Dosimetric Estimates in Biological Tissue Exposed to Microwave Radiation in the Near Field of an Antenna

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ABSTRACT. Human exposure to electromagnetic field (including the microwave radiation range) is limited by international safety guidelines, based on health considerations. Thermal health effects are commonly considered for the radiofrequency range; in particular, for microwave exposure, the absorbed energy that produces heat is quantified by the specific energy absorption rate, as dosimetric reference. Induced electric and magnetic field strengths are also restricted by the exposure guidelines.

We report here a numerical study of the electromagnetic field induced in several biological models by a common microwave applicator. The sensitivity of dosimetric parameters and the compliance with exposure guidelines are evaluated. We have examined the influence of dielectric properties dispersion on dosimetric quantities, useful in the design and validation of experimental settings and numerical models.

1. Introduction

A wide debate developed over the last two decades, both in scientific and social forums, on the possible health effects of human exposure to non-ionizing electromagnetic fields continues to concentrate attention without concluding results. Research activity was therefore developed by the international scientific community aimed at evaluating the risk associated with exposure to this type of radiation. At the same time, various international authorities began to issue recommendations on exposure limits valid for workers and for the population in the frequency range 0 Hz-300 GHz. The limits specified by the guidelines are settled both at workplaces and in the living environment. The specified accepted limits are intended to be used as a basis for planning work procedures, and designing protective facilities, as much as in the assessment of the efficacy of protective measures and practices, or in the guidance on health surveillance.

The most known and accepted are the guidelines developed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1]. Other internationally recognized documents, such as those developed by the Institute of Electrical and Electronics Engineers (IEEE) and American National Standardization Institute (ANSI) [2] in the USA, by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) [3], or by the National Radiological Protection Board (NRPB) in the UK adopt the same basic approach of ICNIRP, although some differences exist in numerical values, and they will be discussed in this paper. In 1999 the Council of the European Union has issued a Recommendation to Member States [4] to adopt a common frame of norms on exposure of the general public to electromagnetic fields that made precisely the indications supplied by ICNIRP for the protection of the population. Presently, about 30 countries have adopted ICNIRP guidelines as national regulations.

The market of wireless devices is presently highly dynamic and competitive. Producers have to find new and commercial solutions, as an optimum of cost, performance, modern design, miniaturization and multifunctionality. The compliance with the safety guidelines is also a restriction, and the manufacturer is required to include the *SAR* limit in the technical specification of each product. This value is then compared by the consumer safety authorities with the limits stated by standards. Also that seems to be a simple and non-controversial process, our study investigates the so called "technical accuracy" of safety and performance parameters assessment, based on valid standards.

2. Basic restrictions and reference levels presently stated by standards

The ICNIRP guidelines [1], as well as the other international standards [3-5], are based on a two-level structure. *Basic restrictions* are defined in terms of "dosimetric quantities" that are directly related to biological effects; these quantities are: the current density (*J*) for low-frequency electric and magnetic fields, and the specific energy absorption rate (*SAR*) and the power density (*PD*) for high-frequency electromagnetic fields (including microwaves). The limits are defined for exposure of all, or only a part, of the human body. For practical reasons, *reference levels* are derived from basic restrictions, through appropriate dosimetric models (simplified computational and experimental models). Reference levels are expressed in terms of physical quantities (electric field strength, magnetic field strength, and equivalent plane wave power density) that can be directly measured outside the exposed body and inside experimental phantoms.

Given the conservative hypotheses assumed in dosimetric models, exposures to fields that are below the reference levels necessarily comply with basic restrictions, but the vice-versa is not true. Even when the reference levels are exceeded, the standard may be complied with, provided it can be proved that basic restrictions are not exceeded under the specific exposure conditions.

We are interested here by the high-frequency electromagnetic field, the microwave range with applications in wireless communications technologies, 0.5 – 3 GHz. The basic restriction for localized exposure (head and trunk) in this frequency range is the specific energy absorption rate (*SAR*) which is set in terms of maximum mass-normalized quantity, as follows:

- 2 W/kg for "any 10g of contiguous tissue" in the ICNIRP guidelines [1] and the European recommendation [4], while "any 10g of contiguous tissue in the shape of a cube" in the Australian standard [3];
- 1.6 W/kg for "1g of tissue in the shape of a cube" in the ANSI/IEEE standard [2].

