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Electromagnetic-Energy Deposition in an Inhomogeneous Block Model of Man for Near-Field Irradiation Conditions

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***Abstract*—The plane-wave spectrum approach is used to calculate the electromagnetic-energy deposition and its distribution in a 180-cell, inhomogeneous block model of man for a prescribed two-dimensional leakage electric field generated by RF sealers and other electronic equipment. The whole-body-averaged energy dose increases approximately as $(\Delta_1^2\Delta_2^2/\lambda^4)$ to the asymptotic plane-wave value, where Δ_1/λ and Δ_2/λ are the vertical and horizontal widths (in wavelengths) of the best fit half-cycle cosine functions to the prescribed leakage fields. The effect of phase variations shows that the worst case (maximum deposition) is always obtained for constant phase in the prescribed fields. The need for exact phase measurements is, therefore, obviated since the upper bound on the deposited energy is often the desired quantity.**

Introduction

A GREAT DEAL of progress has been made in the quantification of electromagnetic absorption by humans under plane-wave irradiation conditions [1], [2]. However, to date, little work has been done with near-field exposure conditions which are of greater concern to workers involved in the operation of equipment using electromagnetic energy for communication, radar, and industrial and biomedical applications. Electromagnetic fields near several pieces of high-power industrial equipment have been measured and found to be fairly intense, with electric fields as high as 500–2000 V/m for 27.12-MHz RF sealers [3], [4], the fields being measured typically within 1 m of the RF source.

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In many near-field problems, the sources are loosely coupled to the human operator, so that the incident field is not altered by the presence of the operator. Such a class of problems has been considered in this paper. Important examples are the leakage fields from RF sealers as well as broadcast and television equipment.

Procedure for Determining Energy-Density Deposition

The 180-cell inhomogeneous block model of man [5] and the coordinate system used in the calculations are illustrated in Fig. 1. Anatomical drawings [6], [7] were used to determine the contents of each cell based on twelve tissue types. The volume-weighted complex permittivity of each cell was calculated using measured values for the various tissue types [8]–[11]. The height of the model is 1.75 m.

The computations require values of the calculated or measured leakage electric fields tangent to a plane (Y–Z plane in Fig. 1) just in front of the intended location of the block model target. The prescribed incident electric-

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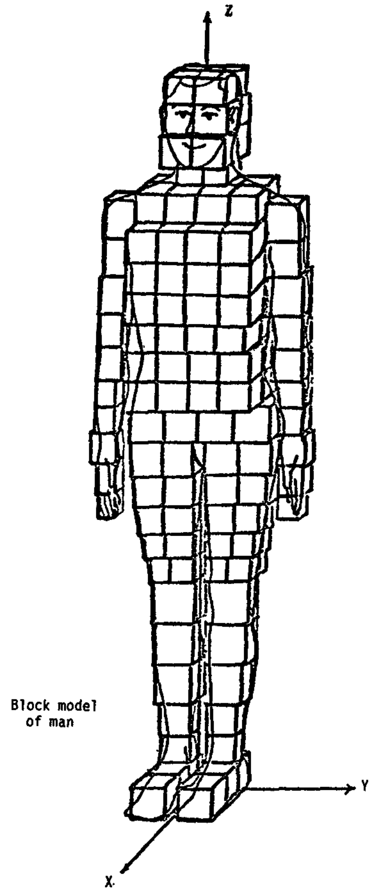


Fig. 1. Coordinate system and geometrical arrangement.

field components E_y and E_z can then be used to calculate, from Maxwell's equations, the remaining field components in the case of *N*-polarization (only H_x, E_y, and H_z may be nonzero) or *P*-polarization (only E_x, H_y, and E_z may be nonzero).

The plane-wave spectrum (PWS) approach of Booker and Clemmow [12], [13], according to which an arbitrary electromagnetic field can be expanded as a series of plane waves traveling in different directions, is used here with the block model of man. This approach has been previously used by us with lossy, semi-infinite homogeneous and layered slab models of man [14], [15]. In order to use Fourier analysis for PWS decomposition, the prescribed fields are repeated with a spatial period that is considerably larger than the physical widths over which the fields are prescribed and also larger than 3–4 free-space wavelengths to prevent interference from the fictitiously repeated sources. The incident electric field at each cell centroid of the block model is calculated by summing the contributions of the plane waves of the spectrum of the prescribed field after allowing for propagation from the Y–Z plane. Implementation of the computationally efficient fast Fourier transform (FFT) [16] and inverse FFT to perform the PWS decomposition at the Y–Z plane and the summation at the cell centroids has allowed usage of as many as 2^{12} or 4096 component plane waves. Many of these waves are evanescent, decaying in amplitude with distance from the Y–Z plane. Moment-method solution of the electric-field integral equation with a pulse function basis and delta functions for testing [5], [17] is used to calculate the electric fields in the various cells of the model from the incident electric fields. At each frequency, for both *N*- and *P*-polarization, it is only necessary to perform one relatively expensive L–U matrix factorization [18]. Thereafter, the stored factors may be used to obtain inexpensive solutions for different incident fields. An interpolant was used to approximate the electric field between cell centroids, thereby increasing accuracy and improving convergence [19].

