A Study of Uncertainties in Modeling Antenna Performance and Power Absorption in the Head of a Cellular Phone User

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***Abstract*—A set of finite-difference time-domain (FDTD) numerical experiments modeling canonical representations of the human head/cellular phone interaction has been performed in order to investigate the effect of specific simulation details (e.g., antenna numerical representation and absorbing boundary conditions) on computed results. Furthermore, hybrid techniques based on the dyadic Green's function and the method of auxiliary sources, and on a hybrid method-of-moments–FDTD technique have been used to compute parameters of interest for comparison with the FDTD evaluated parameters. It was found that small, but potentially significant, differences in computed results could occur, even between groups that were nominally using a very similar method. However, these differences could be made to become very small when precise details of the simulation were harmonized, particularly in the regions close to the source point.**

***Index Terms*—Biological effects of electromagnetic radiation, dosimetry, error analysis, FDTD methods, hybrid numerical techniques, land mobile radio cellular systems.**

I. Introduction

In RECENT years, there has been a growing demand for accurate dosimetric calculations inside lossy bodies exposed to the near field of handheld transceivers to evaluate possible health hazards or to perform compliance testing. In particular, cellular phone compliance tests consist in checking that the power absorption due to mobile telecommunication equipment is below the limits recommended by international safety guidelines [1]–[4]. This analysis can be performed both experimentally and numerically.

While in experimental studies error evaluation is usually performed so that the power absorbed is always reported together with the corresponding uncertainty value, in numerical studies, considerations relating to numerical error have only appeared sporadically.

In numerical dosimetry studies for mobile communications, as well as for mobile phone design, the use of the finite-difference time-domain (FDTD) method has dominated over the other numerical methods in recent years, due to its simplicity and its ability to treat highly nonhomogeneous structures. However, even if intensive research work with the FDTD method has led to high confidence in the obtained results, the exact error estimation of FDTD simulations still remains a difficult task.

In particular, since the field interaction is highly dependent on the shape of the scatterer, which usually does not conform to the FDTD orthogonal lattice, unless some locally conformal grid is used, this can lead to substantial error in the calculations [5]. Thus, factors such as the details for building the head or the handset in the Yee grid, and the source numerical representation, may be responsible for uncertainties in the evaluated parameters. Moreover, even if several approaches for accurate absorbing boundary conditions (ABCs) at the boundary of the computational domain have been proposed [6], improving the approximation of free-space environment with a minimum of air space around the scatterer, the type of ABCs used and the distance between the scatterers and absorbing boundaries can be another source of substantial error in the FDTD results.

The aim of this paper is to examine the main uncertainty components of the FDTD method in evaluating the exposure of human head models to mobile communication devices. To this end, numerical results obtained for 12 canonical cases, modeling the exposure of well-defined head models to simple antennas similar to those of mobile transceivers, have been compared in detail. Special emphasis is given to the estimation of uncertainties related to the antenna numerical representation and the ABCs, by performing a set of appropriate numerical experiments for a test canonical case. In order to also assess "inter-algorithm" variabilities, numerical results obtained by three independent implementations of the FDTD method at the University of Rome "La Sapienza," Rome, Italy, at the Aristotle University of Thessaloniki, Thessaloniki, Greece, and at the University of Bradford, Bradford, U.K., are compared in detail. A semianalytical method based on the dyadic Green's function theory in conjunction with the method of auxiliary sources (Green/MAS), developed at the National Technical University of Athens, Athens,

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Greece [7], [8] and a recently developed hybrid method of moments/finite-difference time-domain (MoM–FDTD) technique from the University of Ancona, Ancona, Italy [9], [10] are used for comparison purposes.

II. Description of the Test Canonical Problems

Numerical canonical problems pertaining to the interaction of spherical or cubical head models with a dipole and a monopole on a metal box have been defined in detail. Simulations have been performed at 900 and 1710 MHz.

Two spherical models of the head were used, each 20 cm in diameter, namely, homogeneous brain and three-layer sphere consisting of skin, skull, and brain. One box model of the head was also used, consisting of a 19-cm cube made of homogeneous brain enclosed in a 0.5-cm-thick dielectric shell. Mass density and complex dielectric permittivity values have been defined according to literature data [11], while the dielectric properties of the dielectric shell correspond to those of Plexiglass ($\varepsilon_r' = 2.7$, $\varepsilon_r'' = 0.032$), which is usually used in experimental dosimetry.

Two types of sources were defined, namely, a half-wavelength dipole, and a quarter-wavelength monopole, both with conductor diameter of 2.5 mm. The monopole antenna was centered on the upper side of a conducting box of 120 mm (length) $\times$ 55 mm (width) $\times$ 20 mm (depth), as shown in Fig. 1(a). The front face of the metal box was covered with a Plexiglass dielectric insulator of 5-mm thickness. The size of the feeding gap was set equal to 2.5 mm.

