COMPUTATION OF RADIOFREQUENCY FIELD DEPOSITION IN BIOLOGICAL EXPOSED MODELS BY AN ANALYTICAL METHOD

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Abstract. In this work, the analytical method of electromagnetic waves scattering (by G. Mie) was used to develop a computer code that allow internal field deposition inside spherical biological models exposed to radiofrequency radiation. Computations may be done over a wide range of size-frequency-modulation types. Physical basis of field deposition inside biological objects was followed especially to underline differences due to modulation characteristics of the excitatory signal. "Window effects", both in frequency and in intensity were reported for biological effects of radiofrequency irradiation, but few commercial programs allow computations of specific modulated excitations. Our code tried to fill that gap of basic knowledge. Obtained results were validated by making use of a professional numerical code. Our findings show that resonances amplitude and their in-depth position may be in some cases dependent upon modulation characteristics.

Key words: radiofrequency dosimetry, bio-electromagnetic interaction, specific absorption rate, spherical model.

INTRODUCTION

Electromagnetic fields interaction with biological systems and the afferent dosimetric needs have become a challenging concern lately, especially due to the wide spreading of the communication technology in the radiofrequency (RF) region of the spectrum and in connection with requirements of protective guidelines for humans.

A theoretical dosimetric approach is followed in the present paper, which deals with the implementation of an analytical method to compute the absorbed radiofrequency power inside spherical models of biological objects. The excitations are signals either in the UHF or SHF bands of the electromagnetic spectrum, and

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may be continuous or digital modulated ones. The biological target is the homogeneous sphere containing human tissue. Features of the distribution of the absorbed power inside the models are followed and discussed and their dependence upon the dimension, dielectric properties of the model and upon the incident radiation characteristics is investigated.

MATERIALS AND METHODS

For 300 MHz – 6 GHz band, the relevant measure of power deposition in biological objects is the specific absorption rate (SAR – in W/kg), which in the local form is given by:

$$\mathrm{SAR} = \frac{P_\mathrm{v}}{\rho_\mathrm{m}} = \sigma \frac{|\mathbf{E}_\mathrm{int}|^2}{\rho_\mathrm{m}} = \omega \varepsilon_0 \varepsilon'' \frac{|\mathbf{E}_\mathrm{int}|^2}{\rho_\mathrm{m}} \tag{1}$$

where P_v is the power dissipated per unit volume, ρ_m is the mass density of the biological material, σ is the effective conductivity, $|\mathbf{E}_\mathrm{int}|$ is the root-mean-square of the **E**-field vector in the interior point of the object, ω is the field pulsation, ε_0 is the free space permittivity and ε" is the relative loss factor.

The algorithm based on the Mie theory of electromagnetic waves scattering [4] was implemented in present paper in Mathcad and Mathematica environments, in order to compute values of $\mathbf{E}_\mathrm{int}$ or local SAR.

We considered an incident RF continuous plane wave irradiating a homogeneous spherical model filled with human tissue. The incident wave (electric component) is linearly polarized along Ox and is propagating along Oz axis, as shown in Figure 1.

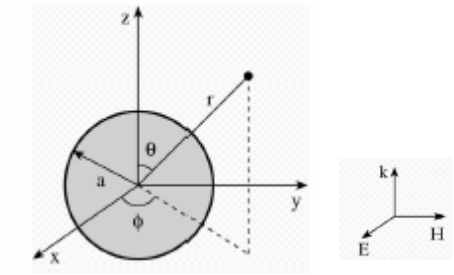

Fig. 1. The spherical model irradiated by the linearly polarised radiofrequency wave.

In spherical coordinates, the incident **E**-field may be written as:

$$\mathbf{E}^\mathbf{i} = \mathbf{a}_\mathbf{x}\, \mathrm{E}_0\, \mathrm{e}^{\mathrm{j}(\omega t - \mathrm{k}\, z)} = \mathrm{E}_0\, \mathrm{e}^{\mathrm{j}\omega t} \sum_{n=1}^{\infty} (-\mathrm{j})^n \frac{2n+1}{n(n+1)} \left[\mathbf{M}_n^{(1)}(\mathrm{k}) + \mathrm{j}\mathbf{N}_n^{(1)}(\mathrm{k})\right] \tag{2}$$

