Boundary Element solution of electromagnetic and bioheat equations for the simulation of SAR and temperature increase in biological tissues

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Abstract — This paper proposes the use of Boundary Element Method for the prediction of SAR and temperature distribution inside human tissues exposed to an electromagnetic source. The induced electric field and SAR are deduced by the solution of an electromagnetic field problem. The obtained results are then used as input in the bioheat equation. The validity of the proposed approach is proved by comparison with analytical and numerical results.

I. INTRODUCTION

Basic limits to human exposure to electromagnetic fields for frequencies beyond 100 kHz are currently given in the ICNIRP Guidelines [1] in terms of power absorbed by human tissues, by defining maximum acceptable values for the Specific Absorption rate (SAR). These limits ensure that the energy absorbed does not induce local thermal damage or whole body termoregulatory problems. Anyway, recent studies have demonstrated that temperature and SAR distributions within body are not always well correlated (see for example [2]), because temperature is greatly affected by the perfusion properties of tissues. Moreover, experiments show that the causative factor for the biological responses is due to the rise in temperature and not the RF energy per se. These results will probably reflects in future revisions of IEEE Standards [3] on an elevation in temperature and not SAR. In this context, methods for predicting SAR and temperature distribution within human phantoms could constitute a useful support for compliance with regulatory limits, also considering that calculations in standardized phantoms are conservative for SAR evaluation [4].

The prediction of SAR and temperature increase within human bodies requires the solution of the Maxwell and Pennes bioheat equations. Disregarding variation of electromagnetic and thermal properties of equivalent tissues with temperature, the two equations can be solved separately, obtaining SAR distribution from Maxwell equation and temperature increase from bioheat equation.

Most of the dosimetric studies make use of different methods, as in particular Finite-Difference-Time-Domain (FDTD) and Finite Integration Technique (FIT) [5-8], while few examples of Boundary Element Method (BEM) application to exposure problems can be found in [9, 10]. Examples of solution of bioheat equation by BEM more concern burns of tissues subjected to a heat source [11,12].

This work presents a computational tool based on BEM. This technique is well suited for studying homogeneous or weakly nonhomogenoues domains, as the human phantoms considered by the technical Standards, which provide methodologies for evaluating compliance with regulatory limits. In addition, a BEM approach for predicting temperature increase could be directly coupled with a non-invasive method, proposed by the Authors, for estimating SAR distribution within phantom starting from surface field measurements [13]. In the following, the modeling approach is described and validation with analytical and numerical results are provided.

II. NUMERICAL MODEL DESCRIPTION

We make reference to a simplified weakly non-homogeneous phantom, constituted by several regions Ω_i, with different electromagnetic and thermal properties (as in the scheme of Fig. 1). Normal **n** is defined in each point of the surfaces. A source (region Ω_S) placed in unbounded region Ω_0, in proximity to the human phantom, produces near field exposure conditions. The electromagnetic source is assumed to be sinusoidal (angular frequency ω) so that the electromagnetic problem can be formulated in the frequency domain, representing fields by phasors. With reference to thermal field, we assume stationary conditions, after thermal transient evolution.

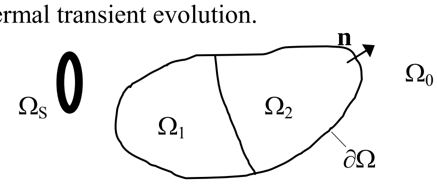

Fig. 1. Scheme of the phantom, composed of two regions with different electromagnetic and thermal properties.

The Green vector identity within each phantom subvolume provides the integral form of Maxwell equations. By applying the BEM approximation, the surfaces ∂Ω are discretized into triangles with the fields **E** and **H** assumed constant on each triangle *e*. The electric field integral equation (EFIE) is written for the internal subvolumes Ω_i (i=1,2 in Fig. 1):

$$T(\mathbf{r})\mathbf{E}^{(i)} = -\sum_e \int_{\partial\Omega_e} \left(\mathbf{n}^{(i)} \times \mathbf{E}^{(i)}\right) \times \nabla\psi^{(i)} ds - \sum_e \int_{\partial\Omega_e} \left(\mathbf{n}^{(i)} \cdot \mathbf{E}^{(i)}\right) \nabla\psi^{(i)} ds + i\omega\mu^{(i)} \sum_e \int_{\partial\Omega_e} \left(\mathbf{n}^{(i)} \times \mathbf{H}^{(i)}\right) \psi^{(i)} ds \quad (1)$$

while the magnetic field integral equation (MFIE) for the external volume (Ω_0):

$$T(\mathbf{r})\mathbf{H}^{(0)} = -\sum_e \int_{\partial\Omega_e} \left(\mathbf{n}^{(0)} \times \mathbf{H}^{(0)}\right) \times \nabla\psi^{(0)} ds - \sum_e \int_{\partial\Omega_e} \left(\mathbf{n}^{(0)} \cdot \mathbf{H}^{(0)}\right) \nabla\psi^{(0)} ds - i\omega\tilde{\varepsilon}^{(0)} \sum_e \int_{\partial\Omega_e} \left(\mathbf{n}^{(0)} \times \mathbf{E}^{(0)}\right) \psi^{(0)} ds + \int_{\Omega_s} \mathbf{J}_s \times \nabla\psi^{(0)} dv \quad (2)$$