Basic references [1], [2] and [4] are issued in the same period of time, 1998-1999, are based on the research and documentation literature available at the time and are still valid. At the first glance the specifications do not seem to be contradictory; however, we found some important differences in their practical use, that we attempt to emphasize on a case study presented further.

3. Physical properties of the model and general assumptions

The work presented here examines the electromagnetic field penetration in human tissue considering several conditions and particularities related to wireless communications in the microwave frequency range [7-9]:

(1) An antenna is the electromagnetic radiation source in our study. The electromagnetic field produced by an antenna can be described as having several components; only one of these actually propagates through space, and 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, and their strength decreases very rapidly with 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 dipole configuration is the most common and conventional type for near field human exposure related to wireless personal communication systems in the GSM frequency range (0.5 to 3 GHz); the harmonic waveform is considered in our study. In numerical and experimental models, the length of the antenna is usually adjusted at the half wavelength, both because of modeling reasons (like symmetry conditions) and to maximize the efficiency of the emission.

(2) The exposed body is represented by a layered biological structure, with an idealized shape, inspired by the human anatomy (head or trunk); the electromagnetic field penetration depth in dispersive dielectrics, like animal tissue, depends on the external shape of the body, on the electric conductivities and dimensions of tissue layers; the skin and fat peripheral layers present screening effect for the electric component of the incident field.

(3) Biological tissues are nonmagnetic and dispersive dielectric materials; for the purpose of this study, they are considered linear, isotropic and homogeneous materials; dielectric properties are expressed in the form 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 electromagnetic field. The specific values for σ and ε considered in our study correspond to data in literature [6]. For illustration, fig. 1 shows the frequency dependence of the electric conductivity σ and relative dielectric permittivity ε, for several anatomical tissues involved in the human body exposure to electromagnetic field (skin, fat, bone, dura, cerebro-spinal-fluid, brain and muscle); the microwave frequency range used by the GSM communication system is considered.

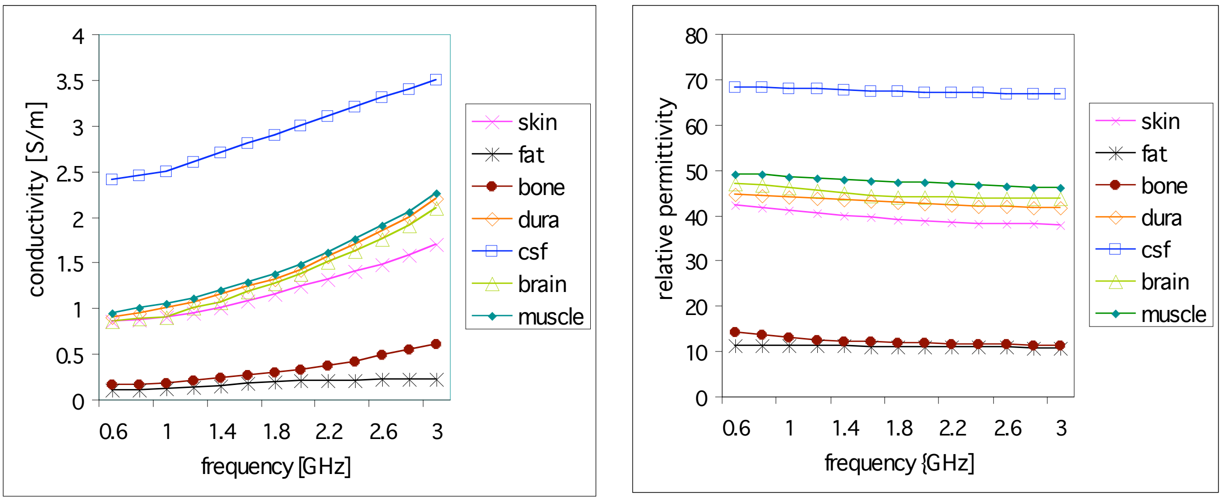


Fig. 1 Frequency dependence of the conductivity and the permittivity of several tissues, in the GSM frequency range

Our research is focused on the study of two idealized anatomic structures:

- **model A_6** - a human (adult) head with external ellipsoidal shape, composed by six tissue layers (skin, fat, bone, dura, csf and brain) [8, 9], and
- **model B_4** - a planar layered structure representing the human trunk, composed by four tissue layers (skin, fat, muscle and bone).