Results of Numerical Calculations

Two classes of problems are treated here: the first in which only a one-dimensional variation of the prescribed fields is considered, and the second in which two-dimensional variation of the fields over the Y–Z plane is considered.

For simplicity, results for *P*-polarization are presented since it is the more common case for most leakage fields considered to date. The whole-body dose with *P*-polarization exceeds that for *N*-polarization for plane waves unless propagation is approximately parallel to the long axis of the model [20]. This is because the electric field is more nearly parallel with the long axis for *P*-polarization.

The three frequencies considered are 27.12 MHz, which is the frequency at which most RF sealers in the United

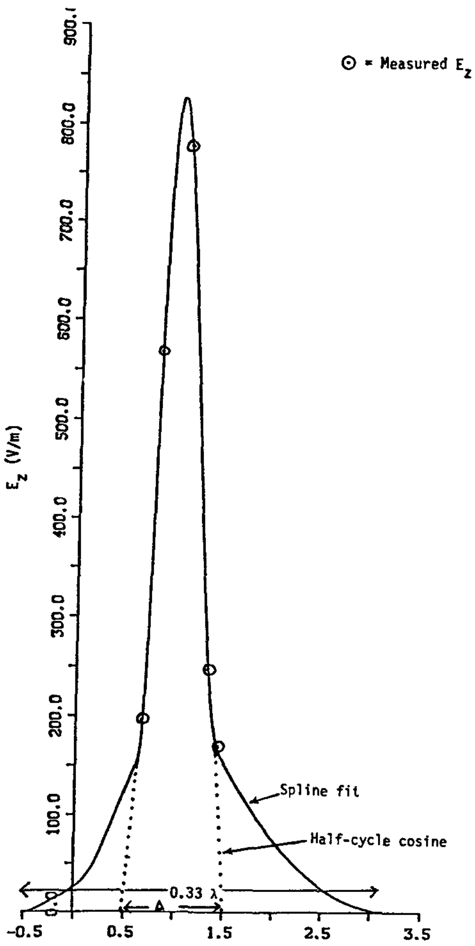


Fig. 2. Prescribed field E_z from a 27.12-MHz RF sealer.

States operate, 77 MHz which is the whole-body resonance frequency of the block model of man [5], and 350 MHz which is the head resonance frequency of the block model [21].

One-Dimensional Variation of the Prescribed Fields

In order to apply the method to a realistic example, the leakage fields measured[1] by BRH/OSHA personnel around an RF sealer operating at 27.12 MHz were used. These measurements were made at a distance of 30 cm from the edge of the table on which the RF sealer was mounted. The measured values of the magnitude of E_z are plotted in Fig. 2, along with a piecewise-cubic spline fit to the data points. Fig. 3 shows the measured values of E_x as well as the E_x distribution generated from E_z in the computations. Zero phase difference was assumed between the various measured values of E_z in preparing Fig. 3. Fig. 4 was obtained by assuming a phase difference in E_z (less than 37° from center to either end of the prescribed E_z) based on differences in retarded time for propagation from the source. A closer agreement of calculated and measured values of E_x is evident in Fig. 4,

[1] Robert Curtis, OSHA, personal communication.

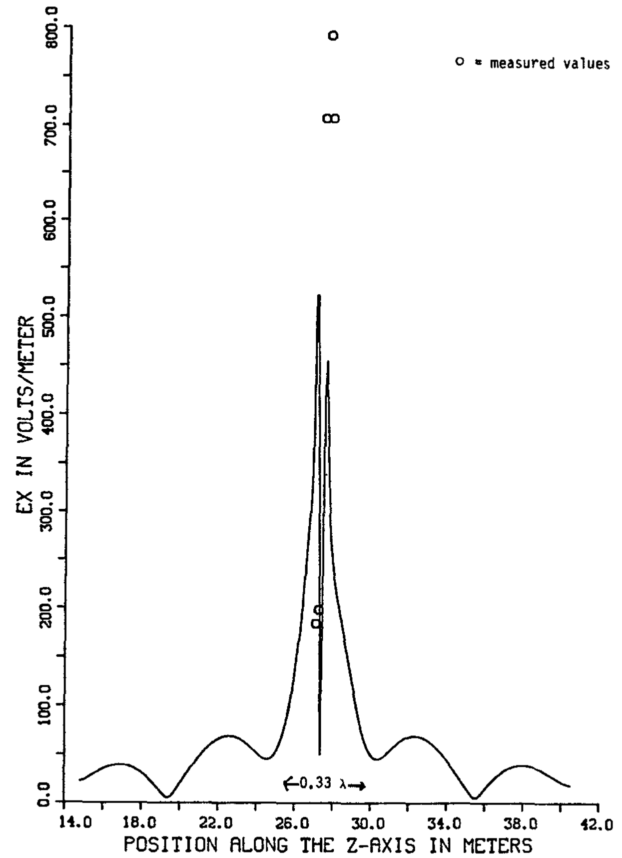


Fig. 3. Electric field E_x for a 27.12-MHz RF sealer calculated from E_z, assuming zero phase difference between the various values of E_z.

