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| ANALYTICS | HUMAN EFFECTS | ANIMAL TOXICITY | WORKPLACE PRACTICES-ENGINEERING CONTROLS | MISCELLANEOUS |

SECONDARY SUBJECT HEADINGS: AN HU AT IH M

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Methods of Analysis

Treatment

Transportation/Handling/Storage/Labelling

# Resonance Absorption of Microwaves by the Human Skull

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*Abstract*-Resonance absorption of microwaves by the human skull is examined by making computerized calculations of theoretical models of the skull. The calculated relative absorption versus frequency is plotted and compared for homogeneous and inhomogeneous skull models. At a frequency of maximum power absorption, the spatial distribution of intracranial field intensity (based upon the theoretical model) is also calculated and plotted.

Modeling the skull as a multilayered sphere corresponding to skin, fat, bone, dura, cerebrospinal fluid, and the brain (six concentric spheres), each layer having a specific conductivity and dielectric constant expressed as a function of frequency, we have developed a computer program for calculating the relative absorption and internal distribution of electric field intensity at microwave freqeuncies. To cover a range of skull sizes, calculations are made for spheres of radius 7 and 10 cm. At frequencies within the 0.1-3-GHz band, our results show a pronounced difference between the incident energy absorbed by the homogeneous and the inhomogeneous (multilayered) skull models. Of particular interest is a broad relative absorption peak near 2.1 GHz that does not appear for the homogeneous skull model. Since the multilayered sphere represents a closer approach to reality in modeling the human skull at microwave freqeuncies, the leakage from microwave ovens operating at 2.45 GHz may be a greater hazard to human health than is now being recognized.

## I. INTRODUCTION

Literature reports and studies conducted in our own laboratory indicate that incident electromagnetic waves at certain frequencies within the 0.1-3-GHz band are resonantly absorbed by the human skull. At frequencies corresponding to peaks of relative absorption, the field intensity inside the skull exists as a standing wave, the pattern of which changes abruptly with frequency. In other words, the amplitude of the standing-wave pattern is maximized at frequencies where relative absorption peaks occur. At these resonant frequencies the brain is most susceptible to damage due to overexposure.

Schwan [1] has published curves showing that the relative absorption for a lossy sphere with a concentric outer layer having different electrical properties differs appreciably from that for a homogeneous sphere and is sensitive to the thickness of this outer layer. Schwan assumed the outer layer to be fatty tissue, and his curves express relative absorption versus spherical radius, but at a specific microwave frequency, since the electrical properties of biological tissue are frequency dependent. In a more recent publication, Kritikos and Schwan [2] have given the maximum heating potential (power absorbed) versus frequency and the internal distribution of heating potential at selected frequencies, but only for homogeneous spheres. Johnson and Guy [3] have also taken the frequency-dependent electrical properties of brain tissue into account for homogeneous sphere models.

To achieve a closer correspondence to reality than is represented by a homogeneous sphere or the addition of an outer layer, we have modeled the human skull as six concentric spheres representing the layers of skin, fat, bone, dura, cerebrospinal fluid (CSF), and the brain, each layer having a conductivity and dielectric constant with a given frequency dependence to be specified later. This concentric-sphere model was used by Shapiro *et al.* [4] in determining the heating within an irradiated cranial structure, but no attempt was made to express the frequency dependence of conductivity and dielectric constant in investigating resonance phenomena.

## II. POWER ABSORPTION BY INHOMOGENEOUS SPHERE

An excellent treatment of scattering of electromagnetic radiation by a multilayered sphere is presented by Kerker [5], and Shapiro [4], building upon the work of Stratton [6], develops equations for determining the internal distribution of absorbed power. The reader should consult these references for a more detailed discussion.

The multilayered sphere, which scatters the incident electromagnetic plane wave, is shown in Fig. 1. The incident wave is propagating in the $z$ direction and is linearly polarized along the $x$ axis. Boundaries between the layers are denoted by $j = 1, 2, \cdots, s$, where $s$ represents the boundary between the last layer and the external medium (in this case, free space). The conductivities and dielectric constants of the layers are $\sigma_1, \sigma_2, \cdots, \sigma_s$ and $\epsilon_1, \epsilon_2, \cdots, \epsilon_s$. From Kerker [5] or Shapiro [4], the relative absorption of electromagnetic energy within the conducting dielectric sphere (of outer radius $a$) in Fig. 1 is given by