In order to define the source positioning with respect to the head phantom, a Cartesian coordinate system attached to the phantom center was considered [see Fig. 1(b)]. In all the cases, the axis of the transceiver model was aligned parallel to the z-axis. For the dipole source, the center of the feeding gap of the source was located on the x-axis, at the point (10.625, 0.0, 0.0) (in centimeters). When the monopole on a metal box was used, the center of the feeding gap was located at the point (12.0, 0.0, 3.125) (in centimeters) so that the x-axis intersects the front face of the metal box at the center of the ear piece [see Fig. 1(a)].

Twelve different combinations of phantom, source, and frequency were defined. Eight of them refer to a spherical geometry of the head (phantom), whereas the rest of them refer to a cubical geometry. They are illustrated in Table I.

III. Methods

A. Description of FDTD Numerical Experiments

The FDTD method has been used successfully to obtain a specific absorption rate (SAR) for whole- or partial-body exposures to spatially uniform or nonuniform (far or near field) electromagnetic fields from extremely low frequencies (ELF) to microwave frequencies [12].

In analyzing the canonical cases defined in Section II, the Aristotle University of Thessaloniki, the University of Rome "La Sapienza", and the University of Bradford have employed self-developed FDTD codes, based on the use of the Yee cell, a rectangular computational grid [13] and the total-field formulation [5]. For the calculations of canonical problems, the second-order Mur [14] or the perfectly matched layer (PML) [6]

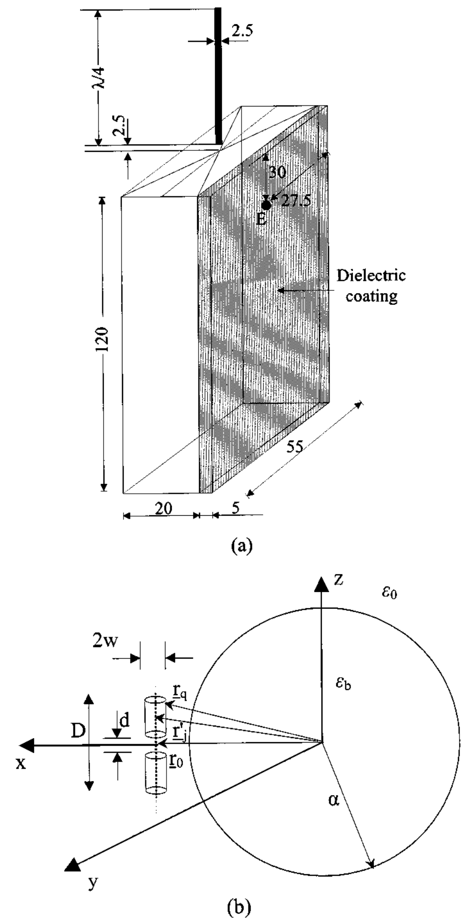

Fig. 1. (a) Monopole on a metal box with front dielectric cover (dimensions in millimeters). Point E corresponds to the ear piece. (b) Homogeneous sphere exposed to the near-field radiation of a finite length dipole.

TABLE I
Codes for the Different Canonical Cases

CASE N°	PHANTOM	TISSUE	FREQUENCY	SOURCE
1	sphere	homogeneous	900 MHz	dipole
2	sphere	homogeneous	900 MHz	monopole
3	sphere	homogeneous	1710 MHz	dipole
4	sphere	homogeneous	1710 MHz	monopole
5	sphere	three-layered	900 MHz	dipole
6	sphere	three-layered	900 MHz	monopole
7	sphere	three-layered	1710 MHz	dipole
8	sphere	three-layered	1710 MHz	monopole
9	cube	homogeneous	900 MHz	dipole
10	cube	homogeneous	900 MHz	monopole
11	cube	homogeneous	1710 MHz	dipole
12	cube	homogeneous	1710 MHz	monopole

ABCs have been used. A cell size of 2.5 mm was used. Computations were terminated after steady state was reached (usually after 10–20 periods).

Regarding the antenna modeling, the dipole and wire of the monopole (on the metal box) can be modeled either by a vertical stack of cells with a high-conductivity value, or by setting the (tangential) E_z component equal to zero along the wire or, finally, by the thin wire algorithm. The half-wavelength dipole at both studied frequencies extended over an odd number of cells to produce symmetrical arms around a central gap. The source excitation was modeled by imposing a harmonic voltage at the feeding gap of the antenna.

Computations were performed on different platforms ranging from PCs to powerful parallel computing platforms, with typical CPU time in the range of 3–15 h.

