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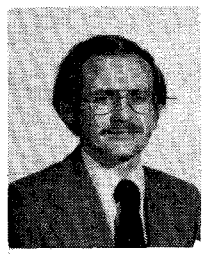

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Limitations of the Cubical Block Model of Man in Calculating SAR Distributions

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Abstract—**Block models of man which consist of a limited number of cubical cells are commonly used to predict the internal electromagnetic (EM) fields and specific absorption rate (SAR) distributions inside the human body. Numerical results, for these models, are obtained based on moment-method solutions of the electric-field integral equation (EFIE) with a pulse function being used as the basis for expanding the unknown internal field.**

In this paper, we first examine the adequacy of the moment-method procedure, with pulse basis functions, to determine SAR distributions in homogeneous models. Calculated results for the SAR distributions in some block models are presented, and the stability of the solutions is discussed. It is shown that, while the moment-method, using pulse basis functions, gives good values for whole-body average SAR, the convergence of the solutions for SAR distributions is questionable. A new technique for improving the spatial resolution of SAR distribution calculations using a different EFIE and Galerkin's method with linear basis functions and polyhedral mathematical cells is also described.

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I. Introduction

In the study of the possible biological effects of electromagnetic (EM) radiation and in medical applications utilizing EM energy, it is important and desirable to determine the internal EM fields and specific absorption rate (SAR) distributions inside the human body. The existing models commonly used to predict the induced EM fields inside the human body are block models consisting of a limited number of cubical cells. Numerical results for these models are obtained based on moment-method solutions of the electric-field integral equation (EFIE) with a pulse function being used as the basis for expanding the unknown internal field [1]–[6]. Although the aforementioned models have provided significant information about the average whole-body and partial-body SAR's, there remains a need to obtain a detailed and more accurate SAR distribution in the human body. Specific suggestions have been made that such accurate numerical results may be obtained by using a larger number of mathematical cells and by further using inhomogeneous models to accurately represent the permittivity inhomogeneities in the body [6].

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In an attempt to improve the spatial resolution of SAR distribution calculations and to calculate the EM power absorption by a fetus when the expectant mother is irradiated by RF near fields, we have studied the stability of the moment-method solution of the EFIE [7]. We began our study first by looking into the effect of subdivisions of cells in a particular region of the body on the SAR distributions in the other regions of the body. During the course of this study, we have found that the pulse-function, moment-method solution of the EFIE provides good values only for whole-body average SAR, but the convergence of the solution for SAR distributions is dependent on the specific subdivision of the model into smaller mathematical cells and its accuracy is, therefore, questionable. In particular, we have found that the expansion of the unknown fields in terms of pulse basis functions cannot satisfy boundary conditions at the mathematical cell surface boundaries. Furthermore, we have shown by subdivision of mathematical cells that this method of solution has some serious deficiencies particularly when applied to inhomogeneous models.

In the next section, some calculated SAR data in some block models are presented. Numerical results presented in this paper are obtained by solving the EFIE, using the method of moments with pulse basis functions. Chen and Guru [1] and Hagmann *et al.* [2] have utilized this method to calculate the induced fields and SAR's inside block models of man irradiated by an EM planewave. Penn and Cohoon [8] have also applied this method to calculate the internal fields and SAR distribution inside a lossy dielectric sphere exposed to an EM planewave. Since a complete description of the method and an upper limit on the dimensions of cells for the required accuracy are given by these authors, we only describe the model and present our calculated values. Our computer program is adapted from a program written by Livesay and Chen for planewave irradiation [9]. We wish to thank Professor K.-M. Chen for furnishing a listing of his program.

II. Effect of Subdivision on SAR

The effect of subdivisions of mathematical cells in a particular region of the body on the SAR distributions in the other regions of the body is investigated, and numerical results are presented in this section. First, calculations of the SAR distributions are carried out in two types of human models: a) a standing block model of an average man, and b) a sitting block model of an average woman. Then, a cubical model is considered to study the effect of subdivision of cells on the local SAR values. The complex dielectric constant values used in calculating SAR, for all of the models considered in this paper, are taken from the curves given in the second edition of the *Radiofrequency Radiation Dosimetry Handbook* [10].

