Dielectric Equivalent Properties for Nonhomogeneous Anatomical Structures

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Abstract

Exposure of living bodies to very high frequency non-ionizing electromagnetic field (EMF) (i.e. microwave (MW) domain, (10^8 – 10^{11}) Hz) is associated to the use of mobile communications, radar detection, dielectric heaters and to several medical procedures (hyperthermia in tumor therapy, neuronal implant growth, imaging techniques, etc.). The development of MW applications, both in wireless transmission technologies and in medicine, requires compliance of electronic equipment EMF emissions with limiting exposure guidelines, in order to avoid any health risk. Artificial materials with electric properties similar to those of anatomical tissues are used in experimental procedures for electronic equipment certification.

The main objective of this work is to propose some quantitative criteria concerning the correspondence between numerical models used in computation and physical models (phantoms) used in measurements for MW macroscopic dosimetry assessment. Several 2D finite element (FEM) models are developed and EMF parameters are computed for different inner structures and heterogeneity levels of the exposed medium. The general characteristics of the MW source and the exposed medium are associated to mobile telephony conditions. The electric properties of the artificial material are evaluated through equivalence between the heterogeneous anatomical structure and the equivalent homogeneous one, concerning the EMF distribution.

Keywords: *dielectric properties, electromagnetic fields (EMF), finite element method (FEM), microwave (MW) dosimetry*

INTRODUCTION

Localized human exposure to low power near fields in MW frequency range can lead to significant absorption of energy and consequently to temperature increase. Biomedical research in this field is based on the analysis of EMF interactions with body tissues and on epidemiological studies. In dosimetric estimates it is a scientific consensus to consider, in MW exposure, that thermal effects prevail and the Specific (energy) Absorption Rate (*SAR)* is the quantity that represents the "dose". At a macroscopic scale, *SAR* [W/kg] is defined as the absorbed power per unit mass at infinitesimal volume of tissue ($SAR = \sigma E^2/\rho$, 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). *SAR* distribution depends on several factors: the incident field parameters, 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.

Experimental approaches are also applied in the determination of *E* and *SAR*. Tissue equivalent "phantoms " are used instead of real bodies in the experimental dosimetry [1]. Miniature isotropic *E*-field sensors are commonly used as implantable probes. The sensor is immersed into tissue equivalent liquid, and the internal electric field in the phantom is measured. The *SAR* is then calculated from internal *E*-field.

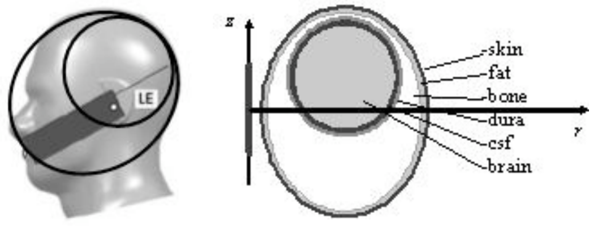
The usefulness of numerical modeling as well as measurements of *SAR* and *E* inside the body has been demonstrated in the assessment of biological effects and in setting the safety exposure guidelines and the certification protocols for harmless MW devices used in medicine and in day-to-day life. Numerical and experimental work in the field of MW penetration in the human body has been extensively done for the evaluation of the mobile telephony impact on users health [2], [3]. In the design of body models (computational or experimental), one needs to know the inner structure (anatomy of the body) and the electric properties of media. The present study is also conducted through this topic. Its main goal is to find equivalent dielectric properties for the design of artificial materials used in the experimental "phantoms" and for the description of simplified numerical models. The equivalence of heterogeneous structures (like thin tissue layers) with homogeneous domains brings numerical simplification (economy of computational resources) and facilitates the validation of the numerical results with experimental data.

Previous studies demonstrated that MW penetration in human head is mainly superficial and the distributions of *E* and *SAR* depend strongly on the geometric shape of the head, while the accuracy of the anatomical structure representation is less important. 2D and 3D computational models with homogeneous equivalent structure were proposed for the numerical and experimental studies [4] [5]. Based on 2D FEM models introduced and validated in [3] and [5] we extend here the computation of the head dielectric equivalent properties at a larger frequency spectrum in the MW range.