B. Description of the Semianalytical Method

In order to provide an accurate solution to the canonical problem of the sphere exposed to a half-wavelength dipole [see Fig. 1(b)], the Green/MAS technique was employed [7], [8]. The method is based on the use of the Green's function of the sphere, which is determined as the response of this object to the excitation generated by an elementary dipole of unit dipole moment, external to the sphere. Then, the contribution of the radiating antenna is taken into account by applying the MAS [15]. To this end, a set of auxiliary current sources is distributed on a virtual surface, which lies inside and usually conforms to the physical surface of the antenna. In the problem treated in this paper, since the dipole antenna has a diameter substantially less than the radiation wavelength, the auxiliary sources (elementary dipoles) are distributed along the axis of the dipole, with corresponding position vectors $\underline{r}_j = x_0\hat{x} + z_j\hat{z}$, where $-D/2 \leq z_j \leq D/2$ and $j = 1, \ldots, J$ [see Fig. 1(b)].

The electric field at any point $\underline{r}$ lying inside (outside) the sphere can be expressed as

$$\underline{E}_{\text{in(out)}}(\underline{r}) = j\omega\mu_0 \sum_{j=1}^{J} \overline{\underline{G}}_{\text{in(out)}}\left(\underline{r}, \underline{r}_j'\right)\underline{L}_j'\left(\underline{r}_j'\right) \qquad (1)$$

where $\overline{\underline{G}}_{\text{in(out)}}(\underline{r}, \underline{r}_j')$ is the dyadic Green's function inside (outside) the sphere and $\underline{L}_j'(\underline{r}_j') = \hat{z}p_j'$ is the dipole moment of the jth elementary dipole, with p_j' being its constant moment magnitude.

By enforcing the boundary conditions for the tangential electric-field component at a finite number of (collocation) points lying along a line on the surface of the dipole [see Fig. 1(b)], with corresponding position vectors $\underline{r}_q = (x_0 - w)\hat{x} + z_q\hat{z}$, where $-D/2 \leq z_q \leq D/2$ and $q = 1, \ldots, J$, a $J \times J$ system of linear equations is obtained, which is solved for the unknown dipole moment coefficients p_j'. Once these coefficients are computed, then the electric field can be calculated at any point inside and outside the spherical head model and thus the quantities of practical interest, such as the SAR and the scattering amplitude in the radiation zone, can be predicted.

From the above description of the MAS technique, it can be observed that the application of MAS for the particular case of the thin dipole is similar with the treatment of thin wires by the traditional MoM [16].

C. Description of the MoM-FDTD Method

A new hybrid technique has been developed by the University of Ancona to solve typical scattering problems, combining a marching in time version of the MoM–FDTD method [9], [10]. In fact, since the source is generally a regular object, whose geometry is often described by simple equations, the radiation problem can be efficiently analyzed by the MoM. This approach requires only the discretization of the domain where the current flows, without analyzing the space surrounding the source, because of the use of the suitable Green's function. On the other hand, the electromagnetic characterization of a physically and geometrically complex object can be very difficult or impossible and time consuming, when approached with the same method. Conversely, the FDTD technique is more powerful dealing with a complex penetrable object such as the human head, but it is not particularly efficient in handling the sources, especially when it is necessary to describe small dimensions. Based on the above considerations, in the hybrid technique, the original complex problem is split into two simpler problems by applying the equivalence principle. The radiation of the antenna is analyzed by the MoM, using the equivalent sources provided by the FDTD method, and the field scattered from the dielectric object is studied by the FDTD method, using the equivalent sources provided by the MoM.

IV. Numerical Results and Discussion

The results obtained for each case included the position and value of the peak SAR within the head phantom, the SAR profiles along x-axis, the SAR distributions at the $y = 0$ cm and $x = 9$ cm planes, the total absorbed power, the antenna input impedance and the antenna radiation patterns at two planes ($\theta = 90°$ and $\phi = 0°$).

For all the graphs presenting the results of the computations, the steady-state power radiated from the antenna (i.e., the power radiated in the far field plus the power dissipated in the head) is 1 W.

Since the safety standards are defined in terms of SAR values averaged over a cube having a mass of 1 g [1], [2] or 10 g [3], [4], the corresponding averaged SAR values have also been calculated. In order to improve comparability between the results obtained by different participating groups, the calculation of the averaged SAR values over 1 and 10 g has been based on standardized procedures.

As an example of the results obtained, the peak SAR values as averaged over 1 g and calculated for the 12 cases of Table I, are reported in Fig. 2.

From this figure, it is evident that, although the canonical cases were carefully described, significant discrepancies can be observed in the results. Similar discrepancies were also evidenced in a study performed within the framework of the COST 244 project [17]. These differences can be explained by considering the specific implementation details of the FDTD method adopted. To better investigate this point, and to identify the error sources, the worst case, in terms of observed differences, has been analyzed in further detail. This worst case has been identified with case 3 of Table I, and is depicted in Fig. 1(b).

