A Mixed FDTD-Integral Equation Approach for On-Site Safety Assessment in Complex Electromagnetic Environments

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***Abstract*—A mixed finite-difference time-domain (FDTD)-integral equation approach for the evaluation of the power deposition in the human body model immersed in a complex electromagnetic environment is proposed. The advantage of the proposed approach is that safety assessment for exposure to generic sources may be performed on-site, in a few minutes, with high accuracy and without the need of a high-power workstation. The method uses previously stored FDTD-computed impulse responses (Green's functions) of the human body model by integrating them with the complex incident electromagnetic field distribution that can be measured on site. The application of this method to the dosimetry of cellular telephone base station antennas is presented to show its versatility and ease of use.**

***Index Terms*—Dosimetry, finite-difference time-domain (FDTD) methods, synthetic aperture radar (SAR) computation.**

I. Introduction

KNOWLEDGE of absorbed energy and its distribution in the human body for complex electromagnetic environments is often of interest for safety assessment. The finite-difference time-domain method (FDTD) [1], [2] has been successfully and extensively used with high-resolution human body models for compliance testing of electromagnetic devices or sources. While results are well known for plane-wave exposures, there is no *a priori* information on the synthetic aperture radars (SARs) induced by space-variant incident electromagnetic far fields. To date, safety assessment due to a generic source is possible only by characterizing the source and simulating its coupling with the human body model. However, due to the large number of FDTD cells that constitute the human body models, simulations for different devices or sources are time consuming and often require high-power computing workstations. In fact, simulations involving high-resolution human body models may require hours, or even days, with current computing workstations.

For field applications, a fast and reliable method to calculate the power deposition in the human body model due to a generic source is desirable. This would allow personnel to determine on-site safety distances from electromagnetic sources, antennas, etc., necessary to meet current regulations [3]. The method suggested here uses FDTD-computed electromagnetic field distributions induced in the human body calculated previously for a number of spatial impulses. Since a measured electromagnetic field distribution incident on the human body can be approximated by a weighted sum of the stored impulses, the specific absorption rates of power, or SARs, may be determined by simply integrating the generic incident field distribution with the set of stored impulse responses. In this way, very little computation is necessary in the field to determine the SAR distribution due to a source of interest. A simple laptop computer equipped with a CD-ROM reader would be enough to determine in a few minutes the necessary information.

Section II will describe the proposed approach. Section III will present test results for a 6-mm human body model exposed to various incident electromagnetic fields. Section IV will show the application of the approach to the dosimetry of two realistic base station antennas for mobile communications. Section V will discuss the computational cost of the method.

II. Computational Method

The main idea for this approach is that the electric field inside the human body model can be expressed by means of the following integral equation:

$$\vec{E}(x, y, z) = \int_{S'} \vec{G}(x, y, z|x', y'z') \cdot \vec{J}(x', y', z')\, dS'. \quad (1)$$

In (1), $\vec{G}$ is the tensor "Green's function" (3×3 matrix) of the human body model, $\vec{J}$ is the incident field, and S' is the plane containing the incident field. The problem can be simplified by considering, at this time, only incident fields polarized along the vertical axis of the human body, these being components of maximum coupling for frontal electromagnetic exposures [4], [5]. Identifying this direction with the z-axis, (1) can be written as

$$\vec{E}(x, y, z) = \int_{S'} (G_{xz}\vec{x} + G_{yz}\vec{y} + G_{zz}\vec{z})(x, y, z|x', y', z') \cdot \vec{J}_z(x', y', z')\, dS'. \quad (2)$$

It should be noted that the "Green's function" depends on the observation point (x, y, z) and the source point (x', y', z'), and not just the separation between observation and source points since the system is not invariant for translations.

The knowledge of the above mentioned Green's function would, obviously, completely solve the problem. Unfortunately,

