Frequency and Orientation Effects on Whole Animal Absorption of Electromagnetic Waves

O. P. GANDHI, SENIOR MEMBER, IEEE

***Abstract*—Experiments using a parallel plate waveguide as the measurement medium have revealed a strong dependence of RF absorption in rats and biological-phantom[1] prolate spheroidal bodies upon the frequency and polarization of electromagnetic fields. The results correlate well to those of free space irradiation. Strongest power deposition is observed for fields polarized along the long dimension of the bodies for frequencies such that the major length is about one-quarter wavelength of radiation. At resonance, an effective absorption area of 2.5 to 3.5 times the shadow cross section is measured.**

INTRODUCTION

This paper addresses the following questions:

1. Does the total power absorbed in a whole animal body vary with frequency?
2. What, if any, are the frequency regions of most absorption for various polarizations of incident waves and what percentage of incident power is absorbed at such frequencies?
3. Can one extrapolate to predict frequency regions of most interest from the point of view of maximum absorption in different orientations for humans?

Prior knowledge on the above subjects consists of theoretical studies on homogeneous lossy spheres [1]-[3] of dielectric properties matching biological tissues. Using Mie theory [4] maximum absorption is predicted for a frequency f such that $ka = 2\pi fa/c$ is on the order of 0.5 where a is the radius of the sphere and c is the velocity of light in free space. Recognizing that most biological systems have different dimensions along the three axes, a theory [5] has recently been developed for homogeneous lossy prolate spheroids of different aspect ratios to more closely match the overall dimensions of the

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The author is with the Department of Electrical Engineering, University of Utah, Salt Lake City, Utah 84112.

[1] For experiments reported in this communication, the composition of the material is that used to simulate the dielectric properties of the brain tissue. The material developed in the Department of Rehabilitation Medicine, University of Washington, Seattle, consists of 7.01 percent Superstuff (obtained from Whamo Manufacturing Company, San Gabriel, California), 29.8 percent polyethylene powder, 0.58 percent NaCl, and 62.61 percent water.

various animals. The analysis is valid in the low frequency ($ka \leqslant 0.3$) approximation and does not consequently predict regions of resonance or maximum absorption in bodies of prolate spheroidal shape.

In order to obtain total power absorbed in the system, it is necessary to work with waveguides rather than horns radiating into free space. For studies over wide bands, it is also essential that such waveguides be capable of propagation down to megacycle frequencies and carrying power in the TEM mode similar to field configuration to those of plane waves. The waveguides that fit this requirement are the coaxial line, the triplate line, and the stripline or the parallel plate line. In the first two lines, it is necessary to use two identical bodies placed above and below the center conductor to maintain the symmetry of the TEM mode. It was consequently decided to use the parallel plate line.

The Parallel Plate Line

To conduct measurements with Wistar rats as the test animal, the parallel plate waveguide, hereinafter called the WG, was designed with a cross section of $6.35 \times 15.9\ \text{cm}^2$. This was to ensure that even the largest 390 gm rats do not overly fill the WG for waves propagating along the length of the animal. It was found in retrospect that for best results the WG dimensions should be such that the bodies to be measured fill between 10–30 percent of the cross section. Under these circumstances the insertion loss is on the order of 1 dB or more so that the measurement errors of the HP8410 microwave network analyzer are minimized by comparison. For behavioral and lethality experiments with higher power densities, WG's of even larger cross sections may be desirable to more closely approach plane wave incidence. The WG with an overall length of 92 cms has a uniform central section of 30 cms to allow placement of bodies for insertion loss measurements. The ground plane is wider (20.3 cm) than the upper plate to allow for the region of fringing fields. Based on a statistical analysis of 15 measurements at each of the 100 frequencies, the values for the VSWR, mean insertion loss, standard deviation, the least and the largest values of attenuation are printed out.

