PENETRATION OF THE ELECTROMAGNETIC RADIATION IN HUMAN BODY, WHEN EXPOSED IN THE NEAR/FAR FIELD CONDITIONS

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The paper presents a numerical finite element (FEM) analysis of electromagnetic field (EMF) penetration in structures that represent models of human anatomical tissues, in specific conditions associated to microware (MW) exposure. 2D FEM models are created, where the human head is exposed at 1.8GHz, either in the *near field* of antennas, or in the (planar wave) *far field*. Biomedical research in these conditions is based on the analysis of EMF interactions with body tissues. In dosimetric estimates it is a scientific consensus to consider that thermal effects prevail in MW exposure and the *SAR* is the quantity that represents the "dose". At a macroscopic scale, *SAR* [W/kg] is defined as the absorbed power per mass unit ($SAR = \sigma E^2/\rho$) where E is the rms value of the electric field strength, σ is the electric conductivity and ρ is the mass density of the tissue). The guidelines formulated by the International Commission on Non-Ionizing Radiation Protection limit the localized (head and trunk) human exposure to EMF with the basic restriction expresed as the averaged value of *SAR*: 2W/kg for 10g of tissue

Introduction

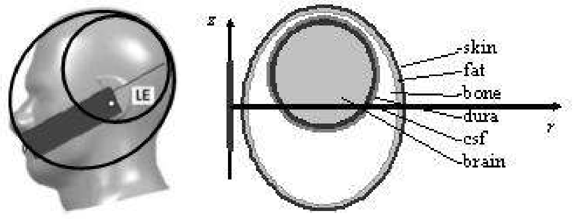
EMF produced by an antenna can be described as having several components. Only one of these actually propagates though space. This component is called the *radiated field* or *the far field*. The strength of the radiated field does decrease with distance, since the energy must spread as it travels. The other components of the electromagnetic field remain near the antenna and do not propagate. There are generally two other components: the static field and the induction field. Even though they do not propagate, their strength decreases very rapidly with the distance. The entire field—all of the components—near the antenna is called the *near field*. In this region, approximately one wavelength in extent, the electric field strength can be relatively high and pose a hazard to the human body. The radiated wave is composed of an electric field and a magnetic field, represented by vectors perpendicular to each other and to the direction of propagation. At large distances from the antenna, say beyond ten wavelengths, the radiated field is essentially a *plane wave*. This means that there is no curvature of the field lines.

Localized human exposure to EMF in MW frequency range is associated to the use of mobile telephony, detection and positioning systems, dielectric heaters and to several medical procedures (hyperthermia in tumor therapy, neuronal implant growth, imaging techniques, etc.). *SAR* distribution depends on several factors: the incident field parameters (near or far field), geometric parameters (shape and structure) of the exposed body, dielectric properties of the tissues (as lossy dielectrics), ground/screen/reflector effects of other objects in the field near the body. The usefulness of numerical modeling as well as measurements of *SAR* and *E* inside the body has been demonstrated in the assessment of biological effects and in setting the safety exposure guidelines and the certification protocols for harmless MW devices used in medicine, transportation and communication systems, and in day-to-day life.

The computational analysis is based on wave equations derived from Maxwell's equations. Calculations can be performed either by analytical [1] or by numerical methods [2], [3], [4]. Early works were done by theoretical analyses assuming a simple model, followed by more detailed models treated by numerical techniques [2]. Method of moments (MoM) [4] or the finite-difference time-domain (FDTD) method [3], [4] made an epoch in this field. The finite element method (FEM) works on adaptive meshes, better suited for heterogeneous media [5], [8]. Our paper presents a FEM based analysis of the human head exposure in the near field and in the far field of an antenna.