In reconsidering case 3, an identical numerical representation of the head was used by all the groups, namely, an even sphere with a diameter of 80 cells. The simulation time was fixed to 20 periods. Moreover, specific numerical experiments were designed and performed in order to investigate the effect of the

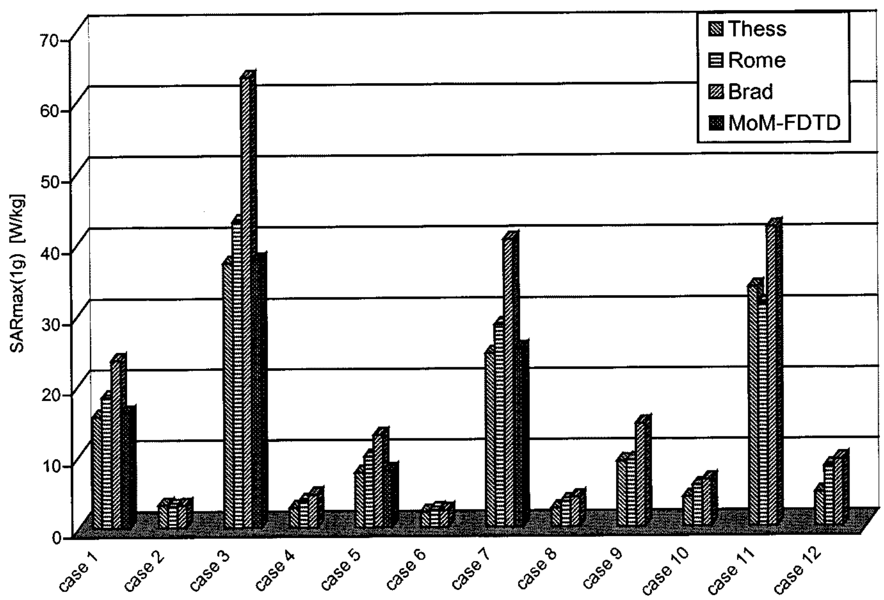

Fig. 2. Peak SAR value averaged over 1 g of tissue for the canonical cases. The antenna input power is 1 W.

ABCs and the dipole modeling on the simulated parameters of interest, referring to the power absorbed by the head and the antenna performance. In particular, numerical experiments were performed using either second-order Mur's ABCs placed at a distance of 20 cells from the nearest scatterer, or PML ABCs (PML with six layers, grading factor 4, and reflection coefficient of 10^{-5}) placed 16 cells away from the nearest scatterer. In order to investigate the effect of antenna modeling, two different numerical models of the dipole were used. The first model was the infinitely "thin" wire approximation, obtained by setting equal to zero the tangential electric-field component along the dipole's axis, with the exception of the feeding gap. The second was the "thick" wire approximation, obtained by assigning to each cell belonging to the dipole, with the exception of the antenna feed-point, the copper conductivity value (5.8×10^7 S/m). In both models, the dipole length was equal to 35 cells, with the central cell corresponding to the feeding gap where a hard sinusoidal source was placed.

A. *Evaluation of Peak SAR Magnitude and Position*

In FDTD numerical experiments and simulations using the Green/MAS technique or the MoM–FDTD technique, the maximum values of local 1-cell SAR, SAR averaged over 1 and 10 g of tissue, were computed. Furthermore, the locations where maximum SAR occurred, were determined.

As an example of the obtained results, peak SAR and SAR(1 g) are shown in Figs. 3 and 4, respectively, for 1 W of radiated power and the case of Fig. 1(b).

In the first simulations of the sphere–dipole combination at 1710 MHz (case 3 in Table I), a difference of the order of 40%–60% had been observed for the 1-cell $\mathrm{SAR}_{\max}$ value, as predicted by the different participating groups. In terms of $\mathrm{SAR}_{\max}$ averaged over 10 g of tissue, the observed differences were of the order of 25%–33%, due to the smoothing effect of the averaging procedure, while a generally good agreement had been observed in the prediction of the $\mathrm{SAR}_{\max}$ (10 g) positions. The above discrepancies are related to slight differences in building the head or the source in the Yee grid, the use of different absorbing boundaries placed at various distances from the scatterers and differences in the simulation time. Furthermore, other simulation details, such as the use (or not) of averaged parameters, as well as slight differences in the SAR averaging procedure, could also be responsible, to some extent, for the observed discrepancies.

Comparison among the results of the numerical experiments obtained when the same phantom numerical model was used shows that the maximum SAR values, either local (Fig. 3) or averaged over 1 g (Fig. 4) or 10 g of tissue are strongly dependent upon source modeling. In fact, the local SAR values obtained using the thin wire model are 18%–20% higher that those predicted using the thick wire model, while the difference between averaged SAR values is of the order of 12%–15%. Finally, the maximum local SAR value is not sensitive to the ABCs used.

When the same numerical model of the head and the same numerical representation of the dipole (thin or thick wire model) were used, the discrepancy among local SAR values computed by the different groups was reduced to 5%–8%, while the discrepancy among averaged SAR values was lower than 5%.