Fig. 1 shows a standing model of man constructed with 114 cubic cells of various sizes ranging from $(5\ \text{cm})^3$ to $(12\ \text{cm})^3$. The orientation of the model with respect to the rectangular coordinate systems is also shown in Fig. 1 for later reference. The model is 175 cm high and is similar to the one reported by Chen and Guru [1], except for some modifications in the thigh and leg regions. It can be seen from Fig. 1(a) that the right half and the left half of the model are the mirror image of each other and, therefore, in numerical calculations, only 57 cells have been used.

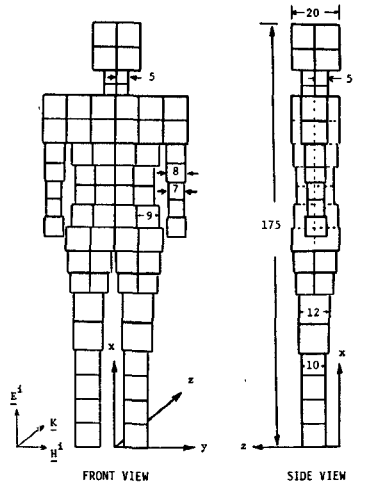

Fig. 1. A standing model of man. The model is constructed with 114 cubic cells of various sizes. The dimensions are given in centimeters.

Fig. 2 shows the SAR distribution inside the standing model irradiated by an EM plane wave at 27.12 MHz. The incident E-field, the incident H-field, and the propagation vectors are along the x, y, and z axes, respectively. The peak value of the incident electric field is 1 V/m. Since the body is symmetrical, the SAR values are shown only in one half of the body. The SAR values for planewave irradiation, Fig. 2, are given here for the purpose of comparing them with the SAR data in a more refined model, which is considered next.

Fig. 3 shows the SAR distributions inside a standing block model constructed with 156 cubic cells and is a modified version of the one shown in Fig. 1. The modifications are as follows: six cells in the abdomen region (the shaded region in Fig. 3) are each divided into eight cubic cells. Comparison of the SAR data in Fig. 3 with those given in Fig. 2 shows that the partitioning of the cells in the abdomen region has changed the SAR distributions in the remainder of the body, especially in the cells close to the partitioned region. For example, the SAR values have changed up to 50 percent in the cells adjacent to the partitioned region. It can also be seen that the rate of change in SAR values decreases as the distance from the partitioned region increases. For instance, the maximum change in the head and feet regions is less than two percent. It is also interesting to note that while the partitioning of the cells in one region of the body, in this case the abdomen region, causes a major change in the SAR distributions, the average SAR in the body remains almost the same. The difference in the average SAR for the model shown in Fig. 2 and the one in Fig. 3 is found to be about three percent.

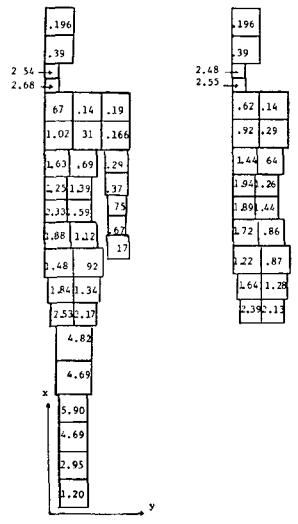

Fig. 2. SAR (μW/kg) distribution inside a standing model of man due to an incident EM plane wave at 27.12 MHz. $\underline{E}^i \| \hat{x}, \underline{K}^i \| \hat{z}, |\underline{E}^i| = 1$ V/m, $\sigma = 0.42$ S/m, $\varepsilon'/\varepsilon_o = 76$.