Using the empty WG for the "connect through" in the calibration of the network analyzer, the base attenuation and reflection may be accounted for in subsequent measurements. Using this method, the insertion loss of the empty WG, as so canceled, is measured to be within ±0.1 dB with VSWR less than 1.042 over the 285–2000 MHz band of the HP8745A S-parameter test set. With the HP8743A test set used for the 2000–4000 MHz band, the corresponding values are within ±0.05 dB for the corrected insertion loss with VSWR less than 1.017 over the entire band. The WG so corrected for the base readings is then used for determination of (additional) insertion loss due to rats, mice, and biological-phantom[1] prolate spheroidal bodies. A check on the validity of the measuring system was made using spheres of the biological phantom material. For nine spheres of diameter ($2a$) varying from 3.3 to 5.6 cm, the frequencies of peak absorption were found to vary from 1610 to 974 MHz, each corresponding to the value of $ka = 0.55$ to 0.59 as compared to the theoretical value [1] (from Mie theory) on the order of 0.50 to 0.52.

Electromagnetic Absorption Characteristics of Rats

The RF absorption of 96, 158, 261, 390 gm anesthetized rats (selected randomly from a rat colony) was measured by placing the animals on a styrofoam sheet to prevent the physical contact with the plates. It was established by prior tests with obstacles of lossy spheres that the observed characteristics were fairly independent of the placement as long as the bodies were kept at a separation of 2 to 3 millimeters from the plates. The mean values of the insertion loss measured for different size rats are shown in Fig. 1. The characteristics to be noted are:

