

Electroconvulsive treatment (ECT) versus transcranial magnetic stimulation (TMS): preliminary data of computer modeling *

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The pilot results from investigations on biophysical processes (current flow) during the electroconvulsive therapy (ECT) and transcranial magnetic stimulation (TMS) are described.

Key words: electroconvulsive therapy (ECT),
transcranial magnetic stimulation (TMS), computer modeling

Introduction

The first electroconvulsive treatment (ECT) was performed more than sixty years ago, i.e., in 1938, by professors Cerletti and Bini in the psychiatric hospital in Rome [cit. after 19]. Since that moment, this physical therapy that consists of “transmitting” through the patient’s head an electric current (electric stimulation) has been included among the instruments of biological therapy in psychiatry [15]. The result of such an operation is the induction of a subsequent discharge of the whole brain neuronal network [2, 24]. Repeatedly applied electroconvulsive treatment leads to specific changes on the level of nerve cells. These changes evoke antidepressant effects (impact on neurotransmitter systems, membrane receptors or/and ion channels) [37]. At the present moment, depressive syndromes are the main disorders in which ECT is applied.

Anatomy of depression

At present, the final “target point” of electroconvulsive therapy is not known yet. The main symptoms of depression (mood disturbances, motor disorders, dysfunction of endogenous rhythms: those of sleep or menstruation as well as appetite) – in their

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classical meaning, in accordance with biological psychiatry – correspond with centrencephalic hypoactivity [38]. This means that the deep structures of the brain, i.e., the area of mesencephalon and diencephalon would be responsible for depression. The newest neuroanatomic research results seem to confirm this hypothesis. They point at the existence of a structural background of affective disorders and place them in the area of hippocampus, amygdaloid formation, thalamus, hypothalamus and base nuclei, that is, in the areas once known as Penfield's centrencephalic system. However, the same neuroanatomic research indicates also comorbidity of depression and structural changes not only in the deep layers of the brain, but also in the cortical structures – especially those of the frontal lobe (mostly in the prefrontal medial area). Cortex of the parieto-occipito-temporal junction and pretemporal cortex are mentioned less frequently [20, 26, 33]. It is interesting that examinations conducted with the use of the techniques of functional neuroimaging also seem to confirm that cortical structures of the brain may be the base of depression. For instance, SPECT and PET examinations evaluating metabolism of brain revealed a significant decrease of brain metabolism in frontal lobes in persons with depression [11].

These results seem to create a bridge between the purely biological theories of depression and the psychological hypotheses derived from the theory of learning, like Beck's cognitive theory or Seligman's "learned helplessness" theory. The latter associates depression not with the deep structures of the brain, but with a specific dysfunction in the frontal lobes cortex (specific disturbances in the sphere of perception and thinking) [3, 25, 32]. Thus, the aim of the electroconvulsive therapy (as well as of pharmacological treatment) is probably to bring about definite functional and structural changes that are to correct both the centrencephalic and cortical dysfunction [38].

The role of convulsive attack

What remains controversial till today is not the problem of electric stimulation of the head, but the occurrence of the accompanying convulsive attack [2, 24]. Since the very beginning, an artificial triggering of an epileptic seizure – even for the therapeutic needs – evoked strong controversy and even stronger protests. Despite its high effectiveness, electroconvulsive therapy remains today the basic method of second choice in treatment of depressive syndromes. This is undoubtedly caused by the problems of moral and ethical nature, which are connected with evoking of "convulsions" [39]. Technical problems connected with execution of electroconvulsive therapy (anaesthetisation, relaxation, use of other anaesthesiological methods) are obviously other reasons why ECT is applied later than drugs and with greater reluctance.

Clinical experience fully confirms the fact that the occurrence of a convulsive seizure is necessary to achieve antidepressant effects and clinical improvement of the patient's health. Methods using sub-convulsive doses of the electric current, including the so-called Giljarowski's electrosleep [12], proved to bring little effect or none at all. Full antidepressant effectiveness of ECT was achieved only when it was accompanied by a convulsive attack.

In our work of 1992, basing on our own calculations as well as on the research of

other authors, we performed an analysis of biophysical processes (here: current flow in the head structure), which constitute the basis for ECT [38]. The analysis consisted in evaluation of the anatomic conditions of the stimulated object, i.e., the head, and the electric properties of the layers constituting this object. The major condition of this preliminary analysis was the thesis that transmission of the electric stimulus to the brain structures was the most important problem in ECT. In the ECT method, electric current encounters on its way obstacles of anatomic-physiological nature (propagation of current in surface layers), which causes its important proportion (ca. 85-95%) to be spread in the surface layers and does not reach the brain.