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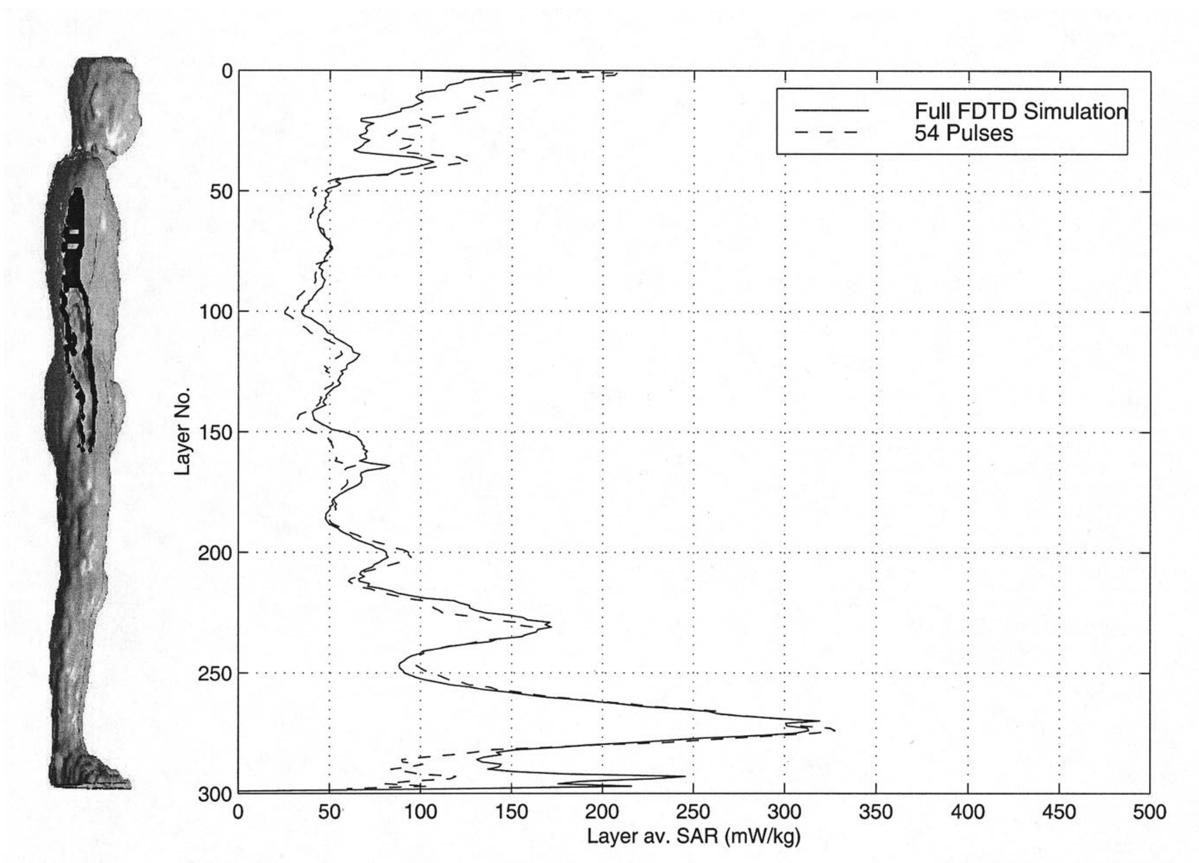

Fig. 1. Layer average SAR (6-mm human body model) for a plane-wave exposure obtained by FDTD simulation and sum of previuosly stored impulse responses. Frequency: 835 MHz, $E_{\rm inc} = 61.4$ V/m rms.

the shape of the human body model and its heterogeneity render it virtually impossible to derive an expression of the Green's function (closed form or integral form) in a usable fashion. However, we can assume as a plane of sources incident on the human body a plane just in front of it grazing the toes, and we can actually numerically calculate the Green's function due to a set of spatially narrow pulses selected on the plane of incidence of the field, or the source plane. Selecting appropriately the position and number N of pulses to be considered, (2) can be rewritten as follows:

$$\vec{E}(x, y, z) \approx \sum_{i=1}^{N} (G_{xz}\vec{x} + G_{yz}\vec{y} + G_{zz}\vec{z})(x, y, z|x_i, y_i, z_i) \cdot \vec{J}_z(x_i, y_i, z_i)\,\Delta x\,\Delta z. \tag{3}$$

Naturally, (3) will not be accurate for cases where the spatial variations of incident fields are extremely rapid, unless the number N of considered pulses is very large. In the majority of the practical cases of human exposure to electromagnetic fields, however, the incident fields are slowly varying over the extent of the body and therefore a reasonable number of pulses will give very accurate results. The approach, therefore, consists in calculating the Green's functions due to N spatial pulses lying in the considered plane of incidence of the electromagnetic fields by using the FDTD method. The x-, y-, and z-components of the electric fields induced in the human body by the selected pulses is then stored in amplitude and phase on a hard disk or CD-ROM. The results due to a generic exposure can, therefore, be obtained by adding, with appropriate amplitudes that will depend upon the measured (or calculated) incident field, the response from each of the precomputed pulses. The results must also be scaled by the ratio of cells in the plane of incidence and the actual number N of the used pulses. Practically, this means that if M sources could be positioned in the considered plane (M "available" J_z positions over the source plane), the final result should be multiplied by M/N to account for the larger area occupied by the N sources. To avoid reflections from the excitation, "transparent" sources have been used as excitation pulses.

