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Personal dosimetry of cellular phone linear and helical antennas for adults and children

S. Koulouridis & K.S. Nikita
School of Electrical and Computer Engineering,
National Technical University of Athens, Greece

Abstract

The coupling between cellular phone arbitrarily shaped wire antennas and human head models is studied through both a novel semi-analytical technique and Finite-Difference Time-Domain (FDTD) simulations. The semi-analytical technique combines the Green's functions theory with the Method of Moments (Green/MoM) and is able to model arbitrarily shaped wire antennas radiating in the close proximity of layered lossy dielectric spheres representing simplified models of the human head. The purpose of the development of an accurate semi-analytical technique is to provide: (1) a powerful tool for preliminary (worst case) estimation of human head exposure to the field generated by different antenna configurations and (2) a testbed for bencmarking of purely numerical techniques, such as the FDTD which has proven to be the most efficient numerical technique for problems related with mobile communication dosimetric assessment. First, the interaction between spherical head models and a half wavelength linear dipole or a normal mode helical antenna, is studied. Then, after appropriate benchmarking, FDTD simulations are used to examine the coupling between a heterogeneous anatomically correct model of the human head exposed to either a quarter wavelength linear monopole or a normal mode helix monopole, both operating at 1710 MHz and 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) inside the human head, total power absorbed by the head and assessment of antenna radiation patterns at 1710 MHz. Emphasis is placed on the comparative dosimetric assessment between adults and children head models.

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1 Introduction

In the last few years various antenna models for cellular handsets, have been proposed, motivated by the need to reduce the handset size while providing radiation characteristics comparable to linear models, extensively used so far. One of the most commonly used antennas is the helical antenna, whose physical dimensions are very small compared to the radiation wavelength, when radiating in normal mode [1].

The estimation of power absorption characteristics in the user's head and antenna performance in the presence of the user's head represent key tasks for both designing and compliance testing of cellular phones. Numerical techniques and especially the Finite-Difference Time-Domain (FDTD) technique can efficiently deal with these tasks. Although FDTD is simple to use and able to model anatomically detailed human head structures, it encounters significant difficulties in modelling antenna structures not conforming to the used grid, such as helical antennas. Furthermore, the exact error estimation of FDTD simulations still remains a difficult task. Uncertainties are involved and discrepancies can be observed in the results obtained by different groups nominally using the same numerical method, even for well-defined canonical cases [2]. In this context, accurate methods able to treat canonical exposure problems are very useful as they may provide an efficient tool for benchmarking of purely numerical techniques, which can then be used to analyse realistic exposure problems.

In this paper, the problem of personal electromagnetic dosimetry of cellular phone linear and helical antennas is treated in detail. A semi-analytical technique is proposed, based on the use of the dyadic Green's function theory [3] and the Method of Moments (Green/MoM), for studying the interaction between a layered spherical head model and an arbitrarily shaped wire antenna. The proposed method provides a means of (worst case) preliminary estimation of the human head exposure to the field generated by different wire antenna configurations such as linear or helical dipoles. It is also employed as a reliable tool for checking the accuracy of FDTD simulations which are then used to examine the interaction between a heterogeneous anatomically correct human head model exposed to a handheld terminal equipped with either a linear or a helical monopole. A detailed comparative study of power absorption and antenna performance between linear and helical antennas for heads of adults and children is carried out based on both Green/MoM and FDTD simulations.

2 Green/MoM technique: Mathematical formulation and analysis.

The problem under consideration is shown in Fig. 1. Human head is modeled by a three-layer sphere with radii α_1, α_2 and α_3. The relative complex permittivity of each layer is $\varepsilon_1, \varepsilon_2, \varepsilon_3$ respectively. The magnetic properties of the layers are defined as $\mu_1 = \mu_2 = \mu_3 = \mu_0$. Free space is assumed for the exterior of the sphere with wavenumber $k_0 = \omega\sqrt{\varepsilon_0\mu_0}$, where ω is the radian frequency, ε_0 and μ_0 are the free-space permittivity and permeability, respectively. A perfectly conducting arbitrarily shaped wire excited by a voltage imposed at a feeding gap, d in length, models the antenna. The time dependence of the field quantities is assumed to be *exp* $(-j\omega t)$.

