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MR 1695

AUTHORS: Lin JC:

DATE: 1976

TITLE: Microwave auditory effect - - a comparison of some possible transduction mechanisms.

SOURCE: J Microwave Power 11:77-81

MAIN SUBJECT HEADING:

[✓ AN] ANALYTICS

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AT ANIMAL TOXICITY

IH WORKPLACE PRACTICES-ENGINEERING CONTROLS

M MISCELLANEOUS

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Microwave Auditory Effect— A Comparison of Some Possible Transduction Mechanisms*

MR 1695

James C. Lin†

ABSTRACT

When human subjects are irradiated with pulse modulated microwave energy they report the perception of a sound that appears to originate from within or slightly behind the head. Three of the possible mechanisms are examined using first order mathematical approximations and several simplifying assumptions. The results show that while all three (radiation pressure, strictive force and thermal expansion) are capable of producing the phenomenon, the stress resulting from thermal expansion may be so great that it masks the effect of the others completely.

INTRODUCTION

It is well known that pulsed electromagnetic energy can produce high frequency acoustic waves upon incidence on or upon their absorption by lossy solid and liquid dielectric materials [1 - 4]. Recently a number of reports have indicated that pulsed microwave energy is capable of producing an auditory sensation in humans [5 - 7]. This effect is of special interest since the average power densities required are considerably lower than those occuring in other microwave biological effects. In the United States the accepted maximum safe exposure limit for long term, whole body microwave irradiation is an average power density of 100 W/m^2. For intermittent exposure of less than 6 minute duration a tolerance dosage of 100 watt-hour/m^2 is recommended [8]. The average power densities at which the auditory effects have been observed are at least an order of magnitude below the current safety standards. It is therefore important for those concerned with evaluating possible hazards associated with microwave exposure to have a clear understanding of the mechanisms responsible for the auditory phenomenon.

The microwave induced sound appears as an audible click, buzz, or chirp depending on such factors as pulse width and repetition rate of the pulse energy used, and seems to originate from within and near the back of the head for the human subject. This effect has recently been authenticated using electrophysiologic recordings of cochlear microphonics, auditory nerve responses, and thalamic-evoked potentials from the cat in response to stimulation by both acoustic and microwave energies [7-10]. The evoked potentials due to microwave stimulation were very similar to those due to stimulation by an acoustic signal from a loudspeaker or a piezoelectric transducer cemented to the particular exposed skull of the cat (see Figure 1). Since cochlear

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* Manuscript received January 28, 1975; in revised form January 19, 1976

† Department of Electrical and Computer Engineering, Wayne State University, Detroit, Michigan 48202.

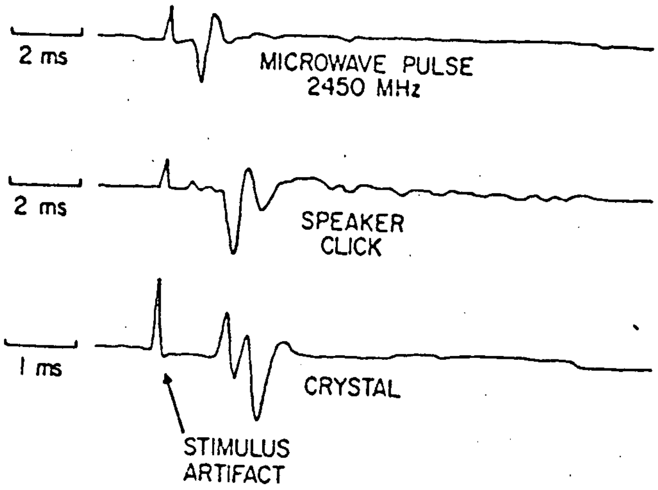

Figure 1 Responses in the round window of the cat cochlea due to acoustic and microwave stimuli[13].

disablement abolished potentials at the sites mentioned above, whether stimulated by acoustic or microwave pulses, there is a strong argument in support of the contention that microwave auditory effects are mediated at the periphery as are the effects of conventional acoustic stimuli. This, however, is in variance with the suggestion that the effect might result from direct stimulation of the auditory system at a site central to the conventional acoustic inputs [11].

