RESONANT ELECTROMAGNETIC POWER DEPOSITION IN MAN AND ANIMALS*

O. P. Gandhi
Electrical Engineering Department
University of Utah
Salt Lake City, Utah 84112

Abstract

Strongest power deposition for biological bodies is found for fields polarized along the longest dimension for frequencies such that the major length is about one-half wavelength of radiation. Peak absorption, in the presence of ground effects, is observed at frequencies one half as much as for bodies isolated in free space. Power distribution under conditions of resonance is determined. At resonance, an effective absorption area of 2.5 to 3.5 times the shadow cross section is measured.

Based on our previous experiments[1] with rats and biological-phantom and saline-filled prolate spheroidal bodies, strongest RF absorption was found for electromagnetic fields polarized with electric field along the long dimension of the bodies. Peak absorption is measured for frequencies such that the major length of the body is approximately one-quarter wavelength of radiation. For adult humans, highest whole body absorption is therefore anticipated for the frequency region 40-55 MHz. The results originally obtained by using a parallel plate waveguide as a transmission medium of plane waves, have since been tested for validity by several experiments[1,2] performed in anechoic chambers. The salient features of the experimentally determined results are:

1. The $\vec{E} \| \hat{L}$ orientation is found to be the most absorbing and $\vec{H} \| \hat{L}$ the least absorbing, with the configuration $\vec{k} \| \hat{L}$ only slightly more absorbing than the $\vec{H} \| \hat{L}$ orientation. The vectors $\vec{E}$, $\vec{H}$, and $\vec{k}$ are along the electric and magnetic fields and along the direction of propagation, respectively, and $\hat{L}$ is along the major length L of the body.

2. The frequencies of peak absorption occur in the reverse order. Maximum absorption for $\vec{E} \| \hat{L}$ occurs at the lowest frequency with $kL = 2\pi L/\lambda$ on the order of 1.5-2.0. Peak absorption for $\vec{k} \| \hat{L}$ and $\vec{H} \| \hat{L}$ orientations occurs at successively higher frequencies with kL for these configurations on the order of L/2b, where 2b is the length of the prolate spheroidal body along the minor axes.

Power deposition more than an order of magnitude is observed at resonance for waves polarized along the long dimension of the body. Alternative experiments using free space plane waves at 1700 MHz to heat saline-filled prolate spheroidal bodies of fixed L/2b ratio of 6 (corresponding to humans) but changing overall dimensions have confirmed the main features of the above results. A notable exception is that for $\vec{E} \| \hat{L}$ polarization, maximum RF absorption is found for bodies of major length approximately[3] 0.4 to 0.5 λ, i.e., at approximately twice the frequency of the values observed in the parallel plate waveguide situation. The reason for this may be 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 parallel plate waveguide) with only a $\lambda/4$ body and its image in the ground plane acting together.

To evaluate the validity of scaling, free space heating experiments have been repeated at 710 MHz for saline-filled prolate spheroidal bodies (L/2b = 6) of larger overall dimensions. The temperature increase for a five-minute exposure to 100 mW/cm^2 radiation is plotted in Fig. 1. From the amount of energy absorbed, the relative absorption coefficient S is calculated[4] and is plotted in Fig. 2. 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 2.5 to 3.5 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[5] Wistar rats were exposed to 100 mW/cm^2 fields at 710 MHz. 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 Figs. 3(a), (b), and (c) for the three orientations. The core temperature read off the calibration chart of the probe is marked alongside the curves in Fig. 3. For an incident power density of 50 mW/cm^2 (Fig. 3(d)), the power deposition in the $\vec{E} \| \hat{L}$ orientation was still much higher than that for the other two configurations at 100 mW/cm^2. For $\vec{E} \| \hat{L}$ 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.

To determine the distribution of power deposition, a 7.25" tall figurine of the female body has been used as a mold to form a cavity in styrofoam. The size of the figurine has been selected such as to allow resonance at 710 MHz for free space radiation and at a frequency about half as much in the parallel plate radiation chamber. In order to simulate ground effects on electromagnetic power absorption, a parallel plate radiation chamber has been designed and fabricated. For the chamber, the central working area consists of a copper plate of width 25" separated by a 10" clearance from the ground plate of 46" width. The overall transmission length of 78" is occupied by two symmetrical tapered sections of 24" axial length, the central working area of 24" length, and two 3" end sections connected to UG58/U input and output coaxial connectors.