$$\frac{P_a}{P_i} = \frac{2}{\alpha^2} \sum_{n=1}^{\infty} (2n + 1)[\,\mathrm{Re}\,(a_n + b_n) - (|a_n|^2 + |b_n|^2)] \tag{1}$$

where

$$P_a = \frac{1}{2} \int_v \sigma |E|^2 \, dV$$

is the power absorbed by the sphere, $P_i = (E_0^2/2\eta)\pi a^2$ is the power incident upon the geometrical cross section of the sphere, $\alpha = 2\pi a/\lambda$, $\lambda$ is wavelength in the external medium, and $\eta$ is intrinsic impedance (377 Ω for free space). The scattering coefficients $a_n$ and $b_n$, which depend upon the conductivity, dielectric constant, and radius of the spherical layers, can be expressed in terms of Bessel functions [4], [5].

For an interior point $(r, \theta, \phi)$ of the multilayered sphere in Fig. 1, the mean power dissipated in watts per unit volume can be expressed as

$$p_a(r, \theta, \phi) = \tfrac{1}{2} \sigma |E|^2 \tag{2}$$

where $\sigma$ and $E$ are the values of conductivity and electric field intensity at the interior point. Hence, from (1), and as described by Shapiro [4], the normalized mean power density $\sigma |E|^2/(2E_0^2)$ or normalized electric field intensity squared $|E|^2/E_0^2$ can be determined at interior points of the skull model. As before, $E_0$ is the electric field intensity of the plane wave incident upon the sphere.

Before computations are made to determine the power absorption versus frequency and the internal distribution of power density, the values and frequency dependence of $\sigma_j$ and $\epsilon_j$ for the layers must be specified. This was done in the following way.

The conductivity and dielectric constant of an electrically polarizable material are [2], [7], [8]

$$\sigma = \sigma_L + (\sigma_H + \sigma_L) \frac{(\omega T)^2}{1 + (\omega T)^2} = \sigma_L \left[ \frac{1 + \frac{\sigma_H}{\sigma_L}(\omega T)^2}{1 + (\omega T)^2} \right] \tag{3}$$

and

$$\epsilon = \epsilon_H + \frac{\epsilon_L - \epsilon_H}{1 + (\omega T)^2} = \epsilon_H \left[ \frac{\frac{\epsilon_L}{\epsilon_H} + (\omega T)^2}{1 + (\omega T)^2} \right] \tag{4}$$

where the subscripts $L$ and $H$ denote low-frequency (dc) and high-frequency (optical) values. For biological tissue with high water content, the relaxation time $T$ is $1/(2\pi f_0)$, where $f_0$, the frequency of rotational resonance of the water molecules, is approximately 20 GHz.

Since the high-frequency and low-frequency values of $\sigma$ and $\epsilon$ for each layer of the skull are not accurately known, it is reasonable to assume that the ratios $\sigma_H/\sigma_L$ and $\epsilon_L/\epsilon_H$ do not differ from one layer of high water content to another. For brain matter these ratios are approxi-

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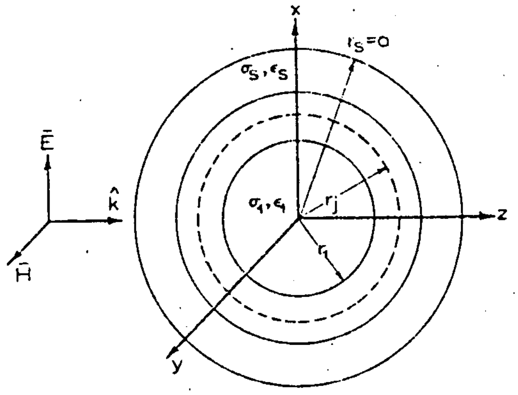

Fig. 1. Multilayered ($s = 6$) sphere model of skull irradiated by incident plane wave propagating in $z$ direction.