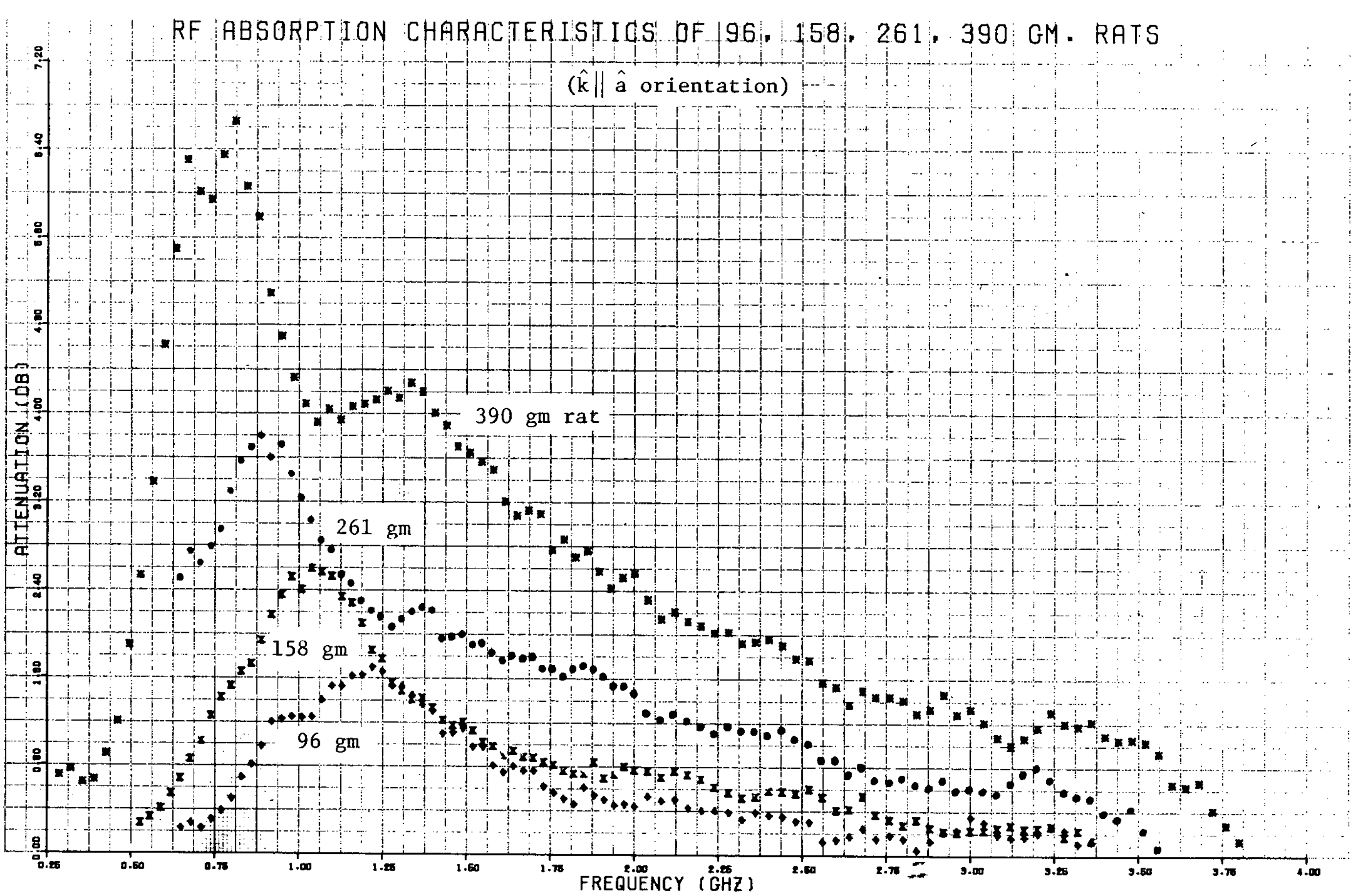

Fig. 1. RF absorption for different size rats.

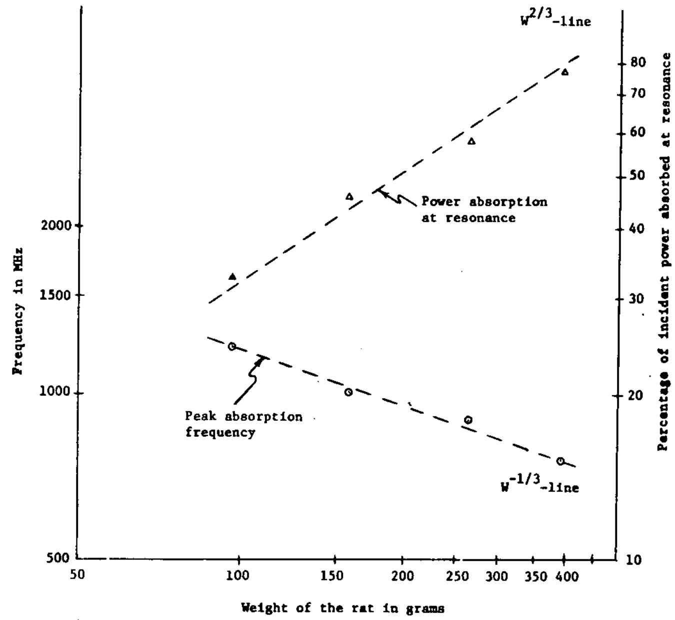

Fig. 2. Variation of the peak absorption frequency and maximum absorption with the rat weight.

TABLE I
RF ABSORPTION AND PHYSICAL DIMENSIONAL DATA FOR RATS OF DIFFERENT WEIGHTS

Weight of the Rat in Grams	Freq. of Max. Absorption MHz	Max. Insertion Loss dB	Percentage Power Absorbed	Rat Length L from Nose to Base of Tail cm	Rat Length in Terms of Half Wave-lengths	$ka \equiv kL/2$	Measured Circumference cms	Nominal Circumference $2\pi b$ in cms	Aspect Ratio a/b of Equivalent Prolate Spheroid	Relative Absorption Coefficient S
96	1217	1.70	32.5	15.5	1.260	1.98	11.5 (body) max. 9.0 (head)	10.80	4.50	3.50
158	1020	2.60	45.0	18.0	1.225	1.92	13.5 (body) max. 9.0 (head)	12.82	4.30	3.33
261	900	3.80	58.3	21.0	1.260	1.98	15.0 (body) max. 10.0 (head)	15.32	4.30	3.13
390	760	6.52	77.7	23.5	1.190	1.87	18.0 (body) max. 11.0 (head)	17.70	4.35	3.13

a. There is a definite frequency region of peak absorption for each of the animals, and the frequency for maximum absorption reduces as $W^{-1/3}$ (Fig. 2) with weight W of the animals.