First, the Green's function of the three-layer 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. Thus, the following expression for the electric type Green's function inside the layered sphere (i=1, 2, 3) and in the air region (i=4) is obtained [3],

$$\underline{\overline{G}}_i(\underline{r},\underline{r}') = \sum_{n=1}^{+\infty}\sum_{m=-n}^{n} \frac{jk_0(-1)^m(2n+1)}{4\pi n(n+1)} \Big\{ [Q_n^{(i,1)}\underline{m}_{mn}^{(1)}(\underline{r},k_i) + Q_n^{(i,2)}\underline{m}_{mn}^{(\ell)}(\underline{r},k_i)] \quad (1)$$
$$\underline{m}_{-mn}^{(3)}(\underline{r}',k_0) + [R_n^{(i,1)}\underline{n}_{mn}^{(1)}(\underline{r},k_i) + R_n^{(i,2)}\underline{n}_{mn}^{(\ell)}(\underline{r},k_i)]\,\underline{n}_{-mn}^{(3)}(\underline{r}',k_0)\Big\}$$

where the notation used in [3] has been adopted.

For the problem of the wire antenna treated in this paper, since its diameter is usually substantially less than the radiation wavelength, the thin wire approximation (TWA) of the MoM is used. The antenna is subdivided into a number of J curved segments, Δt in length, centered at points $t_j = (j-1)\Delta t + \Delta t/2$, j=1,…,J. The electric field at a point $\underline{r}$ lying in any region (i=1,2,3,4), is expressed by means of the corresponding Green's function,

$$\underline{E}_i(\underline{r}) = j\omega\mu_0 \sum_{j=1}^{J} \int_{t_j-\Delta t/2}^{t_j+\Delta t/2} \underline{\overline{G}}_i(\underline{r},\underline{r}')\,\hat{s}(t')\,I_j(\underline{r}')\,dt' \quad (2)$$

where I_j is the unknown current coefficient flowing along the curved jth segment of the antenna wire and $\hat{s}$ is the unit vector tangent to the wire antenna.

Then, the boundary conditions for the tangential electric field component vanishing on the conducting surface of the antenna - with the exception of the feeding gap - are imposed at J points lying along a line on the surface of the antenna wire. Thus a $J\times J$ system of linear equations is obtained, which is solved

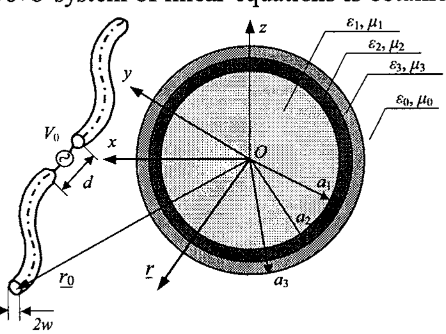


Figure 1: Schematic diagram of a three-layer spherical head model exposed to the radiation of an arbitrarily shaped wire antenna

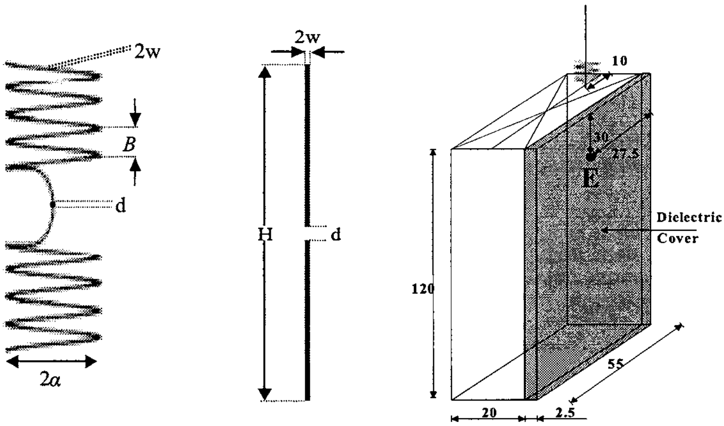
for the unknown current coefficients I_j. Once these coefficients are computed, the electric field at any point inside and outside the spherical head model can be calculated, by using the closed form eqn. (2).

3 FDTD simulations

FDTD simulations have been carried out using an orthogonal grid with a spatial resolution of 1.25x1.25x1.25mm^3, and PML absorbing boundary conditions with 8 PML layers. Converged results have been assured by using 12 time periods. The thick wire model excited by a sinusoidal feeding gap source has been used to simulate linear antennas. A series of small loops and dipoles consisting of a Perfectly Electrical Conducting (PEC) material and excited by a sinusoidal input source, has been used to model helical antennas. The accuracy of FDTD simulations has been assessed against results produced by the Green/MoM technique for canonical exposure problems.