While there is considerable evidence for the human ability to hear pulsed microwave radiation, a number of questions regarding the mechanism responsible for the phenomenon remain. Several mechanisms may be postulated to account for the observed auditory phenomenon. An obvious possibility is that radiation pressure is exerted on the surface of the irradiated cranium which generates an acoustic wave of sufficient amplitude so that it reaches the inner ear through bone conduction [4]. Another likely explanation is that the impinging microwave energy produces surface heating with consequent thermal expansion at the surface of the biological material and the launching of acoustic vibrations which are again detected by the inner ear via bone conduction [13]. Other possible mechanisms include dielectric body forces, induced vibrations in the cranial structures, caloric vestibular stimulation, and direct interaction of the basilar membrane with pulse microwave energy [4, 14, 15]. Clearly, further analysis of the electrical, mechanical and neural mechanisms involved is necessary.

The purpose of this paper is to present first order calculations comparing several possible physical mechanisms which may be involved in the auditory effects of pulse microwave radiation. This is useful since there exists a considerable amount of evidence supporting the interpretation that the microwave auditory effect is exerted in a manner very similar to conventional acoustic stimuli. In order to facilitate interpretation, and for the sake of simple mathematics, a first approximation is performed by considering a simple one-dimensional model. This assumes uniform power absorption at and near the surface of the lossy dielectric body. The forces due to radiation pressure, strictive force, and rapid thermal expansion are compared to indicate that while all three mechanisms may be operating when a human hears microwave pulses, the stress resulting from thermal expansion may be so great that it completely masks the effects of the others.

ANALYSIS

Assume that a uniform plane microwave radiation is incident normally upon the surface of a semi-infinite lossy dielectric medium. The power density at the surface is P_o. The power density at a distance z from the surface is given by

$$P = P_0 e^{-\alpha z} \quad W/m^2 \tag{1}$$

where $\alpha/2$ is the attenuation factor which describes the absorbing characteristics of the medium. This incident microwave energy may exert a radiation pressure on the surface of the absorbing medium and launch an acoustic wave, or it may generate sufficient body forces via dielectric expansion, or it may be absorbed by the lossy dielectric and converted to an acoustic wave as a result of thermal expansion.

That electromagnetic energy exerts mechanical forces upon bodies immersed in its field of influence is well known. These effects include the volume forces which may be present in the dielectric owing to its tendency to contract or expand in an applied field, and the surface forces exerted by the fields just outside the dielectric body which is a pressure exerted by the field on the body.

Radiation Pressure

Radiation pressure exerted by a microwave field upon dielectric bodies is very complex. However, for the simplified geometry under consideration, a first approximation for the radiation pressure, f_s, is given by [15].

$$f_s = 1/2 \cdot K\varepsilon_0 \eta P_0 \quad \text{Newton}/m^2 \tag{2}$$

where K is the relative dielectric constant, ϵ_o is the free space permittivity and η is the intrinsic impedance of the medium.

Strictive Forces

The forces exerted by an electromagnetic field on a unit volume of a dielectric material without free charges and currents and excluding the forces of deformation is given by [16].

$$f_v = 1/2 \cdot E^2 \nabla\varepsilon + [(K-1)/C^2]\partial S/\partial t \tag{3}$$

where ϵ is the dielectric constant, c is the speed of light in vacuum, E is the induced electric field, and S is the Poynting vector. If we assume that the forces associated with the deformation are similar to those associated with electrostatic fields, i.e.

$$f_d = \varepsilon_0/6 \ \nabla[E^2(K-1)(K+2)] \tag{4}$$

the forces due to dielectric striction takes the form of

$$f_v = f_d - 1/2 \ E^2 \nabla\varepsilon + [(K-1)/C^2]\partial S/\partial t \tag{5}$$

