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The electromagnetic-thermal dosimetry for the homogeneous human brain model

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A B S T R A C T

The electromagnetic-thermal dosimetry model of the human brain exposed to electromagnetic (EM) radiation is developed. The EM model based on the surface integral equation (SIE) formulation is derived using the equivalence theorem for the case of a lossy homogeneous dielectric body. The thermal dosimetry model of the brain is based on the form of Pennes' equation for heat transfer in biological tissue. The numerical solution of the EM model is carried out using the Method of Moments (MoM) while the bioheat equation is solved using the finite element method (FEM). Developed EM-thermal model has been applied for the internal dosimetry of the human brain to assess the absorbed EM energy and the consequent temperature rise due to the exposure of 900 MHz plane wave. Due to the variability of various parameters, the sensitivity of the maximum, minimum and the average steady-state temperature, on the various thermal parameters have been examined, as well as the influence of the parameters variation on the temperature distribution in case of EM exposure. The proposed model may be found useful in the rapid assessment of the temperature distribution in the human brain, prior to having to deal with a tedious development of a more complex models.

1. Introduction

Normal brain functioning strongly depends on maintaining a stable temperature within a very narrow range. Deviation from the normothermal state by 1 °C may indicate certain health disorders [1]. Although such an increase in temperature may have effects on almost all body organs, the brain functions seem to be particularly sensitive to heating [1,2]. It is well known that temperature affects the oxygen affinity of hemoglobin as well as the rate of chemical reactions [2].

The most important mechanisms responsible for the mammalian body temperature regulation are very well known. The mammalian brain temperature is determined by the rate at which brain cells generate heat, the amount of the blood flow and the temperature of the blood supplying the brain. Moreover, the temperature of the brain superficial layers is affected by the heat exchange through the scalp and also via the skull base [3]. This thermal equilibrium can be perturbed if the brain is exposed to the EM radiation, typically from cellular phones or other wireless devices. Also, it is a well established fact that the principal biological effect of this high frequency EM radiation is predominantly thermal in nature [4–6].

According to international standards/guidelines [7], the temperature elevation in the human brain is listed as one of the most concerns as well as in the eye. The limit is prescribed in terms of specific absorption rate (SAR) as a surrogate of temperature elevation. The limit is 2 W/kg for general public and 10 W/kg for occupational exposure [7], respectively. Thus, there are many computational studies to relate SAR and temperature elevation in the brain [8–11]. This is because an experimental measurement of the brain thermal response is not possible due to the inability to directly measure the brain temperature in healthy humans. On the other hand, the indirect methods such as the magnetic resonance imaging lack the resolution necessary to record small temperature variations. The animal studies, on the other hand, are of questionable significance due to the interspecies difference. Consequently, the computational modeling appears to be a powerful alternative, especially to discuss the individual variability of induced physical quantities [12].

In addition to modeling the thermal response of the human head or brain exposed to undesired EM radiation [8–11], the thermal model of the brain can be used elsewhere, e.g. to investigate the effects of the targeted brain hypothermia [13,14], the thermal effects due to the deep brain stimulation [15], or can even aid in modeling the temperature regulation in the brain during the

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functional activation [16,2]. These and various other theoretical models range from a geometrically rather simple hemispherical models of the human brain [17,13], to an anatomically based human head models [8–11], featuring the use of a number of various brain tissues.

These detailed models are usually solved via the most commonly used numerical method, i.e. the finite difference time domain (FDTD). This technique is a robust and conceptually simple to implement, but it has some inherent disadvantages. One of the major drawbacks of FDTD is the so-called staircasing effect, where the discretization of the irregular external boundaries may result in the underestimation of the temperature, leading to considerable modeling errors [18,19]. Although, the refinement of the grid may reduce the negative effects to a certain extent in case of EM simulation, the problem in case of thermal simulations still remains [18]. Contrary to FDTD, the finite element method (FEM), or methods such as dual reciprocity boundary element method (DRBEM) and Meshless methods, using the adaptive geometry grid, do not suffer from this problem. The increase in the number of tissues included, as well as the increase in the geometrical complexity, provides higher accuracy at the price of a more complicated development of the model and higher computational cost. In these circumstances, IEEE International Commission on Electromagnetic Safety has established new subcommittee named EMF dosimetry modeling in 2014 in order to resolve the computational uncertainty and provide data/tool.