(4) The electromagnetic coupling between the antenna and the exposed body is quantified by the so called *power transfer factor*, defined as the ratio between the emitted and the absorbed time averaged active powers; this factor depends on: the antenna type, the shape and structure of the body and the distance between the antenna and the body. We adopted for this study a constant emitted power of 1W, regardless the type of the antenna, and for a more realistic evaluation we have expressed the dosimetric quantities in rated (scaled) values, as it is seen in the results section.

(5) Our purpose is to determine some quantitative and qualitative information on dosimetric parameters inside the body exposed to electromagnetic radiation and to relate them to prescriptions stated in human exposure guidelines and standards. Also the configuration of the human body in the vicinity of the antenna does not present any obvious and accurate symmetry, we speculate a reduction of the 3D problem, to a 2D idealized model, based on axial symmetry around the antenna longitudinal axis [8, 9]. This approximation proves to be satisfactory for global estimates, like specific energy absorption rate, or power deposition in a tissue layer, both rated to the total power absorbed by the body, or to the power emitted by the antenna. The approximation is also favored by the fact that the penetration depth of the electromagnetic radiation in biological tissue at microwave frequencies is small (< 30 mm) and the electromagnetic phenomena are superficial. In order to compare the quantitative results obtained with the simplified 2D models with the more realistic ones obtained with 3D models one have to take into account *the power transfer factor* (defined above), whose value is *one* for the 2D models (due to the axial symmetry) and *smaller than one* for the realistic 3D models (generally dependent of the distance between the antenna and the body).

4. Electromagnetic problem formulation

The numerical computation used for the 2D FEM model is based on the FEMLAB software [10], the *Electromagnetics Module*, in the *axisymmetric transversal magnetic (TM) waves* application mode, *time-harmonic* sub mode. The wave equations are applied for dispersive media, characterized by the complex electric permittivity $\underline{\varepsilon}$

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

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

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

The computational domain (fig. 2) is limited with *low-reflecting* boundary conditions

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

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

$$E_r = 0 , \quad \frac{\partial E_z}{\partial r} = 0 , \quad \frac{\partial H_{\varphi}}{\partial r} = 0 . \tag{4}$$

The radiation source is introduced through a nonhomogeneous *magnetic field* boundary condition, simulating the antenna. The magnetic field condition is adjusted for each model, so that the emitted power is constant (1 W) in all studied cases.

The FEMLAB linear stationary solver is based on Gaussian elimination. The FEM mesh is composed of triangular elements (Delaunay mesh with Lagrange quadratic elements), and two accuracy tests were performed to settle its parameters: the constant radiated power and an energetic balance (the radiated power compared with the sum of the power absorbed in the body and the power radiated in the antenna far field). The optimal mesh in our examples is settled to approx. 150000 elements.

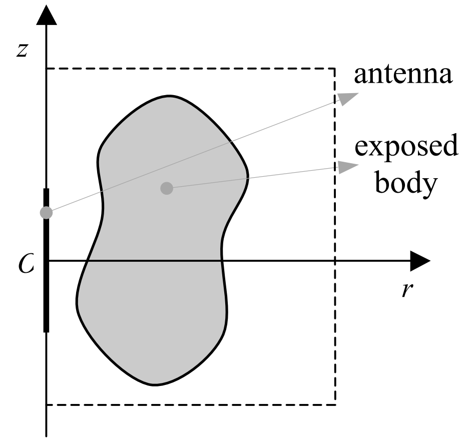


Fig. 2 The general structure of the computational domain based on axial symmetry

5. Equivalent dielectric properties

The anatomical structures presented above are further reduced to more simplified models, 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 2D FEM model described earlier, 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 [9]:

