Title: Electromagnetic-thermal dosimetry of the human brain - Application to transcranial magnetic stimulation (TMS)
(Proposed by Dragan Poljak, University of Split, Croatia)

1. WM topic and description

Transcranial magnetic stimulation (TMS) is a non-invasive and painless technique for stimulation or inhibition of certain brain regions. A stimulating coil placed near the surface of a patient’s head is energized by a very short current pulse, generating the time varying magnetic field of high intensity penetrating into nearby tissues such as skull and brain. According to differential form of Faraday’s law, the time varying magnetic field gives rise to the electric field, thus depolarizing or hyperpolarizing the neuronal cell membranes located within a few centimeters of the cortex. When membrane depolarization reaches certain threshold, the action potential is generated. Macroscopically, brain activation occurs in the regions with the highest values of the induced electric field [1]-[4].

TMS has become a valuable tool in not only the study of specific cortex areas, but also in diagnostics and for therapeutic purposes. In addition to the treatment of depression, which is so far the most commonly studied application of TMS, this technique is applicable in treating various other neurological and psychiatric disorders.

Although TMS is a widely used technique, some more research is still to be done, such as the development of highly sophisticated methods to determine the distribution of the electromagnetic fields induced in the human brain. Modeling of brain stimulation is important for not only to determine the exact location and the level of stimulation, but also to clarify the related underlying mechanisms. Numerical modeling is necessary to provide plausible interpretation of the experimental results and to design efficient stimulation systems, such as multi coil designs for focused and deep brain stimulation [5] –[7].

Also, it is a well established fact that the principal biological effect of high frequency EM radiation is predominantly thermal in nature [8]-[10]. If the total power absorbed by the body is high enough, it may break down the protective thermoregulatory mechanisms. These harmful effects can be quantified by the analysis of the body thermal response or the thermal increase in a particular organ can be considered [11].

In addition to modeling the thermal response of the human brain exposed to undesired electromagnetic radiation, the thermal model of the brain can be used elsewhere, e.g. to investigate the effects of the targeted brain hypothermia [12], [13], the thermal effects due to the deep brain stimulation [53], or can even aid in modeling the temperature regulation in the brain during the functional activation [14], [15].

This WM deals with a sophisticated electromagnetic–thermal dosimetry model of the human brain. The electromagnetic model is based on the surface integral equation (SIE) formulation stemming from the equivalence theorem and the appropriate boundary conditions for the case of lossy dielectric object of an arbitrary shape. The thermal dosimetry model of the human brain based on the form of Pennes’ equation of heat transfer in biological tissue. Of interest is to accurately determine the distribution of the specific absorption rate (SAR) and related temperature increase in tissues.

A particular feature of the proposed electromagnetic-thermal dosimetry model is related to the rigorous model of transcranial magnetic stimulation (TMS) based on the surface integral equation (SIE) approach. To the best of our knowledge similar approach in modeling TMS has not been previously reported, albeit integral equation methods are seeing a revival in
computational electromagnetics community. To account for the inductive and capacitive effects, as well as the propagation effects, often being neglected when using quasi-static approximation, a model of a lossy homogeneous brain has been derived from the equivalence theorem and using the appropriate boundary conditions for the electric field. The model aims to provide a more accurate representation of the TMS induced fields and currents, respectively. The numerical solution of the SIE is carried out by an efficient scheme of the method of moments (MoM).

1.1 References


2. State-of-the-art

From the early days, the differential approach has become the method of choice in the
mathematical formulation of the problems related to the assessment of the distribution of the electric fields induced inside biological tissues, and TMS modeling is no exception. The majority of the present methods use quasistatic approximation in determining the distribution of TMS induced electric fields and electric currents in the human brain [1]-[25]. Contrary to the differential equation approaches based on the entire domain discretization, the integral equation based approaches do not require artificial limitation of the problem boundary. Moreover, it requires only discretization of the problem boundary, allowing an additional benefit of reducing the dimensionality of the problem. Furthermore, since boundary conditions are implicit within the integral formulation, open boundary problems are treated in an exact way.

In recent decades, integral equation based approach is seeing a revival in computational electromagnetics community [26]. There are some TMS studies carried out via the boundary element method [7], [27]. Nevertheless, an application of surface integral equation (SIE) analysis methods to TMS has not been reported in the relevant available literature. The development of a rigorous TMS model using the integral equations would thus provide a means for an alternative sophisticated and accurate physical description of the problem.

2.1 References

3. Gaps and challenges

As TMS related electromagnetic fields are of low frequency, the quasistatic approximation is frequently used. The quasistatic approximation neglects the inductive or capacitive effects, as well as the propagation effects, thus allowing simplification of the expressions used for determining induced field and currents. Consequently, the scalar potential distribution satisfies the Laplace equation while boundary conditions are the same as those in the case of electrostatic or magnetostatic field. Although the approximation is valid for low frequencies, as originally formulated in [1], frequency range of modern stimulating coils often exceeds 1 kHz.