4 Numerical results and discussion

The developed Green/MoM numerical code has been checked in detail for convergence and stability. Several trials have been performed by varying the number of spherical wave vectors used to express the fields inside the sphere layers and in the air region and by increasing the number of segments of the antenna wire. Convergence of the obtained solution at any point in space is assured using a number of 35-65 spherical wave vectors (eqn. (1)), while a significantly lower number (~10) of wave vectors is needed for computations at far-field points. A varying number of segments is required to model the wire antenna, depending on its length and complexity of its shape. Thus, for linear dipole simulations, a number of 70 segments is used, while for helical dipole



(a) (b) (c)

Figure 2: Normal mode helical antenna (a), half-wavelength linear dipole (b), handset equipped with a helix or a linear monopole (c). Dimensions in mm. Point E corresponds to the projection of the ear canal.

Transactions on Engineering Sciences vol 41, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

simulations, a number of 500 segments is required to assure convergence of the obtained solution. Energy conservation has been also examined by comparing the input power computed at the feeding gap, to the sum of the power absorbed by the head and the power radiated in the antenna far-field. An excellent agreement has been observed (difference less than 1%).

The Green/MoM technique has been used to study the interaction between spherical models representing adults heads and dipole antennas operating at 1710 MHz. Two spherical head models have been considered; a homogeneous one consisting of brain tissue, and a three-layer one consisting of skin, skull and brain tissues. Both head models have a diameter of $2a_3 = 20$ cm, while the thicknesses of the skin and skull layers for the layered head model are assumed to be $a_3 - a_2 = a_2 - a_1 = 0.5$ cm. Electrical characterization of the tissues has been based on available literature data. [4]. Calculations have been carried out for a half-wavelength linear dipole and a normal mode helical dipole [5], both operating at 1710 MHz (Fig. 2). In order to investigate differences in energy absorption patterns between adults and children, different sizes of head models have been considered. Spherical models representing children heads have been obtained by altering the dimensions of the adults ones by a factor of $\left(\frac{176}{138}\cdot\frac{32.5}{71}\right)^{1/2}$. This scaling factor was obtained by considering that the height and the weight of an average male adult are176 cm and 71 kg, respectively while in the dosimetry handbook [6], the height and weight for an average 10-year old child are given as 138 cm and 32.5 kg, respectively.

The separation distance between the external head surface and the antenna surface is 5 mm. The helical antenna consists of a right-handed helix connected in series with a left handed helix, being the mirror image of the former with respect to the z=0 plane (Fig. 2). A circular arc is used to provide smooth transition of each helix to the axial feeding. The geometrical details of the examined helical antenna (Fig. 2) 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. The geometrical details of the half-wavelength dipole are: wire thickness $2w$=2.5 mm, total length H=8.75 cm, feeding gap d=2.5 mm.

The maximum values of local SAR, SAR averaged over a reference mass (1gr or 10gr) of tissue, as required by the safety guidelines [7]-[11], have been computed and are shown in Fig. 3 while the power absorbed by the head is shown in Fig. 4. It can be noticed that similar values of maximum SAR (local or averaged) are observed in children and adults head models. Furthermore maximum SAR values either local or averaged induced by the helical dipole are 2-3 times larger than their corresponding values due to the linear dipole. As far as the total absorbed power is considered, a 90-95% of the helical dipole input power is absorbed by both head models, while the absorbed power in the case of linear dipole, decreases to an 80-86% or a 75-80% for adults and children, respectively.

Penetration curves showing the SAR variation normalized to the maximum SAR value along the x-axis, that is "from one ear to the other" of the spherical

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head models, have also been computed by the Green/MoM technique and are presented in Fig. 5. Since the diameter of the children head models is smaller, the SAR value at the opposite from the phone head side is higher than the corresponding one in the adults head models.