FEM models for the EMF near field study

The need for a reliable computational model in MW dosimetry related to mobile phone technology led us to try several approaches to simulate the human head and the EMF source [7], [8]. It is of common practice to generate simplified 3D models of the human head, in a spherical or elliptical layered structure [1], [4], as fig. 1 suggests. However, the realistic representation in 3D requires high computational resources. This is the main reason that sustains the simplified 2D model we have created [7],[8],[9] based on the geometry suggested in fig. 1.b, which is an ensemble of layers, that results from the axial symmetry of a fictive anatomical structure



a. **b.**

Fig. 1 Computational domain based on a multi-layered structure

Previous work [7] presents several tests for the 2D FEM model validation. Two categories of global parameters (absorbed power and averaged *SAR* in each tissue) were computed and the results were compared with similar estimates, based on analytical [1] and numerical [4] methods, applied to 3D models. A fairly good agreement is observed for the compared data and the economy of computational resources is significant for the 2D models.

Paper [7] also demonstrates that the EMF distribution inside the exposed head is sensible to the external shape of the head: a larger curvature of the domain surface leads to lower inside electric field strength. For that reason we selected the ellipsoidal rather than the spherical shape, which models the head closely to the real shape.

The interaction of the time-harmonic EMF and human body at microwave frequencies is usually described in terms of the *complex permittivity* $\underline{\varepsilon} = \varepsilon - j\sigma / \omega$, or the *complex conductivity* $\underline{\sigma} = \sigma + j\omega\varepsilon$, where ε is the dielectric permittivity; σ is the electric conductivity and $\omega = 2\pi f$ is the angular frequency of the EMF. The biological tissues in this frequency range act as conductive (lossy) dielectric materials. The magnetic permeability is considered $\mu_0 = 4\pi 10^{-7}$ H/m. In addition to the electric properties, the *SAR* estimate requires the value of the mass density ρ, for each type of tissue. The specific values for ε, σ and ρ considered in our study correspond to data in literature [1], [6], [10] for the six anatomical-layers head structure. In papers [7] and [9] we also demonstrate that a homogenous head structure provides results in the same value range for *SAR* and *E* as the six layers head structure. The equivalent electric properties for the homogenous structure were established in conditions of energetic equivalence.

The EMF source is considered a center fed half-wavelength dipole antenna. The characteristic dimension of the antenna, oriented on the (*oz*) axis, is accorded with the wavelength in the microwave frequency range used in European GSM mobile system telephony (0.6 – 3) GHz. The dipole antenna is placed symmetrically with regard to the (*ox*) axis. The radiated power is 1 W. The user is exposed (with the head and ear) at a distance of 10 mm, in the near-field of the antenna [6].

The numerical computation used for the 2D FEM model is based on the COMSOL software [12], the *Electromagnetics Module*. The wave equations are applied for lossy media, characterized by the complex electric permittivity $\underline{\sigma}$

$$\nabla \times \left(\frac{1}{\mu_0} \nabla \times \underline{\mathbf{E}} \right) - \omega^2 \underline{\varepsilon}\, \underline{\mathbf{E}} = 0 , \qquad \nabla \times \left(\frac{1}{\underline{\varepsilon}} \nabla \times \underline{\mathbf{H}} \right) - \omega^2 \mu_0 \underline{\mathbf{H}} = 0 \tag{1}$$

where the unknown field variables, in the cylindrical coordinate system and in complex form (the *axisymmetric transversal magnetic (TM) waves* application mode, *time-harmonic* submode) are:

$$\underline{\mathbf{H}}(r,z,t) = \underline{H}_{\varphi}(r,z)\mathbf{e}_{\varphi} e^{j\omega t} , \qquad \underline{\mathbf{E}}(r,z,t) = \left(\underline{E}_r(r,z)\mathbf{e}_r + \underline{E}_z(r,z)\mathbf{e}_z \right) e^{j\omega t} \tag{2}$$

The computational domain is limited with *low-reflecting* boundary conditions and the boundary on the (*Oz*) axis satisfies *axial symmetry* conditions

$$\mathbf{n} \times \left(\frac{\underline{\varepsilon}}{\mu_0} \right)^{1/2} \underline{\mathbf{E}} - H_{\varphi} = -2H_{\varphi 0} , \qquad H_{\varphi 0} = 0 \tag{3}$$