Six years ago we claimed that this problem seemed possible to overcome with the method of transcranial magnetic stimulation (TMS) – a new neuro-physiological method introduced in the clinical practice in 1985 and applied mostly in neurological diagnostics [1, 5, 6]. In 1993, i.e., a year after our presentation of the theoretical assumptions of the new, potential method of treatment of depression that could be alternative to ECT, the first clinical work on this subject was published. The work discussed the results of TMS treatment of two female patients with drug-resistant major depression [16]. Since that time only about a dozen clinical works discussing the results of treatment with the use of TMS have been published. We discussed some of these in our paper of 1996 [41]. Till today, nearly 150 patients with depression have been treated with magnetic stimulation technique. This, however, in comparison with pharmacological experiments on new drugs, is not an imposing number. On the other hand, the results of studies on TMS are so satisfactory as to encourage further clinical and experimental studies.

The present work does not include results of experimental or clinical research. It discusses the results of our computer studies that regard modeling of physical phenomena accompanying the two above-mentioned techniques: ECT and TMS [18, 40, 42]. The physical phenomenon we examine is the flow of electric current in the structures of the head, conditioned by application of a certain electric potential in ECT [8, 9, 14, 22, 29, 31], or induced with the help of impulsive changeable magnetic field in TMS [4, 7, 23, 27, 28, 31, 35, 36]. In its assumptions, the technique of modeling should be used to work out optimum, i.e., effective and safe parameters of both kinds of stimulation. The present paper is not concerned with modeling of the occurrence and propagation of an epileptic attack in the neuronal net of the brain.

Methodology of research

To perform spatial analysis of physical processes accompanying electric and magnetic stimulation of brain, we used software package OPERA-3D+ (by a British firm *Vector Fields Ltd.*, Oxford). OPERA-3D+ is a general 3-dimensional issues solver, while its component ELECTRA is a module for solving eddy current problems (used in modeling of magnetic stimulation), and TOSCA serves for computing of electrostatic problems (in electric stimulation modeling). The created model is based on a set of Helmholtz type differential equations solved numerically with the finite element method [18].

Our first step in the research consisted of creating a three-dimensional structure of

the head, which was to be submitted to the process of electric or magnetic stimulation. To simplify the procedure, we resigned from analyzing the electric anisotropy (various electric properties of tissues towards directions) of particular layers, including the layer of soft tissues of the head – the scalp, and the layer of bone integument of the skull. In the constructed model, we introduced another simplification, introducing an ideal spherical shape of the head and all its layers (in natural conditions, a head section is an ellipse with the longest radius in the front-back projection). The geometrical model applied in magnetic stimulation was slightly different from that used in electric stimulation. The difference consisted in application of different elements constituting subsequent layers, but their electric properties as well as the thickness of particular layers were preserved.

Figure 1 shows the constructed model of human head together with the determined

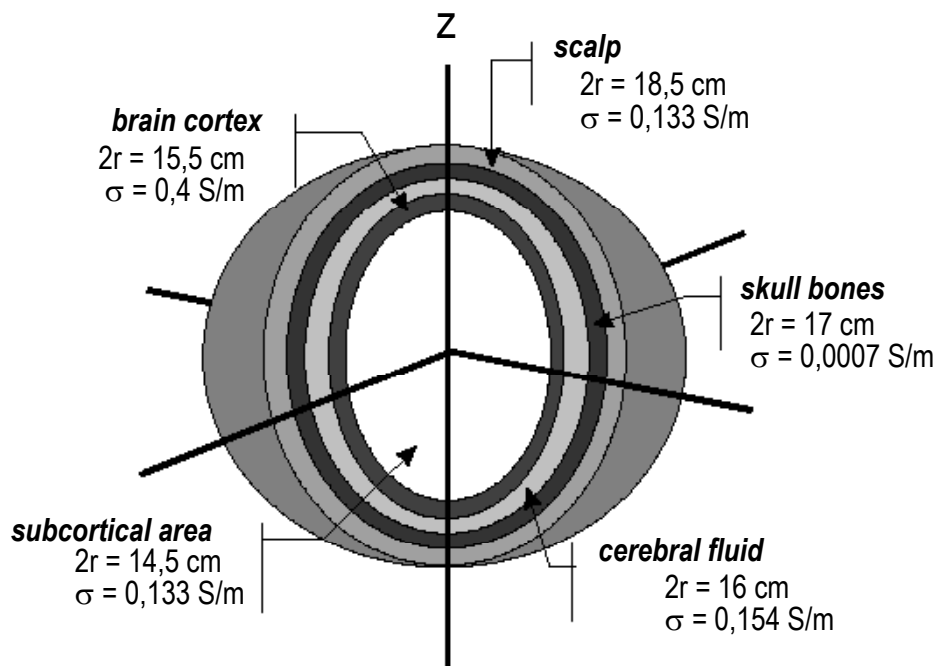


Fig. 1. Five-layer model of the human head: geometrical dimensions and electric properties

geometrical dimensions and selected electric parameters (conductivity) of particular layers.