III. Test Results

We have calculated the impulse response of a 6-mm resolution model of the human body to a set of $N = 54$ pulses at the test frequency of 835 MHz, typical of some today's base-station antennas for mobile communications. The human body model has been described in our previous publications, and it consists of 31 tissue types identified [6]. The cells constituting the model, originally having a resolution of $2 \times 2 \times 3$ mm, have been combined to reduce the size of the model to the mentioned $6 \times 6 \times 6$ mm.

The 54 pulses used to calculate the impulse responses of the human body are equally spaced on a plane of dimensions 45 $\times$ 198 cm [respectively, in the shoulder to shoulder direction (x) and along the height of the model (z)], and they are spread over a grid of 3×18 in the x- and z-directions, respectively. This assumed plane is located grazing the toes of the human body

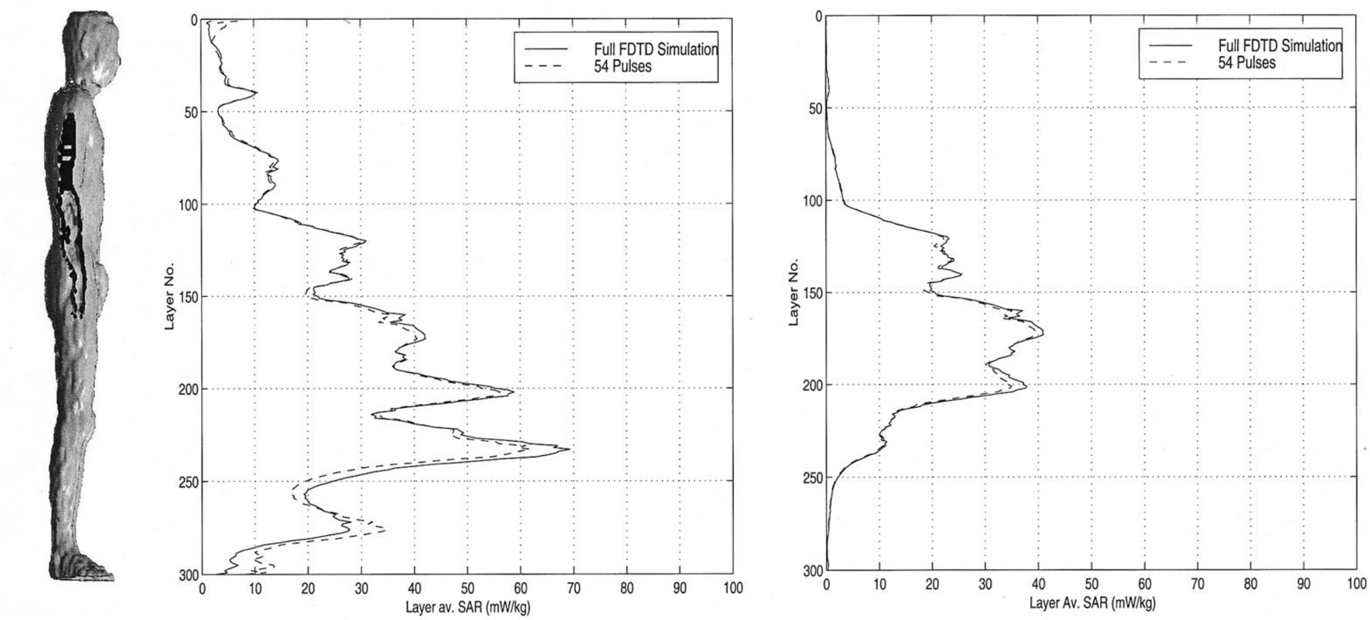

Fig. 2. Layer average SAR (6-mm human body model) for a 2-D sinusoidally varying exposure obtained by FDTD simulation and sum of previously stored impulse responses. Frequency: 835 MHz, $E_{\rm peak,\,inc} = 61.4$ V/m rms. (a) Aperture size: 63 × 180 cm. (b) Aperture size: 63 × 108 cm.

model in order to consider frontal incidence of electromagnetic radiation, but other configurations may also be used.

We have found that the number of sources used is conservatively large, since for most of the cases only a fraction of this number may really be necessary to predict the correct SAR distributions, especially for the cases of spatially limited incident electromagnetic fields (such as those that may be experienced by several categories of workers).