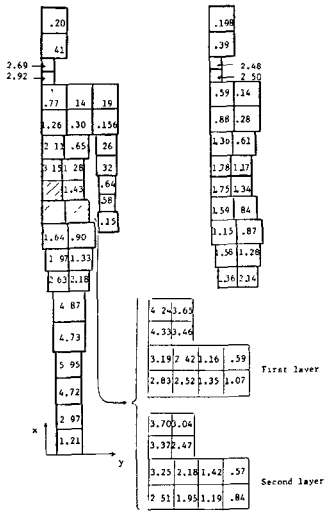

Fig. 3. SAR (μW/kg) distribution inside a standing model of man irradiated by an incident EM plane wave at 27.12 MHz. $\underline{E}^i \| \hat{x}, \underline{K}^i \| \hat{z}, |\underline{E}^i| = 1$ V/m, $\sigma = 0.42$ s/m, $\varepsilon'/\varepsilon_o = 76$.

We then considered a sitting block model of an average woman for calculations of the internal electric field and SAR distributions. Fig. 4 shows such a model constructed with 104 cubic cells of various sizes ranging from $(4.8\text{ cm})^3$ to $(14.4\text{ cm})^3$. The orientation of the model with respect to the rectangular coordinate systems is also shown in Fig. 4. Fig. 5 shows the SAR distribution inside the model when irradiated by an incident EM planewave at 27.12 MHz. The incident E-field, the incident H-field, and the propagation vectors are along the x, y, and z axes, respectively. The peak value of the incident electric field is 1 V/m.

Fig. 6 shows the SAR distributions inside a sitting model of an average woman exposed to an incident EM plane wave at 27.12 MHz. The irradiation conditions are the same as those given in Fig. 4. The model is constructed with 160 cubic cells and is similar to the one shown in Fig. 4, except for some subdivisions in the abdomen region (the shaded region in Fig. 6). Comparision of the SAR data

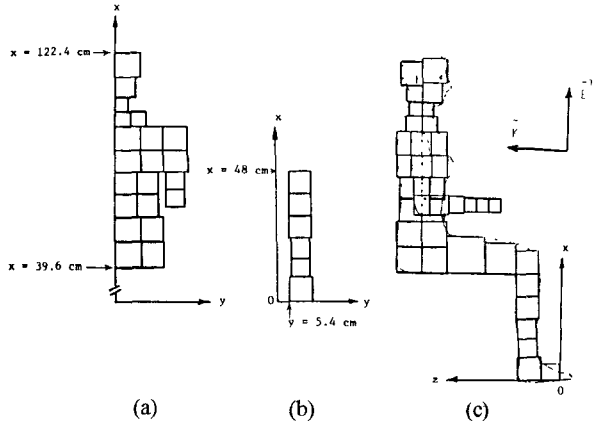

Fig. 4. A sitting model of an average woman exposed to fields of an EM plane wave. (a) Front view of the trunk. (b) Front view of the leg (from knee to ankle). (c) Side view.

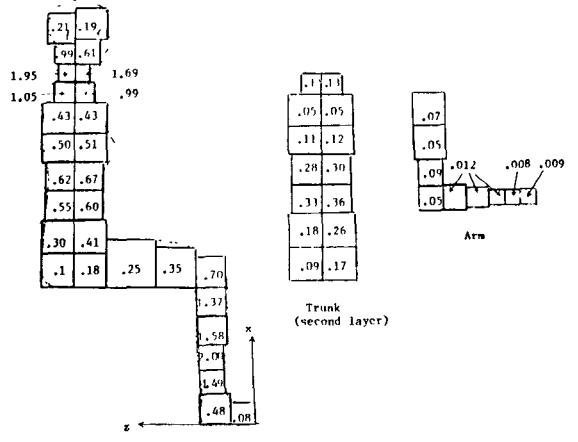

Fig. 5. SAR (μW/kg) distribution inside a sitting model of an average woman due to an incident EM plane wave at 27.12 MHz. $\underline{E}^i \| \hat{x}, \underline{K}^i \| \hat{z}, |\underline{E}^i| = 1$ V/m, $\sigma = 0.42$ S/m, $\varepsilon'/\varepsilon_o = 76$.