b. For frequencies below resonance, the power absorbed varies as $f^{4.75}$ is in good correlation with results on spheres and prolate spheroids to be discussed later.

c. At the absorption peak, the power absorbed (Fig. 2) varies as $W^{2/3}$. Realizing that each of the dimensions increases perhaps as $W^{1/3}$, this is tantamount to an absorption cross section proportional to the shadow cross section of the animals.

d. At frequencies above resonance, the absorption reduces monotonically with increasing frequency.

e. The effect of the tail on the whole animal absorption was found to be minimal.

The data for the various size rats are tabulated in Table I. The percentage power absorbed is calculated from the data on the insertion loss and is listed in column 4 (of Table I). The length L, as actually measured from the nose to the base of the tail for each of the animals, is given in column 5. The rat length in each case is on the order of 1.19 to 1.26 times the half wavelength at the frequency of maximum absorption which corresponds to $ka = kL/2 \simeq 1.9$. It should be recalled that the corresponding quantity for spheres was 0.55.

The body of the rat (without the tail) is approximated to an equivalent prolate spheroid of major and minor lengths $2a$ $(=L)$ and $2b$, respectively. The half length b is obtained from the expression $W = \frac{2}{3}\pi b^2 L\bar{\rho}$, where $\bar{\rho}$ is the average mass density. The nominal circumference $2\pi b$ so calculated (column 9) correlates well with the average circumference actually measured. From the percentage power absorbed, the absorption cross section is calculated from the ratio of power absorbed, divided by the incident power density. Dividing the absorption cross section by the shadow cross-sectional area of πb^2, the relative absorption cross section S at resonance is evaluated and is found to be on the order of 3.13 to 3.50. An

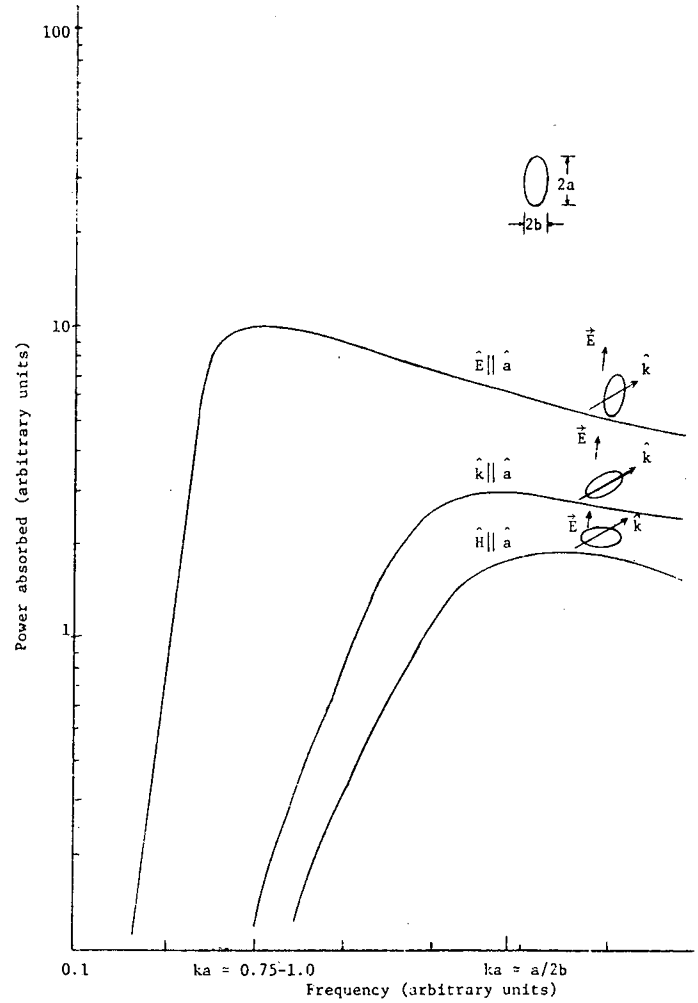

Fig. 3. Typical RF absorption curves for animals and bodies of prolate-spheroidal shape.

absorption of 3 to 3.5 times that called for by the shadow area is observed at resonance.