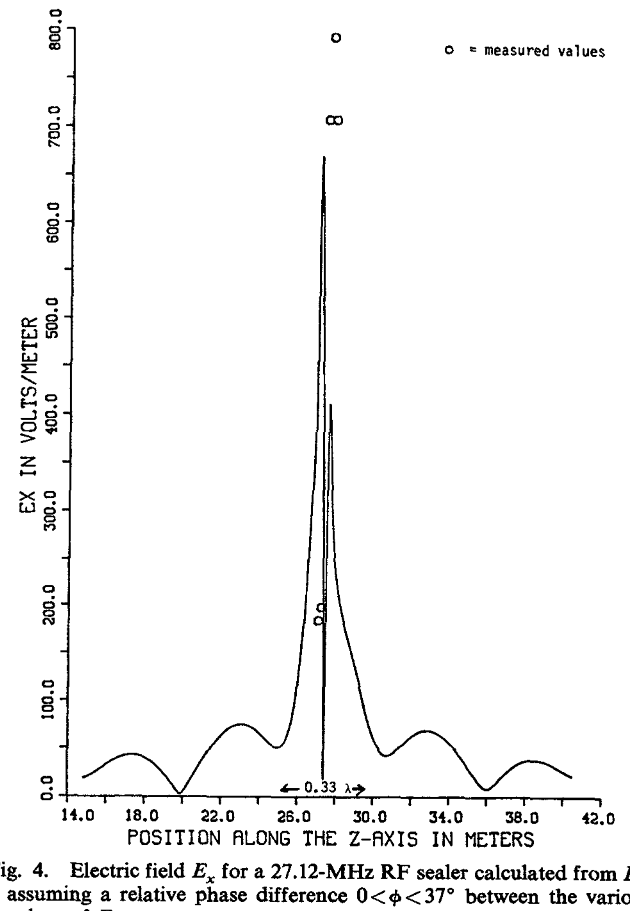
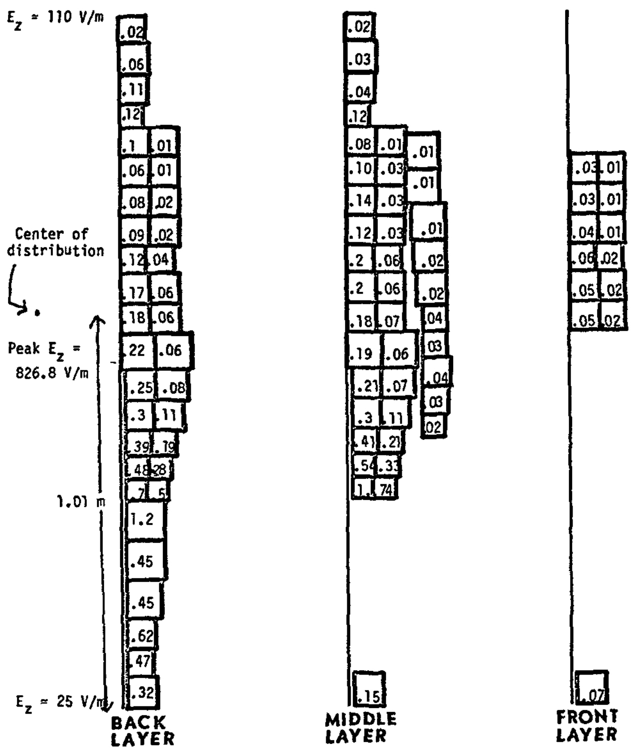


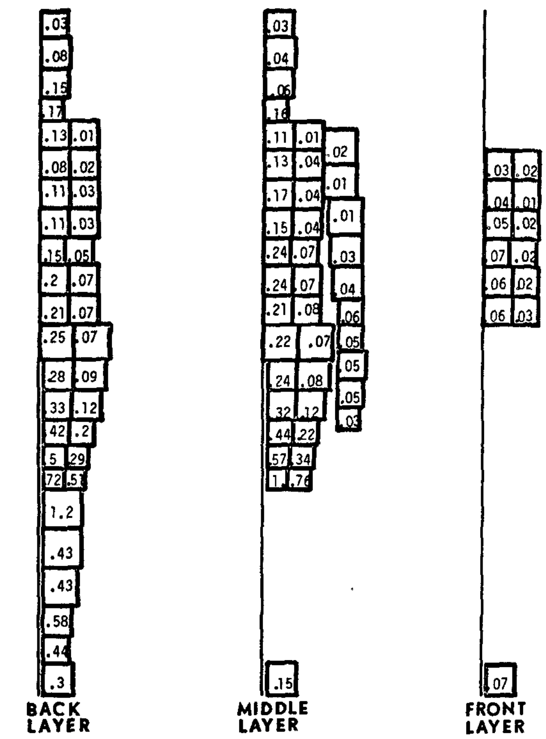
Fig. 4. Electric field E_x for a 27.12-MHz RF sealer calculated from E_z, assuming a relative phase difference $0<\phi<37°$ between the various values of E_z.