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

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

The method presented above is applied to compute the equivalent dielectric properties of the following reduced models, derived from **model A_6** and **model B_4** presented above:

- **model A_2** - *reduced heterogeneous head model with two subdomaines*: **equivalent skull** (skin+fat+bone) and **equivalent brain** (dura+csf+brain);
- **model A_1** - *reduced homogeneous head model*: **equivalent head** tissue;
- **model B_2** - *reduced heterogeneous trunk model*: skin (same properties and thickness as in model B) and **equivalent body** tissue (fat+muscle+bone).
- **model B_1** - *reduced homogeneous trunk model*: **equivalent body** tissue.

Fig. 3 presents the frequency dependence of the mentioned equivalent dielectric properties computed in the GSM frequency range.

The equivalent properties are useful in the design of experimental mannequins. Tissue equivalent “phantoms” are used instead of real bodies in the experimental dosimetry [7]. 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. A typical phantom designed for the certification of communication equipment is described in [7] (i.e., the Specific Anthropomorphic Mannequin – SAM) and it 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 **equivalent brain** in fig. 3.

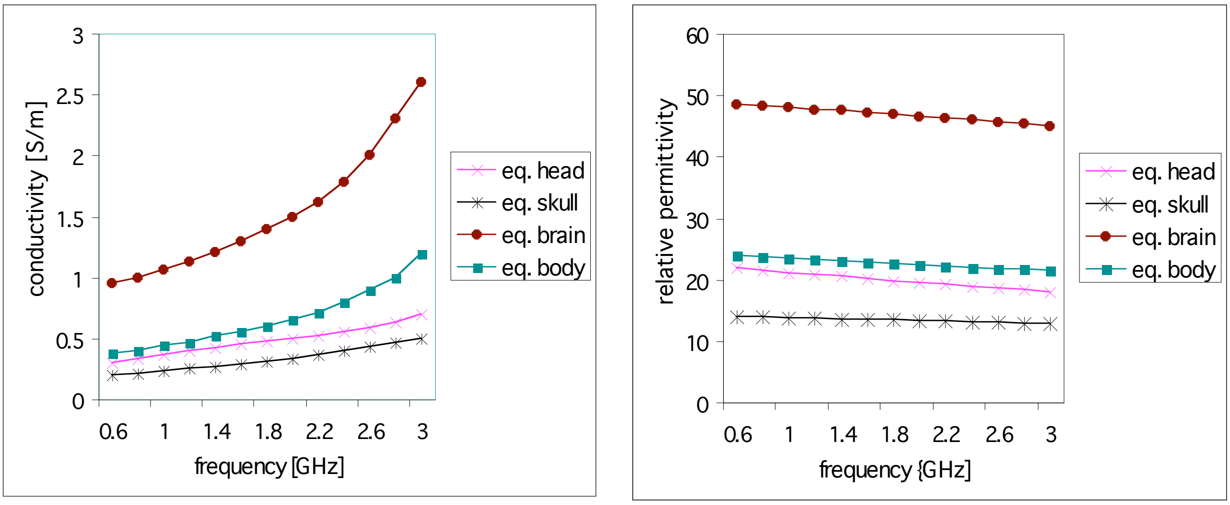


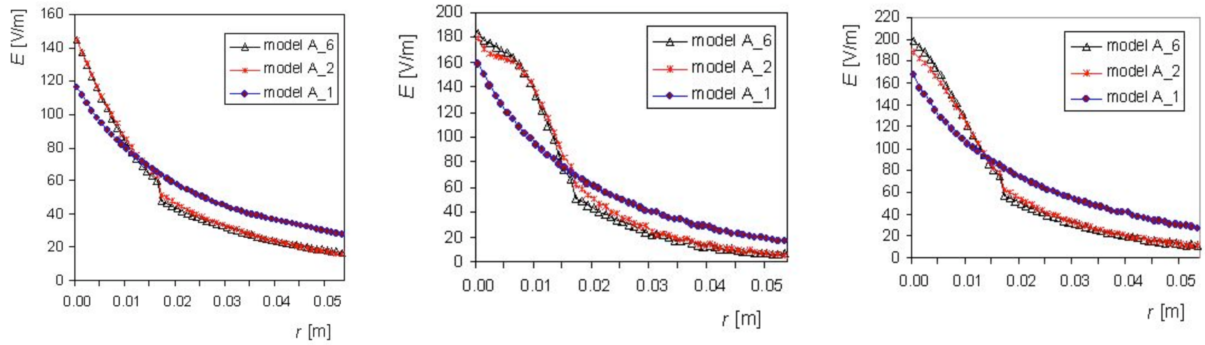
Fig. 3 Frequency dependence of the equivalent dielectric properties (conductivity and relative permittivity), in the GSM frequency range