Furthermore, the position of the local maximum SAR value is independent of both source modeling and ABCs. However, the position of the maximum averaged SAR values depends on the source model used, which can lead to a 0.25–0.75 cm uncertainty along the z-axis.

Some error estimations can be obtained, by comparing the results of numerical experiments performed by different participating groups with those predicted by the Green/MAS and MoM-FDTD technique.

The averaged SAR values obtained using the Green/MAS technique are in closer agreement with those obtained by FDTD "thick wire" modeling with an error on local $\mathrm{SAR}_{\max}$ values that ranges from 2% to 6%. Instead, the error associated with

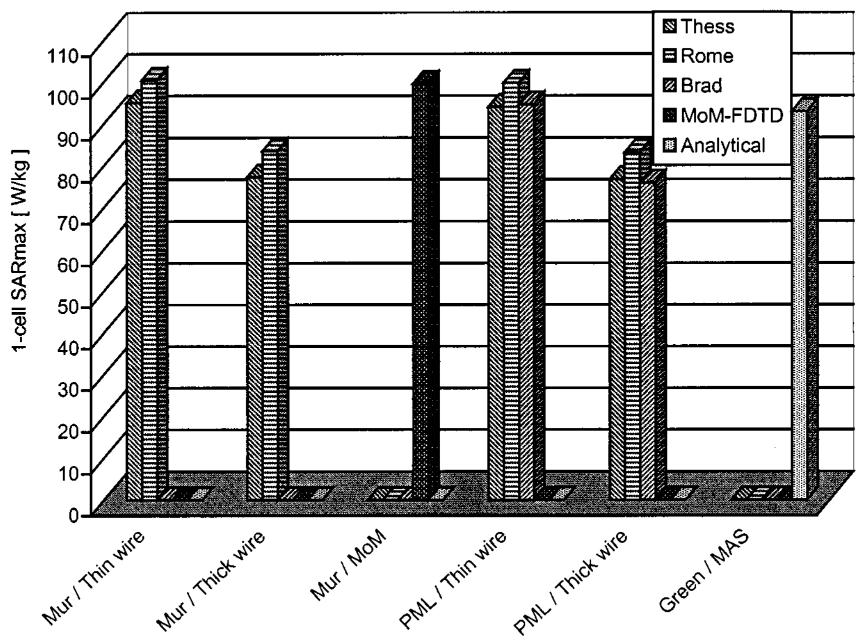

Fig. 3. Peak local SAR magnitude for the canonical case defined in Fig. 1(b). The antenna input power is 1 W.

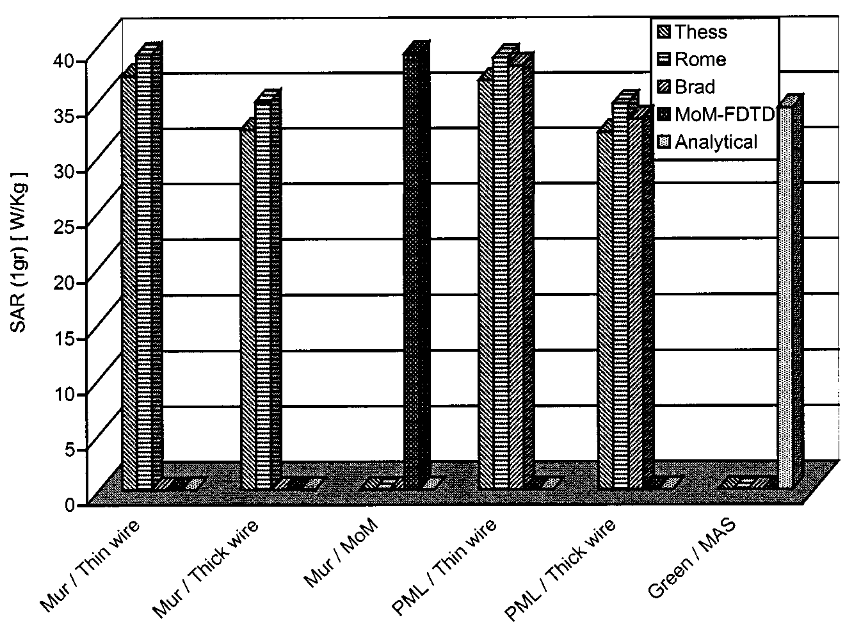

Fig. 4. SAR averaged over 1 g of tissue for the canonical case of Fig. 1(b). The antenna input power is 1 W.

the "thin wire" model is of the order of 7%–14%. Furthermore, it is important to note that the effect of the different ABCs is not of particular significance in the error figures that were obtained.