DESCRIPTION OF THE COMPUTATIONAL MODEL

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 [3], [5]. It is of common practice to generate simplified 3D models of the human head, in a spherical layered structure [4], [6], as fig. 1.a 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 based on the geometry suggested in fig. 1.b., which is a circular or elliptical ensemble of layers, that results from the axial symmetry of a fictive anatomical structure. Even if, at the first glance, the original 3D geometry looks unrealistic, the 2D model proves its usefulness and performance by comparison with 3D models presented in the literature. Previous work [3] showed 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 σ, ε and ρ considered in our study correspond to data in literature [6], [8]. For illustration, table 1 lists ρ, σ and ε for the six tissues involved (skin, fat, bone, dura, cerebro spinal fluid and brain) at the main frequencies used by the GSM mobile phone system (900 and 1800 MHz).



a. **b.**

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

Table 1. Characteristics of tissue subdomains

TISSUE	Radius [mm]	Density [kg/m^3]	Conductivity [S/m]		Relative permittivity	
			900 [MHz]	1800 [MHz]	900 [MHz]	1800 [MHz]
skin	90	1100	0.87	1.18	41.4	38.9
fat	89.3	920	0.11	0.19	11.3	11
bone	87.7	1850	0.14	0.28	12.5	11.8
dura	67.2	1050	0.96	1.32	44.4	42.9
csf	66.7	1060	2.41	2.92	68.7	67.2
brain	64.7	1030	0.86	1.27	46.5	43.9

The EMF source is a center fed half-wavelength dipole antenna; its characteristic dimension, oriented on the (*oz*) axis is accorded with the wavelength in the microwave frequency range used in European GSM mobile system telephony (0.9 – 2.5) GHz. The radiated power is always maintained at the average working power of 0.125 W regardless the other variable factors (frequency, exposed body structure and properties). The user is exposed (with the head and ear) at a distance of 0.5-3 cm, in the near-field of the antenna.

The numerical computation used for the 2D FEM model is based on the FEMLAB software [9], the *Electromagnetics Module*, in the *axisymmetric transversal magnetic (TM) waves* application mode, *time-harmonic* submode. The wave equations are applied for lossy media, characterized by the complex electric permittivity $\underline{\varepsilon}$

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

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

where the unknown field variables, in the cylindrical coordinate system and in complex form are:

$$\underline{\mathbf{H}}(r,z,t) = \underline{H}_\varphi(r,z)\mathbf{e}_\varphi e^{j\omega t},$$

$$\underline{\mathbf{E}}(r,z,t) = \left(\underline{E}_r(r,z)\mathbf{e}_r + \underline{E}_z(r,z)\mathbf{e}_z\right)e^{j\omega t}. \quad (2)$$

The computational domain is limited with *low-reflecting* boundary conditions

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

and the boundary on the (*Oz*) axis satisfies *axial symmetry* conditions

$$E_r = 0,\ \frac{\partial E_z}{\partial r} = 0, \quad (4)$$
$$\frac{\partial H_\varphi}{\partial z} = 0,\ \frac{1}{r}\frac{\partial H_\varphi}{\partial r} - \frac{1}{r^2}H_\varphi = 0.$$

The EMF source is introduced through a nonhomogeneous *magnetic field* boundary condition, simulating the center fed dipole antenna. The magnetic field condition is adjusted each time, so that the emitted power is constant (125 mW) in all studied cases.

The FEMLAB linear stationary solver is based on Gaussian elimination. The FEM mesh is composed of triangular elements, and for its assessment were performed two accuracy tests: the constant radiated power and an energetic balance (the radiated power compared with the sum of the power absorbed in the head and the power radiated in the antenna far field).

RESULTS and DISCUSSIONS

The head structure presented in figure 1 is reduced to a more simplified model, having the same external shape and dimensions and an inner homogeneous structure. The electric properties of the reduced model (σ_{equiv} respectively ε_{equiv}) are computed with the FEMLAB software, by energy based equivalence, considering that the total absorbed power and total electric energy have the same values in the heterogeneous (composed by *i* different subdomaines) and equivalent homogeneous models:

$$\int_i \sigma_i (E_i)^2 \,\mathrm{dv} = \sigma_{equiv} \int_i (E_i)^2 \,\mathrm{dv} \quad (5)$$

$$\int_i \frac{1}{2}\varepsilon_i (E_i)^2 \,\mathrm{dv} = \frac{1}{2}\varepsilon_{equiv} \int_i (E_i)^2 \,\mathrm{dv} \quad (6)$$

The equivalent mass densities are approximated by weighted arithmetic mean.