From electromagnetic field theory, a body reduced by a factor β in all dimensions would result in RF absorption characteristics identical to the full scale body but at frequencies scaled up by a factor of β. It is necessary, however, that the complex permittivity $(\epsilon_1 - j\sigma/\omega\epsilon_o)$ presented by the scaled down model correspond to the value at the lower resonance frequency characteristic of the whole body. Since the projected frequency of maximum absorption for adult humans is on the order of 40 to 55 MHz in the presence of ground effects, the biological-phantom material that is used should have the dielectric properties of the humans in that frequency range. A composition[7] of the material with 3.26 percent NaCl, 8.74 percent Superstuff (obtained from Whamo Manufacturing Company, San Gabriel, California), and 87.0 percent water has a measured dielectric constant of 66 and a conductivity of 4.39 mho/meter. For use at a frequency of 350 MHz, this corresponds to $\varepsilon_r = 66 - j225.6$. By comparison, for muscle, skin, and tissues with high water content, $\varepsilon_r = 88 - j250$ at 50 MHz.[5] Because of the relative closeness of the two dielectric constants, the mixture of above composition was used to fill the figurine-shaped cavity for experiments in the parallel plate[8] radiation chamber. Temperature under irradiation was recorded using the liquid crystal temperature probe.[6] From the increase in temperature the absorbed power density in mW/gm was calculated from the relationship[4] (4200 × temperature increase)/irradiation time in seconds. The relative absorption coefficient α, defined as mW/gm of absorbed power/(mW/cm^2) of incident field intensity for various parts of the body has been calculated and is given in Table 1. For $\vec{E} \parallel \hat{L}$ orientation the strongest intensity of power deposition is observed in the neck area of the body. For the density of power absorption this is followed by the shins, the thighs, the chest, the eyes, and the crotch in that order. In Fig. 4 the thermographic record of the temperature before and after one minute of free space irradiation with field intensity of 100 mW/cm^2 at 710 MHz is shown. The pattern of power deposition bears a remarkable resemblance to the distribution obtained in the parallel plate irradiation chamber. Only minimal changes in temperature were observed for up to 10 minutes of irradiation in the $\vec{k} \parallel \hat{L}$ and $\vec{H} \parallel \hat{L}$ orientations both for free space and for parallel plate radiation chamber exposures. Experiments have also been repeated for free space irradiation at 1700 MHz for the three polarizations and slides of the observed heating patterns will be shown at the meeting.

In summary, 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 bodies at frequencies such that the major length is approximately one-half wavelength of radiation for bodies in free space and one-quarter wavelength of radiation in the presence of ground-caused image. A significant result of the experiments with biological-phantom figurines is that a high power deposition in the neck region is observed. Power absorption coefficient α = 6.76 for the neck region for $\vec{E} \parallel \hat{L}$ orientation is over 16 times larger than the average value. This may be biologically significant and is being investigated further. For $\vec{k} \parallel \hat{L}$ and $\vec{H} \parallel \hat{L}$ orientations, the rate of heating is minimal and for the neck region is a factor of 40 to 50 times smaller than the rate for the $\vec{E} \parallel \hat{L}$ resonance region.

Table 1. Distribution of power deposition in a 7-1/4" tall biological-phantom human figurine.

Frequency MHz	α Neck	α Shin	α Eyes	α Crotch
	$\vec{E} \parallel \hat{L}$ orientation			
230	2.895			
240	3.381	0.788		0.155
270		1.927		
300	5.097	2.256	0.840	0.442
320	5.367			
350	6.761	1.863		
380		4.368	1.148	
395	6.153			
	$\vec{k} \parallel \hat{L}$ orientation			
395	0.094			
	$\vec{H} \parallel \hat{L}$ orientation			
300	0.130			

References

1. O. P. Gandhi, "Polarization and Frequency Effects on Whole Animal Absorption of RF Energy", *Proceedings IEEE*, Vol. 62, August 1974, pp. 1171-1175.

