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Electromagnetic field in transcranial magnetic stimulation

***Abstract**. The results of the research which has been done for the last few years indicate the lack of unambiguous efficiency of transcranial magnetic stimulation (TMS) in the therapeutic area. However, it is effective in the area of diagnosis. In both areas we need to know the electromagnetic field distribution which is determined by the shape of stimulating coil. In the paper we present the analysis of electromagnetic field in the case of the application of a butterfly coil.*

***Streszczenie.** Wyniki badań prowadzonych przez ostatnie kilka lat wskazują na brak jednoznacznej skuteczności techniki przezczaszkowej stymulacji magnetycznej w obszarze terapeutycznym, zawsze jednak pozostaje ona skuteczna w obszarze diagnostyki. W jednym i drugim obszarze dla oceny skuteczności potrzebna jest znajomość rozkładu pola magnetycznego, a rozkład ten determinowany jest, m.in. poprzez kształt cewek stymulujących. W referacie przedstawiamy analizę pola elektromagnetycznego w przypadku zastosowania cewki motylkowej (butterfly coil). (**Pole elektromagnetyczne w procedurze przezczaszkowej stymulacji magnetycznej**).*

Keywords: transcranial magnetic stimulation, eddy currents modelling.
Słowa kluczowe: przezczaszkowa stymulacja magnetyczna, modelowanie prądów wirowych.

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Introduction

Transcranial Magnetic Stimulation (TMS) is a powerful tool with extremely interesting research and therapeutic potentials. Clinical investigations show that active stimulation is indeed more effective than placebo; the antidepressant effect itself is, however, weak. Except the technical parameters of stimulations - the selection of the appropriate stimulation place seems to be the main factor influencing the effectiveness of TMS stimulation in the therapy of the depression. The left dorsolateral prefrontal area is the most often chosen goal of TMS stimulation. It is however one of many places, in which the metabolic dysfunction can be identified in patients with depression [1].

Further understanding of the ways by which TMS changes neuronal function, especially as a function of its use parameters, will improve its ability to answer neuroscience questions as well as to treat diseases. TMS is a procedure that uses magnetic fields to stimulate nerve cells in the brain to improve the symptoms of depression. TMS may be tried when other depression treatments have not worked.

In this study we have used a Low Frequency Magneto-Quasistatic (LF M-QS) algorithm via finite elements method as implemented in the program SEMCAD X (by SPEAG, Schmid & Partner Engineering) [2]. As an applicator of magnetic field we have used butterfly coil placed above the female head model taken form Virtual Family [3].

Numerical model of TMS

Transcranial magnetic stimulation can be treated as an eddy current problem in a low conducting media. The induced currents into human body by a low frequency magnetic field can be computed using three dimensional finite elements and a special formulation of u-A potentials [4] [5] or T-Ω formulation [6].

The magnetic field produced by the butterfly coil (the applicator) is solved using vector Laplace operator equation:

(1) $$-\nabla A = \mu_0 J_c$$

where J_c is the current density vector flowing inside the source coil, A is the magnetic vector potential:

(2) $$H = \frac{1}{\mu_0}\nabla \times A$$

In order to find the eddy current distribution the following equation for scalar potential u must be solved:

(3) $$-\nabla \cdot (\sigma \nabla u) = \nabla \cdot (\sigma (j\omega A))$$

This equation holds in any point inside the human body, provided that the conductivity σ is continuous. At the interface between different tissues the continuity of the normal component of J has to be ensured, that is:

(4) $$(J_2 - J_1)\cdot n = 0$$

and notably at the boundary of the human body one has:

(5) $$J \cdot n = 0 \Rightarrow \frac{\partial u}{\partial n} = -j\omega A \cdot n$$

Equations (3)-(5) represent the strong formulation of the problem. Finally, the eddy currents can be expressed as:

(6) $$J = -\sigma \nabla u - \sigma (j\omega A)$$

It is important to remark that the resolution domain of this problem is bounded to the sole human body.

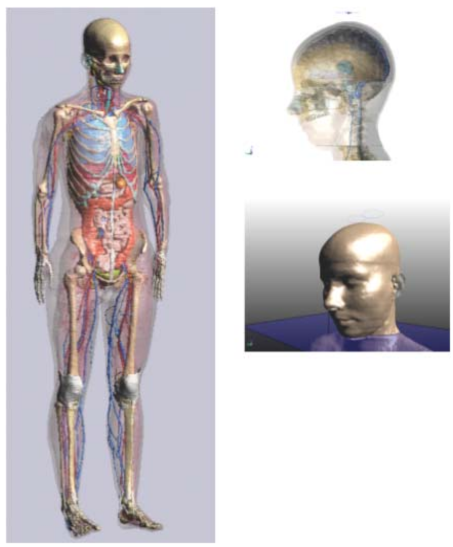


Fig. 1. Ella, 26-year-old woman, height 1.63 m, weight 58.1 kg, 76 segmented tissues

High-Resolution Human Models: Virtual Population

Since 2007, the IT'IS Foundation has been providing the community with state-of-the-art computational whole-body models of humans known as the Virtual Population. Those high-resolution models have been used by more than 300 research groups worldwide and are already regarded as the golden standard in biophysical modelling in whole-body phantoms [vf]. In this research we have used one out of the models called Ella (see Fig. 1). The model under consideration consists of 76 segmented tissues with the spatial resolution of 1 mm.