where **M** and **N** are spherical vector functions and are constructed with spherical Bessel function of the first kind and also contain the derivative of the Legendre function of the first kind, as given in [3]:

$$\mathbf{M}_n(\mathrm{k}) = \frac{1}{\sin\theta}\mathrm{z}_n(\mathrm{k}\,r)\mathrm{P}_n^1(\cos\theta)\cos\varphi\mathbf{a}_\theta - \mathrm{z}_n(\mathrm{k}\,r)\frac{\partial \mathrm{P}_n^1(\cos\theta)}{\partial\theta}\sin\varphi\mathbf{a}_\varphi \qquad (3)$$

$$\begin{aligned}\mathbf{N}_n(k) = {} & \frac{n(n+1)}{kr}\mathrm{z}_n(kr)P_n^1(\cos\theta)\cos\varphi\mathbf{a}_\mathbf{r} + \\ & + \frac{1}{kr}\frac{\partial}{\partial r}\left[\mathrm{z}_n(kr)\right]\frac{\partial P_n^1(\cos\theta)}{\partial\theta}\cos\varphi\mathbf{a}_\theta + \\ & + \frac{1}{kr}\frac{1}{\sin\theta}\frac{\partial}{\partial r}\left[\mathrm{z}_n(\mathrm{k}\,r)\right]P_n^1(\cos\theta)\sin\varphi\mathbf{a}_\varphi\end{aligned} \qquad (4)$$

The induced secondary field consists of two parts. One part applies to the interior of the sphere and is referred to as the transmitted field, while the other applies to the exterior of the sphere and is called the scattered field. Thus the total field outside the sphere is the sum of the incident and scattered fields. The transmitted field inside the sphere is the one that we are looking for, and it is of the form:

$$\mathbf{E}^{\mathbf{t}} = \mathrm{E}_0\mathrm{e}^{\mathrm{j}\omega t}\sum_{n=1}^{\infty}(-\mathrm{j})^n\frac{2n+1}{n(n+1)}\left[\mathrm{c}_n\mathbf{M}_n^{(1)}(k_1) + \mathrm{j}\mathrm{d}_n\mathbf{N}_n^{(1)}(k_1)\right] \qquad (5)$$

where c_n and d_n are the expansion (Mie) coefficients and are given in [2].

The irradiated object is a sphere of radius r, filled with various human tissues, whose complex relative electrical permittivity dispersion (type Cole-Cole, n = 4 th order) as a function of frequency is taken from the parametrical model [2]:

$$\varepsilon^*(\omega) = \varepsilon_\infty + \sum_{n=1}^{4}\frac{\Delta\varepsilon_n}{1+(\mathrm{j}\omega\tau_n)^{(1-\alpha_n)}} + \frac{\sigma_i}{\mathrm{j}\omega\varepsilon_0} \qquad (6)$$

This model was validated for 44 human tissues on the whole RF spectrum and is widely used in present in dosimetric calculations.

The independent variables introduced in the code we wrote for computation are: $\alpha = kr = 2\pi r/\lambda$ (k = propagation constant in the air, λ = wavelength) and $\beta = \mathrm{m}\alpha$, where $m = k_1/k$ is the refraction index of the sphere (k_1 = propagation constant in the tissue). Introducing of α and β variables simplifies the computational chain, and this was the reason for which they were used. Running the code in Mathcad and in Mathematica allows graphic representation of absorbed power distribution and also of total power absorption in the sphere.

Supplementary we made calculations in the case when the wave is a digital modulated one, with the outline that equation (6) is written for each Fourier component separately, and than summed for finding final $\mathbf{E}_{total}$. The modulated used signals were: amplitude shift keying (ASK), frequency shift keying (FSK) and discrete frequency modulation (DFM).

In order to compare the results obtained by our analytical method, a professional software was run and it allowed the computation of the absorption cross section Q_{abs} of the same spherical models, by the numerical method of moments [3], for the case of the continuous wave. The software we used was FEKO [1] and it was developed by EM Software & Systems-S.A (we used the evaluation version).

RESULTS AND DISCUSSIONS

A typical example of the internal field distribution inside a muscular sphere of radius r = 10 cm is given in Figure 2. In Fig. 2a, a continuous wave of f = 910 MHz was incident on the model, while in Fig. 2b, an ASK-modulated signal on the same carrier frequency was used (repetition frequency f_0 = 91 MHz, duty factor τ/T = 1/2). One notes different distribution aspects due to spectral components of the modulated signal.

