Parametric Evaluation of Power Absorption in Human Head Models Exposed to Cellular Phone Radiation at 1800MHz

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Abstract—The aim of this work is to examine the coupling between various human head models and cellular phones operating at 1800 MHz. Simulations have been carried out using an in-house developed accurate semi-analytical method, based on the combination of the Green’s function theory with the Method of Moments (Green/MoM), as well as the Finite-Difference Time-Domain (FDTD) method. Green/MoM simulations concern “canonical” problems, namely a three layered -skin/bone/brain tissue- spherical head model and are used to produce the worst-case preliminary estimation of human head exposure to the field generated by a helical dipole. FDTD simulations are carried out to study the characteristics of power absorption in a heterogeneous anatomically detailed human head model exposed to the radiation of a helical monopole mounted on the top of a metal box representing a realistic mobile communication terminal. The results of Green/MoM and FDTD simulations include calculations of local and average specific absorption rates (SAR’s) over 1g and 10g of tissue inside the human head, as well as the total power absorbed by the head. Moreover, the antenna performance in the presence of human’s head is studied.

The results obtained for helical antennas are compared to those for linear antennas (i.e. half-wavelength linear dipole and quarter wavelength linear monopole mounted on the top of a realistic handset). A comparative dosimetric assessment for adults and children head models is carried out, by considering the varying size and anatomy of the human head, as well as the age-related changes in dielectric properties and the usage distance between the human head and the mobile terminal.

Index Terms—Antenna radiation patterns, biological effects of electromagnetic radiation, dosimetry, helical antenna, semi-analytical and FDTD methods

I. INTRODUCTION

During the last years, there has been a tremendous development of mobile communications which has led to significant use of mobile services by the public and the inevitable concern about the biological effects of RF radiation. In order to provide protection to mobile telephone users, limits of Specific Absorption Rate (SAR) induced in tissues are recommended by international safety guidelines [1]-[2]. Furthermore, the U.K. Independent Group of Experts on Mobile Phones recommends a much more conservative use of mobile phones by children [3].

The estimation of the power absorption characteristics as well as the antenna performance in the presence of the user’s head in connection with usage and age-related parameters is the main objective of the present paper. These tasks can efficiently be addressed by means of computational techniques. In the present study, the accurate semi-analytical Green/MoM technique [4] used to study “canonical” in terms of geometry/antenna problems, provides a powerful tool for benchmarking of purely numerical techniques, such as the FDTD, which has proven to be the most efficient numerical technique for mobile communication dosimetric studies. Moreover, the Green/MoM technique produces the worst-case estimation of mobile phone user’s exposure and provides a means to comparatively assess the impact of variation of the parameters under study.

In order to evaluate the differences in power absorption adult and child heads, different size head models are studied in the proximity of cellular phone device.

Moreover, simulations have been carried out for varying separation distance between the head and the mobile phone. This parameter varies according to the thickness and other age-related changes of the intervening ear [5]-[6].

According to literature, there is a lot of discussion about the age-related dielectric properties and morphology variation which can characterize the head models and can consequently influence the absorbed power [7]. A substantial increase in dielectric properties of small animals’ tissues for younger animals, [8] which may be connected with the tissue water content, [9] triggered an attempt to examine the relation between the dielectric properties of the tissues characterizing the head model and the deposition of electromagnetic energy within biological matter. Although, the data extrapolation to humans is quite difficult, any clear differences in tissues parameters between adults and children can lead to significant changes in power absorption in the head.

The available literature on age-related anatomical morphology of the head development is limited. In [10], a rapid increase in bone thickness with age, especially during
the first year of life, and then a slow steady rate of increase into childhood was reported. The age related development of the scalp thickness follows that of the cranium.

Apart from the head parameters, the design of the radiating element can play a critical role in the coupling between mobile terminal and user’s head. In this paper, a detailed comparative study of power absorption between helical and linear antennas is carried out, since linear antennas represent the most widely employed antenna model in previous handset devices [11].

II. CANONICAL PROBLEMS

In order to evaluate the worst case of user’s exposure to a mobile phone’s radiation, evaluation of the canonical problems’ results, the “canonical” geometry illustrated in Fig. 1 is examined.