The influence of the head models on the radiation characteristics of the linear

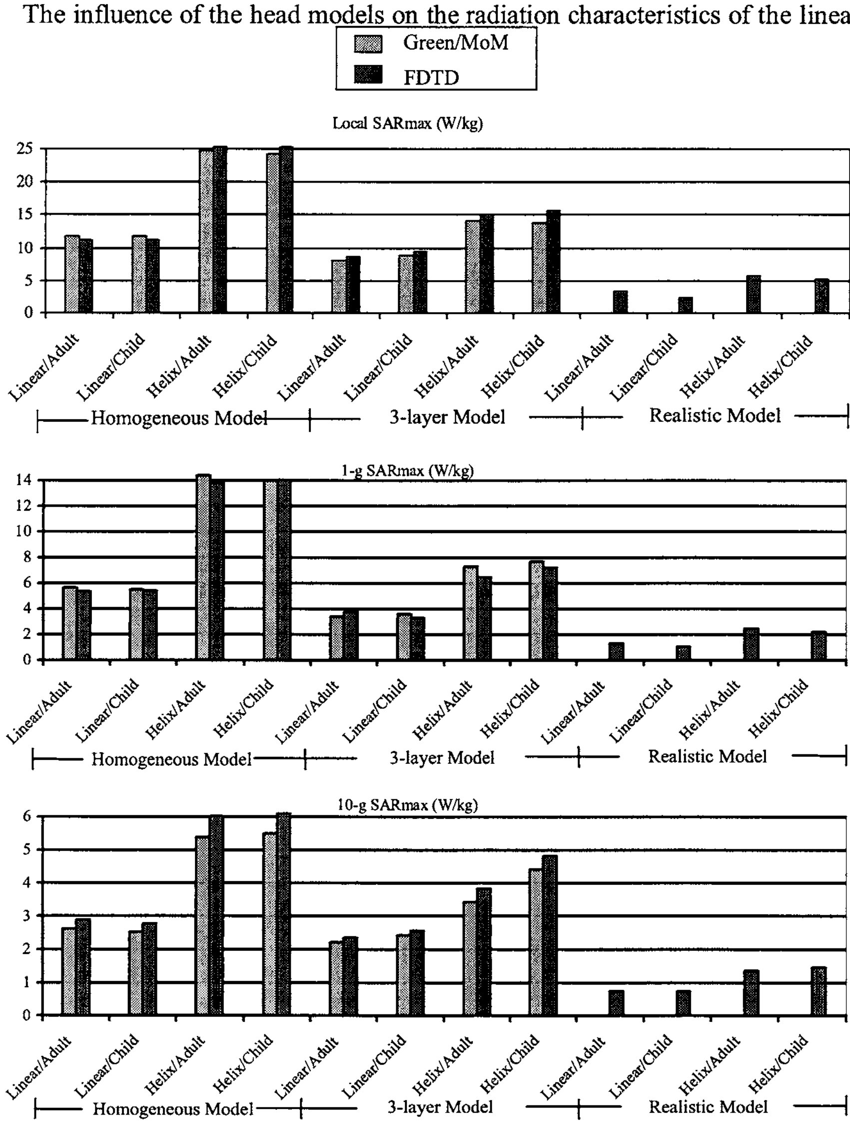

Figure 3: Peak SAR values in adults and children head models. A half-wavelength linear dipole or a normal mode helical dipole is used to simulate the cellular phone in the case of spherical head models while a handset equipped with a linear or a helix monopole is considered in the case of realistic head models. In all cases the total radiated power is 125mW. Computations with Green/MoM and FDTD techniques.

Transactions on Engineering Sciences vol 41, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

and helical dipoles has also been studied. Far field radiation patterns for the examined antenna structures in the presence of the homogeneous or the layered spherical head models have been calculated for the *xy* (θ=90°) and the *xz* (φ=0°) planes and are shown in Fig. 6. The radiation patterns of the examined linear and helical dipoles are similar in shape, while as it was expected, the far-field radiation pattern disturbance in the direction of the head is more significant for the helical dipole since the power is strongly absorbed by the head. The slight asymmetry observed on the *xz* plane for the helical dipole patterns can be explained by the asymmetry of the curved segments providing connection to the axial feeding gap.

FDTD simulations have also been carried out to study the above presented canonical exposure problems. The results obtained are shown, for comparison purposes, in Figs. 3, 4 along with those obtained by the Green/MoM technique. The difference in the predicted values of maximum local SAR ranges from 2 to 12%, with the larger difference corresponding to the layered head models. The difference in averaged SAR values ranges from 0.5 to 8% for 1g and is of the order of 10% for 10g. The rather larger differences observed in the case of averaging over 10g of tissue are related to differences in averaging procedures between FDTD and Green/MoM techniques Moreover, as far as the power absorbed by the user's head is considered (Fig. 4), the discrepancy between Green/MoM and FDTD predictions is of the order of 1-2%.