For a comparison between human exposure in the *near field* and in the *far field* we issued a second model with transverse magnetic (TM) propagation in (xoy) plane and no variation in the z direction. The *time-harmonic* EMF equations are the same as in the previous axisymmetric problem (1), but, the unknown field variables, in the cartesian coordinate system and in complex form are:

$$\underline{\mathbf{H}}(x,y,t) = \underline{H}_z(x,y)\mathbf{e}_z e^{j\omega t} , \qquad \underline{\mathbf{E}}(x,y,t) = \left(\underline{E}_x(x,y)\mathbf{e}_x + \underline{E}_y(x,y)\mathbf{e}_y \right) e^{j\omega t} \tag{4}$$

The domain is equally limited with scattering wave boundary conditions

$$\mathbf{n} \times \left(\nabla \times H_z \right) - jkH_z = -jk(1 - \mathbf{k} \cdot \mathbf{n})H_{0z} \tag{5}$$

The EMF source is introduced through a non-homogeneous *magnetic field* boundary condition. The magnetic field condition is adjusted each time to maintain the absorbed power density on head surface constant.

FEM models for the EMF far field study

The study of the human exposure in the microwaves far field is associated with the conditions around a base station antenna used in cellular telephony. Our 2D FEM model is based on *in –plane transverse magnetic (TM) waves application mode* (3).

The EMF source is introduced by a magnetic field boundary condition, simulating the incident plane wave entering the domain. To create equivalent exposure conditions with those used in the model for near field study, we set same power density on the head surface, as in the near field exposure.

The exposed body was first a head modeled similar to the six layered structure described earlier and than a homogenous head structure with equivalent dielectric properties [7], [9].

For both 2D FEM models, the COMSOL linear stationary solver based on Gaussian elimination was applied.

RESULTS AND DISCUSSIONS

The study investigates the *E*-field and the *SAR* distributions two situations: (1) head exposed in the *near field* of a dipole antenna (further called *NF-homogenous and NF-six layers*), and (2) head exposed in the *far field* of an antenna (*FF- homogenous and FF-six layers*).

The first step in our study was to compare the *SAR* and *E* results in axial and in-plane symmetry in the near field exposure. We found that both *SAR* and *E* have variation of maximum 20% which is acceptable, so we validate the in-plane TM wave propagation for *NF-model* and, also, we can further use the conclusions of [7], [8], [9].

Fig.2 compares the electric field strengths distribution in the analyzed condition as *E*-field value rated to the maximum value in the domain, *Emax*. Due to the head-domain electric properties the electric field strengths reduced its value with 50% in the first 20% of deep penetration.

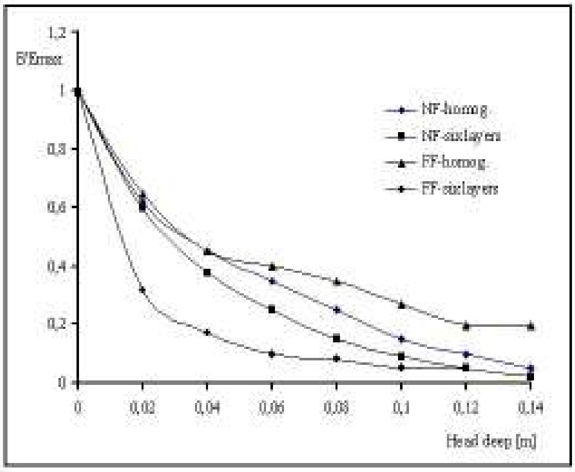


Fig.2. Electric field strengths rated to maximum value Emax

The human exposure to EMF provides different values of SAR due to the distance of exposure. In near field exposure, maximal SAR values are in the range of (6.53-6.55) W/kg depending on the head structure, for the same power density. In far field, maximal SAR values are in the range of (0.3- 0.303) W/kg in the same conditions of exposure (head structure and power density).