The numbers indicated are in watts/kg. The numbers in parentheses are for normal planewave irradiation.

Whole-body average:	0.16 (1.22)	Neck:	0.12 (1.9)
Torso:	0.08 (0.68)	Leg:	0.38 (2.5)
Head:	0.05 (0.79)	Arm:	0.02 (0.17)

Fig. 5. Distribution of energy deposition in the block model of a man placed in the leakage field of a 27.12-MHz RF sealer, assuming a zero phase difference in the incident field E_z; peak $E_z = 826.8$ V/m.



The numbers indicated are in watts/kg. The numbers in parentheses are for normal planewave irradiation.

Whole-body average:	0.16 (1.22)	Neck:	0.15 (1.9)
Torso:	0.09 (0.68)	Leg:	0.35 (2.5)
Head:	0.06 (0.79)	Arm:	0.03 (0.17)

Fig. 6. Distribution of energy deposition in the block model of a man placed in the leakage field of a 27.12-MHz RF sealer, assuming a relative phase difference $0<\phi<37°$ in the incident field E_z; peak $E_z = 826.8$ V/m.

suggesting that phase measurement would be required if more exact calculations were to be made. Also, a larger number of data points should be used in future field specifications to obtain a more accurate representation of the field distribution. The calculated values of whole-body-averaged energy deposition and its distribution for the fields of Figs. 2–4 with and without phase information are shown in Figs. 5 and 6, respectively. The plane of the prescribed field distribution was located immediately in front of the block model of man (tangent with the toes) in these and successive calculations. Also shown in these figures are the values of energy deposition calculated for a ventrally incident plane wave with a peak electric field of 826.8 V/m corresponding to the maximum electric field measured from the RF sealer. A whole-body-averaged energy deposition on the order of 13-14 percent of the plane-wave value is calculated for the prescribed fields. It is interesting to note that the inclusion of the relative phase causes very little difference (<2 percent) in the whole-body-averaged value of energy deposition. The relative unimportance of phase is attributed to the frequency being so low that the wavelength is considerably larger than the length of the target.

From Fig. 2 it is apparent that for many real-life near-field situations, it may be possible to approximate the leakage fields by a single half-cycle cosine function of physical width Δ. Such an approximate field variation of E_z is shown dotted in Fig. 2 and covers a width Δ of 1.0 m. In order to allow an approximate calculation of electromagnetic energy deposition in man for real-life problems, fields E_z having a half-cycle cosine variation and P-polarization over physical widths $0.003 \leq \Delta/\lambda \leq 2$ were used as the incident fields. The whole-body-averaged deposition and its distribution in the block model were calculated and plotted in Figs. 7 and 8 for 27.12 and 77 MHz, respectively.

The important points to note from these results are as follows:

1) At both frequencies the whole-body-averaged dose, as well as the dose in the various parts of the model, increase approximately as $(\Delta/\lambda)^2$ to the asymptotic plane-wave values indicated by the horizontal lines.

2) For both the frequencies, the values of energy deposition for field distribution widths Δ on the order of 1.5–1.8 times the height of the block model are given with reasonable accuracy by the plane-wave values. This is because for this Δ, the half-cycle cosine field distribution is nearly constant over the height of the block model and closely approximates a plane wave.

A cross has been used in Fig. 7 to indicate the whole-body-averaged dose corresponding to an approximate width Δ of 1.0 m as indicated by dotted lines in Fig. 2. The 1.0-m width ($\Delta/\lambda = 0.09$) corresponds to a dose of 0.18 W/kg for a peak $E_z = 826.8$ V/m, where the dose