Absorption Characteristics of Lossy Prolate Spheroids

In order to develop a more general picture, RF absorption characteristics of biological-phantom prolate spheroidal bodies of aspect (a/b) ratios 2, 3, 5, and 5.3 are measured for the three orientations $\hat{E} \| \hat{a}$, $\hat{H} \| \hat{a}$, and $\hat{k} \| \hat{a}$, where $\hat{E}$, $\hat{H}$, and $\hat{k}$ are along the electric and magnetic fields and along the propagation vector of the waves, and $\hat{a}$ is along the major length of the body. The salient features of the experimentally determined results (qualitatively sketched in Fig. 3) are:

1. The $\hat{E} \| \hat{a}$ orientation is the most absorbing and $\hat{H} \| \hat{a}$ the least absorbing, with the configuration $\hat{k} \| \hat{a}$ only slightly more absorbing than the $\hat{H} \| \hat{a}$ orientation.
2. The frequencies of peak absorption occur in the reverse order. Maximum absorption for $\hat{E} \| \hat{a}$ orientation occurs at the lowest frequency with ka on the order of 0.75 to 1.0. Peak absorption for $\hat{k} \| \hat{a}$ and $\hat{H} \| \hat{a}$ orientations occurs at successively higher frequencies with ka for these configurations on the order of $a/2b$.
3. Absorption in the below-resonance region diminishes rapidly with frequency. An $f^{4.75}$ dependence similar to that for spheres and rats is observed for all orientations.

Alternative experiments using free space plane waves at 1700 MHz to heat saline-filled prolate spheroidal bodies of fixed a/b ratio of 5.75 but changing overall dimensions have confirmed the main features of the above results. Temperature increase curves for the three orientations show a remarkable resemblance to Fig. 3. A notable exception is that for $\hat{E} \| \hat{a}$ polarization maximum RF absorption is found for bodies of major length approximately 0.4 to 0.5 λ; i.e., at twice the frequency of the values observed in the parallel plate waveguide situation. The reason for this is that while a body isolated in free space is required to be one-half wavelength for resonance, the same condition is met in the presence of a ground plane (such as in the WG) with only a λ/4 body and its image in the ground plane acting together.

To evaluate the validity of scaling, free space heating experiments were repeated at 710 MHz for saline-filled prolate spheroidal bodies ($a/b = 6.0$) of larger overall dimensions. The temperature increase for a five-minute exposure to 100 mW/cm^2 radiation is plotted in Fig. 4. From the amount of energy absorbed, the relative absorption coefficient S is calculated [3] and is plotted in Fig. 5. Maximum absorption is observed once again for bodies of major length on the order of 0.4 to 0.5 λ, and whole body deposition of 3 to 4 times as much as that called for by the shadow area is measured.

In order to dramatize the polarization-dependent variability of electromagnetic hazard, 250 gm[2] Wistar rats were exposed to 100 mW/cm^2 fields. The core temperature of the animal was measured under irradiation, using the nonperturbing liquid crystal fiberoptic temperature probe [6]. The digital voltmeter reading as a function of time was recorded and is given in Fig. 6 (a), (b), and (c), for the three orientations. The core temperature read off the calibration chart of the probe is

[2]This particular weight was selected to observe $L \simeq \lambda/2$ condition for maximum absorption in the free space $\hat{E} \| \hat{a}$ orientation.