This paper proposes a compromise between the two opposed requirements. The EM-thermal dosimetry model of a homogeneous human brain of arbitrarily complex shape is presented.

The use of electromagnetic model based on the surface integral equation (SIE) formulation provides a benefit of reducing the dimensionality of the problem since discretization of only the boundary is necessary. Moreover, the surface of the brain can be described to a desirable level of detail, without having to tackle the staircasing problem. The same staircasing problem can be alleviated also in the thermal dosimetry model. At the present state, the numerical solution to this part was obtained using FEM, while, in the future, boundary element method implementation could also be possible.

The paper is organized as follows. In the first part the EM model based on the SIE formulation is derived by using the equivalence theorem and the appropriate boundary conditions for the case of lossy dielectric object of an arbitrary shape. An efficient scheme of the MoM for the solution of the set of coupled integral equations is used. The second part deals with a thermal model of the human brain based on the form of Pennes' equation and the appropriate boundary conditions. The obtained numerical results for the electric and magnetic fields, respectively, on the brain surface are given, as well as the SAR distribution. The numerical results for the steady-state temperature distribution in the brain, as well as the temperature rise due to exposure to plane EM wave, are given in the following section. Finally, the sensitivity analysis of the results due to variations of the thermal parameters is carried out for the steady-state case as well for the case of a human brain exposed to plane wave radiation.

2. Methods

2.1. Electromagnetic dosimetry model

The human brain exposed to incident EM radiation is treated as a classical scattering problem. The EM dosimetry model can be derived from the equivalence theorem and the appropriate boundary conditions for the electric field leading to the SIE formulation.

The human brain, represented by an arbitrary shape S of a complex parameters (ε_2, μ_2) is placed in a free space with given properties (ε_1, μ_1), as shown in Fig. 1a. The complex permittivity of the brain is given by

$$\varepsilon_2 = \varepsilon_0 \varepsilon_r - j\frac{\sigma}{\omega} \tag{1}$$

where ε_0 is the permittivity of the free space, ε_r is the relative permittivity, σ is the electrical conductivity of the brain, and $\omega = 2\pi f$ is the operating frequency.

The lossy homogeneous object representing the human brain is exposed to the electromagnetic field $(\vec{E}^{inc}, \vec{H}^{inc})$. This incident

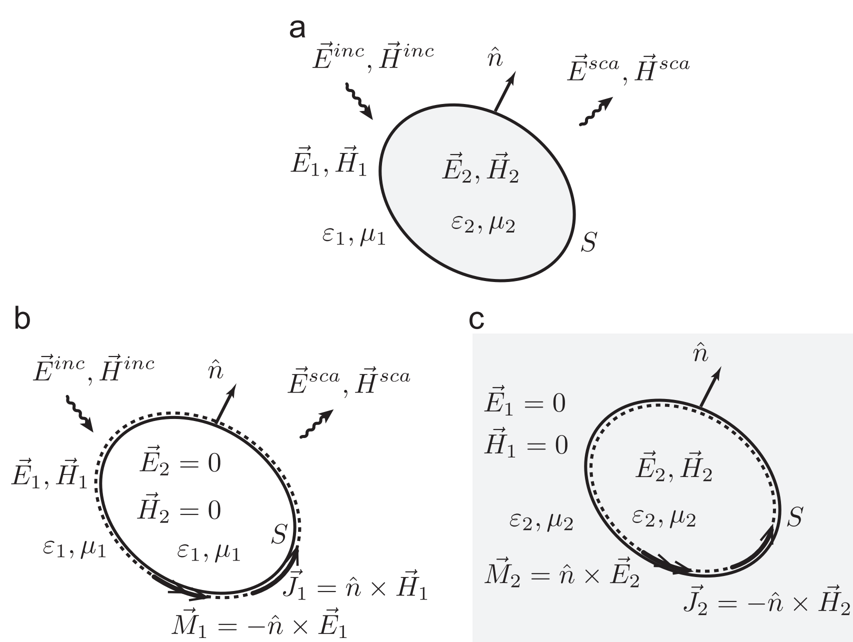

Fig. 1. Scattering from arbitrarily shaped lossy homogeneous dielectric placed in the incident field $(\vec{E}^{inc}, \vec{H}^{inc})$. (a) Original problem. (b) Equivalent problem for exterior region. (c) Equivalent problem for interior region.