2. T. Darryl Hawkins and John Schrot, to be published.

3. This result is in agreement with a recently completed study[2] at Walter Reed Army Institute of Research, Washington, D. C., on the lethality of 100 (110 ± 10) and 400 (390 ± 10) gm rats and 25 (27.5 ± 2.5) gm mice when exposed to microwave radiation at 710, 985, 1700, 2450, and 3000 MHz (the various frequencies selected on account of the available facilities).

4. A. Anne, M. Saito, O. M. Salati, and H. P. Schwan, "Relative Microwave Absorption Cross Sections of Biological Significance", pp. 153-177 in Vol. 1 of *Biological Effects of Microwave Radiation*, Plenum Press, 1960.

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

6. T. C. Rozzell, C. C. Johnson, C. H. Durney, J. L. Lords, and R. G. Olsen, "A Nonperturbing Temperature Sensor for Measurements in Electromagnetic Fields", *Journal of Microwave Power*, Vol. 9, 1974, pp. 241-249.

7. A. W. Guy, C. C. Johnson, J. C. Lin, A. F. Emery, and K. K. Kraning, "Electromagnetic Power Deposition in Man Exposed to HF Fields and the Associated Thermal and Physiologic Consequences", Report SAM-TR-73-13 prepared for USAF School of Aerospace Medicine, Brooks Air Force Base, Texas, December 1973.

8. For free space irradiation experiments the composition of the material used is 9.25 percent NaCl, 8.25 percent Super-Stuff (obtained from Whamo Manufacturing Company, San Gabriel, California) and 82.5 percent water. This mixture, having a measured dielectric constant of 66 and a conductivity of 10.09 mho/meter, corresponds to a complex relative permittivity $\varepsilon_r = 66 - j255$ when used at 710 MHz.

* This work was supported by U.S. Army Medical Research and Development Command under Contract DAMD 17-74-C-4092.

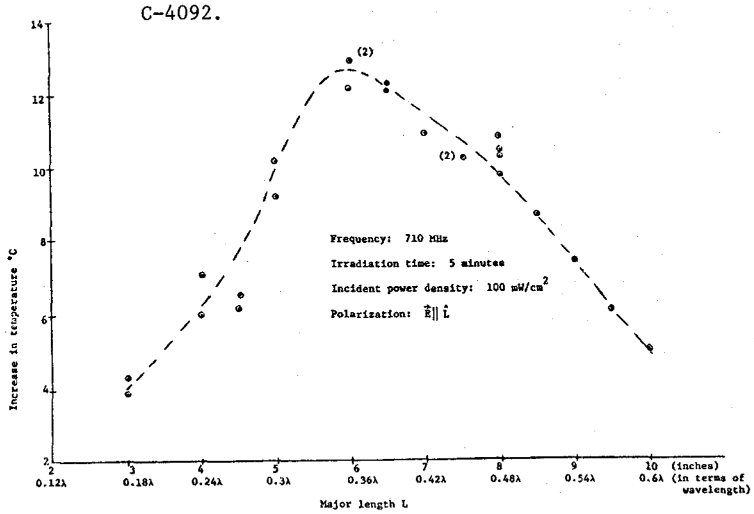


Fig. 1. Temperature rise in saline-filled prolate spheroids of aspect ratio L/2b = 6.

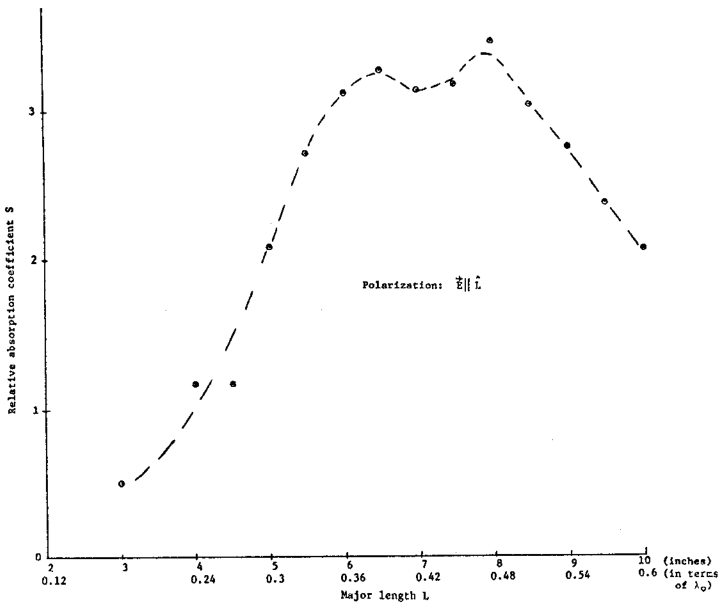


Fig. 2. Relative absorption coefficient S for different size prolate spheroids (L/2b = 6 in each case).