Next, the interaction between a realistic head model developed from MRI scans of a human head and a handset equipped with a linear or a helical monopole has been studied using the FDTD code. The head model, provided by Bradford University [12], has a spatial resolution of 1.25 mm and consists of 13 different tissues/organs. Literature data [4] were used for the electrical characterization of the head tissues. The realistic child head model has been produced from the adult one by first applying the same scaling factor, as in the

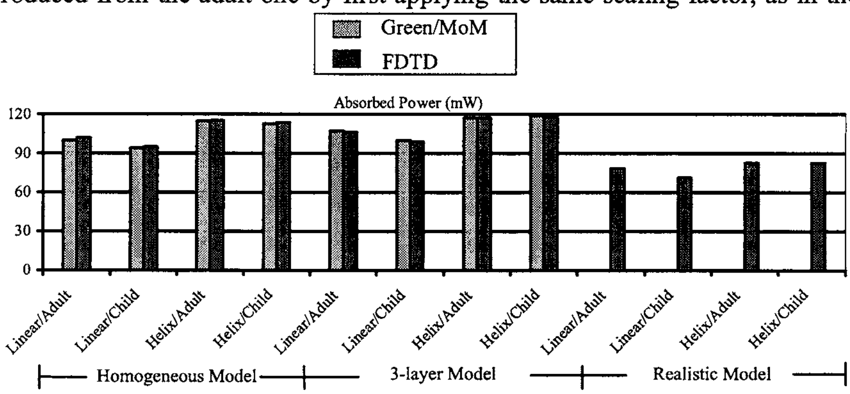

Figure 4: Absorbed power in adults and children head models. A half-wavelength linear dipole or a normal mode helical dipole is used to simulate the cellular phone in the case of spherical head models while a handset equipped with a linear or a helix monopole is considered in the case of realistic head models. In all cases the total radiated power is 125mW. Computations with Green/MoM and FDTD techniques.

Transactions on Engineering Sciences vol 41, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

canonical exposure problems, to the adult head model and then by resampling with either a quarter-wavelength linear monopole or a right handed small helix the altered head model into a 1.25 mm grid size. A metal handset box equipped monopole, as shown in Fig. 2c has been examined. The monopoles are identical with the upper parts of the dipole antenna models used in the simulations of canonical exposure problems. The dimensions of the metal handset box are showed in Fig. 2c. Its front face is covered with a low loss dielectric (ε_r = 2.7 - j0.016). The handset is placed on a vertical position in direct contact with the ear.

Results for maximum local and averaged SAR values, along with power absorption are presented in Figs. 3, 4. It can be noticed that although the local SAR value observed in the child's head is lower than the corresponding one in the adult's head, similar or even slightly higher values of SAR averaged over 10g are produced in the child's head. For direct contact of the handset to the head, a 57-63% of the input power is absorbed by the adult's or the child's head, in the case of the handset equipped with the linear monopole, while almost 65% of the input power is absorbed by the child's or the adult's head, in the case of the handset equipped with the helix monopole (Fig. 4).

5 Conclusions

The interaction between linear or helical type antennas and human head models corresponding to both adults and children has been studied in detail. A semi analytical technique has been proposed for analysing the interaction between a layered spherical model of the human head and an arbitrarily shaped wire

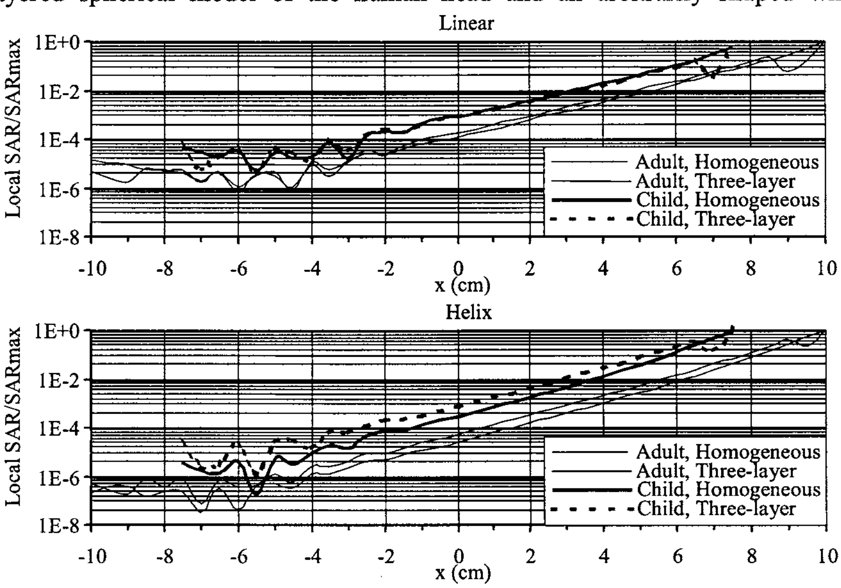

Figure 5: Local SAR/SAR_{max} distribution along x-axis induced in adults and children spherical head models by the half-wavelength linear or helical dipoles as calculated by Green/MoM technique.

