POWER DEPOSITION IN A SPHERICAL MODEL OF MAN EXPOSED TO 1-20 MHz EM FIELDS

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Abstract

EM power deposition in a spherical model of man exposed to HF fields may be derived from a simple approximate equation where the absorbed power due to electric field coupling can be calculated separately from that due to magnetic coupling. The latter is an order of magnitude greater for a plane wave.

Summary

In order to assess the environmental impact of high frequency (HF) transmitters on man, one must be able to quantitatively describe the electromagnetic fields and power deposition in the tissues. The human body is a very complex geometrical structure, thus it is extremely difficult to obtain exact theoretical descriptions. We desire simple analytic expression which can be used to predict the nature and degree of power deposition in man as a function of body size and shape, source frequency, and field type. A tractable first approximation to this problem consists of a homogeneous sphere of tissue placed in a plane wave field. This model can then be used to obtain first quantitative estimates of the effect of body volume and weight on total electromagnetic power absorption and the internal distribution of absorbed power.

For a plane wave propagating in the z direction, with $\underline{E}$ polarized in the x direction, the internal field in a spherical model of man according to Mie [1] is

$$\underline{E}_t = E_o e^{-i\omega t} \sum_{n=1}^{\infty} i^n \frac{2n+1}{n(n+1)} \left[a_n^t \underline{m}_{oln}^{(1)} - i b_n^t \underline{n}_{eln}^{(1)} \right] \qquad (1)$$

where a_n^t and b_n^t are absorption coefficients and $\underline{m}_{oln}^{(1)}$ and $\underline{n}_{eln}^{(1)}$ are characteristic spherical vector functions which depend on the complex dielectric constant $N^2 = \varepsilon_1 + i\varepsilon_2$ and the wave number k, and can be expressed in terms of spherical Bessel functions and associated Legendre polynomials.

For a spherical 70 Kg man, the sphere radius a is approximately 25cm. In the HF band of 1 MHz to 20 MHz, the free space ka factor, the complex refractive index $|N|$ of man, and the factor $|Nka|$ vary as follows:

$$0.005 < ka < 0.1,$$
$$23 < |N| < 91$$
$$0.5 < |Nka| < 2.5 \quad .$$

Solving Eq. 1 under the approximation that Nka is small, we obtain

$$\underline{E}_t = E_o e^{-i\omega t} \left[\frac{3}{N^2} \hat{\underline{x}} + i \frac{kr}{2} (\cos\phi \, \hat{\underline{\theta}} - \cos\theta \sin\phi \, \hat{\underline{\phi}}) \right] \qquad (2)$$

↑ quasi-static electric term ↑ quasi-static magnetic term

The electric term is polarized along the x axis like the incident wave E field. The field is uniform in the sphere and identical to the electrostatic solution for a sphere. Thus, complex dielectric surface polarization is set up which generates a uniform internal field. The magnetic term is much different in form and an order of magnitude greater in amplitude than the electric term, and is identical to the quasi-static magnetic solution obtained from $i\omega\mu \int \underline{H} \cdot \underline{dA} = \oint \underline{E} \cdot \underline{dl}$.

The physical insight gained from recognizing that the total electric field inside the sphere is the sum of electric field-induced and magnetic field-induced components makes it possible to infer the effects of absorbed power by impressed fields of variable E/H ratio.

The time-average power density inside the sphere can be obtained from the relation

$$W_L = \frac{1}{2} \sigma \underline{E}_t \cdot \underline{E}_t^*$$

This results in

$$W_L = \frac{1}{2} \sigma E_o^2 \left[\frac{9}{\varepsilon_1^2 + \varepsilon_2^2} - \frac{3\varepsilon_2 kr \cos\theta}{\varepsilon_1^2 + \varepsilon_2^2} + \left(\frac{kr}{2} \right)^2 (\cos^2\phi + \cos^2\theta \sin^2\phi) \right] \qquad (3)$$

Integrating over the sphere volume gives total time-average absorbed power W_t, from which average power and average power per surface area can be calculated.

$$W_t = \frac{1}{2} \sigma E_o^2 \frac{4\pi a^3}{3} \left[\frac{9}{\varepsilon_1^2 + \varepsilon_2^2} + \frac{(ka)^2}{10} \right] \qquad (4)$$

↑ quasi-static electric term ↑ quasi-static magnetic term

In order to estimate the validity and range of applicability of this simple solution, the maximum absorbed power densities were calculated from this solution and compared with the exact Mie results as shown in FIG. 1. Within the HF band 1-20 MHz, the difference in the two solutions is quite small. The spatial distributions of absorbed power along the z axis calculated from Eq. 3 is compared with the exact solution as shown in FIG. 2 for 1, 10 and 20 MHz. The average power comparisons are shown in TABLE I.