The method presented above is applied to compute the equivalent dielectric properties of two reduced head models:

(1) reduced heterogeneous model with two subdomaines: equivalent **skull** (skin+fat+bone) and equivalent **brain** (dura+csf+brain);

(2) reduced homogeneous model: equivalent **head** tissue.

Fig. 2 presents the frequency dependence of the equivalent electric conductivities (fig. 2a) and of the equivalent dielectric permittivities (fig. 2b), in the frequency range used in the GSM European system.

a. Conductivity

b. Relative permittivity

Fig. 2 Frequency dependence of the equivalent dielectric properties

The phantom proposed by [1] (i.e., the Specific Anthropomorphic Mannequin – SAM) consists of a 2 mm polyurethane shell (σ_{shell}= 0.0012 S/m respectively ε_{shell}= 5), filled with **simulant tissue solution** ($\sigma_{simulant} = 0.7$ S/m, $\varepsilon_{simulant} = 48$, at 0.835 GHz and $\sigma_{simulant} = 1.7$ S/m, $\varepsilon_{simulant} = 41$

at 1.9 GHz). As one could see, the mentioned values of the **simulant tissue solution** are comparable to the **brain** equivalent dielectric properties in fig. 2.

Our study further investigates the uncertainties introduced in EMF parameters evaluation by the use of different 2D FEM models. We compare the *SAR* and *E* distributions inside the head, at different frequencies, considering the following models:

(A) heterogeneous six layers model presented in figure 1 with specific properties

(B) reduced heterogeneous model with two sub-domains (skull and brain)

(C) reduced homogeneous model

(D) homogeneous phantom - SAM model

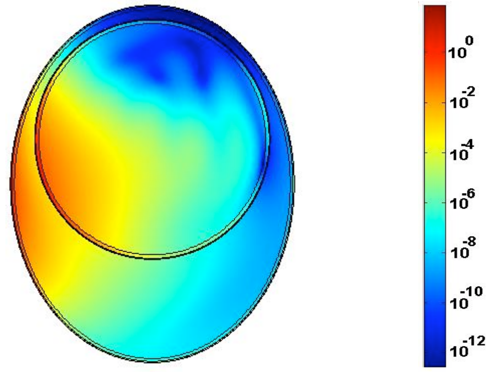
The dielectric properties are presented above. Paper [5] shows that in the near field of the antenna the equivalent dielectric properties do not change significantly with the distance between the antenna and the head. Therefore we maintain here a constant distance of 5 mm. In all cases the antenna is a half-wavelength dipole placed symmetrically at the left side of the head.

Fig. 3 and 4 show the *SAR* spectra inside the head at 0.9 GHz respectively at 2.5 GHz, for the *heterogeneous model (A)* and for *the reduced homogeneous model (C).*

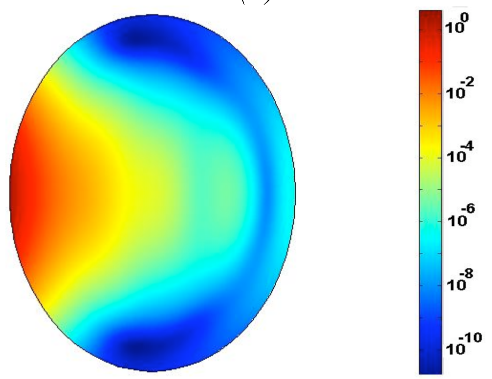
One could observe that the heterogeneity level becomes less important at higher frequencies in the MW investigated domain, because the penetration depth decreases and the inner *E* field distribution is more superficial with frequency increase. Heterogeneous models absorb higher energies, as the color scales show, compared to homogeneous correspondent models. At higher frequencies the half wavelength antenna becomes shorter and the EMF penetration inside the head is more localized.

Electric field penetration in the exposed head (rms values) is presented for the models *(A) – (D)* in fig. 5, at the main frequencies in the MW considered range (0.9 GHz, 1.8 GHz and 2.5 GHz). Due to the position of the antenna, the *E* values on the (*Or*) axis are the highest in the domain.

