Accuracy of Block Models for Evaluation of the Deposition of Energy by Electromagnetic Fields

MARK J. HAGMANN, MEMBER, IEEE, AND RONALD L. LEVIN

Abstract—**Numerical solutions were made for block models using as many as 3048 cubes to approximate a prolate spheroidal model of man at 100 and 225 MHz. A high-frequency modification of Hohmann's formulation (HFH) gave values of mean absorption within five to seven percent of those with the Iterative Extended Boundary Condition Method (IEBCM). Arrangement of the cells for a best-fit approximation of the spheroid is essential for such high accuracy. Numerical quadratures using the cubical shape of the cells verified the high accuracy of the closed-form expressions used for HFH matrix elements. Quadratures over spheres having the same volume as the cells gave inaccurate values for the matrix elements. Values of average absorption calculated with 296, 560, 1376, and 1944 cell models of the prolate spheroidal model of man differed from each other by no more than 17 percent at frequencies of 10 to 400 MHz, and by 5.0 percent at the resonant frequency of 75 MHz.**

I. INTRODUCTION

BLOCK MODEL SOLUTIONS obtained using the Method of Moments [1] have had many applications, including the evaluation of biological hazards from exposure to electromagnetic fields [2], [3] and geophysical prospecting [4]. Solutions for block models of man have correctly predicted such phenomena as selective heating of the neck [3] and head resonance [5], as well as ground and reflector effects [6]. Two different formulations have been used with block models of man. One was developed by Chen [2] and the other was developed by Hagmann [3], who made high-frequency corrections of a routine written earlier by Hohmann for use in geophysical prospecting [4]. The second procedure will be referred to as the High-Frequency Hohmann (HFH) formulation.

Solutions also have been presented for less detailed models of man such as the prolate spheroid [7]. It has been claimed that the total absorption of electromagnetic energy by man is approximately the same as that for a prolate spheroid having equal height and volume, but this may not be valid for plane waves having certain orientations [8]. Certainly, local values of deposition or phenomena such as head resonance could not be accurately predicted using such a model.

Some have suggested that block model solutions may diverge as the number of cubical cells is increased [9]–[11], while others have suggested that such solutions may converge to an erroneous answer [1], [12]. These criticisms of the block model solutions have themselves been questioned [13]. It is the objective of the present work to show that it is possible to obtain reliable, high-accuracy solutions with block models if proper care is used in their implementation. Hyperthermia offers considerable promise for the adjuvant treatment of cancer, but it is essential that the heat be delivered to the patient with a high degree of precision [14]. Our study has been made as one step in an examination of block models to determine if they are suitable for the evaluation of dosimetry in hyperthermia.

Manuscript received September 13, 1985; revised January 3, 1986.

The authors are with the Biomedical Engineering and Instrumentation Branch, Division of Research Services, National Institutes of Health, Bethesda, MD 20892.

IEEE Log Number 8607973.

II. METHODS

Both the Chen and the HFH formulation use a "hat" or pulse-function basis in which the unknown electric field in each cubical cell is approximated by a constant [1]. Pulse functions have an advantage over other bases in that they permit use of the maximum number of cubes for a given computational effort, thus allowing maximum detail in the block model. The increased detail is highly desirable when attempting to characterize the interaction of electromagnetic energy with man. Pulse functions, however, are only appropriate if the electric field is slowly varying between adjacent cells [15]. Unusually large numbers of cells have been used in parts of the present study in an attempt to minimize the variations between adjacent cells in order to increase the accuracy of the block model solutions. We have modified a previously written program [3] so that it is capable of using either the first approximate formulation given by Chen [2], or the previously-derived HFH matrix elements [3] in order to perform the current study.

The matrix elements used in a block model solution may be grouped as "self" terms and "coupling" terms representing the interaction of each cell with itself and with the other cells, respectively. Each of the matrix elements must be evaluated by approximating an integral over the volume of a cubical cell. Each integral has two expressions which represent the effects of current and charge, respectively [16].

Calculation of the self terms is complicated by the fact that the charge portion of the integral is singular [16], [17]. Chen obtained his expression for the self terms by performing an integration over a sphere having the same volume as

0018-9480/86/0600-0653$01.00 ©1986 IEEE

a cubical cell with the use of principal value corrections described by Van Bladel [2], [17]. In the HFH formulation, we have followed Hohmann's procedure of transforming the singular charge integral to a nonsingular surface integral which is evaluated over the surface of a cubical cell [4], [16]. The nonsingular current portion is much less sensitive to cell shape than the charge portion [4]. For this reason, in the HFH formulation, the current portion of the self term is evaluated by integrating over a sphere having the same volume as a cubical cell. We have found that the Chen and HFH expressions for the self terms, though derived by different procedures, give values that are in close agreement. Self terms calculated using the two expressions typically differ by less than 0.1 percent in magnitude. Changes of similar magnitude are found in values of energy deposition calculated when these two different expressions for self terms are interchanged. In contrast, there are significant differences in values of the coupling terms calculated using the two formulations.