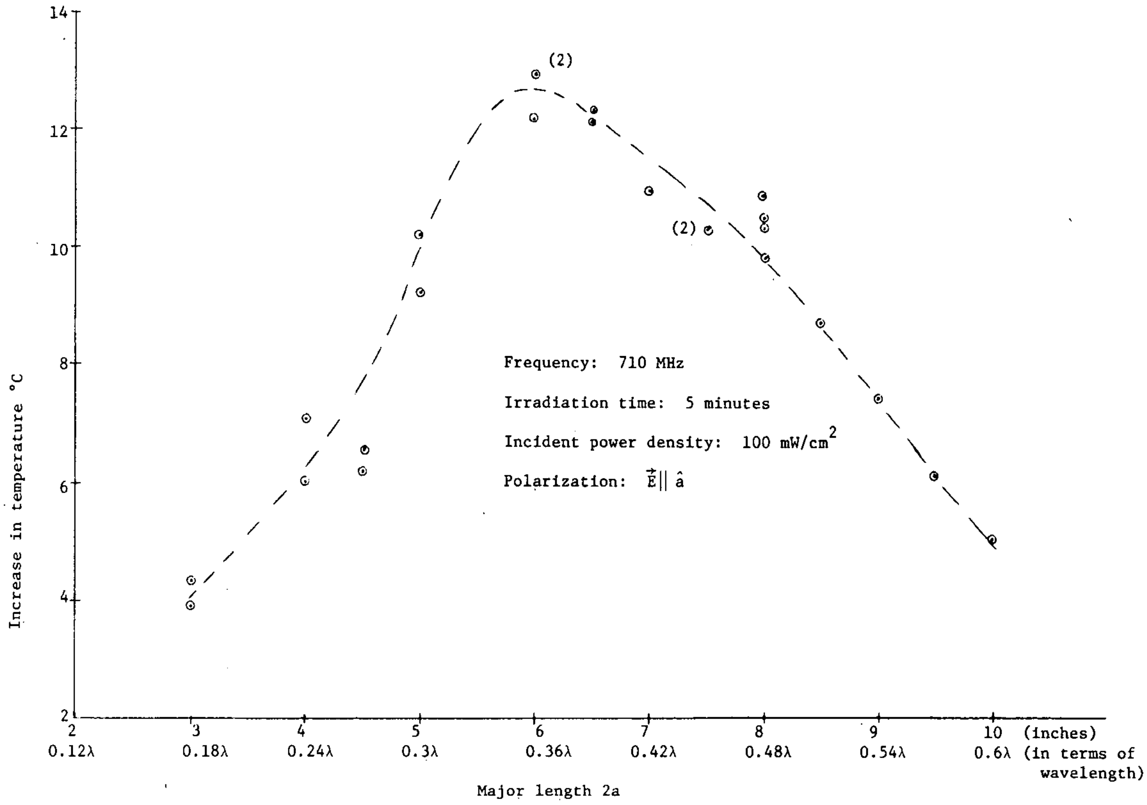

Fig. 4. Temperature rise in saline-filled prolate spheroids of aspect ratio 6.0.