The results presented in fig. 5 support the good agreement among equivalent models (especially the heterogeneous ones). This is a good reason to use

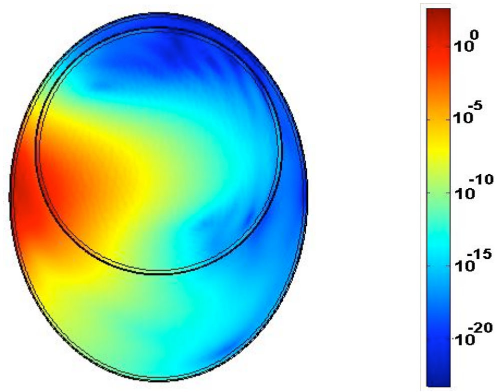


model (A)

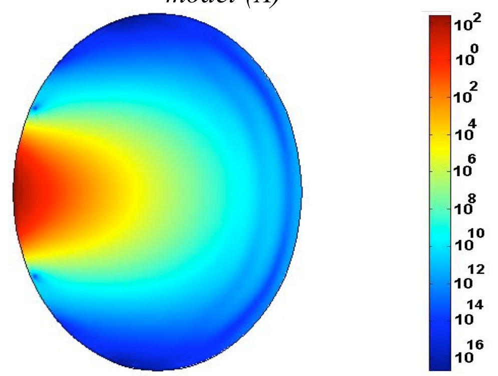


model (C)

Fig. 3 *SAR* [W/kg] distribution spectra for 2D FEM models (0.9 GHz)



model (A)



model (C)

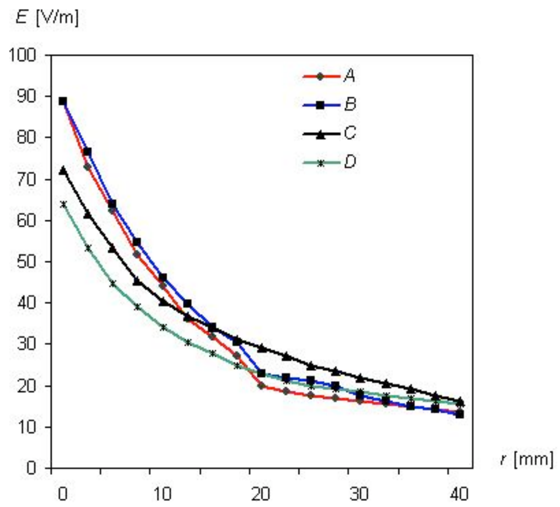
Fig. 4 *SAR* [W/kg] distribution spectra for 2D FEM models (2.5 GHz) the values determined for equivalent electric properties in the design of 3D FEM models for the human head. In a 3D numerical model, the degree of heterogeneity is crucial for the complexity of the model and computational resources; thin layers (like skin, fat, dura and csf) should be covered with a very dense FEM mesh. Consequently, any possibility to simplify the structure is appreciated. Between the two homogeneous models, the reduced structure (*model C*) is closer to the heterogeneous structure (*model A*), and a revision of the dielectric properties proposed in [1] for SAM design is suggested. The presence of the polyurethane shell has a screening effect on the *E* field penetration that should be compensated by the simulant properties.

The reduced heterogeneous structure (*model B*) proves to achieve the most desirable compromise between the accuracy of anatomical representation and the economy of computational resources. The uncertainty between *E* field values computed for the heterogeneous layered structure (*model A*) and for the reduced heterogeneous structure (*model B*) are in the limit of 10%, while for the reduced homogeneous structure (*model C*) the uncertainties go to 20% (fig. 5).

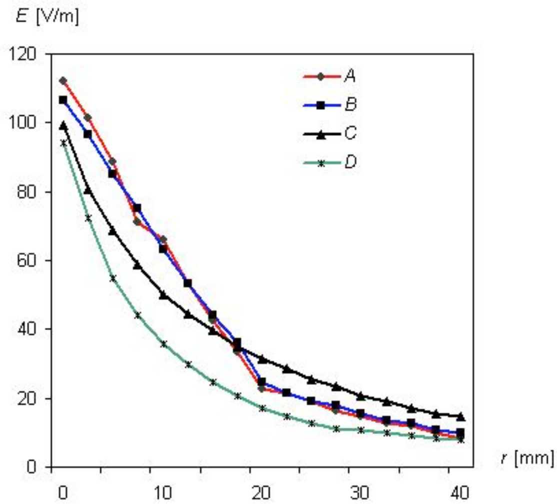
The *E* field penetration depth was estimated for the three presented models (*A, B* and *C*), in the considered frequency range. Fig. 6 shows that the frequency dependence of the penetration depth for the heterogeneous model (*A*) and heterogeneous reduced model (*B*) are very similar, while the same function for the homogeneous model (*C*) has a noticeable different shape.