B. Absorbed Power

Fig. 5 depicts the power absorbed by the spherical head model for 1-W radiated power. A good agreement is observed among the different groups. In the first simulations, when the sphere representations were slightly different, a difference of the order of 10%–15% had been observed for the case of the dipole antenna at 1710 MHz. In the simulations reported in Fig. 5, where the same spherical head numerical model has been used by all participating groups, a discrepancy of the order of 1%–2% is observed between results when the same ABC and source model are used. Slight differences of the order of 1% are observed when different ABCs are used, while the discrepancy related to the use of different source models is of the order of 2.5%.

In comparing the absorbed power, as computed in FDTD numerical experiments, with the absorbed power obtained by the Green/MAS technique, the associated error ranges from 1% to 6.5%.

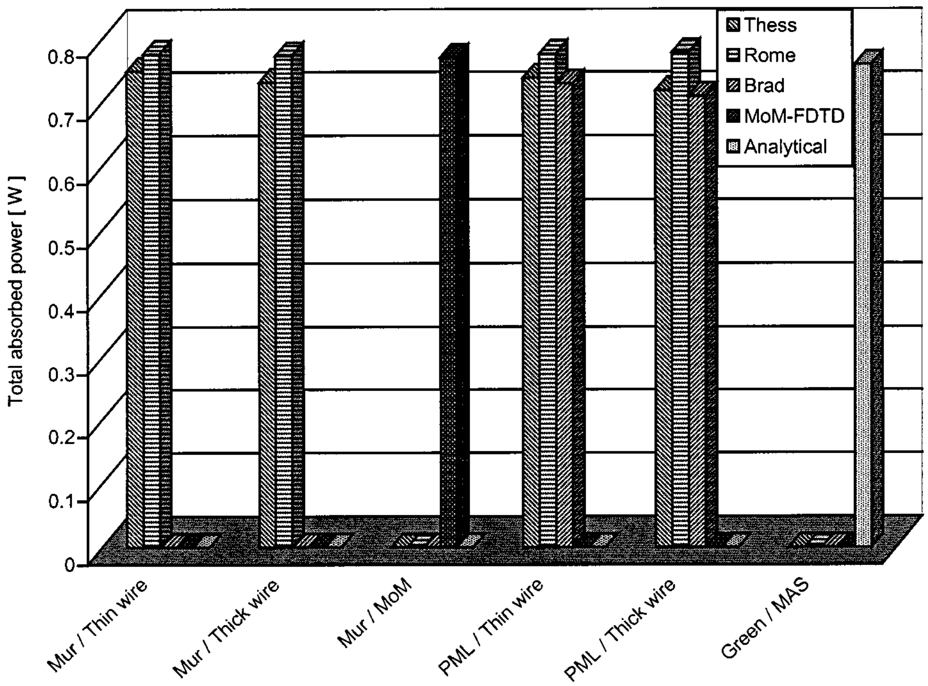

Fig. 5. Power absorbed by the head for the canonical case of Fig. 1(b). The radiated power is 1 W.

C. Input Impedance

The input impedance was calculated either by using the discrete Fourier transforms (DFTs) of the feed voltage and current (University of Thessaloniki) or by evaluating the maximum value and the phase of both current and voltage at the feeding gap (University of Rome "La Sapienza," University of Bradford, MoM–FDTD).

Concerning the prediction of the input impedance, a difference of the order of 10%–15% in the real part had been observed in the first series of experiments, for the examined canonical case of Fig. 1(b). However, differences of the order of 300% had been observed in the prediction of the imaginary part. In the second series of numerical experiments, different source models and ABCs were used, resulting in variations of the simulated input impedance.

In Figs. 6 and 7, the real and imaginary parts, respectively, of the antenna input impedance for the canonical case of Fig. 1(b) are presented. Due to the small source–head distance and the resulting strong electromagnetic coupling effect, the input impedance shifts far from resonance, exhibiting a significant imaginary part. The feed-point impedance is strongly dependent on the model used for the dipole. Thus, when the thick wire model is used, the real and imaginary parts of the impedance are multiplied by factors of two and four, respectively, compared with their values when the thin wire model is used. Furthermore, it can easily be observed that the feed-point impedance is almost independent of the ABCs used.

The error in computing the real part of the input impedance as compared with that predicted using the Green/MAS technique is of the order of 2%–3% for thin wire modeling. A difference of the order of 6% is observed between the input impedance real part, as predicted in the MoM–FDTD experiment and that predicted by the Green/MAS technique. A significant difference, of the order of 70%–85%, is observed in the prediction of the input impedance real part, when the thick wire model of the dipole is used.

Concerning the prediction of the input impedance imaginary part, errors of the order of 100% are observed for the thin wire modeling, while the associated error for the thick wire modeling can be as high as 600%. Finally, a difference of approximately 90% is observed, in comparison with the input impedance imaginary part predicted in MoM–FDTD and that predicted by the Green/MAS technique.

D. Comparison and Discussion

A detailed comparison between the results obtained by different participating groups for the canonical cases presented can lead to important observations concerning the estimation of uncertainty components in evaluating specific parameters of interest in mobile communications dosimetry studies. These observations are related to the study of canonical cases and can be summarized as follows.