Three test cases, typical of some exposure conditions, have been considered at the frequency of 835 MHz and solved by means of complete FDTD simulation and by using the previously stored impulse responses. These include exposure to vertically polarized plane wave and two two-dimensional (2-D) spatially sinusoidally modulated radiation of different size [apertures of sizes (a) 63 × 180 cm and (b) 63 × 108 cm, respectively]. The electric field intensity for the plane-wave case has been assumed to be 61.4 V/m rms (1 mW/cm^2 incident power density), while for the remaining two cases the spatial peak amplitude of the electric field is 61.4 V/m rms only in the central position of the aperture, decaying to 0 because of sinusoidal variation toward the ends.

The agreement of the layer average SAR between complete FDTD simulation and sum of previously stored impulse responses for these three cases is shown in Figs. 1 and 2(a) and (b). All of the considered cases show excellent agreement between the two methods. Some slight difference can be observed in the case of plane-wave near the ends of the human body model (head and feet) due to the use of a finite size plane to simulate a plane wave exposure that can cause some "end" effects at the edges of the model. The two spatially sinusoidally varying incident fields exhibit instead a remarkable agreement between the two methods. It is worth noticing that due to the space-limited nature of the considered incident fields for some of these cases, less than 54 pulses have been necessary to reconstruct the solution. In fact, while case (a) has been solved by means of the whole set of 54 pulses, only 30 pulses have been used for case (b). An even smaller number of pulses would be necessary for narrower apertures, increasing considerably the efficiency of the method. In fact, for an aperture size of 63 × 48 cm only 15 pulses were necessary to reconstruct the SAR deposition in the human body model.

TABLE I
1-g SARs FOR DIFFERENT APERTURE TYPE INCIDENT ELECTROMAGNETIC FIELDS SINUSOIDALLY VARYING ALONG THE TWO AXES OF A PLANE ASSUMED IN FRONT OF THE INTENDED LOCATION OF THE OPERATOR. RESULTS ARE GIVEN FOR BOTH THE FULL FDTD SIMULATION AND THE PROPOSED METHOD

Case	Aperture Size (cm)	1 g Av. SAR (W/kg) - Full FDTD Simulation -	1 g Av. SAR (W/kg) - Pulses Method -
A	63 × 180	0.81	0.87
B	63 × 108	0.74	0.77
C	63 × 48	0.48	0.48

We have also compared the 1-g SARs for these cases, and the results are given in Table I. It is evident from Table I that, even for peak 1-g SARs needed for safety assessment, the proposed method provides results within ±10%.

For lower frequencies, it is possible to use a lower-resolution human body model and a lower number of pulses. At the frequency of 200 MHz, for example, we have found that 27 pulses are adequate to cover an aperture of the size of the human body. Moreover, at this frequency it was possible to use the 12-mm resolution body model. Fig. 3 shows the layer average SAR at the frequency of 200 MHz for an aperture of size 63 × 180 cm with a spatial peak amplitude of the electric field equal to 61.4 V/m rms in the central position of the aperture, decaying to zero