However, many studies have shown this approximation to be inappropriate at higher frequencies, as the propagation effects at very high values [2] of tissues permittivity [3], [4], as well as capacitive effects [5] are no longer negligible, and their exclusion could lead to an incorrect determination of the stimulated area [6]-[8]. Nevertheless, as already emphasized, the majority of the commonly used methods are based on quasistatic approximation in determining the distribution of TMS induced electric fields and currents in the human brain.

Experimental studies on the brain thermal response are not possible due to inability of direct measurement of the brain temperature in healthy humans. Also, the indirect methods such as
magnetic resonance imaging lacks the resolution necessary to record small temperature variations. The animal studies, on the other hand, are of questionable significance due to the obvious interspecies difference. Consequently, the development of sophisticated computational models appears to be a powerful alternative.

3.1 References


4. Objectives to be achieved

This WM deals with a rigorous integral equation based model of transcranial magnetic stimulation aiming to provide an accurate physical representation of the problem thus avoiding the use of oversimplified quasistatic approximation. This enhanced human brain model will be of some use not only in therapeutic purposes but also in gaining a fundamental knowledge regarding potential adverse effects on human health due to undesired exposure to non-ionizing electromagnetic radiation. Developed mathematical model could take into account various dimensions, positions, orientations and other parameters of the stimulating device, as well as different values of tissue parameters due to difference in age or sex, for both healthy and ill individuals. Thus, this highly customizable mathematical model could enable the efficient and cost effective method for selecting the optimal parameters for stimulation, as well as the optimization of therapy procedures, i.e. personalized therapy.

5. Proposed research activities

The proposed research activities within the future work will be focused on further improvements of the developed model for the analysis of the human brain exposed to electromagnetic fields. The specific research activities (RA) are, as follows:
RA 1: On one hand, the future work will be related to the development of a more detailed geometrical nonhomogeneous electromagnetic-thermal model of the human brain, that will take into account complex cortical columnar structures, as well as additional tissues such as skin and skull bones.

RA 2: On the other hand, the optimization and improvement of the numerical solution method will be undertaken, as well. This will require some comparisons with well established numerical techniques in dosimetry, such as FDTD, FEM and some hybrid techniques and related trade-off between different numerical methods.

RA 3: An exhaustive analysis of the most important types of TMS coils by using analytical and numerical procedures will be carried out. Particular emphasis will be given to coil efficiency regarding the deep brain stimulation. It will be also worthwhile to compare the obtained results with the results published in relevant literature.

RA 4: The relationship between TMS-induced electromagnetic fields and the propagation of action potentials along nerve fibers will be investigated. Moreover, an antenna theory model of the human nerve exposed to an external electromagnetic field excitation will be developed. This enhanced nerve model will find the application not only in diagnostics and therapeutic purposes but also in gaining a fundamental knowledge regarding potential adverse effects on human health due to undesired exposure to time harmonic or transient electromagnetic fields, respectively. Studies on electrical excitation of nerves, among other aspects will involve; nerve excitation using stimulating electrodes, nerve conduction velocity tests, non-invasive stimulation of nerves via electromagnetic fields, external field coupling to nerves due to the human exposure to electromagnetic radiation sources. Antenna model of the human nerve exposed to an external electromagnetic field excitation will be based on the corresponding Pocklington integro-differential equations in the frequency domain. The governing equations will be numerically handled by using Galerkin-Bubnov Boundary Element Method (GB-IBEM).

Dragan Poljak
(Selected references)

Book chapters


Papers in journals with IF

1. Cvetković, Mario; Poljak, Dragan; Peratta, Andres, FETD computation of the temperature distribution induced into a human eye by a pulsed laser. // Progress in electromagnetics research-pier. 120 (2011) ; 403-421.


Papers in other journals


4. Čavka, Damir; Poljak, Dragan; Peratta, Andres, Comparison Between Finite and Boundary Element Methods for Analysis of Electrostatic Field Around Human Head Generated by Video Display Units. // Journal of communications software and systems. 7 (2011) ; 22-28.

5. Peratta, Cristina; Peratta, Andres; Poljak, Dragan, BEM Modelling of High Voltage ELF electric field applied to a 3D pregnant woman model. // Journal of communications software and systems. 6 (2010) ; 31-38.

6. Amoruso, Vitanantonio; Calò , Giovanna; Lattarulo, Francesco; Poljak, Dragan; Peratta, Andres; Gonzalez, Cristina, A Comparative Study on the Induced Current Density in Humans Exposed to ELF Electric Fields. // Journal of communications software and systems. 3 (2007) , 1; 17-25.


Invited papers on conferences


Conference papers