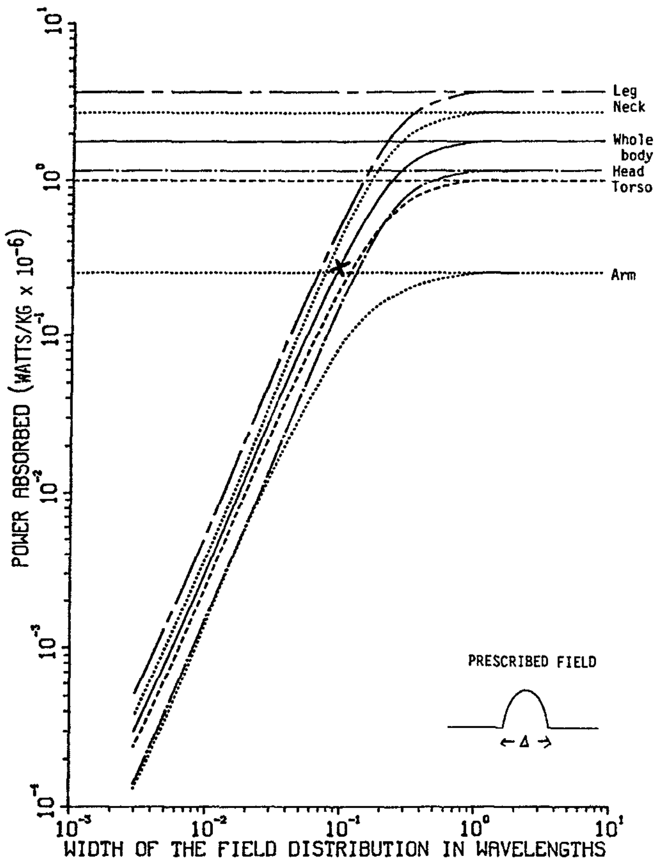


Fig. 7. Average whole- and part-body energy deposition in the block model of a man placed in front of a half-cycle cosine field E_z with P-polarization; frequency=27.12 MHz, $E_z|_{max}=1$ V/m.

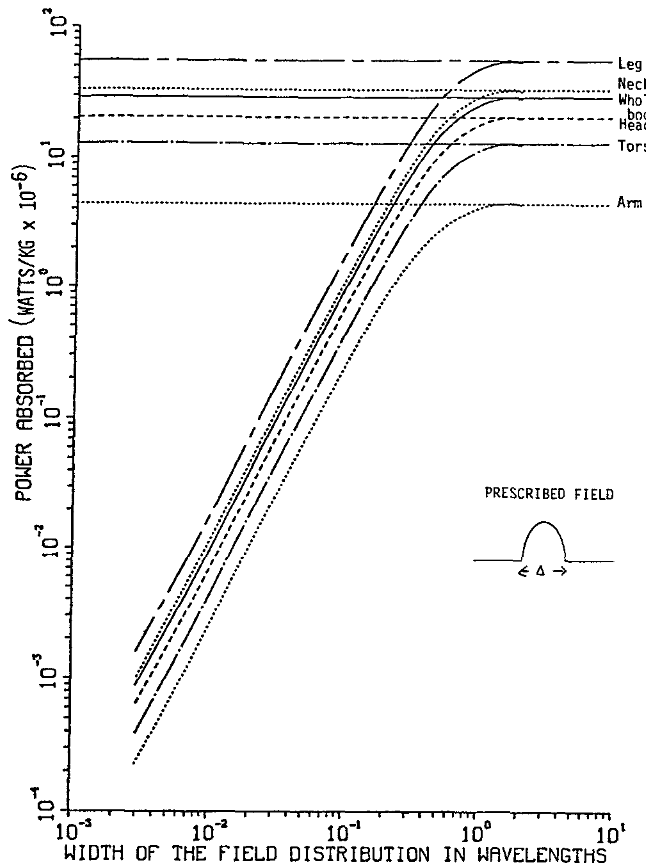


Fig. 8. Average whole- and part-body energy deposition in the block model of a man placed in front of a half-cycle cosine field E_z with P-polarization; frequency=77 MHz, $E_z|_{max}=1$ V/m.

was calculated on the basis of a half-cycle cosine distribution (Fig. 7). This value compares reasonably well with the value 0.16 W/kg (see Fig. 5) obtained from the exact calculations. Thus while exact calculations based on measured values may be necessary for some cases, in many instances it may be possible to use the results for the best fit half-cycle cosine function to the prescribed field distribution. Other test cases have also confirmed this conclusion.

Effect of Phase Variation

It is likely that phase variation in the prescribed field distribution will be important at higher frequencies. In order to test this, the whole-body-averaged energy deposition in the block model were calculated for the following cases:

1) a linear, symmetric phase variation at 77 MHz;
2) a linear antisymmetric phase variation at 77 MHz;
3) a linear antisymmetric phase variation at 350 MHz.

For each of the above phase variations, a prescribed half-cycle cosine field distribution E_z with P-polarization and $\Delta/\lambda=0.5$ was used. The results are plotted for the three cases in Figs. 9–11, respectively. The important points to note are:

1) In all the three cases, as far as whole-body-averaged deposition is concerned, the maximum deposition occurs when there is zero phase variation along the distribution.

2) At the higher frequency of 350 MHz, there are larger variations in the energy deposition in small parts of the block model like the arm.

Thus one may conclude that the calculations of whole-body-averaged energy deposition assuming zero phase variation will give an upper bound on the energy dose since phase measurements are not easily made in practice. For exact calculations, especially at higher frequencies, the phase variation would have to be considered.