A three-layer sphere with radii \( a_1, a_2 \) and \( a_3 \) is used to model the head. The three layers are used to simulate skin, bone and brain tissues, characterized by relative complex permittivities \( \varepsilon_r, \varepsilon_r, \varepsilon_r \) and magnetic permeabilities \( \mu_1 = \mu_2 = \mu_3 = \mu_0 \), respectively, where \( \mu_0 \) is the free-space permeability. Free space is assumed for the exterior of the sphere with wavenumber \( k_0 = \omega \sqrt{\varepsilon_0 \mu_0} \), where \( \omega \) is the radian frequency and \( \varepsilon_0 \) is the free-space permittivity. Table I summarizes the mass density \( \rho \), the conductivity \( \sigma \) and the dielectric constant \( \varepsilon_r \) of the tissues used for the calculations at 1710 MHz [12].

Both adult and child cases are studied. In order to model a 10 years old child head, uniform [11] and non-uniform [13] scaling down to an adult head is applied. ChildA is derived from the adult head by changing all the adult head’s dimensions by a factor \( \frac{176}{138} \frac{V}{T} \). This factor is defined by considering the height and weight of the average adult and the average 10 years old child [14]. However, the age-related anatomical differences in the morphology of various organs make the non-homogeneous scaling down of the adult head model essential. Thus, ChildB has been defined by applying a non-uniform scaling down to the adult head, based on data for head width measurements [15] and age related trends reported for temporal bone thickness [10]. Table II summarizes the geometrical details of the spherical head models used in this study.

### Table II

<table>
<thead>
<tr>
<th>Spherical Head Model</th>
<th>( a_1 ) (cm)</th>
<th>( a_2 ) (cm)</th>
<th>( a_3 ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>adult</td>
<td>9.0</td>
<td>9.5</td>
<td>10.0</td>
</tr>
<tr>
<td>childA (10 y.o.)</td>
<td>6.88</td>
<td>7.26</td>
<td>7.64</td>
</tr>
<tr>
<td>childB (10 y.o.)</td>
<td>6.3075</td>
<td>6.6775</td>
<td>7.0975</td>
</tr>
</tbody>
</table>

The head is exposed to the near field radiation of an antenna, which is modeled by a perfectly conducting arbitrarily shaped wire excited by a voltage imposed at the feeding gap of length \( d \). Both a helical antenna and a linear half-wavelength dipole operating at 1710 MHz (Fig. 2), are studied. The geometrical details of the examined helical antenna are: radius \( a=2.5 \) mm, pitch \( B=1.25 \) mm, wire thickness \( 2w=0.2 \) mm, total number of turns \( L=4+4 \), feeding gap \( d=0.2 \) mm [16]. The geometrical details of the linear dipole are: wire thickness \( 2w=2.5 \) mm, total length \( H=8.75 \) cm, feeding gap \( d=2.5 \) mm.

![Fig. 2. Geometrical characteristics of (a) normal mode helical antenna (b) half-wavelength linear dipole](image_url)

The Green’s function of the three layered sphere is determined as the response of this object to the excitation.
generated by an elementary dipole of unit dipole moment, external to the sphere. The antenna of the problem under consideration is modeled by applying the Method of Moments (MoM). Since its diameter is substantially less than the radiation wavelength, the Thin Wire Approximation (TWA) is adopted. By imposing the boundary conditions for the tangential electric field component vanishing on the conducting surface of the antenna-with the exception of the feeding gap-a system of linear equations is obtained, which is solved for the unknown current coefficients. The interested reader can find the detailed description of the Green/MoM mathematical formulation in [4].

Once the electric field inside the spherical head model is computed, then the SAR at any point inside the head can be calculated as,

\[
SAR(x) = \frac{\sigma(t) |E_x(t)|^2}{\rho(x)}
\]

(1)

where \(\sigma\) (Si/m), \(\rho\) (kg/m³) represent the specific conductivity and the mass density, respectively, of the tissue at the point of interest, \(|E_x(x)|\) is the magnitude of the electric field at the same point and \(x=1, 2, 3\). Calculation of SAR averaged over a reference mass \(M\) (1 g or 10 g) of tissue, as required by the safety guidelines [1]-[2], is carried out using the equation,

\[
\text{SAR}_{M}(x) = \frac{\iiint_{V=0} \int_{d1}^{d2} \int_{d3}^{d4} \text{SAR}(x) |E_x(x)|^2 \, dr \, d\theta \, d\phi}{\iiint_{V=0} \int_{d1}^{d2} \int_{d3}^{d4} \rho(x) |E_x(x)|^2 \, dr \, d\theta \, d\phi}
\]