Database of tissues properties

Dealing with bioelectromagnetic simulations dielectric properties of human tissues play a crucial role like, for example, electrical conductivity which has to be taken into account in eddy current problem formulation. That is why a newest data has to be used and applied in mathematical models.

The database [7] aims not only at providing the most up-to-date and comprehensive estimation of tissue material parameter values but also information about the spread and standard deviation per tissue for the different thermal parameters. This is important when assessing the uncertainty contribution for a quantity of interest due to the selection of the material parameters. For some material parameters (e.g., perfusion), the variation can be large, which, in turn, can strongly affect simulation results.

Electrical Conductivity (S/m)	Direction	Average	Standard Deviation	Number of Values	Min	Max
Blood		6.50E-1	5.00E-2	2	6.00E-1	7.00E-1
Bone	Along	1.70E-1	0.00E+0	1	1.70E-1	1.72E-1
Bone	Mixed	9.50E-2	1.00E+0	2	2.00E-2	1.17E+0
Brain (Grey Matter)	Along	2.55E-1	0.00E+0	1	2.55E-1	2.55E-1
Brain (Grey Matter)	Mixed	1.85E-1	1.00E+0	4	7.50E-2	2.55E-1
Brain (Grey Matter)	Across	1.95E-1	0.00E+0	1	1.95E-1	1.95E-1
Brain (White Matter)	Mixed	3.69E-1	3.42E-1	5	5.30E-2	1.12E+0
Brain (White Matter)	Across	9.88E-2	1.88E-2	2	8.00E-2	1.18E-1
Brain (White Matter)	Along	7.97E-1	3.27E-1	2	4.70E-1	1.12E+0
Cerebellum	Mixed	5.79E-1	3.63E-1	7	9.53E-2	1.31E+0
Cerebellum	Across	3.10E-1	9.00E-2	2	2.20E-1	4.00E-1
Cerebellum	Along	1.21E+0	9.60E-2	2	1.12E+0	1.31E+0
Cerebrospinal Fluid		1.79E+0	2.05E-1	2	1.59E+0	2.00E+0
Fat		5.00E-2	3.00E-2	2	2.00E-2	7.80E-2
Heart Muscle	Along	3.90E-1	0.00E+0	1	3.90E-1	3.90E-1
Heart Muscle	Across	1.77E-1	0.00E+0	1	1.77E-1	1.77E-1
Heart Muscle	Mixed	2.92E-1	1.30E-1	5	8.20E-2	4.80E-1
Liver		9.17E-2	2.83E-2	4	3.60E-2	1.40E-1
Lung (Deflated)		1.58E-1	4.78E-2	2	1.10E-1	2.05E-1
Lung (Inflated)		5.52E-2	1.32E-2	2	4.20E-2	6.84E-2
Muscle	Along	1.27E-1	5.78E-2	3	4.00E-2	1.90E-1
Muscle	Across	4.05E-1	1.30E-1	4	1.50E-1	6.00E-1
Muscle	Mixed	2.86E-1	1.75E-1	7	4.00E-2	6.00E-1
Skin (Dry)		1.25E-4	7.50E-5	2	5.00E-5	2.00E-4
Skin (Wet)		1.21E-3	7.85E-4	2	4.30E-4	2.00E-3
Urine		1.71E+0	1.60E-1	2	1.55E+0	1.87E+0

Fig.2. Selected tissues properties taken from [7]

Results

The simulation was carried out using the following parameters: butterfly coil's current amplitude I_{rms} = 1.0 [A], frequency f = 100 [Hz], coil radius r = 2.25 cm, distance between the coil and the head model d = 2 cm. The dielectric parameters of the tissues were calculated for the frequency of the applicator [Hasgall].

Magnetic flux density distribution generated by the coil can be seen in Fig.3 while the magnetic flux profile along the green line in Fig.4. Maximum flux density (i.e. B_{rms} = 13.2 mT) was found in the middle of the butterfly coil, as expected.

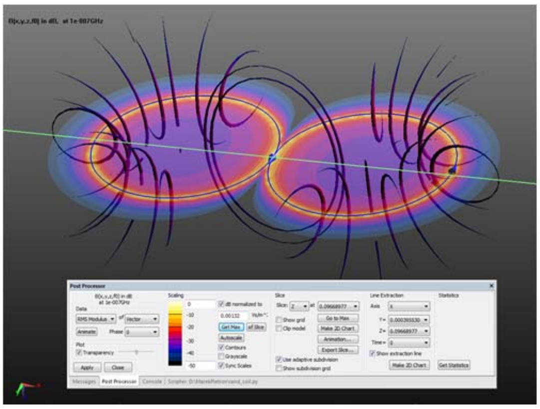


Fig. 3. Magnetic flux density distribution from butterfly coil used as an applicator.