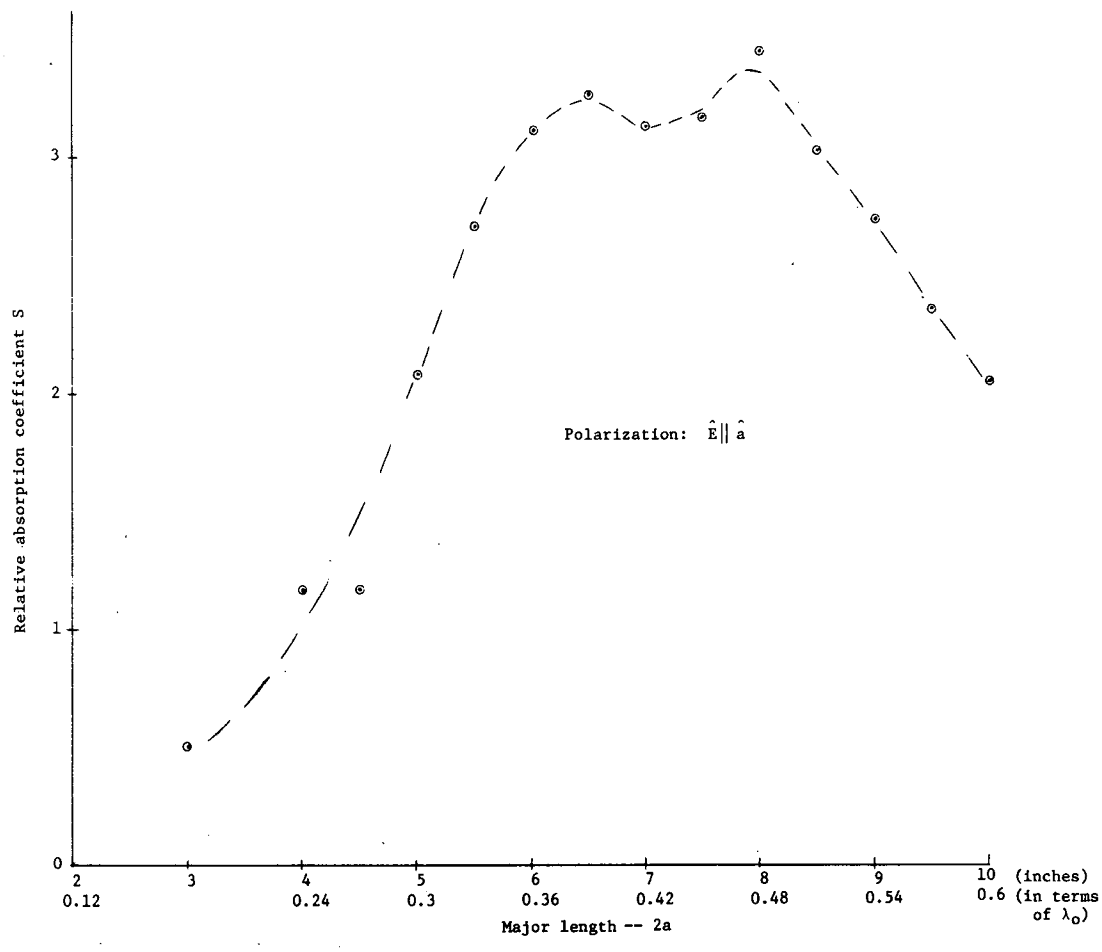

Fig. 5. Relative absorption coefficient S for different size prolate spheroids (a/b = 6.0 in each case).