(2)

where the denominator represents the reference mass \(M\). The power absorbed by the head is computed as,

\[
P_{abs} = \int_{0}^{\pi} \int_{0}^{\pi} \int_{0}^{\phi} \sigma(t) |E(x)|^2 r^2 \sin \theta \, dr \, d\theta \, d\phi
\]

(3)

III. REALISTIC PROBLEMS

FDTD simulations have also been carried out to study the interaction between a heterogeneous anatomically correct model of the human head and a mobile terminal, using the commercially available software package XFDTD [17]. A rectangular computational grid, based on the Yee cell, with a spatial resolution of 1.25 mm and the total field formulation have been used, while PML absorbing boundary conditions with 8 PML layers have been employed [18]. The boundaries were placed 30 cells away from the nearest scatterer.

The anatomically detailed head model has been developed from human head MRI scans, has a spatial resolution of 1.25 mm and consists of 13 tissues [19]. Due to poor MRI data derived from children head scans, in the present study, the realistic child head model has been produced from the adult one by first changing the spatial resolution of the adult head model by the scaling down factor \(\frac{176}{138} = 1.25\) and then by resampling the altered head model into 1.25 mm grid size.

The geometrical details of the mobile terminal, used in FDTD simulations, are shown in Fig. 3. The terminal consists of a metal box equipped with the upper half parts of the dipoles illustrated in Fig. 2. The front face of the terminal is covered by a dielectric with \(\varepsilon_r = 2.7 - j0.016\). In the FDTD grid, the helix antenna monopole has been constructed as a rectangular helix of wires with horizontal sections consisting of four cells and a vertical step of one cell [4].

Calculations of SAR averaged over a reference mass \(M\) (1 g or 10 g) of tissue have been carried out, using an appropriate interpolation scheme [17]. The power absorbed by the human head as well as the radiation pattern of the mobile terminal are also calculated.

IV. NUMERICAL RESULTS AND DISCUSSION

A. Separation distance

In order to assess the effect of the usage distance on the power absorption patterns in spherical human head models of adults and children (childA), exposed to the helical dipole antenna of Fig. 2a, Green/MoM simulations have been carried out, for a separation distance \(D_{min}=5\) mm and \(D_{max}=15\) mm. Moreover, FDTD simulations have been carried out for realistic problems, for a separation distance \(D'_{min}=0\) mm and \(D'_{max}=10\) mm between the ear of the MRI based head model and the mobile terminal of Fig. 3(a).

Table III summarizes the maximum values of local SAR, SAR averaged over 1 g or 10 g of tissue and the power absorbed by the head. A substantial decrease in the maximum SAR values and in the absorbed power is observed with increasing separation distance. By comparing the results between adult and child, it can be observed that smaller size of
TABLE III
PEAK SAR VALUES AND ABSORBED POWER IN THREE-LAYER SPHERICAL AND REALISTIC HEAD MODELS EXPOSED TO THE HELICAL ANTENNA AT 1710 MHz FOR SEPARATION DISTANCE VARIATION. THE TOTAL INPUT POWER IS 125 mW. RESULTS PRODUCED WITH GREEN/MoM AND FDTD(*) TECHNIQUES

<table>
<thead>
<tr>
<th>Min distance</th>
<th>Local SAR (W/kg)</th>
<th>1g SAR (W/kg)</th>
<th>10g SAR (W/kg)</th>
<th>Absorbed Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult</td>
<td>14.09/5.70*</td>
<td>6.97/2.42*</td>
<td>3.42/1.35*</td>
<td>117.32/82.81*</td>
</tr>
<tr>
<td>Child</td>
<td>13.88/5.14*</td>
<td>7.70/2.20*</td>
<td>4.41/1.45*</td>
<td>113.00/82.45*</td>
</tr>
</tbody>
</table>

head models might increase the SAR values averaged over 1 g or 10 g of tissue.

The influence of the spherical head models presence on the radiation characteristics of the helical dipole has also been studied in connection with the separation distance. Far field radiation patterns for the helical dipole in the presence of the three-layered spherical head models have been calculated for the xy (θ=90°) and the xz (φ=0°) planes and are shown in Fig. 4. The far-field radiation pattern in the direction of the head is significantly disturbed since the power is strongly absorbed by the head.