6. Electric field strength and penetration depth in the exposed body

We computed the *E*-field strength (rms-values) distribution inside the two anatomical structures exposed in the near field of the antenna at different frequencies; the antenna is placed at 0.01 m distance from the body surface. In the case of the head (models of type A) the antenna is a center fed, half wavelength dipole and in the case of the trunk (models of type B) the antenna is a lower end fed, quarter wavelength monopole. The antenna emitted power is set at 1W in all cases in order to express the *E*-field as rated (per power) values, giving the possibility to better analyze them and to scale them for any other value of the emitted power. Electric field penetration in the exposed head (the models of type A) is presented in fig. 4, at the main frequencies in the MW considered range (0.9 GHz, 1.8 GHz and 2.5 GHz). The presented distributions of the electric field strength are computed on the axes of maximal values.

In a 3D numerical model, the degree of heterogeneity is significant 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. The results presented in fig. 4 support the good agreement among equivalent models. This is a good reason to use the values determined for equivalent dielectric properties in the design of 3D FEM models or in experimental phantoms for the human body.

The reduced heterogeneous structures (**models A_2** and **B_2**) prove to achieve the most desirable compromise between the accuracy of anatomical representation and the economy of computational resources.



a. at 0.9 GHz **b.** at 1.8 GHz **c.** at 2.5 GHz

Fig. 4 *E* distribution (rms values) versus distance *r*, measured from the surface of the skin – head models

The *E*-field *penetration depth* was estimated in the GSM frequency range for the presented models. Figures 5 and 6 show that the frequency dependence of the penetration depth for the heterogeneous models (**A_6** and **A_2**, respectively **B_4** and **B_2**) is very similar, while the same function for the homogeneous model (**A_1**, respectively **B_1**) has a noticeable different distribution.

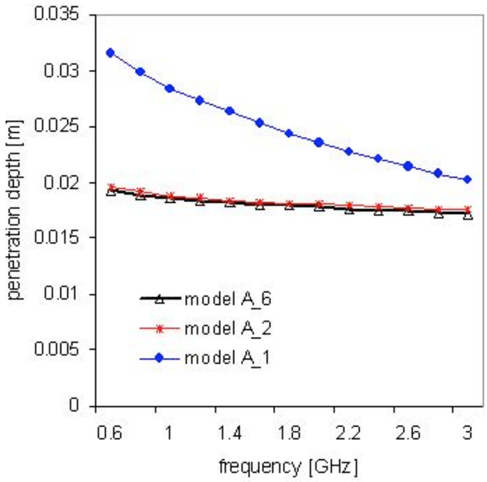


Fig. 5 Frequency dependence of the penetration depth, for type A (head) models

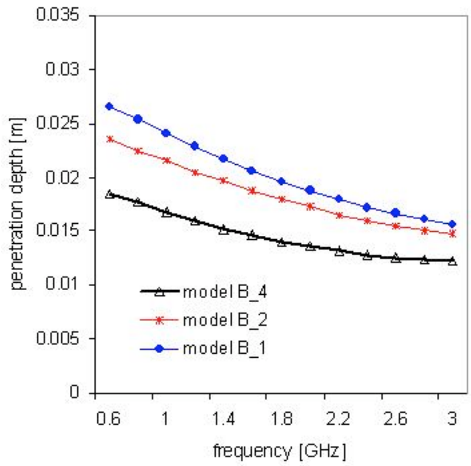


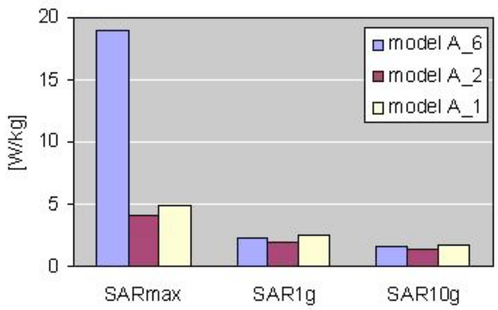
Fig. 6 Frequency dependence of the penetration depth, for type B (trunk) models