Since the factor $1/c^2$ in the last term of (5) is extremely large, the contribution of the last term will be infinitesimal of the second order. If we considered only materials which are homogeneous and isotropic, f_v and f_d become equivalent. Moreover, the relative dielectric constants for biological materials at microwave frequencies are very high. Therefore,

$$f_v \cong (K^2\varepsilon_0/6\eta) \cdot \nabla P \tag{6}$$

where $P = \eta E^2$. For $P = P_o e^{-\alpha z}$ the peak body force density becomes

$$|f_v| = K^2/6 \cdot \alpha\varepsilon_0/\eta \cdot P_0 \quad \text{Newton}/m^3 \tag{7}$$

Thermal Expansion

In the process of absorption of the microwave energy, a portion of the incident radiation is converted into heat which generates a temperature gradient normal to the surface. This temperature gradient produces as a result of thermal expansion, strains in the dielectric material and leads to the generation of stress waves which propagate away from the surface. For the one-dimensional model under consideration, the maximum stress for unconstrained surfaces is given by [2]

$$\sigma_m = \upsilon\beta P_o/(2Js) \quad \text{Newton/m}^2 \tag{8}$$

where J is the mechanical equivalent of heat, 4.185 Joules/cal, and υ, β and S are defined in Table I.

A Comparison

It is of interest to obtain the relationships between thermal expansion and radiation pressure, and between strictive forces and radiation pressure. Comparing (2) and (8) we obtain

$$\sigma_m/f_s = \upsilon\beta/(JsK\epsilon_o\eta) \tag{9}$$

The total forces generated in a semi-infinite rectangular region with unit surface may be compared to the total forces exerted by radiation pressure on the unit surface.

$$F_v/F_s = (\int_v f_v dv)/(\int_a f_s da) = K/3 \tag{10}$$

Conclusion and Discussion

The electrical and mechanical properties of brain and muscle are listed in Table I. These are typical values obtained from the literature [2, 17, 18], except for the coefficient of thermal expansion for muscle which does not seem to have been measured in the past. The value for the muscle coefficient of thermal expansion were assumed to be 60% of the corresponding value for water, since water is by far the most abundant component of animals, and constitutes approximately 60% of man's total body weight. A comparison of the magnitude of the acoustic energy generated by the three mechanisms is shown in Table II for the data listed in Table I. It is seen that

TABLE I
PROPERTIES OF BIOLOGICAL MATERIAL

	Muscle	Brain
Dielectric constant (K)	47	34
Electrical conductivity (σ, mho/m)	2.21	2.05
Intrinsic impedance (η, ohm)	53.5	63.7
Velocity of sound propagation (υ, m/sec)	1558	1500
Coefficient of thermal expansion (β, /°C)	41.4×10^{-6}	41.4×10^{-6}
Specific heat (s, cal/Kgm°C)	0.750×10^3	0.83×10^3

TABLE II
COMPARISON OF MECHANISMS OF ENERGY CONVERSION

	muscle	brain
σ_m/f_s	923	932
F_v/F_s	16	11

thermally induced forces exceed radiation pressure by a large margin. While the strictive forces are high in comparison with radiation pressure, they are much smaller than thermal expansion in both water and muscle material. If we assume a 6% coupling efficiency and a peak absorbed power density of 2400 watt/m^2 which was found to be the minimally effective value for 2450 MHz microwave radiation to produce audible signals in an adult with normal hearing, the computed maximum stress σ_m is approx. 0.02 Newtons-m^{-2} for both muscle and brain. This value is clearly above the established threshold of hearing for bone conduction [11]. Table II indicates that while all three mechanisms may be operating at the given absorbed power density, the large values due to thermal expansion may completely mask the effect of the others.

While the calculations made in this study are probably not accurate enough to predict the precise amplitude of the induced acoustic wave in the human head, they show the importance and applicability of various transduction mechanisms. In particular, the study indicates that the amplitude of the stress generated acoustic signal is of such magnitude that it is clearly a most attractive explanation of the microwave pulse induced auditory phenomenon in man.

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