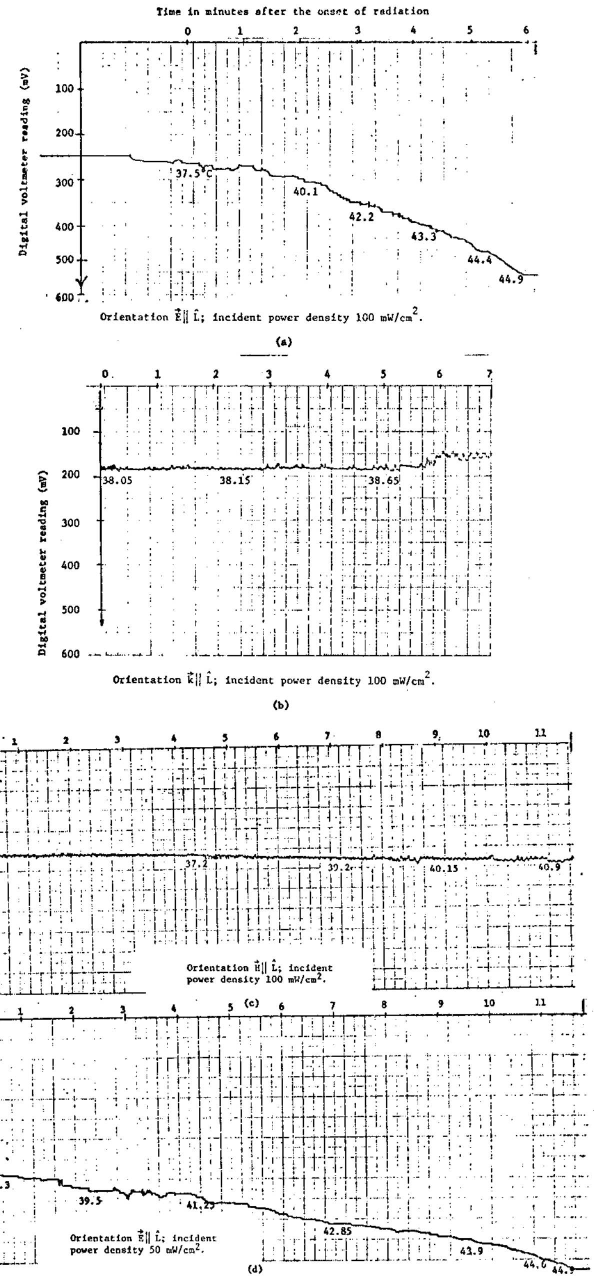
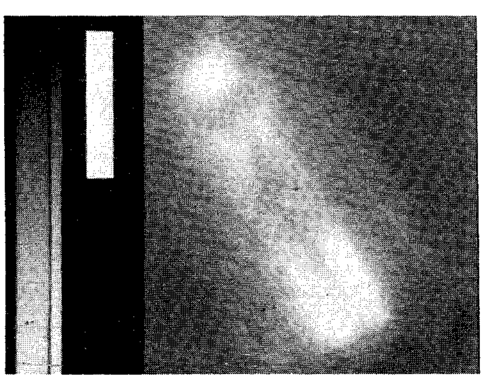


Fig. 3. Core temperature of 250 gm rats exposed to 710 MHz radiation.

a. Before exposure to radiation, 8.5° C baseline; 3° C full scale.



b. After irradiation in the $\vec{E} \parallel \hat{L}$ configuration; waves incident on the front side of the body, 6° C baseline; 10° C full scale.

Fig. 4. The thermographic recording of the central section of a 7-1/4" biological phantom figurine before and after free space plane wave irradiation for one minute at 100 mW/cm^2 at 710 MHz.