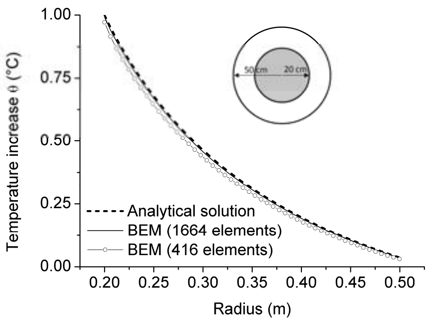

Fig. 2. Radial distribution of temperature increase within two concentric spheres. A value of P_{SAR} of 120 W/m^3 is imposed in the inner sphere.

where $T(\mathbf{r})$ is the singularity factor, $\tilde{\varepsilon} = \varepsilon - i\sigma/\omega$ the complex permittivity, σ the electrical conductivity, μ the magnetic permeability and $\mathbf{J}_s$ the current density flowing in the antenna loop Ω_S. The Green function is defined as $\psi = e^{-ik_e r}/(4\pi r)$, being $k_e = \omega\sqrt{\mu\tilde{\varepsilon}}$ a complex constant. Interface conditions over the surfaces separating domains with different properties link normal and tangential components of electric and magnetic fields belonging to the two separated volumes. From the current density $\mathbf{J}^{(i)} = i\omega\tilde{\varepsilon}^{(i)}\mathbf{E}^{(i)}$, the local SAR values are deduced as $SAR = P_{SAR}/\rho = \Re\left(EJ^*\right)/\rho$, being ρ the mass density of the medium and $\Re$ the real part of the argument.

The bioheat equation, which provides the temperature distribution inside the human body, accounts for the thermal conduction within the tissues, the effects caused by the blood flow (through a blood perfusion rate coefficient), and the transfer of heat into the environment through convection. The application of Green scalar identity to bioheat equation leads to the following discretized integral equation for each subvolume, where nonhomogeneous Neumann boundary conditions are included to account for the convection heat exchanged with the air:

$$T(\boldsymbol{r})\theta = -\sum_e \int_{\partial\Omega_e} \theta \frac{\partial\psi}{\partial n} ds - \sum_e \frac{h_{amb}}{\lambda} \int_{\partial\Omega_e} \theta\psi ds + \sum_v \frac{1}{\lambda} \int_{\Omega_v} P_{SAR}\psi dv \qquad (3)$$

where θ is the temperature rise, h_{amb} the ambient convection coefficient, and λ is the thermal conductivity. The Green function is defined as $\psi = e^{-k_t r}/(4\pi r)$, being $k_t = \sqrt{h/\lambda}$ a real constant, depending on blood perfusion rate coefficient h. In Eqn. (3), the last integral is evaluated by discretizing the internal volumes of phantom in tetrahedra. Interface conditions over surfaces separating volumes with different properties link temperature rise and its normal gradient between adjacent volumes.

III. MODEL VALIDATION

The BEM thermal solution is first validated by comparison with analytical solution, considering two concentric spheres, where a P_{SAR} is imposed in the inner one. The accuracy of the numerical solution is shown in Fig. 2, considering two meshes of the sphere surfaces.

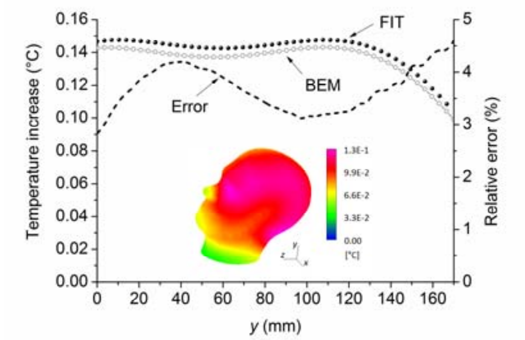

Fig. 3. Spatial behavior of temperature increase computed along a vertical line in the centre of SAM phantom: the BEM and FIT solutions are compared. The distribution of temperature increase on the phantom surface obtained by BEM is also shown.

The exposure of a phantom (Specific Anthropomorphic Mannequin) to the electromagnetic field generated by a 100 MHz antenna loop is finally considered. The power absorbed by the phantom is 100 mW, giving rise to the temperature increase shown in Fig. 3, where results computed by BEM are compared with the ones provided by a Finite Integration Technique.

IV. REFERENCES

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