The second step in our research consisted of submitting the created model of the head to the procedures of electric and magnetic stimulation. Qualitative evaluation was conducted as regards current density (I , [A/m²]) – a physical value reflecting the effectiveness of current flow in biological structures better than its “ordinary” value of current (I , [A]), and values of the so-called current vectors.

Results and discussion

Electroshocks

Electroconvulsive therapy (ECT) consists in attaching to the patient's head contact metal electrodes ($2r = 4-5$ cm; resistance of transmission diminished by a layer of electrolyte gel) connected with the so-called electroconvulsant apparatus (electric stimulator). The apparatus generates alternating electric current of the following technical parameters: voltage $U = 80-250$ V; current $I \leq 1000$ mA; frequency $f = 50-100$ Hz; duration of stimulation $t = 0,2-2$ s; sinusoid or rectangular shape impulse).

In the process of modeling, the following parameters of stimulation were applied: $U = 100$ V; and $f = 50$ Hz. The electrodes were attached precisely on the opposite poles of the head. The research results presented below refer to the electric conditions directly preceding the occurrence of a convulsive attack. Figure 2 shows the distribution of current density for $U = 100$ V.

The cor

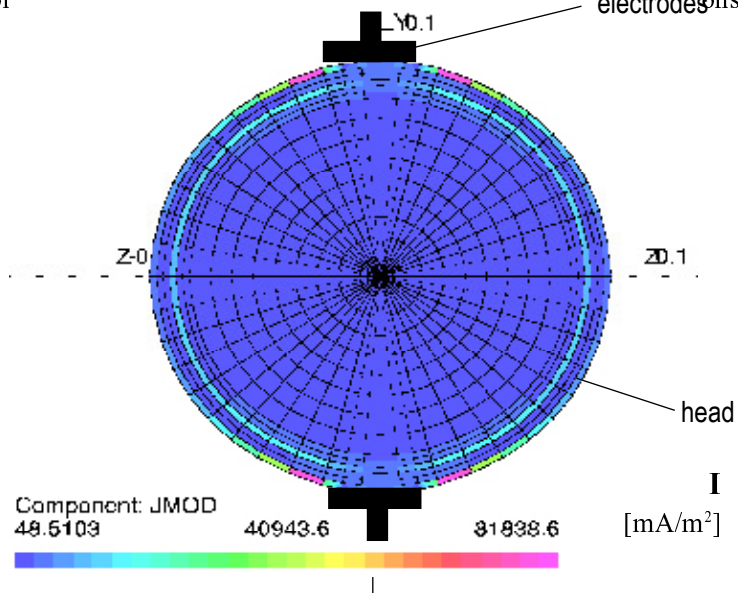


Fig. 2. Electric stimulation of the head (ECT): distribution of current density

assumptions regarding the flow of electric current during ECT. It confirmed distinctly the occurrence of the spreading/crawling effect, i.e., flow of the electric current in the layer of high electric conductivity, below which a layer of higher resistance (lower conductivity) is situated. Distribution of current density and of current vectors in particular layers is demonstrated in Figure 3.

Our analysis of the values of current vectors in particular layers of the head re-