Two-Dimensional Variation of the Prescribed Fields

The preceding calculations were extended to the more realistic case of prescribed leakage fields having variation in both the Y and Z directions. Since in real life it may often be possible to approximate prescribed fields by the best fit half-cycle cosine functions, the field component E_z was assumed to have this variation in the Y and Z directions with physical widths Δ_2 and Δ_1, respectively. For simplicity, the fields were assumed to be separable. Once again the three frequencies 27.12, 77, and 350 MHz were used.

The separability of the Y and Z dependence of the fields allowed usage of a 4096-point one-dimensional FFT algorithm for the PWS decomposition. The incident electric field at each cell centroid was calculated by summing

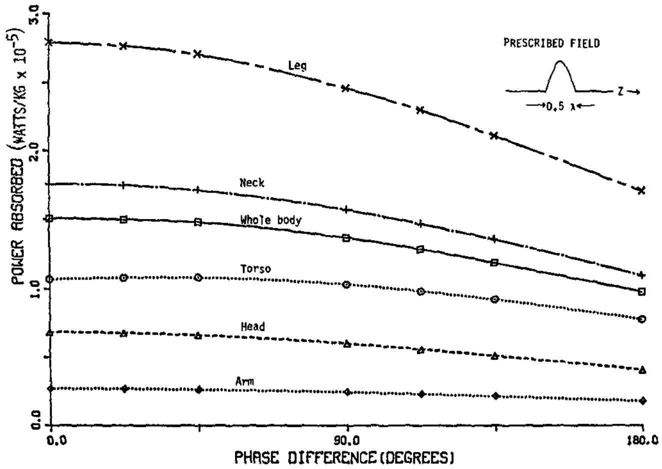


Fig. 9. Average whole- and part-body energy deposition in the block model of a man placed in front of a prescribed field distribution with half-cycle cosine amplitude variation with P-polarization and a linear symmetric phase variation in the z direction; frequency = 77 MHz, $\Delta/\lambda = 0.5$, $|E_z|_{max} = 1$ V/m.

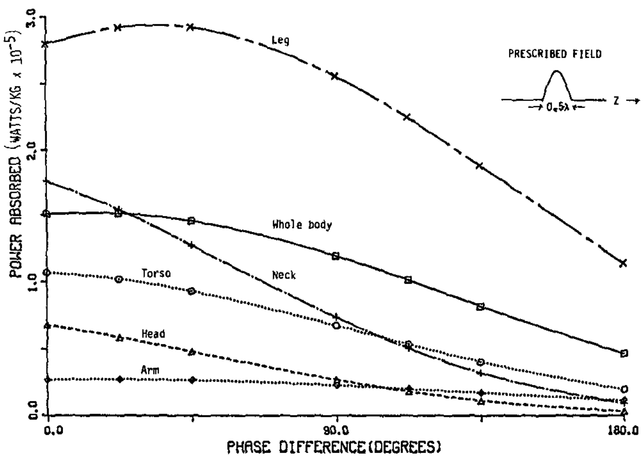


Fig. 10. Average whole- and part-body energy deposition in the block model of a man placed in front of a prescribed field distribution with half-cycle cosine amplitude variation with P-polarization and a linear antisymmetric phase variation in the z direction; frequency = 77 MHz, $\Delta/\lambda = 0.5$, $|E_z|_{max} = 1$ V/m.

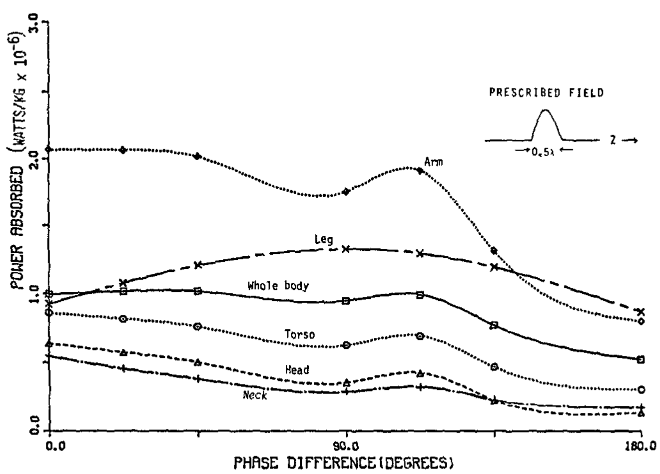


Fig. 11. Average whole- and part-body energy deposition in the block model of a man placed in front of a prescribed field distribution with half-cycle cosine amplitude variation with P-polarization and a linear antisymmetric phase variation in the z direction; frequency = 350 MHz, $\Delta/\lambda = 0.5$, $|E_z|_{max} = 1$ V/m.