Plots of W_L along the z axis for a muscle sphere are shown in FIG. 3 for variable E/H (impedance) values of the impressed field. For predominantly magnetic fields the absorption becomes much more intense and proportional to z^2, whereas for predominantly electric fields, the absorbed power is reduced and approaches the uniform absorbed power pattern of the quasi-static electric solution.

We believe the implications of these results are significant with regard to the estimation of HF microwave hazards from survey meters which read E fields only. It is the magnetic fields which are the primary sources of absorbed power for field impedance magnitudes less than 1200π, and these need to be measured to obtain any kind of estimate of HF hazard.

Reference

1. J.A. Stratton. Electromagnetic Theory, McGraw-

Hill, New York, 1941, Section 9.25.

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TABLE I

Average Power Absorption in a Muscle Sphere

Frequency (MHz)	Exact Mie Solution (mW/cm^3)	Approximate Eq. 3 (mW/cm^3)
1	4.6079×10^{-6}	4.5441×10^{-6}
2	2.6755×10^{-5}	2.6322×10^{-5}
5	1.8048×10^{-4}	1.7941×10^{-4}
10	6.8233×10^{-4}	6.8848×10^{-4}
20	2.4249×10^{-3}	2.6213×10^{-3}
27.12	3.8844×10^{-3}	4.9710×10^{-3}

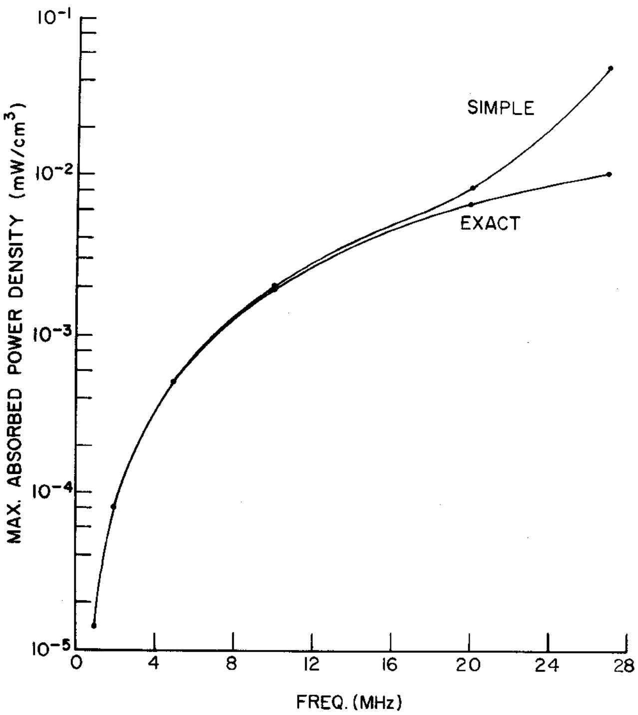

FIG. 1 Maximum absorbed power densities given by exact Mie solution and the simplified solution.