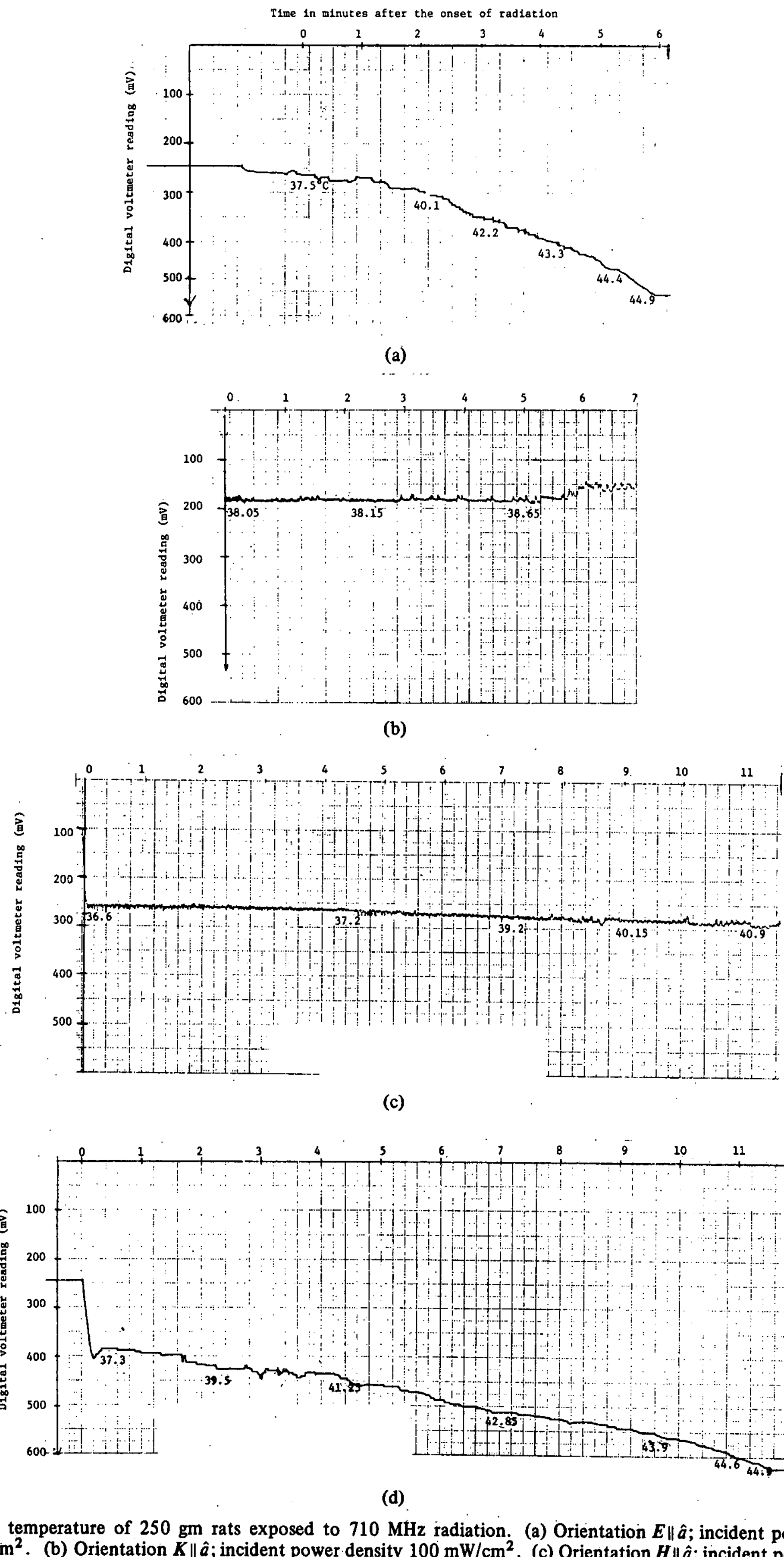

Fig. 6. Core temperature of 250 gm rats exposed to 710 MHz radiation. (a) Orientation $E \parallel \hat{a}$; incident power density 100 mW/cm^2. (b) Orientation $K \parallel \hat{a}$; incident power density 100 mW/cm^2. (c) Orientation $H \parallel \hat{a}$; incident power density 100 mW/cm^2. (d) Orientation $E \parallel \hat{a}$; incident power density 50 mW/cm^2.

marked alongside the curves in Fig. 6. For an incident power density of 50 mW/cm^2 (Fig. 6(d)), the power deposition in the $\hat{E} \parallel \hat{a}$ orientation was still much higher than that for the other two configurations at 100 mW/cm^2. For $\hat{E} \parallel \hat{a}$ configuration the relative absorption coefficients S of 2.995 and 2.880 are calculated from the temperature rise of the animal for 100 and 50 mW/cm^2 incident field intensities, respectively.

From the preceding results, the RF power deposition is found to vary significantly with orientation and with frequency. The strongest absorption is found for waves polarized along the long dimension of the bodies at frequencies such that the major length is approximately one-quarter wavelength of radiation in the presence of ground caused image. At resonance a whole body deposition of approximately three times as much as that called for by the shadow area is observed. By extrapolation the highest whole body absorption for adult humans is anticipated for the frequency region 40 to 50 MHz.

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