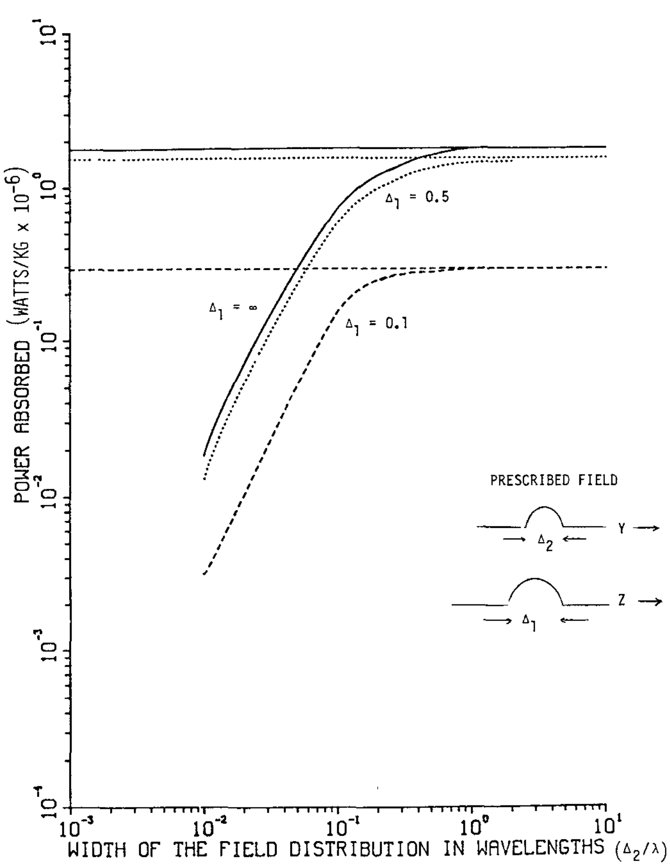


Fig. 12. Average whole-body energy deposition in the block model of a man placed in front of a two-dimensional varying prescribed field distribution with P-polarization and half-cycle cosine variation in the y and z directions; frequency = 27.12 MHz, $E_z|_{max} = 1$ V/m.

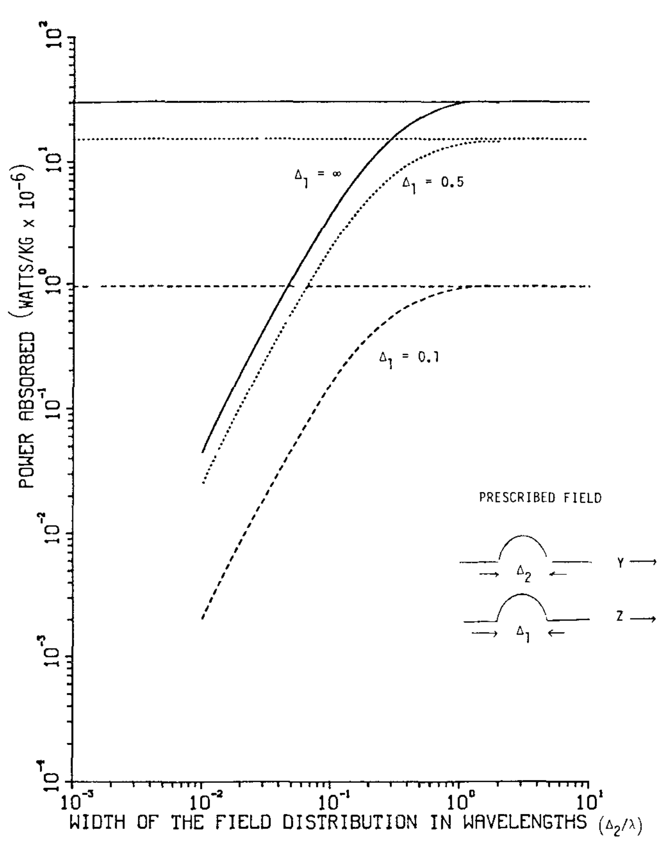


Fig. 13. Average whole-body energy deposition in the block model of a man placed in front of a two-dimensional varying prescribed field distribution with P-polarization and half-cycle cosine variation in the y and z directions; frequency = 77 MHz, $E_z|_{max} = 1$ V/m.