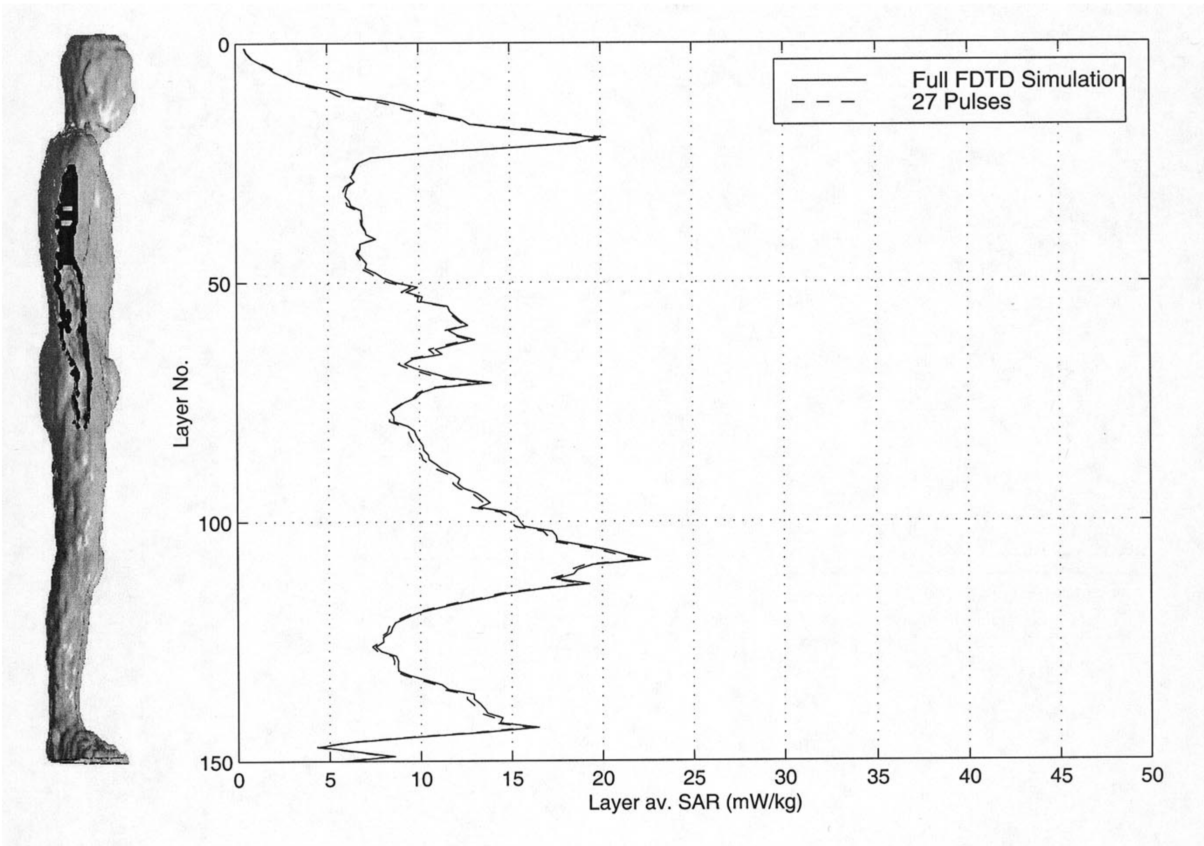

Fig. 3. Layer average SAR (6-mm human body model) for a 2-D sinusoidally varying exposure obtained by FDTD simulation and sum of previously stored impulse responses. Frequency: 200 MHz, $E_{\mathrm{peak,\,inc}} = 61.4$ V/m rms. Aperture size: 63 × 180 cm.

by sinusoidal modulation toward the ends. The agreement between full FDTD simulation and pulses method is extremely good.

IV. SAR Calculations for Fields Radiated by Mobile Communications Base-Station Antennas

We have applied the proposed method to the calculation of the SARs induced in the human body for two typical base station antennas used for mobile communications.

For safety assessment tests, two methods may be used to determine the field distributions incident on the human body model. The first and more likely used method would use the measured field distributions on-site and using this information in the computer program that will add the fields induced by the pulses with appropriate amplitude and phases and provide in real time the desired SAR information. This is, of course, the preferred method because of the rapidity with which this can be carried out with computation times on the order of 2–3 min.

Since we did not have data of electric field measurements in front of the considered base station antennas, we have used the second method of obtaining the necessary incident electromagnetic fields, that is by computer simulation (FDTD). The assumption in this case is that the human body model is not strongly coupled to the radiating source. This means that the distance between the radiating source and the human body model is such that the presence of the model does not significantly alter the radiating characteristics of the source. This allows us to simulate the desired antennas with coarser resolution but still using cell sizes less than $\lambda_0/10$ required by the FDTD method. In this way, we can obtain the field distribution in front of the antennas in the absence of the human body model with computation time on the order of 2–3 min.

The first of the considered base-station antennas is a horn antenna with a rectangular aperture of dimensions 30 × 90 cm, radiating a time-averaged power of 120 W for all the channels in the frequency band 825–849 MHz. To calculate the fields radiated in front of this antenna for the purpose of SAR calculations, we have assumed all of this power to be at the center frequency of 835 MHz. We have simulated the antenna alone, with a resolution of 4 cm for the FDTD cell size. The simulated radiation pattern has been compared with the data provided by the manufacturer to insure the accuracy of the simulation and it is reported in Fig. 4.

We have then calculated the SARs that would be induced in the human body for exposure to this antenna at distances d of 1, 2, 3, and 4 m by using the pulse superposition method. Results for the layer averaged SARs are shown in Fig. 5 at the considered distances. As expected, the layer average SAR approaches that for the plane waves exposure at larger distances. Table II gives the 1-g SARs values calculated for each of these distances.