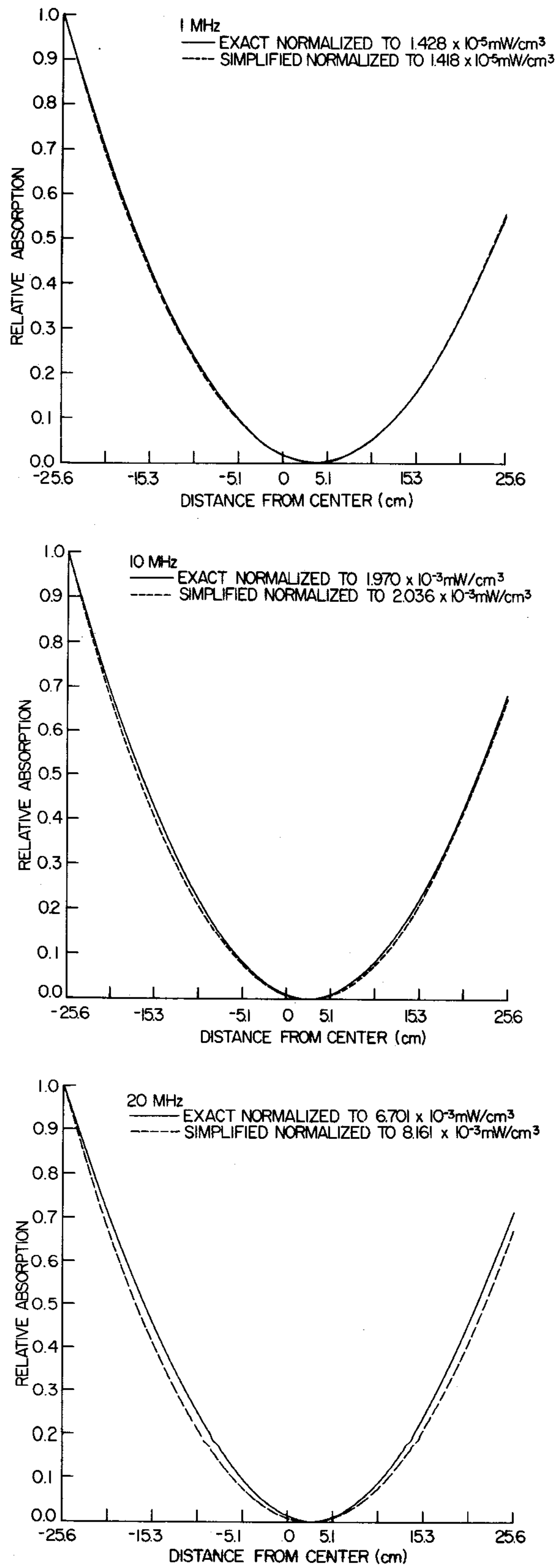

FIG. 2 Normalized absorbed power distributions calculated from the exact Mie solution and the simplified solution.

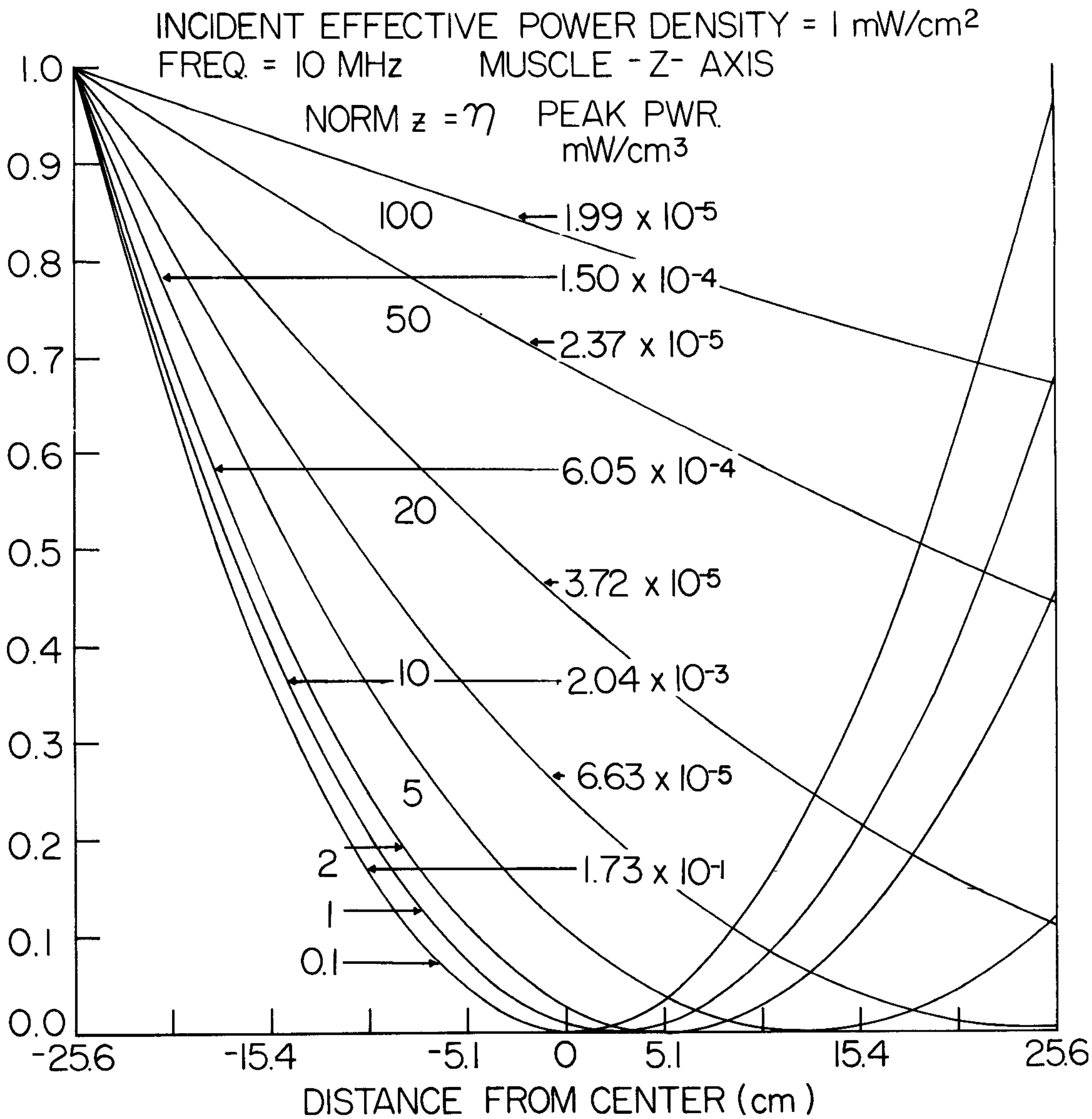

FIG. 3 Absorbed power density as a function of normalized impedance η, where $\eta = E/(\eta_0 H)$, η_0 is the E/H value for a plane wave in the external medium.