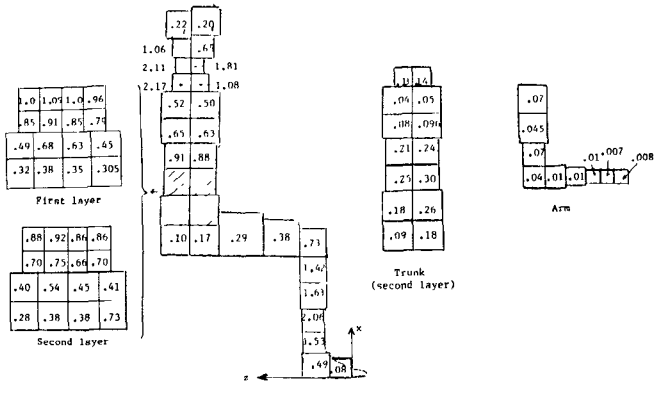

Fig. 6. SAR (μW/kg) distribution inside a sitting model of an average woman irradiated by an incident EM plane wave at 27.12 MHz. $\underline{E}^i \| \hat{x}, \underline{k}^i \| \hat{z}, |\underline{E}^i| = 1$ V/m, $\sigma = 0.42$ S/m, $\varepsilon'/\varepsilon_o = 76$.

shown in Fig. 6 with those given in Fig. 5 shows that the subdivision of cells in one region of the body has, again, caused a major change in the SAR distributions.

The calculated SAR data presented in Figs. 2–6 raise the following question. Why does subdivision of the cells in one particular region of the body change the SAR distributions in the remainder of the body? This effect is particu-

larly questionable since, for the cases considered so far, the block models were homogeneous (i.e., the complex permittivity was assumed to be constant throughout the models) and, furthermore, the linear dimension of the largest cell in all the models was chosen to be sufficiently small, compared with the wavelength inside the cell, to comply with the upper bound criteria. In an attempt to answer these questions and in order to gain a better physical insight into the moment-method solutions of the EFIE, we considered simpler models, such as cubical models, and will first present the effect of subdivision of cells on the SAR and the convergence procedures in these models.

Fig. 7 shows a cubical tissue block model ($30\times30\times30$ cm^3) illuminated by an incident EM planewave. The polarization of the EM field vectors and the orientation of the cube with respect to the rectangular system of coordinates are also shown in Fig. 7. The cube is first divided into 27 cells, each having a side 10 cm long. Fig. 8 shows the local SAR values in the center of each cell due to an incident planewave at 27.12 MHz.

Fig. 9 shows the SAR distributions in a cubical tissue block model for which a cell at the very center of the cube has been subdivided into eight cells. Comparision of the SAR data given in Figs. 8 and 9 shows that partitioning of a cell at the center of the cube does not perturb the SAR values in the neighboring cells. The only change occurs in the value of the SAR in the partitioned cell. In this case, the value of the SAR in the center of the cube has changed by ten percent and the average SAR in the cube has remained unchanged.

Fig. 10 shows the SAR distributions in a cubical tissue block model for which a cell on one surface of the cube (a cell at the center of the first layer in the $x-y$ plane) has been subdivided into eight cells. In this case, it can be seen that the values of the SAR in the undivided cells have not changed, compared to the values given in Fig. 8.

Fig. 11 shows the SAR distributions in a cubical tissue block model for which a cell at a corner of the cube has been subdivided into eight smaller cells. It is interesting to note that partitioning of a cell at a corner of the cube has changed the value of the SAR in the neighboring cells up to 60 percent (compare these values with those given in Fig. 8). The SAR value at the corner, i.e., in the subdivided region, has increased, approaching a value 49 percent greater than that estimated value using one cell. It is also interesting to note that the change in the average SAR in the cube is only four percent.