The second antenna we have considered is a dipole antenna of length 0.45 λ backed by a finite-size metal reflector placed at a distance of 0.18 λ, and radiating a total power of 10 W at 835 MHz. The field radiated by this antenna has been calculated

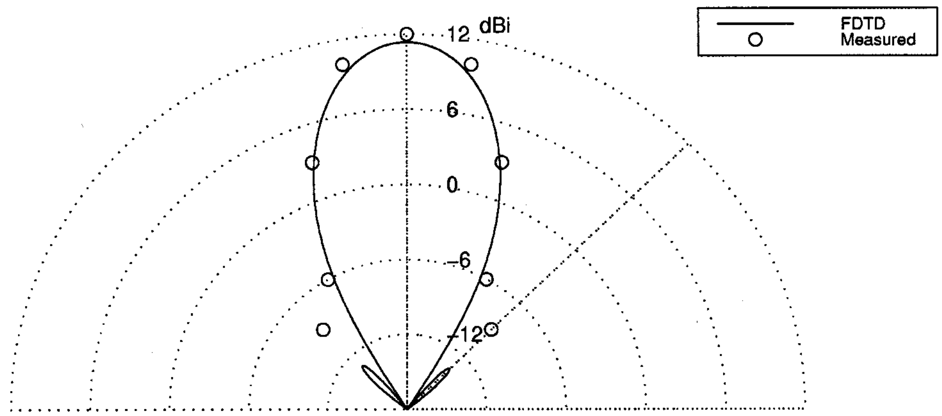

Fig. 4. Comparison of the simulated and measured radiation patterns for the base station horn antenna with a rectangular aperture of dimensions 30 × 90 cm, radiating a time-averaged power of 120 W in the frequency band 825–849 MHz.