B. Dielectric properties

Even though there is poor information about the age-related variation of human tissues’ dielectric properties, simulations for head models with a ±10% variation in the dielectric properties of Table I have been carried out, while keeping the mass density constant. Table IV summarizes the results of the simulations, considering the minimum separation distance.

By comparing the case of lower to that of higher dielectric properties, for both canonical and realistic problems, a reduction in SAR values can be observed.

TABLE IV
PEAK SAR VALUES AND ABSORBED POWER IN THREE-LAYER SPHERICAL AND REALISTIC HEAD MODELS EXPOSED TO THE HELICAL ANTENNA AT 1710 MHz FOR DIELECTRIC PROPERTIES VARIATION. THE TOTAL INPUT POWER IS 125 mW. RESULTS PRODUCED WITH GREEN/MoM AND FDTD(*) TECHNIQUES

<table>
<thead>
<tr>
<th>10%</th>
<th>Local SAR (W/kg)</th>
<th>1g SAR (W/kg)</th>
<th>10g SAR (W/kg)</th>
<th>Absorbed Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult</td>
<td>14.95/5.76*</td>
<td>8.03/2.57*</td>
<td>3.63/1.41*</td>
<td>117.44/81.46*</td>
</tr>
<tr>
<td>Child</td>
<td>14.86/5.42*</td>
<td>8.34/2.29*</td>
<td>4.69/1.53*</td>
<td>114.10/82.41*</td>
</tr>
</tbody>
</table>

Fig. 4. Radiation pattern (dBs) for a helical dipole radiating in the presence of adult and child, three-layer spherical head models at 1710 MHz, for varying separation distance. Computations with the Green/MoM technique.

C. Morphological differences

In order to evaluate the impact of the morphological differences in the power absorbed by the head, a study between the two spherical child head models (childA and childB) has been carried out using the Green/MoM technique, for the minimum separation distance. Table V shows insignificant differences in maximum local SAR values and total absorbed power, while a slight difference in averaged
SAR values can be observed due to the structural differences in the two head models.

<table>
<thead>
<tr>
<th>Local SAR max</th>
<th>1 g-SAR max</th>
<th>10 g-SAR max</th>
<th>Absorbed Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W/kg)</td>
<td>(W/kg)</td>
<td>(W/kg)</td>
<td>(mW)</td>
</tr>
<tr>
<td>13.88/13.88*</td>
<td>7.7/7.89*</td>
<td>4.41/4.05*</td>
<td>113.00/113.38*</td>
</tr>
</tbody>
</table>

**D. Radiating element**

In this section, the effect of the type of the radiating element (linear/helical) on the power absorption by the user’s head is studied. Numerical results for spherical and realistic head models, at the minimum separation distance, are presented in Table VI. In general, significantly larger SAR values are induced by the helical radiating element as compared to those induced by the linear one due to the greater field concentration produced by the physically shorter helical antenna.

<table>
<thead>
<tr>
<th>Local SAR max</th>
<th>1 g-SAR max</th>
<th>10 g-SAR max</th>
<th>Absorbed Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W/kg)</td>
<td>(W/kg)</td>
<td>(W/kg)</td>
<td>(mW)</td>
</tr>
<tr>
<td>Linear Adult</td>
<td>8.19/3.51*</td>
<td>3.41/1.31*</td>
<td>2.21/0.74*</td>
</tr>
<tr>
<td>Child/Adult</td>
<td>8.88/2.23*</td>
<td>3.61/1.05*</td>
<td>2.42/0.73*</td>
</tr>
<tr>
<td>Helical Adult</td>
<td>14.09/5.70*</td>
<td>6.97/2.42*</td>
<td>3.42/1.35*</td>
</tr>
<tr>
<td>Child/Adult</td>
<td>13.88/5.14*</td>
<td>7.70/2.20*</td>
<td>4.41/1.45*</td>
</tr>
</tbody>
</table>

**V. CONCLUSIONS**

The objective of the present paper was to comparatively evaluate the SAR and the absorbed power values in connection with usage and age-related parameters. Canonical and realistic dosimetric problems were examined using the Green/MoM and the FDTD techniques, respectively. The obtained results revealed that children absorb similar levels of electromagnetic power as compared to adults. Furthermore, the increase of the separation distance and the decrease of the dielectric properties resulted in a significant reduction of SAR values. On the other hand, morphological changes in child head models did not affect the radiation behaviour of the system. Finally, higher SAR values are produced by the helical antenna, as compared to the linear one.

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