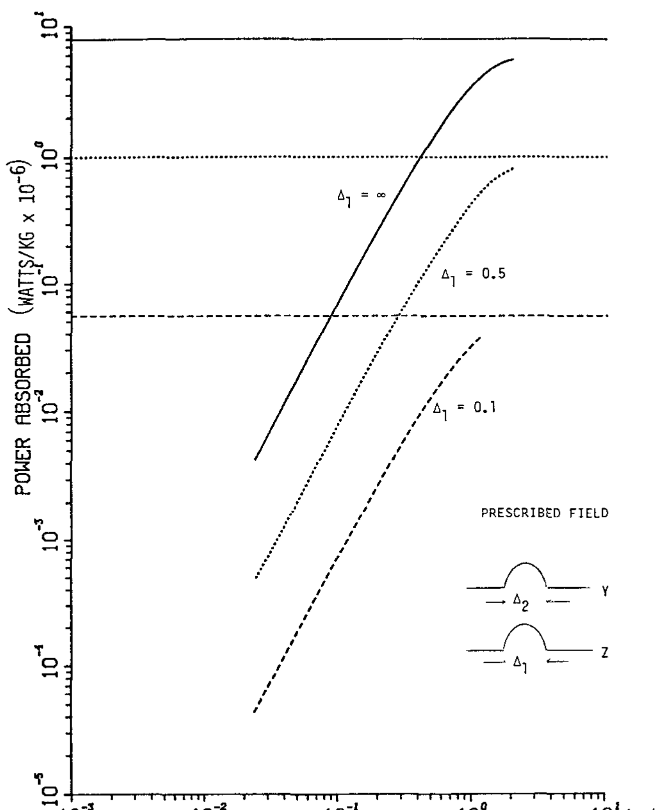


Fig. 14. Average whole-body energy deposition in the block model of a man placed in front of a two-dimensional varying prescribed field distribution with P-polarization and half-cycle cosine variation in the y and z directions; frequency = 350 MHz, $E_z|_{max} = 1$ V/m.

the contributions of the plane waves. Convergence tests were made to assure that the number of plane waves used in the summation was sufficient. The method of moments was again used to obtain the energy deposition in the block model. Calculations could easily be extended to nonseparable prescribed leakage fields at a considerable increase in expense.

The results of the computations for two-dimensional distributions are plotted in Figs. 12–14. The width Δ_2 was varied from 0.01 to 2 times the free-space wavelength for $\Delta_1 = \infty$, 0.5, and 0.1 times the wavelength, where $\Delta_1 = \infty$ corresponds to the case of no variation in the z direction.

In Figs. 12–14, the whole-body-averaged energy deposition and its distribution in the block model increase approximately as $\Delta_1^2 \Delta_2^2 / \lambda^4$ to the asymptotic value which corresponds to the values obtained in the case of one-dimensional variation. It is also observed that for the three frequencies used, the energy dose for Δ_1 of the order of 1.5–1.8 times the height of the block model and Δ_2 larger than 3–4 times the width of the model approaches the plane-wave values [20]. These results can be used to predict the approximate energy deposition at any frequency if the asymptotic value is known. Also the effective aperture or equivalent area over which the block model extracts energy from a plane wave at 77 MHz is seen to be given by 0.13 λ^2 which is the effective aperture of a half-wave dipole. This has also been pointed out previously [22]. The effect of phase variation on the en-

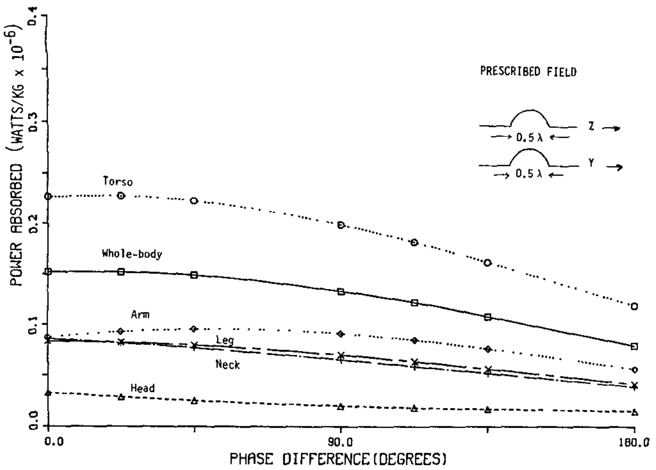


Fig. 15. Average whole- and part-body energy deposition in the block model of a man placed in front of a two-dimensional varying prescribed field distribution with half-cycle cosine amplitude variation and a linear symmetric phase along the y and z directions; frequency $=350$ MHz, P-polarization, $\Delta_1/\lambda=\Delta_2/\lambda=0.5$, $|E_z|_{max}=1$ V/m.

ergy deposition due to a two-dimensional varying field at 350 MHz was also studied. A linear symmetric phase variation was assumed in the Y and Z directions of a prescribed field E_z whose magnitude varies as a half-cycle cosine function of width 0.5 λ in the two directions. The results are plotted in Fig. 15. It is noted that, as before, the greatest deposition is obtained for zero phase variation in the prescribed fields.

Conclusions

The results presented in this paper indicate that it is possible to approximate a measured or calculated leakage field by the best fit half-cycle cosine function and obtain a good approximation for the energy deposition and its distribution in the block model. For the frequencies 350 MHz or below at which the 180-cell block model is a good representation of man, the energy deposition under near-field conditions is always less than or equal to the far-field plane-wave value. As far as whole-body-averaged energy deposition is concerned, the effect of phase is only to lower the dose. Thus if an upper bound on the energy dose is required, phase measurement is not necessary. Also, although a two-dimensional varying field is more realistic, it is possible to obtain an upper bound on the energy deposition by neglecting the variation in the horizontal direction.

The computations are being extended to include ground effects, using image theory [23]. Experiments are presently underway to test the highlights of the numerical results.

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