In the HFH formulation, the charge portion of the coupling terms is evaluated by taking a surface integral over the cubical cells as was just described for the self terms [4], [16]. As in the case of the self terms, the current portion of the coupling terms is evaluated by integrating over a sphere having the same volume as a cubical cell. The coupling terms in Chen's first approximate formulation were obtained using the approximation that the integrand is a constant [2]. We consider this to be a poor approximation for nearby cells because the three parts of the integrand are inversely proportional to the first, second, and third powers of the distance between the source and field points [2]. Since the largest off-diagonal terms in the matrix correspond to the coupling of nearby cells, errors in such terms cause significant errors in the solution. Errors due to this approximation are present regardless of the cell size and frequency. In fact, we have observed that the approximation tends to be most severe in quasi-static solutions for which the most rapidly varying part of the integrand (inversely proportional to the cube of distance) is dominant. We have found that the coupling terms given by Chen are identical to those obtained when the integrations are performed analytically over a sphere having the same volume as a cubical cell if variation of the exponential term in the dyadic Green's function is neglected. This observation does not validate the expressions since the results presented in the present paper indicate that the coupling terms calculated for a cubical cell differ significantly from those for a sphere of equal volume.

At the time that he first presented his expressions for the matrix elements, Chen suggested that his approximate expressions for the coupling terms might yield adequate results if the number of cells is sufficiently large, but that numerical quadratures could be used in order to obtain greater accuracy [2]. While it was not stated in any of his later publications, Chen has used numerical quadratures with eight or 27 points arranged within each cubical cell to improve the accuracy of the coupling terms in most of his subsequent work [18]. We appreciate that one of the reviewers first brought this to our attention.

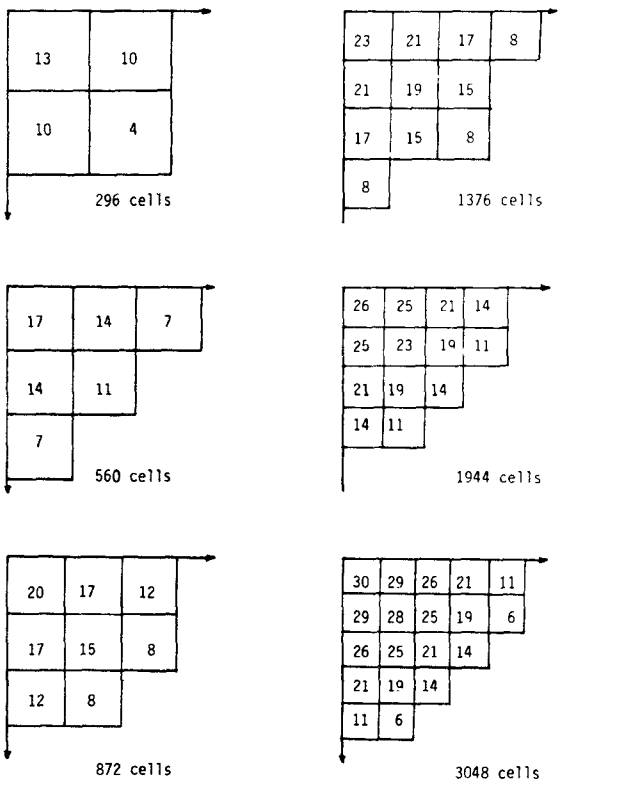

Fig. 1. Location of cubes in one octant of each block model of a prolate spheroid.

The Extended Boundary Condition Method (EBCM) has found considerable usage in evaluating the absorption of electromagnetic energy by prolate spheroidal models of man and animals [7]. Recently, an iterative modification of the EBCM, termed "IEBCM", has allowed extension of the calculations to frequencies greater than whole-body resonance [20]. We have chosen to use IEBCM solutions for a prolate spheroidal model of man as the standard for testing block model calculations. Our reason is that the IEBCM has been shown to have fast convergence and high numerical stability [20], and we consider the prolate spheroid to be more "man-like" than other objects for which solutions with equal or greater validity are available (e.g., the sphere and infinite cylinder). The prolate spheroidal model of man is defined as having a major axis of 1.75 m and a volume of 70 ltr.

