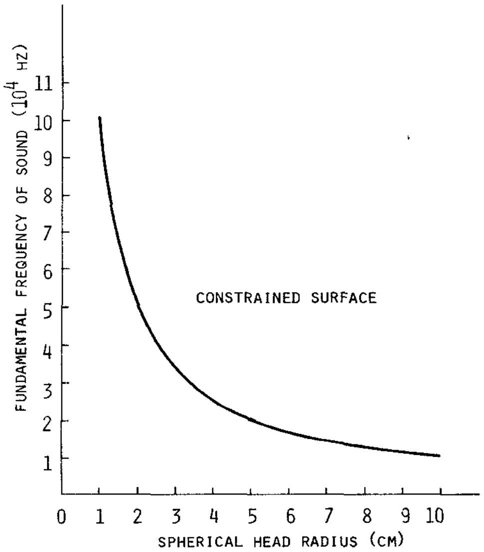

Fig. 2. Computed fundamental frequency of sound generated in a spherical head model irradiated with pulsed microwave energy.

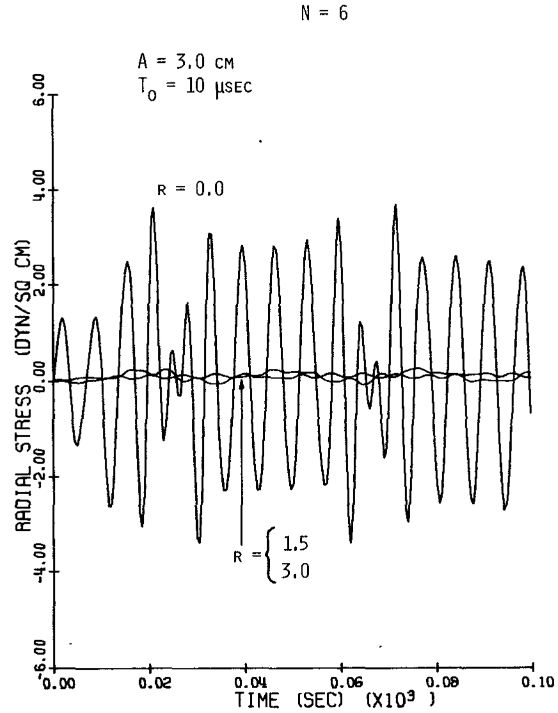

Fig. 3. Acoustic pressure (radial stress) generated in a 3-cm-radius (cat-sized) spherical head irradiated with 2450-MHz radiation. The incident peak power density is 589 mW/cm^2 and the peak absorbed energy is 1000 mW/cm^3.

known facts of auditory physiology nor is it in conflict with the observations that a necessary condition for auditory perception of microwaves is the ability to perceive auditory signals above 5 or 8 kHz [1], [5].

It should be noted that the frequencies predicted by this paper are about 70 percent higher than those calculated earlier based on stress-free boundary conditions [13]. Since the head is neither entirely stress free nor is it rigidly constrained, it is possible that the actual fundamental sound frequency falls somewhere between that predicted by these two approaches.

Radial Stress (Pressure) and Displacement

Fig. 3 is a plot of pressure σ in a 3-cm-radius spherical head irradiated with 2450-MHz radiation as a function of time for a 10-μs pulse. The curves are evaluated at $r = 0, 1.5$, and 3.0 cm. It is seen that the pressure is the highest in the center of the spherical head. After a transient buildup, which lasts for the duration of the pulsewidth, the pressure oscillates at a constant level because of the lossless assumption for the elastic medium. It is also important to note that the high-frequency oscillation is modulated by a low-frequency envelope whose frequency is the same as the fundamental frequency of sound given in Fig. 2 for a spherical head with $a = 3$ cm. The peak pressure generated at the center of the spherical head is 3.69 dyn/cm^2 for a peak absorption of 1000 mW/cm^3, which corresponds to 589 mW/cm^2 of incident power [19].

There are two sets of experimental data that are particularly suitable for comparison with the results described above. In one case the threshold incident power density was reported to be 2200 mW/cm^2 [3], [4]. For the other, the threshold was said to be about 1300 mW/cm^2 [5]. The corresponding peak pressure amplitude is therefore between 8.14 and 13.8 dyn/cm^2; i.e., 92–97 dB relative to 0.0002 dyn/cm^2. Assuming that perception by bone conduction for cats is the same as for humans, the minimum audible sound