TABLE I
DIMENSIONS AND ELECTRICAL PROPERTIES OF MULTILAYERED SPHERE MODEL OF HUMAN SKULL

| Layer | Radius (cm) | Conductivity (millimhos/cm) | Relative dielectric constant |
|---|---|---|---|
| skin | a | $8[\frac{1+62(f/f_0)^2}{1+(f/f_0)^2}]$ | $4[\frac{12+(f/f_0)^2}{1+(f/f_0)^2}]$ |
| fat | a-0.15 | 1 | 6 |
| bone | a-0.27 | 2 | 5 |
| dura | a-0.70 | $8[\frac{1+62(f/f_0)^2}{1+(f/f_0)^2}]$ | $4[\frac{12+(f/f_0)^2}{1+(f/f_0)^2}]$ |
| CSF | a-0.80 | $8[\frac{1+62(f/f_0)^2}{1+(f/f_0)^2}]$ | $7[\frac{12+(f/f_0)^2}{1+(f/f_0)^2}]$ |
| brain | a-1.10 | $6[\frac{1+62(f/f_0)^2}{1+(f/f_0)^2}]$ | $5[\frac{12+(f/f_0)^2}{1+(f/f_0)^2}]$ |

*Note:* $f_0 = 20$ GHz.

mated by [2] $\sigma_H/\sigma_L = 62$ and $\epsilon_L/\epsilon_H = 12$. Incorporating these assumptions into (3) and (4), the frequency dependent $\sigma$ and $\epsilon$ become

$$\sigma = \sigma_L \left[\frac{1 + 62(f/f_0)^2}{1 + (f/f_0)^2}\right] \tag{5}$$

and

$$\epsilon = \epsilon_H \left[\frac{12 + (f/f_0)^2}{1 + (f/f_0)^2}\right] \tag{6}$$

where $f_0 = 20$ GHz.

Adjusting the term outside the brackets in (5) and (6) to agree with available data [4], [8], [9] within the 0.1-3-GHz frequency range, representative values of $\sigma$ and $\epsilon$ for each layer of the skull model are given in Table I. The fat and bone layers, which have low water content, are assigned frequency independent values of $\sigma$ and $\epsilon$.

## III. COMPUTED RESULTS AND DISCUSSION

To obtain convergence of the series expansion for $P_a/P_i$ in (1), it was necessary to evaluate the scattering coefficients to a high degree of accuracy. This was accomplished by expanding the Bessel functions in terms of trigonometric functions and by using double-precision arithmetic (16-decimal digits) on the real and imaginary parts. The evaluation of terms in the series expansion was continued until the scattering coefficients satisfied the requirement

$$|a_n|^2 + |b_n|^2 \leq (10)^{-14}. \tag{7}$$

Using the values of $\sigma$ and $\epsilon$ in Table I to determine the scattering coefficients in (1), the relative absorption of multilayered spheres with

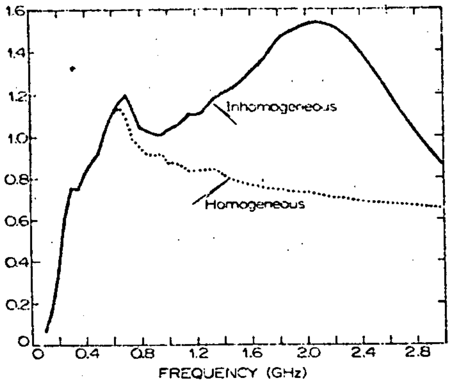

Fig. 2. Relative power absorption versus frequency for inhomogeneous (six-layered) and homogeneous (one-layered) sphere models of outer radius $a = 7$ cm.

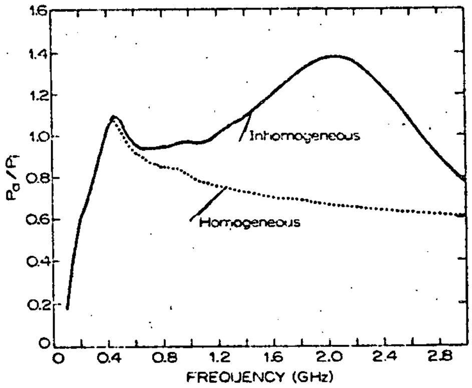

Fig. 3. Relative power absorption versus frequency for inhomogeneous (six-layered) and homogeneous (one-layered) sphere models of outer radius $a = 10$ cm.

an outer radius of 7 and 10 cm is shown as the upper curve in Figs. 2 and 3. The lower curve was obtained by letting all the layers have the same $\sigma$ and $\epsilon$ as brain matter (homogeneous sphere) and is offered for comparison. Note that the absorption peak at about 2.1 GHz of 1.52 for $a = 7$ cm and 1.38 for $a = 10$ cm does not appear if one takes the human skull to be represented by a homogeneous sphere. As one would expect, the resonant peaks are shifted downward in freqeuncy as the radius is increased from 7 to 10 cm.