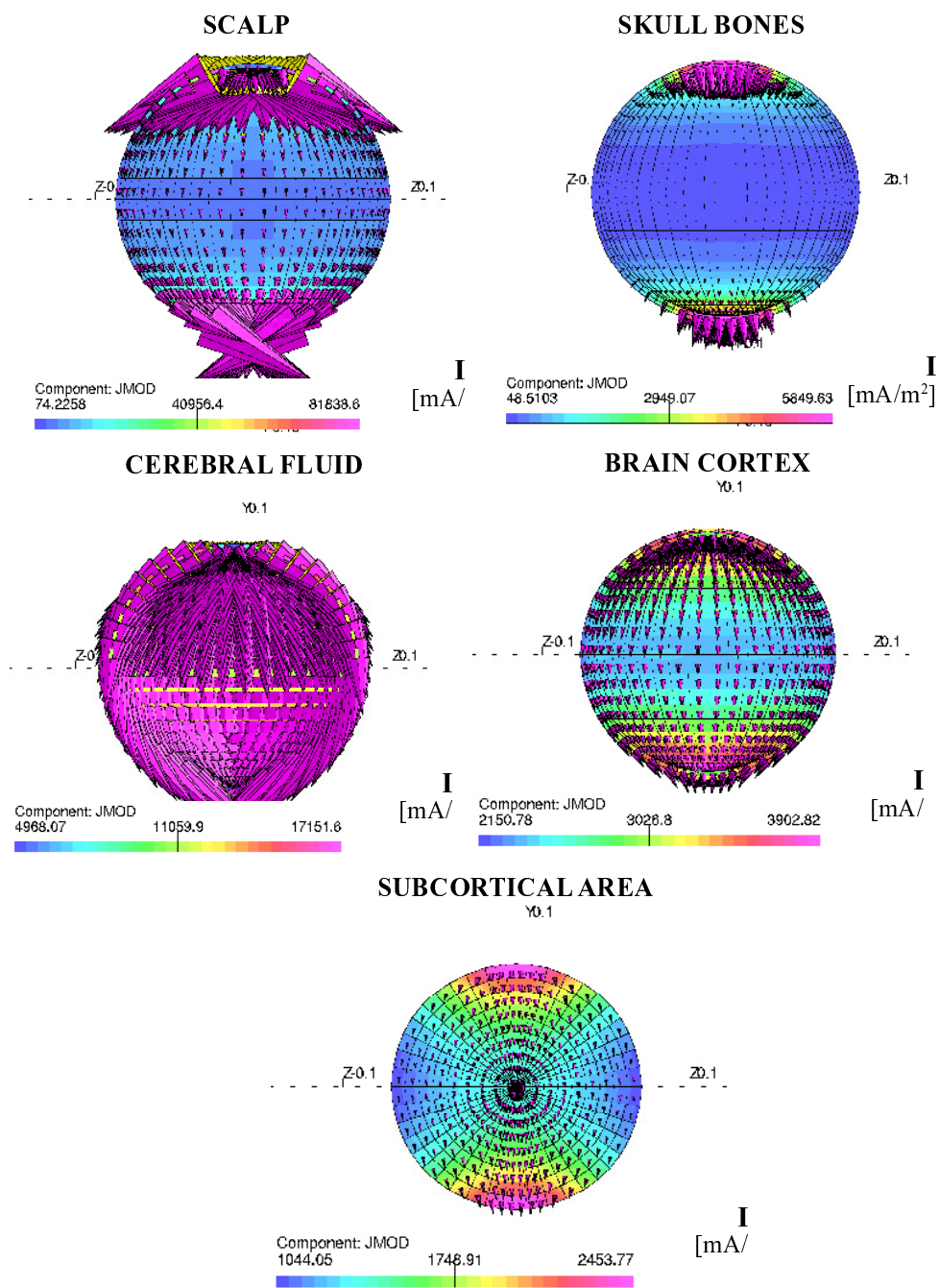


Fig. 3. Distribution of current density and current vectors during electric stimulation of the head – separately for each layer of the head

vealed the existence of not one but two spreading/crawling effects. This effect occurs not only in the scalp layer, but also in that of cerebrospinal fluid. This phenomenon is conditioned by the fact that layers of lower conductivity are situated underneath the former ones – skull bones and brain tissue respectively. The figures presented above as well as our calculations show that it is in the layer of cerebrospinal fluid where the spreading/crawling effect is stronger than that in the scalp. This phenomenon may be explained by the significantly higher value of conductivity in the cerebrospinal fluid than in the scalp, and by the geometrical conditions of situation of the electrodes on the head surface. If the electrodes were placed not on the opposite poles of the head (180°; e.g., bitemporally) but at a much lesser distance, e.g., bifrontally, as it is done in clinical practice ($\approx 90^\circ$), the strongest current flow would occur in the scalp layer. In such a situation, only a minimal quantity of the current applied reaches the deeper layers.

The aim of the “electrostimulating” examinations conducted by the authors was to acquire comparative data for subsequent “magnetostimulating” investigations. The most important of these was information concerning current density in the layers of brain tissue. The values ranged from 1 to 5 mA/mm², and determined the optimum parameters of electric stimulation, i.e., parameters effective for triggering of a subsequent convulsive attack, and safe (not burdening for the brain tissue). Basically, these values did not exceed limiting current for the brain tissue (10mA/mm²), below which no “energetic” disturbances of an organ should be expected [17]. Thus, the method of computed modeling of ECT confirmed that the parameters of stimulation that are selected empirically and applied in commercial electroconvulsors, are biologically safe. Current density in the brain tissue during ECT does not seem to achieve values that are harmful for nerve tissue of the brain. Reservations concerning the possibility of structural injury of the brain during ECT seem to find no sufficient justification in the results of our model investigations.