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antenna radiating at its close proximity. The proposed technique is based on the combination of the Green's function methodology with the MoM. Numerical results for homogeneous and three-layer head models exposed to the radiation of a small helical dipole and a half-wavelength linear dipole antenna at 1710 MHz have been presented. The proposed technique has served as a testbed for checking the accuracy of FDTD simulations and then FDTD has been used to treat the problem of a realistic handset equipped with either a linear quarter -

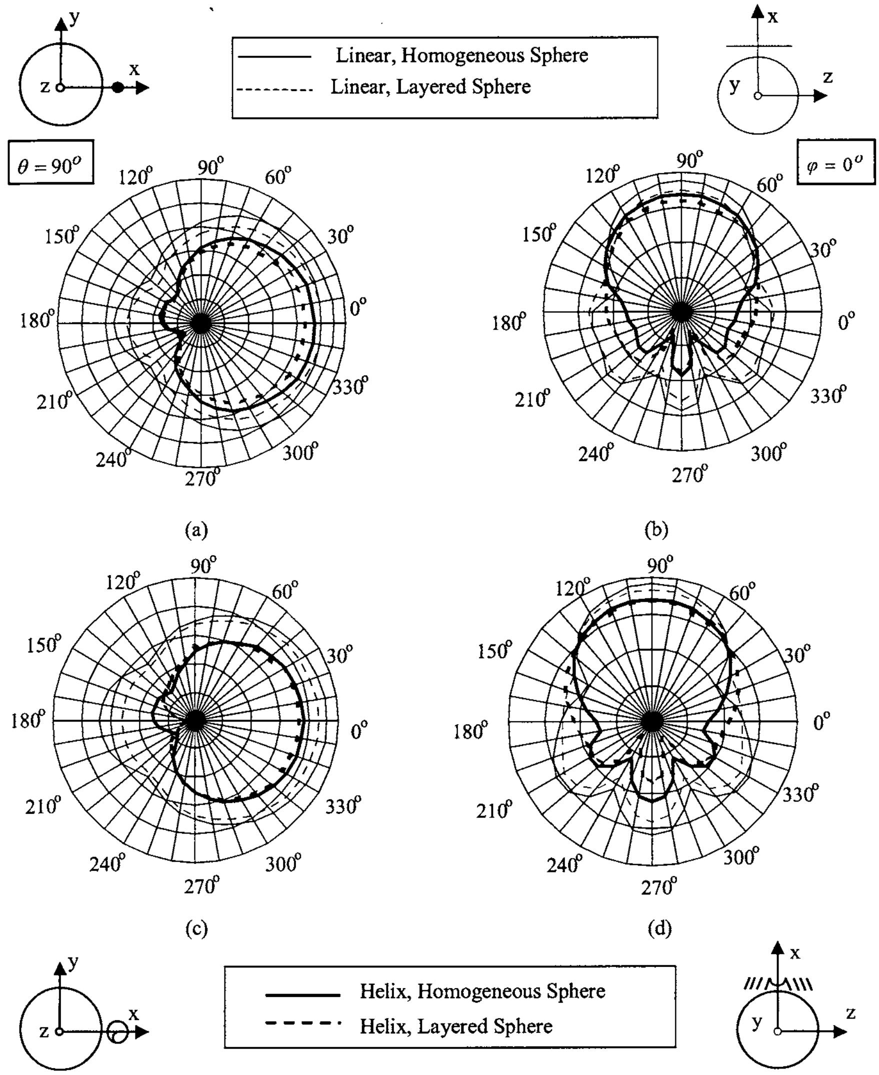

Figure 6: Radiation patterns for a linear dipole or a helical dipole radiating in the presence of adults (a), (b) and children (c), (d), homogeneous or three-layer spherical head models at 1710 MHz. Computations with the Green/MoM technique.

wavelength monopole or a small helix monopole, placed in the close proximity of a realistic head model based on MRI scans. Simulations indicate that peak SAR values and power absorbed by the user's head are higher for helical type antennas as compared to linear type antennas, while similar power levels are absorbed by adults and children head models.

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