The internal distribution of electric field intensity ($|E|^2/E_0^2$) within the inhomogeneous sphere for the resonant peak near 2.1 GHz is shown in Fig. 4 for $a = 7$ cm and in Fig. 5 for $a = 10$ cm. The distribution is shown along the direction of propagation (the $z$ axis), in the $x$-$z$ plane in Fig. 1. To obtain the mean power density at any point along the $z$ axis, the ordinate in Fig. 4 or 5 is simply multiplied by $\sigma/2$ or 5 mmho/cm, since the conductivity of the brain matter, over which the distribution is given, is 10 mmho/cm at 2.1 GHz (from Table I). This means that if $E_0 = (7.54)^{1/2}$ V/cm, corresponding to 10 mW/cm$^2$ incident upon the sphere, the mean power density at the peak near midbrain is $5(0.23)7.54 = 8.7$ mW/cc for $a = 10$ cm, and $5(0.55)7.54 = 20.8$ mW/cc for $a = 7$ cm. By the measure used by Kritikos and Schwan [2], these peaks in local power density would represent intense hot spots. Other investigators have not reported such large peaks, but our computer program checks with their data in the following ways. 1) Using Shapiro's multilayered sphere data [4] at 3 GHz, we were able to repeat his plots of mean power density and to obtain the same absorption cross section. 2) The lower curve in Figs. 2 and 3, obtained from our program by letting all the layers have the same $\sigma$ and $\epsilon$ as brain matter (homogeneous sphere), seems consistent with the results of other investigators, and the relative absorption peak at 0.65 GHz for $a = 7$ cm in Fig. 2 is the same as obtained by Johnson and Guy [3] for the same size homogeneous sphere.

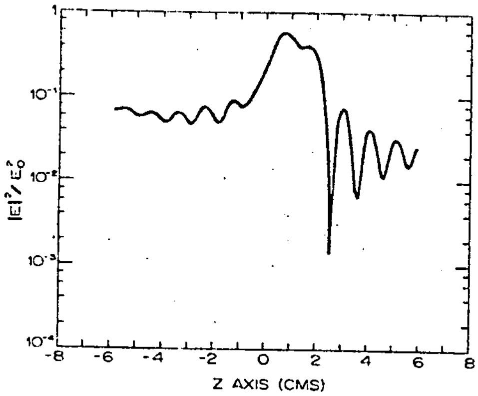

Fig. 4. Z-axis distribution of normalized electric field intensity squared inside the simulated brain matter (first layer) of the six-layered sphere model. $a = 7$ cm, $f = 2.1$ GHz.

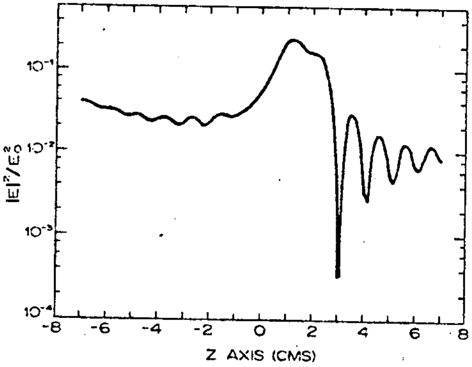

Fig. 5. Z-axis distribution of normalized electric field intensity squared inside the simulated brain matter (first layer) of the six-layered sphere model. $a = 10$ cm, $f = 2.1$ GHz.

At a given frequency, the values of $\sigma$ and $\epsilon$ in Table I, which are intended to represent a typical human skull, may vary from one individual to another, and certainly the layer thicknesses are subject to individual variations. *In vitro* measurements [4] indicate that the dielectric constant may vary as much as ± 30 percent of the mean and conductivity ± 40 percent. From available data it would be difficult, if not impossible, to determine how much variation is due to measurement errors and how much is due to actual differences in the chemical composition of cranial layers from one skull to another. For this range of variation in $\sigma$ and $\epsilon$, the maximum relative absorption in Fig. 2 (upper curve) would range from about 1.30 to 1.65 at a freqeuncy between about 1.7–2.5 GHz. Although variations in layer thickness would further increase the range of peak absorption and resonant frequency, the point is that a range of uncertainty does exist. And while Figs. 2 and 4 (or 3 and 5) may accurately depict the absorption and distribution of energy for a given human skull irradiated by microwaves, the situation may be quite different for another skull of the same physical size (outer radius).