Fig. 12 shows the SAR distribution in a cubical tissue block model for which a cell on one surface of the cube (a cell at the center of the third layer in the $y-z$ plane in Fig. 7) has been subdivided into eight cells. Note that the subdivided cell is located in a surface which is perpendicular to the incident E-field vector. Comparison of the SAR data given in Figs. 8 and 12 shows that partitioning of a cell at a surface of the cube, which is normal to the incident E-field, has changed the value of the SAR in the neighboring cells up to 70 percent. The SAR value in the subdivided region has increased approaching a value 55

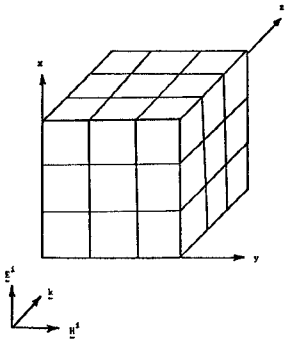

Fig. 7. A dielectric cube ($30\times30\times30$ cm^3) irradiated by an incident EM plane wave.

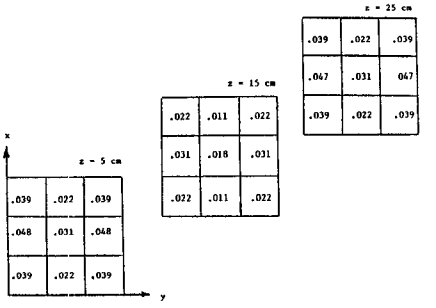

Fig. 8. SAR (μW/kg) distribution in a cubical tissue block model ($30\times30\times30$ cm^3) irradiated by an incident EM plane wave at 27.12 MHz. $\underline{E}^i \| \hat{x}, \underline{H}^i \| \hat{y}, |\underline{E}^i| = 1$ V/m, $\sigma = 0.42$ S/m, and $\varepsilon'/\varepsilon_o = 76$.

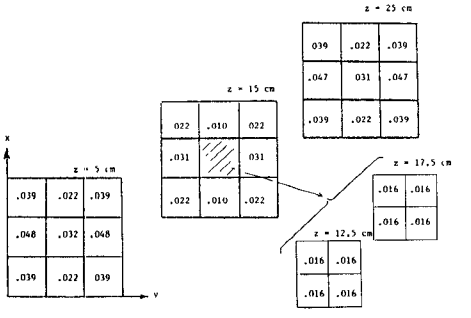

Fig. 9. SAR (μW/kg) distributions in a cubical tissue block model ($30\times30\times30$ cm^3) irradiated by an incident EM plane wave at 27.12 MHz. $\underline{E}^i \| \hat{x}, \underline{H}^i \| \hat{y}, |\underline{E}^i| = 1$ V/m, $\sigma = 0.42$ S/m, $\varepsilon'/\varepsilon_o = 76$. The average SAR is 3.102×10^{-5} mW/kg.

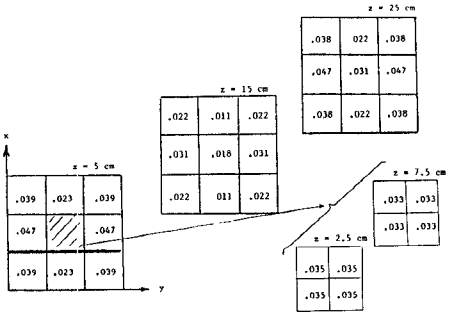

Fig. 10. SAR (μW/kg) distributions in a cubical tissue block model ($30\times30\times30$ cm^3) irradiated by an incident EM plane wave at 27.12 MHz. $\underline{E}^i \| \hat{x}, \underline{H}^i \| \hat{y}, |\underline{E}^i| = 1$ V/m, $\sigma = 0.42$ S/m, $\varepsilon'/\varepsilon_o = 76$. The average SAR is 3.105×10^{-5} mW/kg.