1) Uncertainties related to some simulation details, such as the use or not of dielectric constant and field averaging in evaluating the SAR inside the head model, are not significant. Furthermore, if a sufficient distance is used between scatterers and the FDTD boundary, the results are not sensitive to the choice of ABCs used.
2) In evaluating the peak SAR averaged over 10 g of tissue, the related uncertainty can be of the order of 30%, while the corresponding uncertainty in assessing the 1-cell $\mathrm{SAR}_{\max}$ value can be of the order of 40%–60%, even for well-defined canonical cases. These uncertainties are mainly related to the phantom and the source modeling.

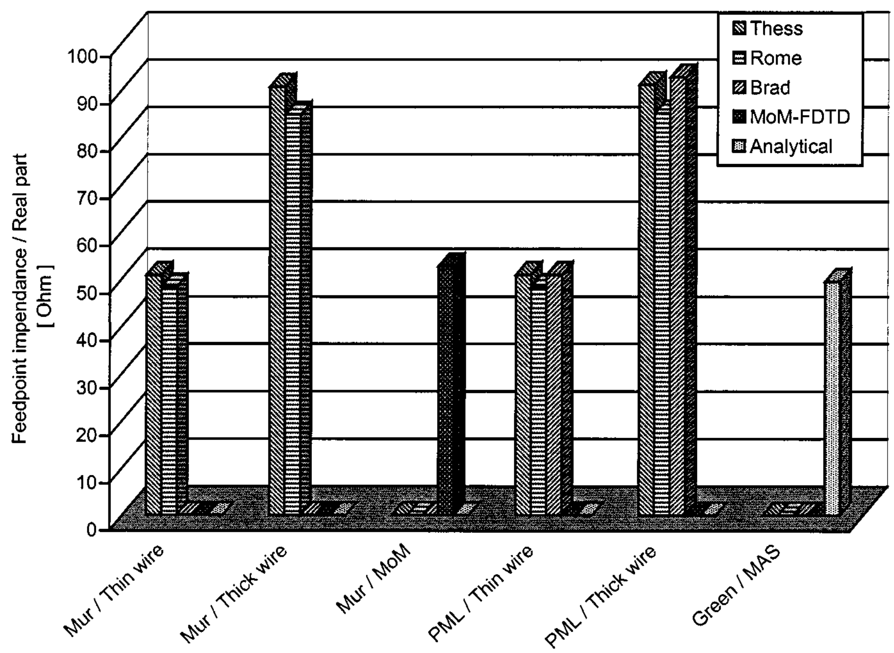

Fig. 6. Real part of the antenna input impedance for the canonical case of Fig. 1(b).

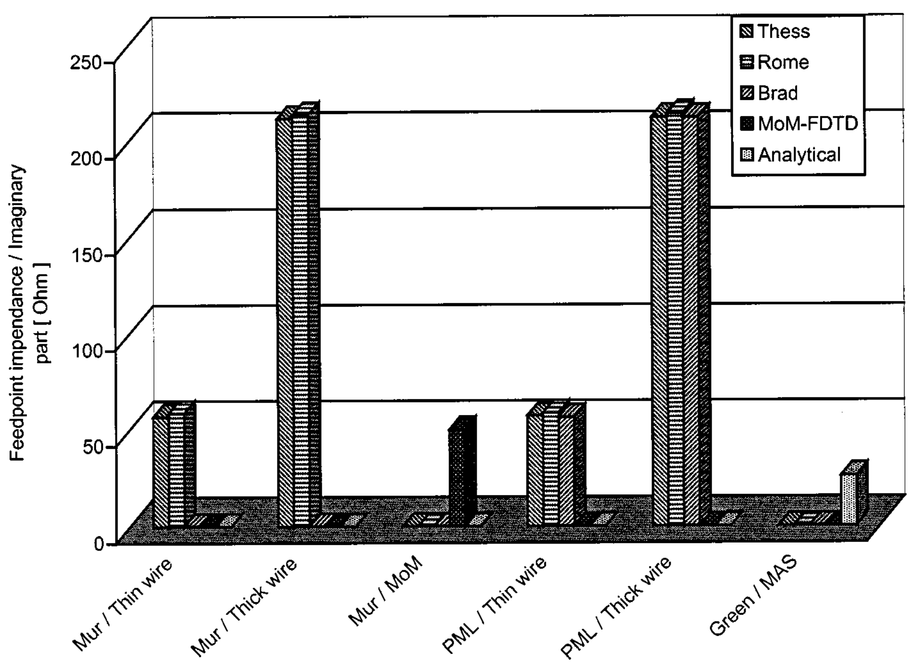

Fig. 7. Imaginary part of the antenna input impedance for the canonical case of Fig. 1(b).