## IV. CONCLUSIONS

The multilayered sphere model of the human skull used in this study shows pronounced resonance absorption effects in the 0.1–3-GHz frequency range that are not present in the homogeneous sphere model. Variations in measured values of $\sigma$ and $\epsilon$ indicate that the peak absorption near 2.1 GHz in Fig. 2 may occur anywhere from 1.7 to 2.5 GHz. Hence, the leakage from microwave ovens operating at 2.45 GHz (or any other high-power source in the 1.7–2.5-GHz range) may be a greater hazard to human health than is now being recognized. The range of frequencies over which a health hazard may exist could possibly be narrowed considerably if one knew exactly how much $\sigma$ and $\epsilon$ of cranial layers could change from one human skull to another. More accurate measurements of $\sigma$ and $\epsilon$ at more frequencies in the microwave range could help resolve the problem.

## REFERENCES

[1] H. P. Schwan, "Microwave biophysics," in *Microwave Power Engineering*, vol. 2, E. C. Okress, Ed. New York: Academic, 1968, pp. 213–244.
[2] H. N. Kritikos and H. P. Schwan, "Hot spots generated in conducting spheres by electromagnetic waves and biological implications," *IEEE Trans. Bio-Med. Eng.*, vol. BME-19, pp. 53–58, Jan. 1972.
[3] C. C. Johnson and A. W. Guy, "Nonionizing electromagnetic wave effects in biological materials and systems," *Proc. IEEE*, vol. 60, pp. 692–718, June 1972.
[4] A. Shapiro, R. F. Lutomirski, and H. T. Yura, "Induced fields and heating within a cranial structure irradiated by an electromagnetic plane wave," *IEEE Trans. Microwave Theory Tech. (Special Issue on Biological Effects of Microwaves)*, vol. MTT-19, pp. 187–196, Feb. 1971.
[5] M. Kerker, *The Scattering of Light and Other Electromagnetic Radiation*. New York: Academic, 1969.
[6] J. A. Stratton, *Electromagnetic Theory*. New York: McGraw-Hill, 1941.
[7] P. Debye, *Polar Molecules*. New York: Dover, 1945.
[8] H. P. Schwan, "Electrical properties of tissues and cells," *Advan. Bio. Med. Phys.*, vol. 5, pp. 147–209, 1957.
[9] A. S. Presman, *Electromagnetic Fields and Life*. New York: Plenum, 1970.

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# Ultrasound Dosage for Nontherapeutic Use on Human Beings—Extrapolations from a Literature Survey

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*Abstract*—A practical method for analyzing the biological effects of nontherapeutic ultrasound was applied to the data of 21 different principal investigators. The data were compiled so that individual investigators could develop tentative guidelines of their own regarding the hazards of diagnostic ultrasound in human beings. One set of guidelines developed suggested that exposures of minimal hazard lie below a log/log line connecting 100 $\mu$s of 100 W/cm$^2$ ultrasound with 200 s of 100 mW/cm$^2$ ultrasound. An ultrasonic intensity of 100 mW/cm$^2$ or less was of little or no hazard for at least 10 000 s. These guidelines applied to both continuous- and pulsed-wave ultrasound doses that were described by *average intensity* multiplied by *total exposure time*. The proposed schedule was valid for 0.5–15 MHz and for all anatomic sites except the eyes.

## INTRODUCTION

The increasing popularity of ultrasonic diagnostic devices in the practice of medicine has raised questions of their safety [4], [10], [14], [16], [22], [29]. In any diagnostic procedure, the physician must compare the hazards of the procedure with the probability that useful information will be gained. The engineer who designs either industrial or medical equipment may encounter specifications that inadequately state limitations imposed by physiological hazard. Fortunately, the research community (which may not understand the imperatives felt by practicing physicians and engineers) can temper premature or inappropriate usage on theoretical and experimental grounds. Of particular current interest are ultrasonic imaging devices such as the acoustic–optical imaging (AOI) system described by Buckles and Knox [5]. Refinement of the AOI system for general diagnostic use in human beings, however, may require exposure to ultrasound pulses with peak power in excess of 500 W/cm$^2$; therefore, guidelines for reasonably safe ultrasound exposures should be established.

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