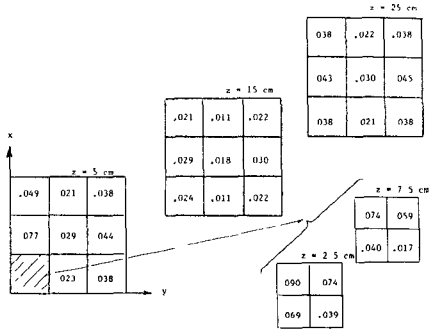

Fig. 11. SAR (μW/kg) distributions in a cubical tissue block model ($30\times30\times30$ cm^3) irradiated by an incident EM plane wave at 27.12 MHz. $\underline{E}^i \| \hat{x}, \underline{H}^i \| \hat{y}, |\underline{E}^i| = 1$ V/m, $\sigma = 0.42$ S/m, $\varepsilon'/\varepsilon_o = 76$. The average SAR is 3.237×10^{-5} mW/kg.

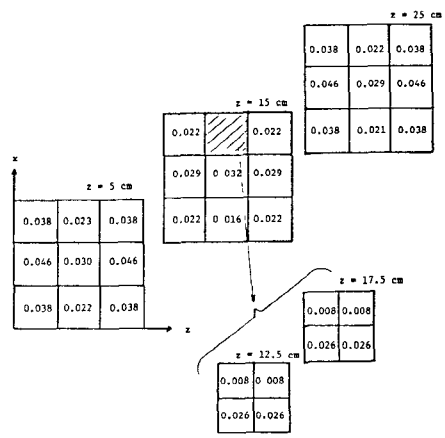

Fig. 12. SAR (μW/kg) distribution in a cubical tissue block model ($30\times30\times30$ cm^3) irradiated by an incident EM plane wave at 27.12 MHz. $\underline{E}^i \| \hat{x}, \underline{H}^i \| \hat{y} \, |\underline{E}^i| = 1$ V/m, σ0.42 S/m, and $\varepsilon'/\varepsilon_o = 76$. The average SAR is 3.133×10^{-5} mW/kg.

percent greater than that estimated using one cell. Once again, it is interesting to note that the change in the average SAR in the whole cube is only one percent.

SAR calculations in cubical models were carried out to study the effect of subdivision of cells on SAR and the convergence procedure of the moment-method solution of the EFIE using pulse-basis functions. Based upon the calculated SAR data given in this paper, the effect of subdivisions of the cells on the local fields and SAR values can be summarized as follows.

1) If the subdivided cell is surrounded by other cells in the body (a buried cell), or if the subdivided cell is located on a surface which is parallel to the incident E-field vector, the subdividing has almost no effect on the SAR in the remainder of the cells in the body.
2) If the subdivided cell is located in a corner or on an edge, or is on a surface which is perpendicular to the incident E-field vector, the subdividing will cause a considerable change in the value of the local fields and SAR in the neighboring cells in the body.
3) While the partitioning of the cells in one region of the body may cause a major change in the SAR distributions, the average SAR in the body remains almost the same.

III. Conclusions and Remarks

Studies have been carried out to determine the general accuracy of the local SAR values calculated by the pulse-function, moment-method solution of the EFIE. We have shown, by subdividing the mathematical cells, that the aforementioned method has some serious deficiencies which make accuracy of the SAR distribution calculations inadequate, especially for inhomogeneous models of humans and test animals. The deficiencies of the method for calculating the SAR distributions are summarized as follows.

1) Numerical solutions of the electric-field integral equation using a pulse function basis can only be reasonably accurate if there is no variation of the fields within each part of the dielectric identified as a cell.
2) The pulse functions cannot satisfy the boundary conditions at the surfaces between mathematical cells of different permittivities. This occurs because the boundary conditions generally require the field to have one value on one side of the cell and a different value on the other side of the cell. Since a pulse function is constant throughout the cell, it cannot have different values at the various boundaries, and therefore cannot satisfy the boundary conditions between the cells.
3) The severe dielectric discontinuities, particularly at the corners, have a strong effect on the accuracy of the results. This has been demonstrated by subdividing one cell into smaller cells and comparing calculated SAR's in neighboring cells before and after subdivision. The reason for the strong effect appears to be mainly related to the presence of field components normal to significant dielectric discontinuities at these corners.