Calculations have been made for block models of prolate spheroids using 296, 560, 872, 1376, 1944, and 3048 cubical cells of equal size. Other studies [21], [22] showed that when progressively finer discretizations are made by merely subdividing the cells of a block model, the magnitude of the electric field tends to be large near the unintended corners and edges of the model. For this reason, care was taken to obtain a best-fit of the prolate spheroid in each discretization. First a three-dimensional lattice was constructed with cubes of fixed size such that the lattice contained one octant of the prolate spheroid. Only cubes

having centroids contained within the boundary of the prolate spheroid were retained. Finally the size and locations of all cubes were normalized so that the total volume was equal to that of the prolate spheroid. The array of cubes constituting one octant of a block model may be described as a series of stacks aligned parallel to the major axis of the prolate spheroid. Fig. 1 defines each of the six block models by giving the number of cubical cells contained within the stacks for each discretization. The numerical solutions made use of three planes of symmetry in the models to reduce the size of the resulting matrices.

III. Results

Figs. 2 and 3 show the errors in values of mean Specific Absorption Rate (SAR) calculated for block models approximating a prolate spheroidal model of man at 100 and 225 MHz, respectively. SAR is defined as the rate of energy deposition per unit mass. In each case, the incident field was a plane wave having the electric vector parallel to the major axis of the spheroid. The power density of the plane wave was 1 mW/cm^2. Values of complex relative permittivity used in the calculations were $45-j115$ at 100 MHz and $38-j70$ at 225 MHz. IEBCM solutions obtained for the prolate spheroid employing identical parameters were used as the standard for comparison [23].

The values of mean SAR obtained using the HFH formulation appear to approach the IEBCM solutions as the number of cells is increased, the difference being only five to seven percent with the finest discretizations. By contrast, values of mean SAR obtained using the matrix elements of Chen's first approximate formulation (without quadratures) have significantly greater error, and their convergence appears uncertain at the higher frequency. Earlier studies with a special class of model also suggested that Chen's approximation caused greater errors than the HFH formulation [24].

A "bad" 2368 cell model was made for comparison by keeping the outer boundary of the 296 cell model and dividing each cube into eight new cells. When the HFH formulation was used with the "bad" model, the mean SAR at 100 MHz had an error of 10.1 percent. This error is about twice what is shown in Fig. 2 for similar (large) numbers of cells and exceeds even the error of the 296 cell model, thus showing the importance of a best-fit arrangement of cells in a block model.

While IEBCM local values of SAR were not available for comparison, we note that the difference between values of local SAR in adjacent cells was found to decrease monotonically as the number of cells was increased in the calculations made for both frequencies with the HFH formulation. The difference in values of local SAR between adjacent cells was approximately two percent when using the maximum of 3048 cells. Such slow cell-to-cell variation lends some credence to the use of a pulse-function basis. Oscillations suggesting instability were present in the values of local SAR obtained when large numbers of cells were used with Chen's first approximate formulation.

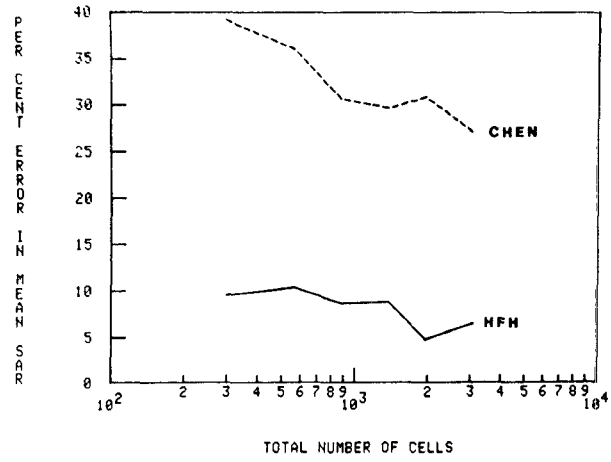

Fig. 2. Errors in mean absorption calculated for block models of a prolate spheroid at 100 MHz. Solid line is for the HFH formulation. Dash line is for Chen's first approximate formulation.

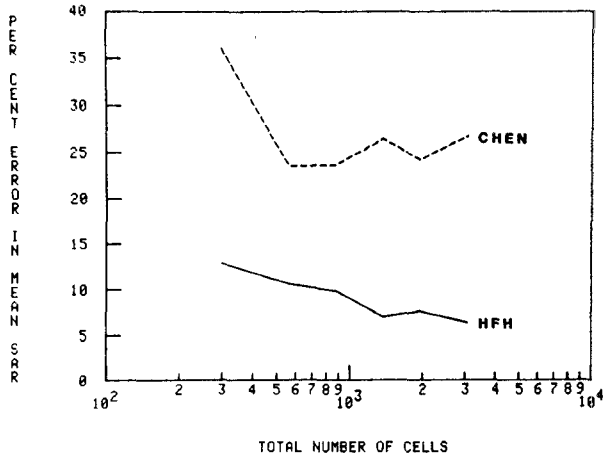

Fig. 3. Errors in mean absorption calculated for block models of a prolate spheroid at 225 MHz. Solid line is for the HFH formulation. Dash line is for Chen's first approximate formulation.