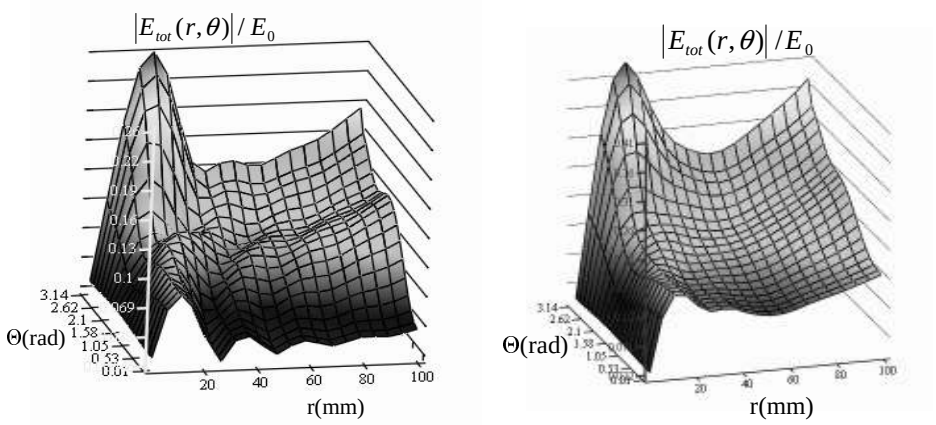

Fig. 2. The distribution of the normalized **E**-field intensity in the meridian plane $\Phi = \pi/3$, inside the muscular sphere, for a continuous wave (a) or for an ASK-modulated wave on the same carrier frequency (b).

In Figure 3 it is represented the normalized **E**-field distribution along the rectangular axes of the muscular sphere with r = 10 cm, in the EHK polarization (**E** ‖ x, **H** ‖ y, **K** ‖ z). One notes that $\mathbf{E}_x$ component is the highest only in the central part of the sphere. Fig. 4 shows the influence of the radius value on the field distribution, when the same continuous wave is incident: f = 910 MHz, but radius was increased to r = 20 cm for the muscular sphere.

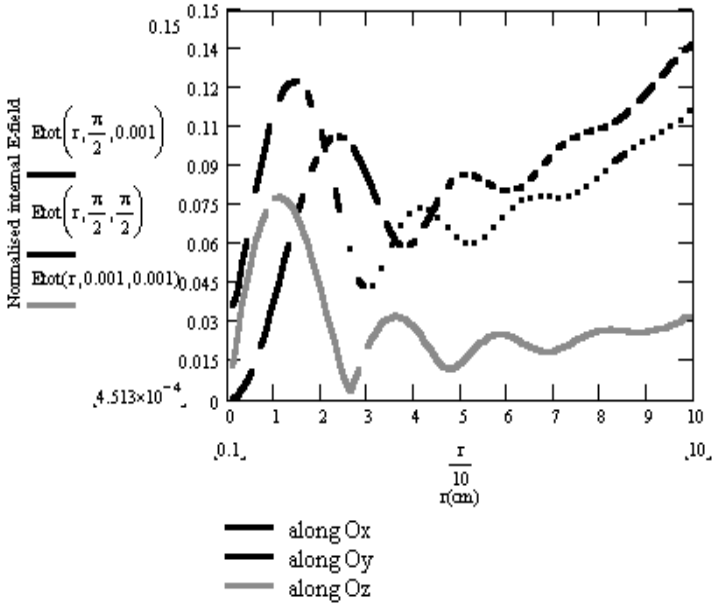

Fig. 3. Normalized **E**-field distribution along the rectangular axes of the r = 10cm sphere (EHK polarization).

For results comparison, the absorption cross sections calculated by our analytical method were also computed by making use of the numerical method – method of moments (in frequency domain) – by running the FEKO professional software. The results are given in table 1, where a very good agreement is seen. The comparison is only possible in the case of continuous wave excitation, since FEKO software doesn't allow computations for digital modulated signals.

Different types of digital modulated waves were used to excite the spherical model and the results obtained by applying the analytical method offered a valuable understanding of the physical nature of the deposition phenomena.