In an attempt to develop a better method of calculating SAR distributions, we have evaluated both the various forms of the integral equations and the various types of basis functions that can be used to expand the unknown fields. Our initial evaluation indicates that:

1) The following electric-field integral equation is perhaps the best one to start with:

$$\underline{E}(\underline{r}) = \frac{1}{4\pi}\int \frac{\nabla'\cdot\underline{E}(\underline{r}')}{R}\psi(\underline{r},\underline{r}')\hat{R}\,dv' + j\frac{k_o}{4\pi}\int \nabla'\cdot E(r')\cdot\psi(\underline{r},\underline{r}')\,\hat{R}\,dv' - j\frac{\omega\mu}{4\pi}\int \underline{J}_p(\underline{r})\psi(\underline{r},\underline{r}')\,dv' + \underline{E}_{inc}(\underline{r}) \quad (1)$$

where

$\psi(\underline{r},\underline{r}') = e^{-jk_oR}/R$,
$\underline{r}$ is the vector from the origin to the field point,
$\underline{r}'$ is the vector from the origin to the source point,
$R = |\underline{R}| = |\underline{r} - \underline{r}'|$,
$\hat{R} = \underline{R}/R$,

$\underline{J}_p(\underline{r}')$ is the so-called polarization current density,
k_o is the free-space propagation constant,
μ_o is the permeability of free space,
$\underline{E}_{\text{inc}}$ is the incident electric field.

This EFIE appears to offer the greatest advantage in SAR distribution calculations. This is due to the facts that, first, it includes an explicit expression for the electric charge density at the surfaces between the various mathematical cells (see the first two terms in (1)), and, secondly, it is less singular that the EFIE used by Chen and Guru [1] and Hagmann *et al.* [2].

2) Pulse functions should be replaced by a better approximation. The next obvious better approximation than pulse functions is a linear approximation; that is, instead of assuming that the field is constant in a cell (the pulse function), assume that the field varies as $ax + by + cz + d$, and solve for the parameters a, b, c, and d. Thus, the field would vary linearly with x, y, and z in the cell, and could approximately satisfy the boundary conditions at the surfaces of the cell.
3) Cubical cells should be replaced by polyhedrons. In similar work using a quasi-static solution for a two-dimensional model [11], it has been found that polygonal cells appear to work well with the linear basis functions. Consequently, we will use polyhedrons in place of cubical cells. This would allow us to represent the curvature of bodies much more realistically.
4) We have also found, in the previously mentioned two-dimensional quasi-static technique, that Galerkin's method offers significant advantages over point-matching techniques. Consequently, we will apply Galerkin's method to obtain a matrix equation from the integral equation with linear basis functions. Galerkin's method amounts to using weighting functions that are equal to the basis function and integrating over the cells to obtain a matrix equation.

Initial steps for formulation of the problem, as outlined above, have been completed. As a test case, a computer program for the SAR distributions inside homogeneous and layered spheres has been developed. Since the analytical solutions for homogeneous and layered spheres are known, the test program would allow comparison of our numerically calculated results with known analytical results. Using our new technique, we have calculated the phase and magnitude of the internal electric field at every point in a homogeneous lossy dielectric sphere at low frequencies with ± 7 percent for complex dielectric constant up to $20 - j20$ [12]. A complete description of the new technique, along with some preliminary data on test dielectric spheres, will be presented in a forthcoming publication.

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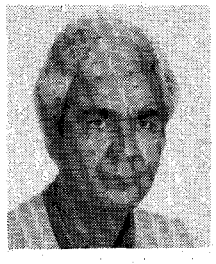

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From 1958 to 1959, he was employed as an Associate Research Engineer with the Boeing Airplane Company, Seattle, WA, where he studied the use of delay lines in control systems. He has been with the University of Utah since 1963, when he was appointed to be Assistant Research Professor of Electrical Engineering.

From 1965–1966, he was employed at the Bell Telephone Laboratories, Holmdel, NJ, while on leave from the University of Utah. During this time, he worked in the area of microwave avalanche diode oscillators.