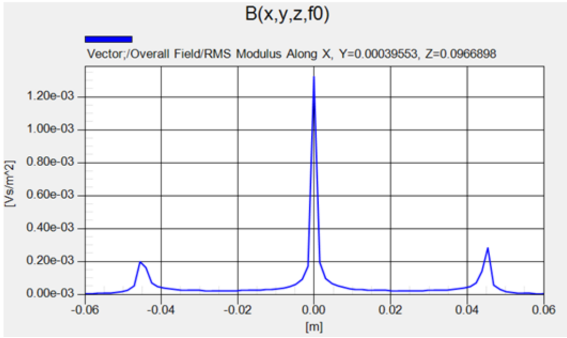


Fig. 4. B-field profile along the green line in Fig. 3.

In Fig.5 can be seen also magnetic flux density but referenced to the head with maximum flux density about $14\ \mu T$.

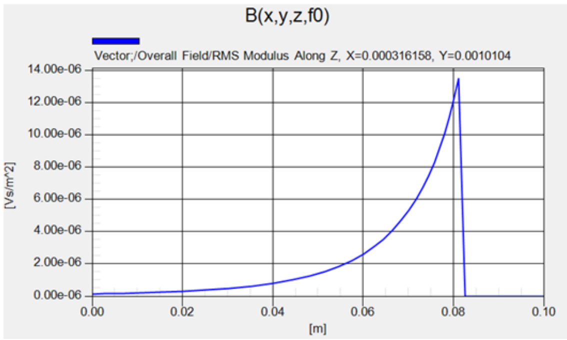
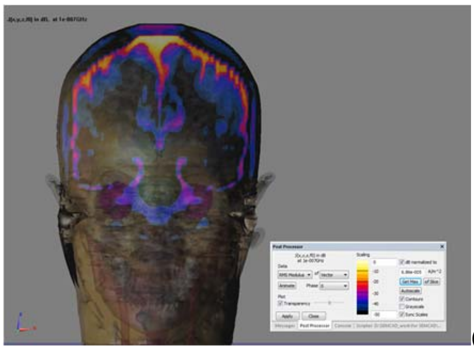


Fig. 5. B-field profile along z-axis in the head.

In Fig.6 can be seen eddy currents distributions and their profile along z-axis in the middle of the head model (see Fig.7.).



(a)

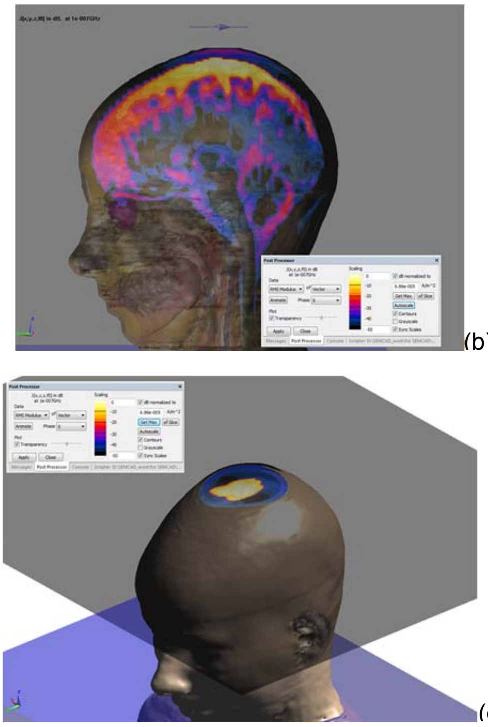


Fig.6. Eddy current distribution in the head (a- coronal plane, b – sagittal plane, c – 3D view).

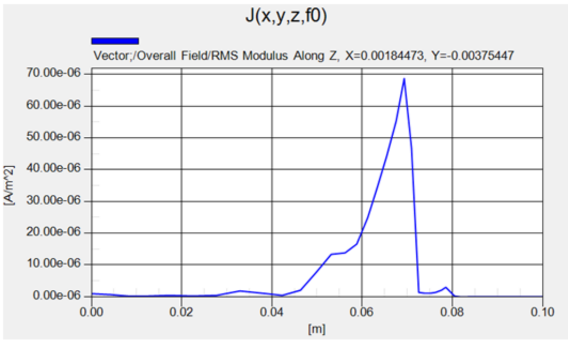


Fig. 7. Eddy current profile along z-axis The attenuation of eddy current as a function of depth in the brain

Conclusions

Transcranial Magnetic Stimulation (TMS) is non-invasive, technique for studying human brain activity by generating a pulsed electric field in the brain. Simulating the exposure generates information concerning the exact location of stimulations, which is important during TMS. In this study the field in the brain is generated with a figure of eight current loop (butterfly coil) placed 2 cm above the head.

Because TMS is a relatively new depression treatment - approved by the Food and Drug Administration (FDA) in 2008 - more studies can help to determine how effective it is, which treatment techniques work best and whether it has any long-term side effects.

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