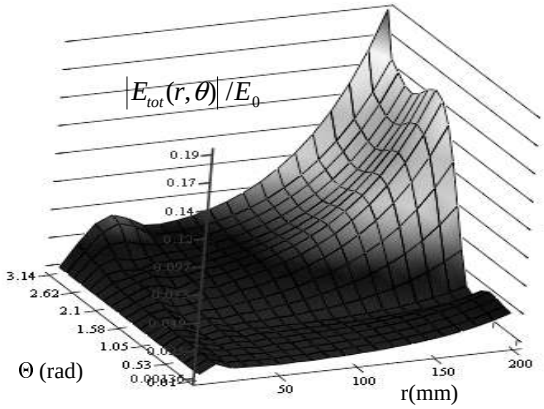

Fig. 4. The distribution of the normalized **E**-field intensity in the meridian plane $\Phi = \pi/3$, inside the muscular sphere of radius r = 20cm.

Table 1

Comparison of absorption cross section obtained by the original method and by the method of moments

Radius (cm)	Tissue	Frequency (MHz)	Q_{abs} (m^2)	
			Numerical method (FEKO)	Analytical method (MATHEMATICA)
10	muscle	100	0.004836	0.006420
12	muscle	100	0.011538	0.013465
15	muscle	100	0.025723	0.024939
10	muscle	900	0.030492	0.026768
4	muscle	910	0.006222	0.004834
5	muscle	910	0.008411	0.008889
2	muscle	1500	0.001257	0.001248
10	muscle	450	0.034778	0.032839
10	fat	450	0.026186	0.032839
10	grey matter (brain)	450	0.035053	0,033226
5	grey matter (brain)	450	0.007485	0.006304
8	grey matter (brain)	450	0.019703	0.019161

Running of many examples indicated that the ratio between the dimension of the sphere and the frequency of the wave significantly influence field deposition features inside the model. Differences between continuous wave and modulated RF signals distribution inside the model may be observed. In the studied cases, for low θ angles (Fig. 1), higher absorption in the external 2/3-rds of the sphere for modulated fields were present comparative to the continuous wave excitation.

The DFM signal was the mostly absorbed signal for angles θ low (due to the presence of spectral components with higher amplitudes on a wider frequency band). The FSK signal was the mostly absorbed for all radiuses and all θ angles. Peak absorption positions were the same for all signals, but relative amplitude of the peaks were different. The maximum absorption in the case of our specific calculations appeared at 1.15 cm from the center of the sphere (of 10 cm radius), and was the highest for the FSK signal.

Since mobile communications use modulated signals, an estimation of the impact of the spectral content on the modification of the internal field distribution inside a biological object (human head, etc.), compared to the case when continuous wave illuminates the target, may be of interest.

CONCLUSIONS

Analytical methods for dosimetric assessment of radiofrequency fields give exact solution of Maxwell equations inside biological models. There are inherent disadvantages connected especially to the restrictions imposed in model geometry and in its dielectric heterogeneity definition. However, these methods allow a precise understanding of the nature of electromagnetic field deposition when the excitation is a modulated wave. Not only carrier frequency may be of importance, but also the modulation characteristics ("window effects" – as reported in references on biological effects). Most of the professional dosimetric programs currently available (based on numerical methods) do not allow excitations by complex signals.

On the basis of the Mie theory of electromagnetic waves scattering, the code we developed can be successfully applied for computations of both continuous wave and (digital) modulated RF power deposition in spherical homogeneous or layered biological models. Internal field distribution over a wide range of size-frequency-modulation type combinations may be obtained.

Comparison of the results was done by making use of a professional code based on the numerical method in frequency domain – called the method of moments – by computing the absorption cross section.

In the simple planar model case that we used in the past, by superimposing of the "transfer function" on the spectral content of the incident signal, one can get the

field deposition aspect. When a spherical model is used, supplementary geometric resonances may appear, and they depend upon the sphere radius: when this increases the resonance frequency decreases. The spectral content may shift the "hot spots" position by comparison to the case when a continuous wave is used. The absorption is also dependent upon the dielectric properties of the sphere material (tisular content).

In this regard, in data transmission activities, where wide spectrum signals are used, special precautions may be needed for operator's biological protection.

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