Block model calculations for the prolate spheroidal model of man at 100 and 225 MHz were repeated using numerical integration for evaluation of the matrix elements. Since no quadrature rule was known to have a weight function similar to the integrands, the quadratures were performed using simple summation of the values obtained by approximating each cell with different numbers of sub-cells. We used 8, 27, 125, 343, 729, 1331, and 2197 sub-cells for quadratures within the cubical cells. Calculations also were made using quadratures over spheres having the same volume as each cubical cell. In these spherical-cell quadratures we used 8, 160, 672, 1736, and 3544 sub-cells. Each arrangement of sub-cells for a spherical-cell quadrature was made using the same "best-fit" procedure that was used to determine the array of cubical cells used to fit the prolate spheroidal model of man. Since quadratures were used in evaluating all of the matrix elements, considerable computational effort was required. For this reason, these tests were only made for the 296 cell block model.

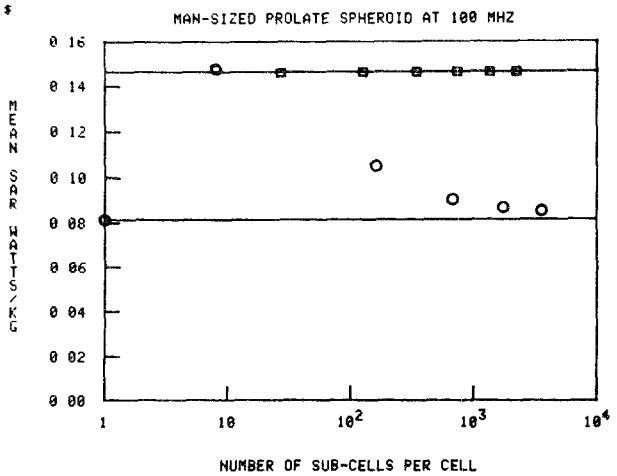

Fig. 4. Calculated mean absorption for a 296 cell block model of a prolate spheroid at 100 MHz using quadratures. Squares and circles represent cubical and spherical cells, respectively. Upper horizontal line is for the HFH formulation. Lower horizontal line is for Chen's first approximate formulation.

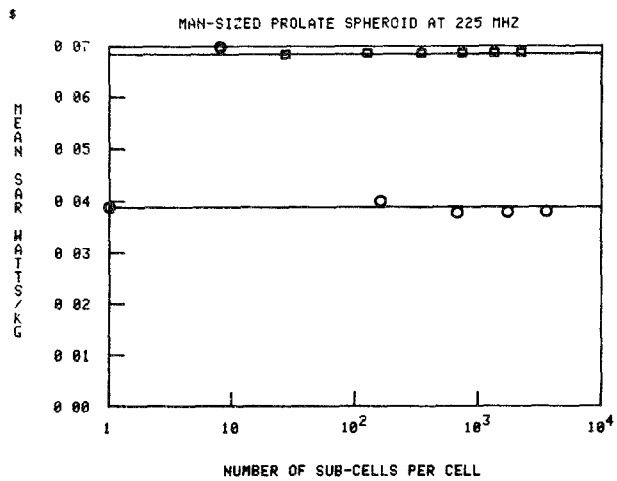

Fig 5. Calculated mean absorption for a 296 cell block model of a prolate spheroid at 225 MHz using quadratures. Squares and circles represent cubical and spherical cells, respectively. Upper horizontal line is for the HFH formulation. Lower horizontal line is for Chen's first approximate formulation.

Figs. 4 and 5 show the values of mean SAR determined using quadratures for the matrix elements at 100 and 225 MHz, respectively. Horizontal lines in the two figures represent the values obtained using the HFH and Chen's first approximate formulation. The 1 sub-cell solutions in both figures correspond to Chen's approximate formulation since integrations were neglected in evaluating the coupling terms for that formulation. The 8 sub-cell solutions are the same for the two types of quadrature since they correspond to the same arrangement of sub-cells.