Again, in 1971, he was engaged in study and research involving microwave biological effects at the University of Washington Seattle, while on leave from the University of Utah. From 1977 to 1982, he was chairman of the Electrical Engineering Department at the University of Utah, where he is presently Professor of Electrical Engineering and engaged in teaching and research in electromagnetics, engineering pedagogy, and microwave biological effects.

Dr. Durney is a member of The Bioelectromagnetics Society, Commission B of URSI (International Union of Radio Science), Sigma Tau, Phi Kappa Phi, Sigma Pi Sigma, Eta Kappa Nu, and the American Society for Engineering Education. He also served as Vice President (1980–1981) and President (1981–1982) of The Bioelectromagnetics Society, as a member (1979–present) and Chairman (1983–present) of the IEEE Committee on Man and Radiation (COMAR), as a member of the American National Standards Institute C95 Subcommittee IV on Radiation Levels and/or Tolerances with Respect to Personnel (1973–present), as a member of the editorial board of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES (1977–present), and as a member of the editorial board of *Magnetic Resonance Imaging* (1982–present). In 1980, he received the Distinguished Research Award from the University of Utah, and the Outstanding Teaching Award, College of Engineering, University of Utah. In 1982, he received the American Society for Engineering Education Western Electric Fund Award. He was named a College of Engineering Distinguished Alumnus by Utah State University in 1983.

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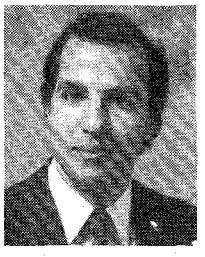

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In 1976, he was awarded a National Research Council of Canada Postdoctoral Fellowship at the University of Manitoba. Since March 1977, he has been with the Department of Electrical Engineering and the Department of Bioengineering at the University of Utah, Salt Lake City, where he is currently an Associate Professor of Electrical Engineering. In 1981, he received the University of Utah President David P. Gardner Faculty Fellow award and spent the academic quarter on leave as a Visiting Associate Professor at the Department of Electrical Engineering and Computer Science, Polytechnic Institute of New York, Brooklyn, N Y.

Dr. Iskander edited two special issues of the *Journal of Microwave Power*, one on "Electromagnetics and energy applications," March 1983, and the other on "Electromagnetic techniques in medical diagnosis and imaging," September 1983. He has contributed chapters to four research books and has published in technical journals and presented more than 130 papers. In 1983, he received the College of Engineering Outstanding Teaching Award and the College Patent Award for creative, innovative, and practical invention. In 1984, he was selected by the Utah Section of IEEE as the Engineer of the Year. He is a member of the editorial board of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES and a member of the editorial board of the *Journal of Microwave Power*. His present fields of interest include the use of numerical techniques in electromagnetics to calculate scattering by dielectric objects, antenna design, and the evaluation of the biological effects as well as the development of medical applications of electromagnetic energy.

Average SAR and SAR Distributions in Man Exposed to 450-MHz Radiofrequency Radiation

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Abstract—**Fifth-scale phantom models were exposed to 2450-MHz electromagnetic fields to obtain the average specific absorption rate (SAR) and SAR distribution in man exposed to 1 mW/cm^2 450-MHz radiofrequency radiation for various polarizations and body positions. The average SAR was measured calorimetrically and SAR distribution was determined thermographically using an interactive computer system. The mean SAR, as averaged over the body, remained relatively constant at 0.050 W/kg, with a standard deviation of ±0.007 W/kg for all polarizations and body postures considered in the study. Peak SAR values were as high as 0.650 W/kg, occuring typically in the wrist.**

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I. INTRODUCTION

AS ONE PART of a project for evaluating the health of laboratory rats exposed under conditions simulating those of human exposure in order to assess the effects of long-term low-level 450-MHz radiofrequency radiation (RFR) on man [7], this paper reports the measurement of the average specific absorption rate (SAR) of energy and the SAR distribution in man under various conditions of exposure.

Basically, the same techniques were used in these studies as had been previously reported [6]. Approximately 1/4- to 1/10-scaled models of man composed of synthetic muscle tissue were exposed to frequencies from 4 to 10 times higher than the exposure frequency for a full-sized man. In

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