CONCLUSIONS

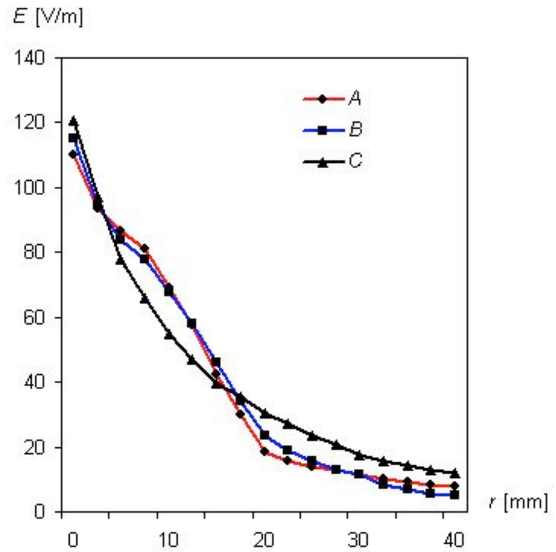
The construction of the simplified 2D FEM model arise from the necessity to evaluate EMF parameters distribution in layered structures like anatomical tissues when exposed to MW either in day-to-day activities (as mobile phone use) or in medical therapy (hyperthermia, stimulation, etc.). Compared with more sophisticated models, the 2D FEM model demonstrates its advantages in economy of resources, accessibility and rapidity, while the results are sufficiently accurate for global estimates and for comparison with experimental *SAR* and *E* distributions from measurements on phantom human models. The results presented here are specific for the conditions related to mobile phone use near the head, but the method of equivalence between the heterogeneous anatomical structures and the homogeneous equivalent domains could be



a. at 0.9 GHz



b. at 1.8 GHz



c. at 2.5 GHz

Fig. 5 *E* distribution (rms values) versus distance *r*, measured from the surface of the skin, for 2D FEM models

also applied to other parts of the body. The results are promising for the opportunity of the 2D model extension to a 3D model, with an optimized shape and internal structure.

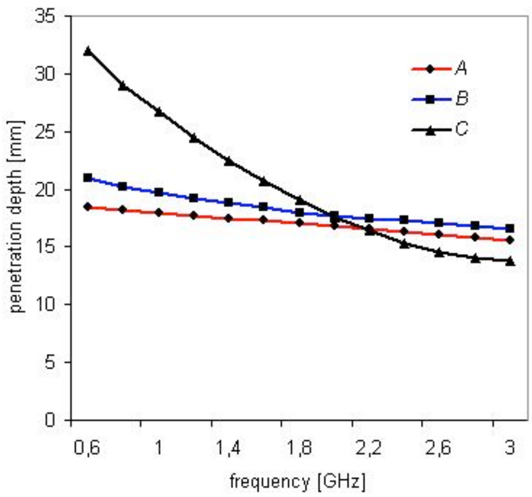


Fig. 6 Frequency dependence of the penetration depth, for 2D FEM models

We have proposed a quantitative correspondence between numerical models and physical models (phantoms) used in measurements for microwave macroscopic dosimetry assessment. In the evaluation of EMF penetration in tissue exposed to microwaves the *E* and *SAR* distributions were determined. Dielectric properties, conductivity and permittivity of tissue-equivalent simulant were compared with equivalent properties determined from computational modeling. Our results show that the inner distribution of the electric field has a low sensitivity to the dispersion of dielectric properties (in reasonable limits usual for practical situations) and to the heterogeneity level of the anatomical structure. In numerical and experimental modeling of human body exposure to ELF in the MW range it is important to reproduce the external shape of the body, but the models could be simplified in their inner structure.

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