In Figs. 4 and 5, the values of SAR obtained using quadratures that preserve the cubical shape of each cell (square markers) agree well with those obtained with the HFH formulation. The differences between the values obtained using quadratures over cubical cells with 2197 sub-cells and those with the HFH formulation are 0.11 percent at 100 MHz and 0.56 percent at 225 MHz. This is a verification of the accuracy of the closed-form expressions used for matrix elements in the HFH formulation. The two figures show rapid convergence in the solutions for cubical cells as the number of sub-cells is increased. The 8 and 27 sub-cell quadratures on cubical cells correspond to procedures that Chen has used to correct his original approximate formulation [18]. The results in Figs. 4 and 5 suggest that Chen's use of 8 and 27 sub-cells is adequate, at least for the models and parameters used in the present calculations.

Figs. 4 and 5 show the importance of preserving the cubical shape of each cell, rather than using the spherical-cell approximation, for evaluating the matrix elements. The values obtained using quadratures with the spherical-cell approximation (circular markers) diverge from those for the HFH (and IEBCM) formulation at both 100 and 225 MHz. The patterns of the circular markers in Figs. 4 and 5 suggest that in the limit as large numbers of sub-cells are used, the results for the spherical-cell approximation approach those for Chen's first approximate formulation. The validity of this apparent limit is further supported by our observation that the coupling terms given by Chen [2] are the same as the expressions obtained when the required integrations are performed analytically over spheres having the same volume as the cubical cells, if the variation of the exponential term in the dyadic Green's function is neglected. We have found that most of the error caused by the spherical-cell approximation is in the charge portion of the coupling terms. Our interpretation is that the errors in the spherical-cell approximation are caused by a distortion of the effects of surface charge densities near the corners and edges of the cubical cells.

We have also used the HFH formulation to evaluate the mean SAR with four different block models approximating the prolate spheroidal model of man at 28 frequencies from 10 to 2450 MHz. As in the previous examples, the incident field was a plane wave having the electric vector parallel to the major axis of the spheroid. The power density of the plane wave was 1 mW/cm^2. The complex permittivity was chosen to be two-thirds that of muscle, based upon the range of experimental data reported by others for measurements of biological tissues [7]. Figs. 6 and 7 show the values of dielectric constant and conductivity used for this series of calculations. The comparisons presented earlier in this paper for 100 and 225 MHz were made using dielectric parameters specified by others in examples of the IEBCM method [23]. For this reason, the values of dielectric constant and conductivity at 100 and 225 MHz in Figs. 6 and 7 are not identical to those that we used in the earlier calculations. Fig. 8 shows the values of mean absorption computed using block models having 296, 560, 1376, and 1944 cells at 28 frequencies from 10 to 2450 MHz.

The values obtained using the four different discretizations differ from each other by no more than 17 percent at frequencies from 10 to 400 MHz. The minimum difference, being 5.0 percent, occurs at the resonant frequency of approximately 75 MHz. These results suggest that the use of 296 cells is adequate for calculations of mean SAR at

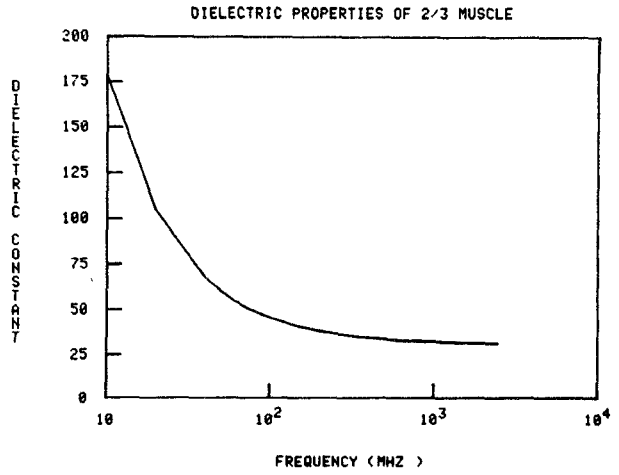

Fig. 6. Dielectric constant used for frequency-dependent calculations.