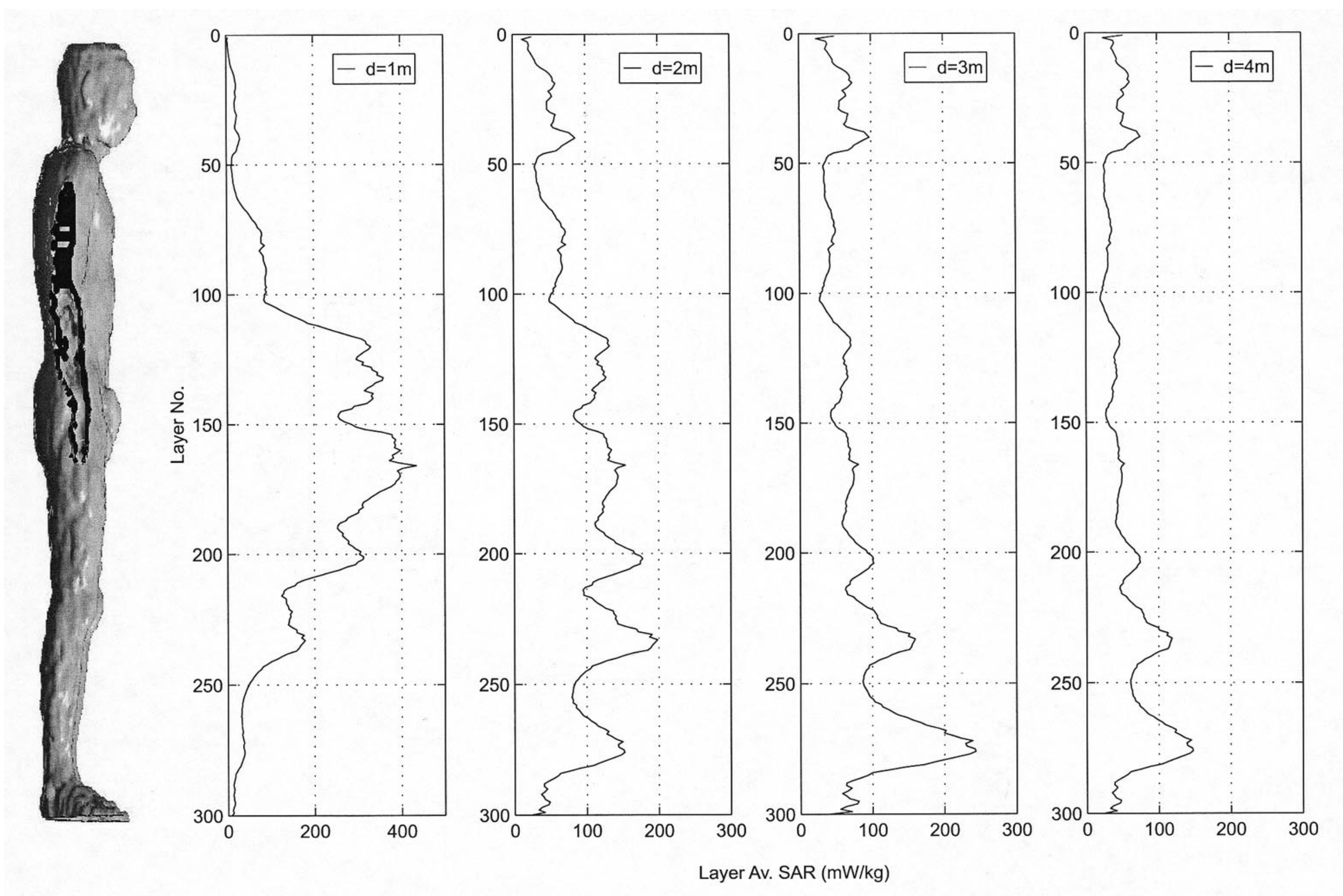

Fig. 5. Layer average SAR (6-mm human body model) induced by a base station horn antenna at the distance $d = 1$, 2, 3, and 4 m calculated by sum of previously stored impulse responses. Frequency: 835 MHz, radiated power: 120 W.

by a FDTD simulation that used a cell size of 2 cm. We have calculated the SAR induced in the human body model by this antenna for distances $d = 0.5$, 0.75, and 1 m by using the pulse superposition method. The layer average SARs for this case are shown in Fig. 6, while the results for the 1-g SARs are given in Table III.

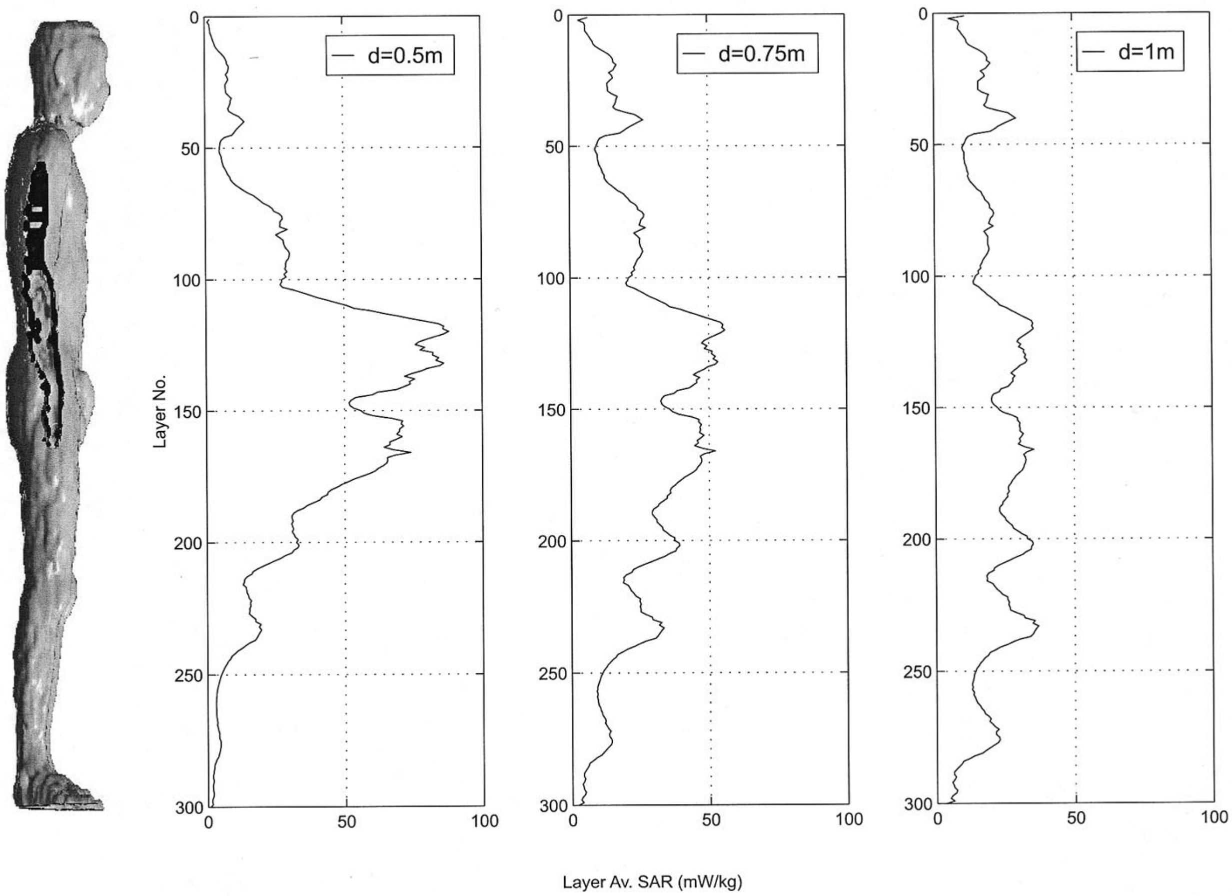

Fig. 6. Layer average SAR (6-mm human body model) induced by a base-station dipole antenna at the distance $d = 0.5$, 0.75, and 1 m calculated by sum of previously stored impulse responses. Frequency: 835 MHz, radiated power: 10 W.