In the heterogeneous models, the presence of the superficial layers (skin fat and bone) has a screening effect for the electric field. The skin has a relatively high permittivity and concentrates the electric field and the absorbed power at the surface of the body; one could see in figure 4 the high initial *E* values. The fat and the bone, with their lower permittivities act like a barrier for *E*-field penetration. These observations support the lower level of the penetration depth for heterogeneous models and the almost constant value regardless the frequency.

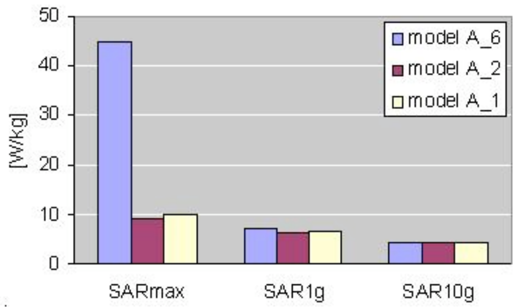
7. *SAR* evaluation

We mentioned in section 2 that the main dosimetric quantity in microwave exposure of living bodies is the specific energy absorption rate (*SAR*), considered as the *basic restriction* by the most referred standards. It is defined as the absorbed power per unit mass at infinitesimal volume of tissue ($SAR = \sigma E^2/\rho$ [W/kg], 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 (near or far field), geometric parameters (shape and structure) of the exposed body, physical properties of the tissues (as lossy dielectrics), ground/screen/reflector effects of other objects in the field near the body.

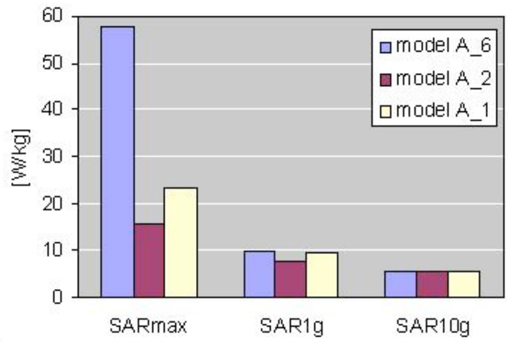
In this section we discuss the significance of the mass-normalized *SAR* over 1g versus 10g of tissue, which represents, for an average biological tissue with the mass density of 1000 kg/m^3, a volume associated to a cube with the edge of 0.01 m, respectively 0.022 m. The standards suggest that the cube volume should include the maximal local *SAR* values in the exposed area. Because the *SAR*, like the *E*- field in the exposed region is maximal at the surface of the body, the volume is selected with one face on the body surface (in practical cases the curvature could be neglected). Figures 7 and 8 display, for three significant frequencies and for the models presented in this case study, the following *SAR* quantities: the local maximal *SAR* (*SAR*max) and the averaged *SAR* values for 1g and 10g of tissue (*SAR*1g, *SAR*10g). The emitted radiation power is 1W in all studied cases and the exposed body is placed at the same distance (0.01m) of the antenna.