In particular, the uncertainty related to the source modeling in predicting the averaged SAR values is of the order of 12%–15%, while the corresponding uncertainty for local SAR values can be as high as 18%–20%.

3) It is important to note that the position of maximum local SAR value was found to be independent of both source modeling and ABCs. However, in evaluating the position of maximum averaged SAR values, an uncertainty of the order of 1–3 cells (0.25–0.75 cm) along the z-axis was observed, related to the source model used. The averaged SAR values obtained using the Green/MAS technique were found to be in closer agreement with those obtained in FDTD simulations for "thin wire" modeling.

4) The total uncertainty in computing the power absorbed by the head for well-defined canonical cases, can be of the order of 10%–15%, which is mainly related to phantom modeling. The uncertainty related to the ABCs was found to be lower than 1%, while an uncertainty of the order of

2.5% was related to the source modeling. The discrepancy among absorbed powers predicted by different participating groups using the same head model and different sources and ABCs can be of the order of 5%.

5) Concerning the prediction of the input impedance, source modeling can result in large uncertainties of the order of 100% and 600% in the simulated real and imaginary part of the input impedance, respectively. Furthermore, it was observed that the simulated feed-point impedance, in the presence of the head, is almost independent of the ABCs used.
6) With regard to radiation patterns, which have not been shown for brevity, a difference of the order of 1–2 dBi was observed in the main field polarization in the direction where the head is located, associated with the use of different source models. However, it was observed that the radiation patterns are not dependent on the ABCs used, when a sufficient distance between the boundary and the near-to-far field transformation surface is used.

As a final comment, it must be noted that the above given uncertainty figures refer to well-defined canonical head models and simple sources. Even more simulation difficulties and error components are encountered when heterogeneous anatomically correct head models and complex device structures are to be treated.

V. Conclusion

In FDTD dosimetric studies, it is very difficult to perform general reliable uncertainty assessments. Despite its simplicity, FDTD studies may lead to some differences in simulated parameters of interest, depending on specific simulation details. Thus, mobile phone compliance testing with the FDTD method involves many different uncertainty components associated with the discretization in space and time, the necessary numerical representation of the source and phantom, etc.

In this paper, a set of FDTD numerical experiments has been performed in order to investigate the effect of specific simulation details on obtained results. Furthermore, a hybrid technique based on the dyadic Green's function and the MAS and a hybrid MoM–FDTD technique have been used to compute parameters of interest for comparison with the FDTD evaluated parameters.

The obtained results show that large differences in SAR can be produced depending on the numerical phantom used, as well as on the source modeling. With reference to the source, the crucial parameters to model are the accurate locations, magnitudes, and distributions of the surface currents on the device and antenna, when the device is placed against the phantom. Furthermore, the accurate definition of the antenna position relative to the phantom in the discretized space is of major importance since the SAR is predominantly caused by H-field coupling of the reactive near-field components with the head. Even when the same cell size is used, the details for building the source in the Yee grid can produce discrepancies in the simulated parameters of interest. For example, the exact number of cells used for modeling a simple dipole, if the associated electrical size does not correspond to an integer number of cells, has a significant effect on the obtained results. Special care should also be taken to accurately evaluate the antenna output power since its setting can constitute a large uncertainty component.

The way in which the modeling techniques used affect the simulated parameters depends strongly on the design of the specific device. Thus, it is not possible to define a general procedure that can be applied for all devices to provide an *a priori* known uncertainty in simulated parameters of interest (SAR, antenna input impedance, etc.) related to the details of the modeling techniques used. Therefore, every device model should be validated by near-field measurements in the presence of a phantom.

Concerning average SAR values, the details of the procedure for SAR averaging over 1 or 10 g may also produce some differences. The most crucial problem is the evaluation of average SAR at points on the surface, which are of great importance, since high 1-cell SAR values are observed at these points. The sub-volumes to consider for evaluating the average SARs at such points have not been clearly defined in the safety guidelines [1]–[4]. This fact may lead to different treatments and resulting variabilities that could be hard to resolve. Thus, an important point that has to be always clarified when presenting SAR averaged values is the exact averaging procedure used and whether averaging over a tissue mass lower than the reference mass has been performed for points lying close to the head boundary.

In conclusion, dosimetric studies related to the use of mobile phones are sensitive to a multitude of parameters that should be accurately described. These parameters include: modeling of the device and device parameters, position of the device, shape and internal anatomy of the head and constituting tissue parameters, detailed procedures for SAR averaging, and external factors such as the presence of a hand.

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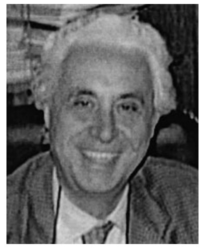

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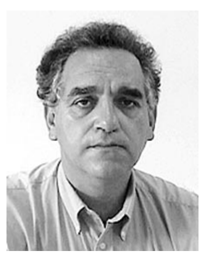

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