TABLE II
1-g SARs FOR VARIOUS DISTANCES FOR A CELLULAR TELEPHONE BASE STATION USING AN APERTURE ANTENNA OF DIMENSIONS 30 × 90 cm. FREQUENCY: 835 MHz. RADIATED POWER: 120 W

Distance (m)	1 g Av. SAR (W/kg) - Pulses Method -
1	12.75
2	4.26
3	2.55
4	1.70

TABLE III
1-g SARs FOR VARIOUS DISTANCES FOR A CELLULAR TELEPHONE BASE STATION USING A DIPOLE-REFLECTOR ANTENNA. LENGTH OF THE DIPOLE: 0.45 λ. DISTANCE OF THE REFLECTOR: 0.18 λ. FREQUENCY: 835 MHz. RADIATED POWER: 10 W

Distance (m)	1 g Av. SAR (W/kg) - Pulses Method -
0.5	2.7
0.75	1.7
1	1.06

V. COMPUTATIONAL COST

The proposed method has the considerable advantage in that it requires minimal computation for rapid assessment of the SAR induced in the human body by generic spatially varying electromagnetic fields. This gives the possibility of performing SAR tests "on-site," in a few minutes, by using a laptop computer equipped with a CD-ROM where the necessary "Green's function" data has been stored. Even the memory requirements for this approach can be efficiently minimized, since the only computation required to process the data is the sum in amplitudes and phases of the impulse responses with appropriate weights.

The complete FDTD simulation that could be used as an alternative requires a considerably longer computational time and a much larger computer memory, which renders impossible the safety assessment of electromagnetic exposures on site. Two possibilities to solve the complete FDTD problem are available: the simulation that includes in the FDTD space the antenna and the human body model (case A), and the simulation that instead includes only the human body model and in which the incident electromagnetic field is prescribed at a plane in immediate front of the intended location of the human (case B). Obviously, the first possibility would lead to simulations that can easily become unfeasible as soon as the distance between the human body and the antenna increases.

Case B takes approximately 50 min to run and reach complete convergence, for a frequency of 835 MHz on a computer equipped with a 450-MHz Pentium II processor, with the code compiled with Fortran GNU compiler. For simulations involving lower frequencies than the one considered in these examples, the length of the simulation can increase dramatically because of the larger number of iterations. For a 400-MHz simulation, the code runs in approximately 90 min, while for a 100-MHz simulation, it may take up to 190 min (note that times are not proportional since different frequencies may need a different number of cycles to converge). Computer-memory usage could also represent a problem in these cases. The full FDTD code for the complete simulation requires approximately 120 Mb for a 6-mm human body model (accounting for additional free space above and below the human body, necessary to correctly represent the fields on the extremities of the body itself).

The proposed method, on the other hand, suffers from the necessity of storing large amount of precalculated data for the internal E-field distributions. For a 6-mm human body model, approximately 9 Mb are required to store the results for each field component due to each pulse. However, compression techniques are currently under consideration to reduce the storage requirements. For the 12-mm human body model, the storage requirements reduce to approximately 1.2 Mb for each field component due to each pulse. SAR distributions can be obtained in approximately 5 min by loading the set of 54 electric field distributions in the human body prestored in the hard disk.

VI. Concluding Remarks

We have proposed a new approach for the calculation of the SAR distribution for a human body model exposed to generic spatially varying incident electromagnetic fields. The method uses prestored FDTD-computed electric field distributions induced in the human body model by a set of spatial pulses, assumed for a plane in front of the model. The method may be generalized by considering pulse distributions that completely surround the model, rather than being just in front of it.

The method has great potential for being used on-site for actual SAR testing of electromagnetic exposures, base station antennas, etc., since it may be run by a simple laptop computer. The problem of reducing the amount of data to be stored is currently under investigation. Potential compression techniques based on wavelets are being considered.

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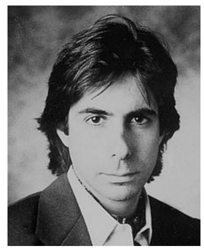

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