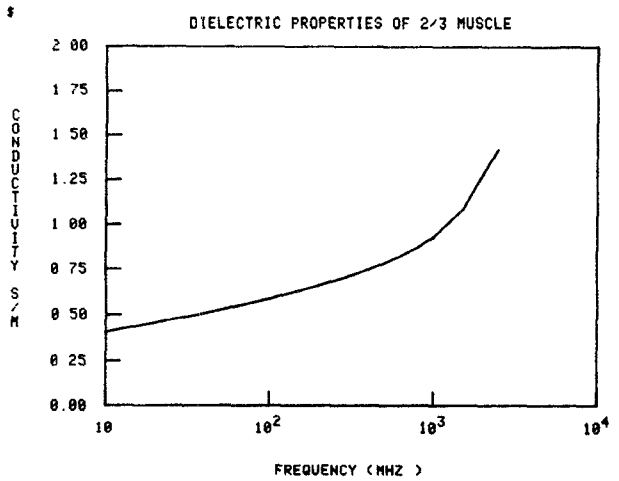

Fig. 7. Conductivity used for frequency-dependent calculations.

frequencies as high as 400 MHz with this model of man. The point at which high-frequency failure occurs with block models is determined by the value of $|k_\epsilon|\Delta$, where $|k_\epsilon|$ is the magnitude of the complex propagation vector within the dielectric, and Δ is the length of a side of a cubical cell [15]. With the 296 cell block model at 400 MHz, $|k_\epsilon|\Delta = 3.572$, $\Delta/\lambda_\epsilon = 0.5255$, and $\Delta/\delta = 1.363$, where λ_ϵ and δ are the wavelength and depth of penetration within the dielectric. While we do not have IEBCM or other standards for comparison, it should be noted that the value of $|k_\epsilon|\Delta$ for the 296 cell block model at 400 MHz is similar to that for the 560, 1376, and 1944 cell models at 500, 700, and 800 MHz, respectively. We anticipate that the three models would be adequate for calculations of mean SAR at frequencies up to these respective limits. As high-frequency failure occurs successively with each block model, the values of mean SAR are lower than those for the solutions having greater accuracy (larger numbers of cells). This tendency toward underestimation at high frequencies has been observed in earlier studies [21], [22] and is attributed to low-pass filtering due to failure of the pulse-function basis to allow for components of the electric field having high spatial frequencies.

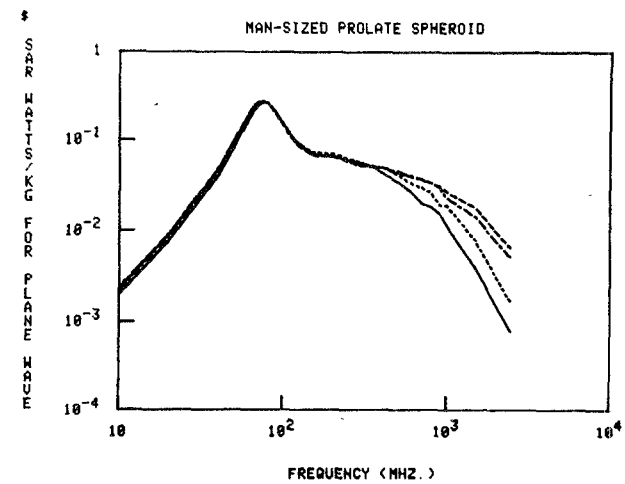

Fig. 8. Mean absorption for block models of a prolate spheroid. Solid = 296 cells, dot = 560, chain dot = 1376, dash = 1944.

The values in Fig. 8 are in good agreement with those obtained earlier for a 180 cell block model of man having considerably greater realism [3]. One significant difference, however, is the absence of significant "bumps" present in such curves for the block model of man. These "bumps" occur at specific frequencies corresponding to part-body resonances at which the deposition in regions such as the head, arms, etc., is sufficiently large to alter the mean SAR [21]. The approximate frequency and magnitude of the head resonance have been confirmed in experiments with figurines and animals [5].

IV. Discussion and Conclusions

The present study suggests that high accuracy may be obtained with block models if sufficient care is taken in their use. It is essential that accurate expressions be used for the matrix elements. It is also important that the array of cubical cells be a best-fit of the object to be modeled. We attribute some of the difficulties that others have reported, to the use of arrangements of cells that created unintended corners and edges not present in the object being modeled [9]–[11], [13].

In the present work, we have emphasized the use of relatively large numbers of cells and multiple discretizations to determine the effects of differences in matrix formulations on convergence with block models. The convergence of values of local SAR has not been examined in these computations. We have previously presented results for multiple discretizations of a dielectric cube that suggest that the local values are reasonably accurate, even in a body having a highly heterogeneous field, at low frequencies [22].