	NF-homog.	NF-six layers	FF-homog.	FF-six layers
SARmax [W/kg]	6.54	6.53	0.3	0.303
SAR [10g] [W/kg]	3.16	3.41	0.13	0.15
SAR [1g] [W/kg]	3.56	4.47	0.14	0.19

Table 1. SAR values for different head structures and exposure condition

To compare these different results we choose to calculate the SAR peak according to the standards: averaged on 10g of tissue and 1g of tissue (recommended by ANSI/IEEE Standards at 1.6W/kg) (*SAR*$_{max}$/ average value on 10g or 1g, named *SAR[10g]* and *SAR[1g]*) –see Fig.3 and Fig4.

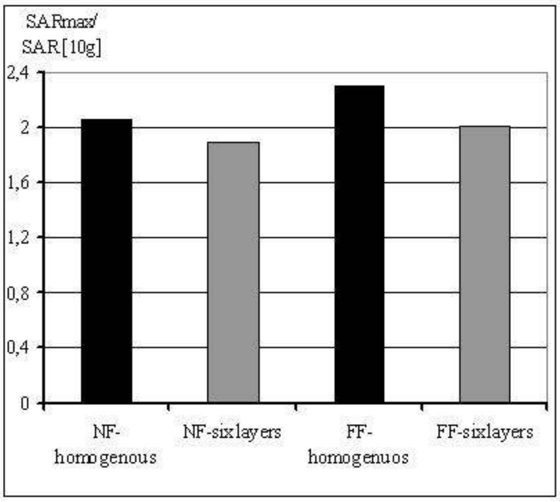


Fig.3. SAR peak over average SAR for 10g tissue

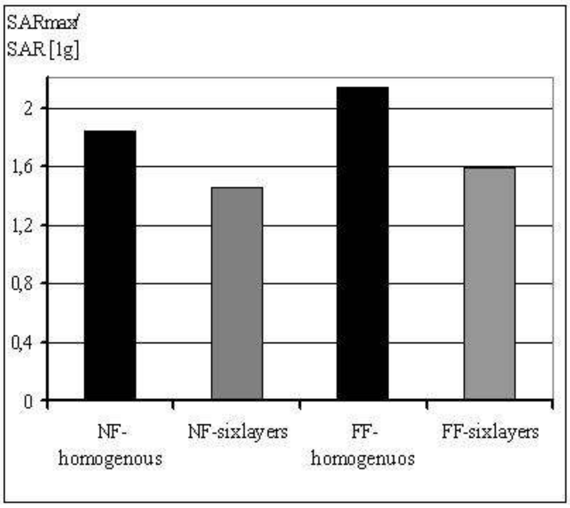


Fig.4. SAR peak over average SAR for 1g tissue

Due to the low penetration deep of microwaves, the *SAR* maximal values averaged over 10g of tissue do not present large differences for the analyzed conditions. On the contrary, the *SAR* maximal values averaged over 1g of tissue show grater variability for the same compared models

Because of the high values of average *SAR* over 1g or 10g in the near field, we calculated these values for continuous brain tissue where a higher potential of illness exists. We obtained 0.9W/kg for average *SAR* over 10g and 1.21W/kg for SAR over 1g, both values under the safety guidelines values.

CONCLUSION

This study estimates the effects of EMF radiation in microwave range frequencies on a biological structure (human head), in terms of *SAR*. We compare the effects of human radiation in the near field and in the far field of antennas, finding that the average value of SAR for the far field exposure is ten times lower as in the near field exposure. As for the near field radiation we calculate *SAR* value in the domain with brain dielectric properties, finding that the average value over 1g is 30% greater than the average value over 10g. Due to the different values between the two averaging methods (over 10g or 1g), for the exposure in the near field, it could be an accurate estimation of *SAR* the computation of average value over 1g of anatomical tissue.

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