a. at 0.9 GHz

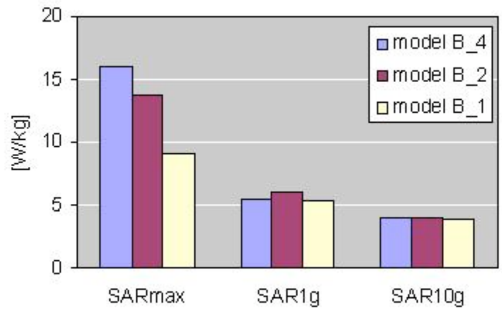


b. at 1.8 GHz

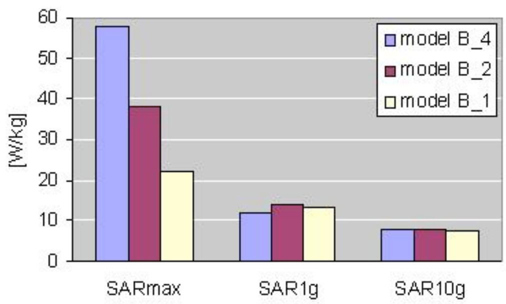


c. at 2.5 GHz

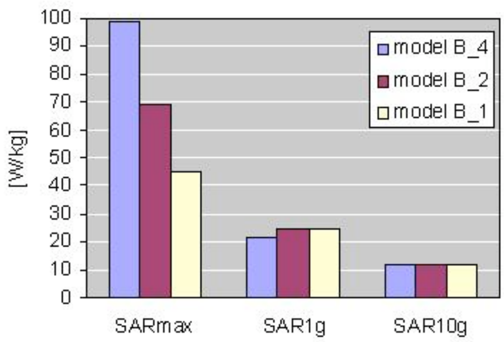
Fig. 7 *SAR* estimates for the type A (head) models (at 1W emitted power)



a. at 0.9 GHz



b. at 1.8 GHz



c. at 2.5 GHz

Fig. 8 *SAR* estimates for the type B (trunk) models (at 1W emitted power)

One could observe several characteristics:

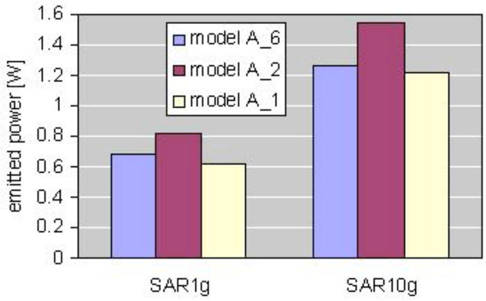
- *SAR*max is highly dependent on the model heterogeneity; the layered models A_6 and B_4 concentrate a large amount of the total absorbed power at the surface of the body because the skin (the peripheral layer which is very thin) has a higher dielectric permittivity than fat and bone; however, in all models, *SAR* distribution is highly focused in the area proximal to the antenna, and decreases rapidly inside the body (as the penetration depth and electric field distribution show).
- On the contrary, the averaged values, both for 1g and 10g of tissue, are similar for all the compared models; they are insignificantly affected by the heterogeneity. This is because the volume of integration is not negligible in size and its characteristic dimension is larger than the thickness of the tissue layers.
- For the same exposure conditions, *SAR*10g is considerably smaller than *SAR*1g because *SAR* distribution is highly nonuniform and decreases rapidly with the distance from the peak. Following the restrictions stated by the exposure standards, one could see the opposite relation: the limit imposed by ICNIRP for 10g (2 W/kg) is more permissive (higher) than the limit imposed by IEEE/ANSI for 1g (1.6 W/kg).

A more confusing situation appears when we try to solve the "inverse problem", that is to estimate the admissible power of the radiation source, that produces the SAR1g, respectively the SAR10g permitted by the standards. Figures 9 and 10 present the values of the emitted power able to produce SAR1g = 1.6 W/kg and SAR10g = 2 W/kg, for each of the models considered in our case study.

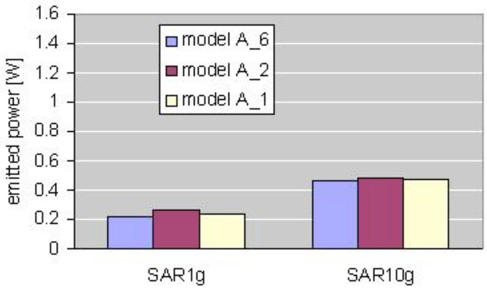
The three compared models give similar values for the maximal admitted antenna power, because the heterogeneity of the model significantly affects local SAR values, but seems to be less important for spatial averaged values, especially at higher frequencies (the depth of penetration decreases with the frequency rise). However, the controversy between the two referred standards is evident and confirmed in all considered examples: the limit values derived from the ICNIRP guidelines [1] are twice more permissive than the ANSI/IEEE standard [2].