The results presented in Figs. 4 and 5 suggest that significant errors may be introduced when integrals required for the evaluation of matrix elements are simplified by changing the shape of the region of integration. This observation has broad consequences regarding some of the formulations that have been used to date in electromagnetics. Harrington has noted that Richmond's two-dimen-

sional solutions are accurate for TM polarization [25] but not for TE polarization [26], and has ascribed the difference to an instability inherent in the use of a pulse-function basis [1]. In both of his solutions, Richmond simplified the integrals required for matrix elements by replacing square cells with circles having equal area [25], [26]. In yet unpublished work, we have found that correction of the matrix elements by numerical quadratures causes a significant improvement in the accuracy of TE solutions for homogeneous dielectric cylinders having small electrical size. A 1.0-mm radius infinite cylinder of muscle was modeled with 120, 164, 216, 256, 316, and 392 square cells. For the case of TE excitation by a plane wave at 10 MHz, the six different discretizations gave values of mean SAR having an average error of 100.3 percent using the Richmond matrix elements [26], and 23.3 percent when using four sub-cell quadratures to correct the matrix elements. We do not claim that the circular-cell approximation is the only problem in the Richmond TE formulation. We have found that differences in the charge portion of the coupling terms are responsible for most of the errors from the circular-cell approximation, which observation agrees with the results obtained for the spherical-cell approximation as described earlier in this paper. We attribute the accuracy of Richmond's TM solution to the absence of a charge term in the Green's function for that case.

ACKNOWLEDGMENT

The authors appreciate that Prof. M. F. Iskander supplied them with two examples in which the IEBCM was used to determine the mean SAR in a man-sized prolate spheroid. These served as the standards for the tests made at 100 and 225 MHz. The authors also appreciate the assistance of R. O. Creecy of ROB/COP/DCT/NCI.

REFERENCES

[1] R. F. Harrington, *Field Computation by Moment Methods*. New York: Macmillan, 1968.

[2] D. E. Livesay and K. M. Chen, "Electromagnetic fields induced inside arbitrarily-shaped biological bodies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 1273–1280, Dec. 1974.

[3] M. J. Hagmann, O. P. Gandhi, and C. H. Durney, "Numerical calculation of electromagnetic energy deposition for a realistic model of man," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 804–809, Sept. 1979.

[4] G. W. Hohmann, "Three-dimensional-induced polarization and electromagnetic modeling," *Geophys.*, vol. 40, pp. 309–324, Apr. 1975.

[5] M. J. Hagmann, O. P. Gandhi, J. A. D'Andrea, and I. Chatterjee, "Head resonance: Numerical solutions and experimental results," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 809–813, Sept. 1979.

[6] M. J. Hagmann and O. P. Gandhi, "Numerical calculation of electromagnetic energy deposition in man with ground and reflector effects," *Radio Sci.*, vol. 14, pp. 23–29, Nov.–Dec. 1979.

[7] C. H. Durney *et al.*, *Radiofrequency Radiation Dosimetry Handbook*, USAF School of Aerospace Medicine, Brooks Air Force Base, TX, SAM-TR-80-32, Aug. 1980.

[8] M. J. Hagmann, I. Chatterjee, and O. P. Gandhi, "Dependence of electromagnetic energy deposition upon angle of incidence for an inhomogeneous block model of man under plane-wave irradiation," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 252–255, Mar. 1981.

[9] J. F. Deford, O. P. Gandhi, and M. J. Hagmann, "Moment-method solutions and SAR calculations for inhomogeneous models of man with large number of cells," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 848–851, Oct. 1983.

[10] E. H. Wissler, "Thermal and nonthermal effects of microwave radiation," National Institutes of Health grant GM27844, Final Rep., Dep. Chem. Eng., Univ. of Texas at Austin, Mar. 1983.

[11] H. Massoudi, C. H. Durney, and M. F. Iskander, "Limitations of the cubical block model of man in calculating SAR distributions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 746–752, Aug. 1984.

[12] D. H. Schaubert, D. R. Wilton, and A. W. Glisson, "A tetrahedral modeling method for electromagnetic scattering by arbitrarily-shaped inhomogeneous dielectric bodies," *IEEE Trans. Antennas Propagat.*, vol. AP-32, pp. 77–85, Jan. 1984.

[13] M. J. Hagmann, H. Massoudi, C. H. Durney, and M. F. Iskander, "Comments on 'Limitations of the cubical block model of man in calculating SAR distributions'," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 347–350, Apr. 1985.

[14] G. M. Hahn, "Hyperthermia for the engineer: A short biological primer," *IEEE Trans. Biomed. Eng.*, vol. BME-31, pp. 3–8, Jan. 1984.

[15] M. J. Hagmann, O. P. Gandhi, and C. H. Durney, "Upper bound on cell size for moment-method solutions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 831–832, Oct. 1977.

[16] J. Van Bladel, *Electromagnetic Fields*. New York, McGraw-Hill Book Co., 1964.

[17] J. Van Bladel, "Some remarks on Green's dyadic for infinite space," *IRE Trans. Antennas Propagat.*, vol. AP-9, pp. 563–566, Nov. 1961.