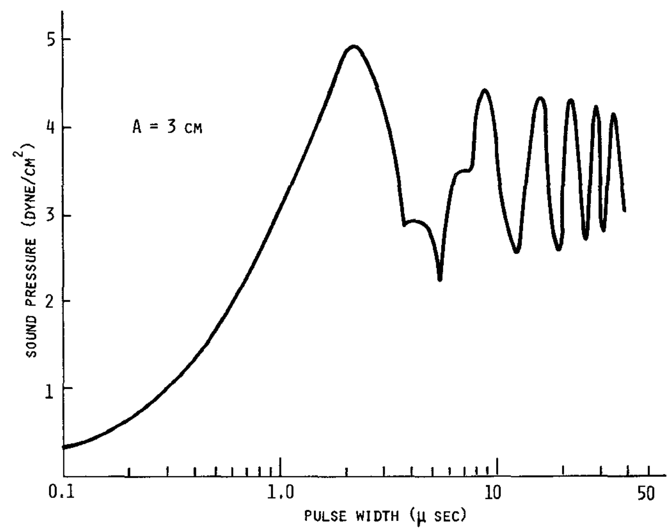

Fig. 4. Peak pressure generated in a 3-cm-radius spherical head irradiated with 2450-MHz radiation as a function of the incident pulsewidth. See Fig. 3 for other parameters.

pressure at 40 kHz is about 120 dB according to [25]. Thus the theoretically predicted threshold incident power density is close to the measured value.

The computed peak pressure as a function of pulsewidth is shown in Fig. 4 for a 3-cm-radius sphere exposed to 2450-MHz radiation. The curve is evaluated at a peak absorbed microwave energy of 1000 mW/cm^3. We see that an optimum pulsewidth for pressure generation occurs around 2 μs. This is similar to the free-surface formulation.

The displacement in the spherical model of the cat's head

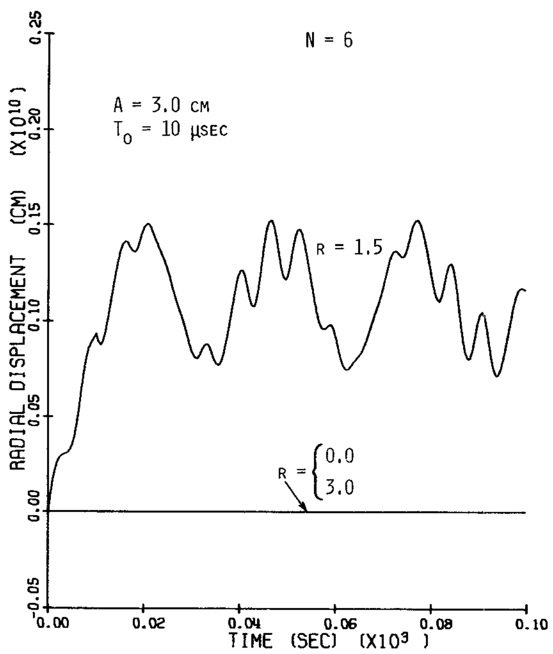

Fig. 5. Radial displacement as a function of time. See Fig. 3 for other parameters.

is shown in Fig. 5. As expected, the displacement is zero at both the center and the surface; the frequency of oscillation is also in accordance with that shown in Fig. 2.

Computations of pressure and displacement have also been performed for other sphere sizes, such as a 7-cm radius sphere simulating an adult human head exposed to 918-MHz radiation. The general features are similar to those illustrated above. For this case, the peak pressure at the center is 6.82 dyn/cm^2 for a peak absorption of 1000 mW/cm^3 and an incident power density of 2183 mW/cm^2. Although specific measurements have not been made for humans exposed to 918-MHz radiation, Frey and Messenger [2] have conducted a series of measurements at 1245 MHz for humans and have reported the threshold peak incident power density to be around 80 mW/cm^2. Assuming that the absorption characteristics at 918 and 1245 MHz are similar, the computed pressure of 0.25 dyne/cm^2 is 62 dB relative to 0.0002 dyn/cm^2. The minimum audible sound pressure for bone conduction is about 60 dB at frequencies between 6 and 14 kHz [25], [26]. Clearly, there is agreement between theory and measurement.

Conclusions

A model for auditory signals generated in humans and animals during microwave irradiation has been derived by considering a spherically symmetric energy absorption pattern and assuming that the impinging plane wave consists of a single rectangular pulse. The results indicate that the frequency of the auditory signals generated is independent of both the frequency of the incident microwave and the absorbed energy distribution; it is only a function of head size and the tissue acoustic property (velocity of acoustic wave propagation). The results also show that there is an optimum pulsewidth for the efficient conversion of microwaves to acoustic energy. The agreement between theoretical calculations and reported experimental measurements of sound frequency and threshold parameters clearly demonstrated the applicability of the thermoelastic stress-production mechanism for microwave-induced hearing in mammals.

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