8. Conclusions

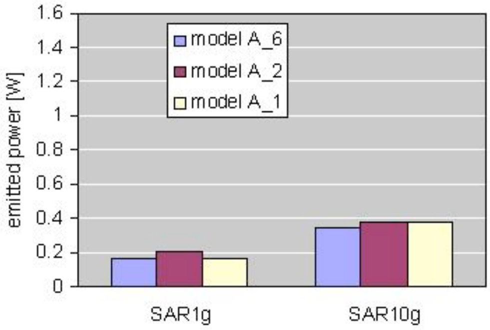
The construction of the simplified 2D models used in this study arises from the necessity to evaluate dosimetric parameters in layered structures like anatomical tissues when exposed to microwave radiation in wireless communications. Compared with more sophisticated models, the 2D models demonstrate 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 method of equivalence between the heterogeneous anatomical structures and the homogeneous equivalent domains could be applied in different configurations. The results are useful for the optimal design of 3D models.



a. at 0.9 GHz

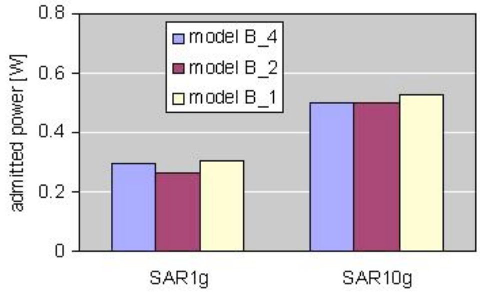


b. at 1.8 GHz

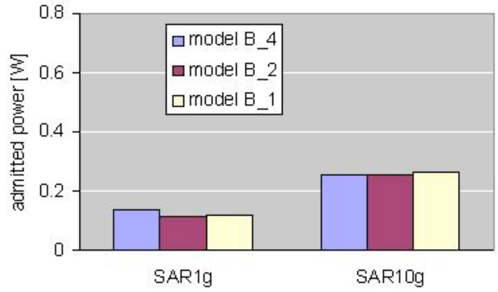


c. at 2.5 GHz

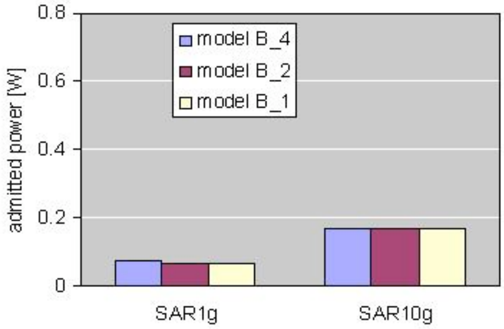
Fig. 9 Antenna emitted power to produce SAR1g and SAR10g admitted values in the type A (head) models



a. at 0.9 GHz



b. at 1.8 GHz



c. at 2.5 GHz

Fig. 10 Antenna emitted power to produce SAR1g and SAR10g admitted values in the type B (trunk) models

This work presents the electric field distribution inside models representative for parts of the human body (head and trunk) in different exposure conditions. The penetration depth and the specific energy absorption rate are also computed. A critical study for the evaluation of *SAR* shows some controversies produced by important differences between the most known and referred human exposure international standards; this situation is quite confusing for manufacturers and for end-users of wireless devices. The normalization method for *SAR* limit evaluation should be reconsidered and made more appropriate to the structure of the exposed body; we consider that the characteristic dimension of the integration volume should be made smaller for a more accurate estimate both in numerical and experimental models. Besides, the averaged value on a volume in the shape of a cube, over tissues with different physical properties seems to have a poor physical significance. A more localized *SAR* evaluation could be important both for the assessment of thermal and non-thermal biological effects.

It is the role of international standardization authorities, International Electrical Commission (IEC), European Committee for Standardization in Electrotechnic (CENELEC), The Institute of Electrical and Electronic Engineers (IEEE) to synthesize reliable research and to edit technical standards for the design, manufacture and conditions of use of the electric and electronic equipment.

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