[18] K. M. Chen, Dep. of Elec. Eng. Syst. Sci., Michigan State Univ. personal communication.

[19] J. W. Penn and D. K. Cohoon, "Analysis of a Fortran program for computing electric-field distributions in heterogeneous penetrable nonmagnetic bodies of arbitrary shape through application of tensor Green's functions," USAF School of Aerospace Medicine, Brooks Air Force Base, TX, SAM-TR-78-40, Dec. 1978.

[20] M. F. Iskander, A. Lakhtakia, and C. H. Durney, "A new procedure for improving the solution stability and extending the frequency range of the EBCM," *IEEE Trans. Antennas Propagat.*, vol. AP-31, pp. 317–324, Mar. 1983.

[21] M. J. Hagmann, "Numerical studies of absorption of electromagnetic energy by man," Ph.D. Dissertation, Dep. of Elec. Eng., Univ. of Utah, Salt Lake City, UT, Dec. 1978.

[22] M. J. Hagmann and R. L. Levin, "Convergence of local and average values in three-dimensional moment-method solutions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 649–654, July 1985.

[23] M. F. Iskander, Dep. of Elec. Eng., Univ. of Utah, Salt Lake City, personal communication.

[24] M. J. Hagmann, "Convergence tests of several moment-method solutions," *IEEE Trans. Antennas Propagat.*, vol. AP-29, pp. 547–550, May 1981.

[25] J. H. Richmond, "Scattering by a dielectric cylinder of arbitrary cross-section shape," *IEEE Trans. Antennas Propagat.*, vol. AP-13, pp. 334–341, May 1965.

[26] J. H. Richmond, "TE wave scattering by a dielectric cylinder of arbitrary cross-section shape," *IEEE Trans. Antennas Propagat.*, vol. AP-14, pp. 460–464, July 1966.

✠

Mark J. Hagmann (S'75–S'78–M'79) was born in Philadelphia, PA, on February 14, 1939. He received the B.S. degree in physics from the Brigham Young University, Provo, UT, in 1960, and the Ph.D. degree in electrical engineering from the University of Utah, Salt Lake City, in 1978. His doctoral dissertation focused on numerical evaluation of the absorption of electromagnetic energy by man.

Subsequent to receiving his doctorate he served as a Research Associate and Research Professor at the University of Utah. He was a Visiting Professor in the Department of Electrical Engineering at the University of Hawaii from 1981 to 1982.

Since 1982, he has worked as a Senior Staff Fellow in the Biomedical Engineering and Instrumentation Branch of the Division of Research Services of the National Institutes of Health in Bethesda, MD. His general research interests include numerical procedures for electromagnetics, electromagnetic imaging, biomedical applications of microwaves, and electromagnetic biological effects. Currently, he is involved in both theoretical and experimental studies regarding electromagnetic applicators for use in hyperthermia.

Dr. Hagmann is a member of the Bioelectromagnetics Society, the Radiation Research Society, and Sigma Xi. He is the Chairman of the Engineering in Medicine and Biology Society for the Washington, DC, and Northern Virginia chapters and a member of the Executive Committee for the Washington, DC, chapter of the IEEE.

✠

Ronald L. Levin was born in Philadelphia, PA, on September 14, 1951. He received the S.B. (with Honors) and S.M. degrees in mechanical engineering from the Massachusetts Institute of Technology, Cambridge, in 1973 and the Sc.D. degree in mechanical engineering from the Massachusetts Institute of Technology in 1976. His doctoral dissertation dealt with the numerical modeling of the water and solute transport processes associated with the cryopreservation of biological cells at low temperatures.

Subsequent to receiving his doctorate, he served as a Research Fellow for $1\frac{1}{2}$ years in the Biophysical Laboratory of Harvard Medical School. He then was an Assistant Professor for 3 years in the Sibley School of Mechanical and Aerospace Engineering of Cornell University, Ithaca, NY. Since 1981, he has been a Biomedical Engineer in the Biomedical Engineering and Instrumentation Branch of the Division of Research Services of the National Institutes of Health in Bethesda, MD, and an Adjunct Assistant Professor in the Department of Biomedical Engineering of the Johns Hopkins School of Medicine, Baltimore, MD. His general research interests include bioheat and mass transfer phenomena and pharmacokinetics. Currently, he is involved in both hyperthermia and cryobiology research.

Dr. Levin is a member of the Radiation Research Society, the Cryobiology Society, the American Society of Mechanical Engineering, and the American Institute of Chemical Engineering. He has just completed a term as the Chairman of the ASME Technical Committee on Bio-Heat and Mass Transfer.