Magnetic stimulation

In the method of magnetic stimulation (TMS), it is also electric current that is the physical factor stimulating nerve cells. This current, however, comes from a source completely different than that of the current applied in electric stimulation (ECT).

The current flowing in the applicator (the so-called stimulating coil placed close to the head) causes the occurrence of a magnetic field, which can freely penetrate the stimulated area of the head (Fig. 4).

The strong, impulsive (i.e., time varying) magnetic field influencing the conductor

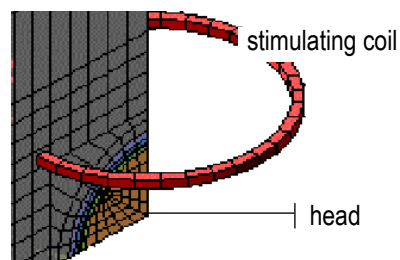


Fig. 4. Topographical structure of the head and the stimulating coil during transcranial magnetic stimulation

(here: closed circuits of neuronal net – brain tissue) causes an electric field of intensity E in its surroundings, which is directly proportional to the changing rate of the magnetic field dB/dt and the radius of the loop radius r :

where B is induction of magnetic field [T] (tesla), t – time in which the value of this

$$E \approx \frac{dB}{dt} \times r$$

field increases to maximum [s], r – radius of neuronal loop [m].

The current flowing in the conductor will be of value I (in fact, current density: [A/m²]), directly proportional to the electric field intensity E ([V/m]) and conductivity of medium s ([S/m]):

$$I \approx \sigma \times E$$

Having exceeded a definite threshold value, this current (called eddy current) is able to stimulate nerve cells, whose activation can be evaluated with the help of various neurophysiological or biochemical techniques.

In the TMS technique, the magnetic field applied to the patient's head is characterized by the following parameters: magnetic field induction $B = 1-2$ T, stimulation frequency $f = 0.25-60$ Hz, duration of a single impulse $t_{\text{wide}} = 0.1-1$ ms, time of impulse rise $t_{\text{rise}} = 10/50-200$ ms, time of impulse decline $t_{\text{decline}} = 100/200-1000$ ms.

In the magnetostimulating model, current parameters of the virtual coil were selected so that magnetic field of induction equal to 1 T was induced on its frontal plane (Fig. 5). This corresponded with current input 3000 A/mm² in the coil of the radius equal to the radius of the head. The rate of impulse courses of 50 Hz frequency and rise times as above was approximated by a sinusoid course with 2500 Hz frequency. From clinical studies we know that this kind of field is able to stimulate nerve cells – at least in the cortex layer.

Figure 6 demonstrates distribution of density of current and current vectors in the head submitted to magnetic stimulation.

It can be seen that the distribution of vectors in all layers of the head is fairly uni-

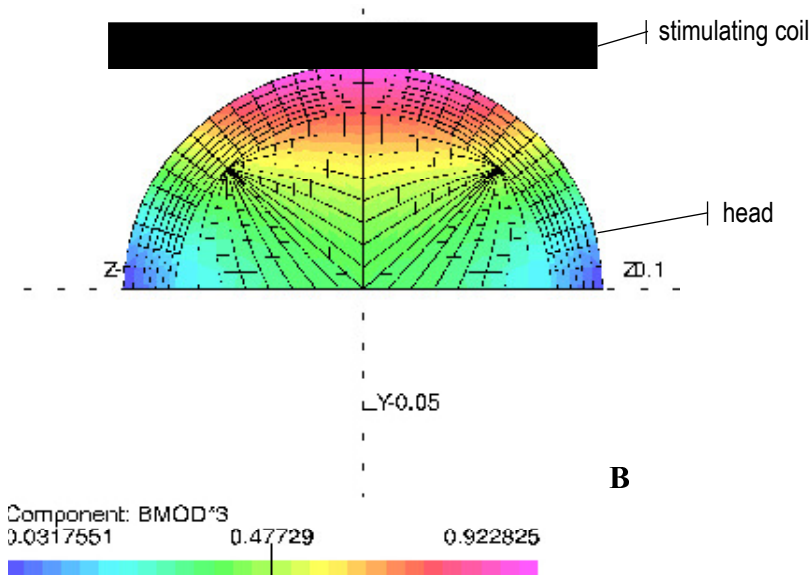


Fig. 5. Distribution of magnetic induction in the head submitted to magnetic stimulation

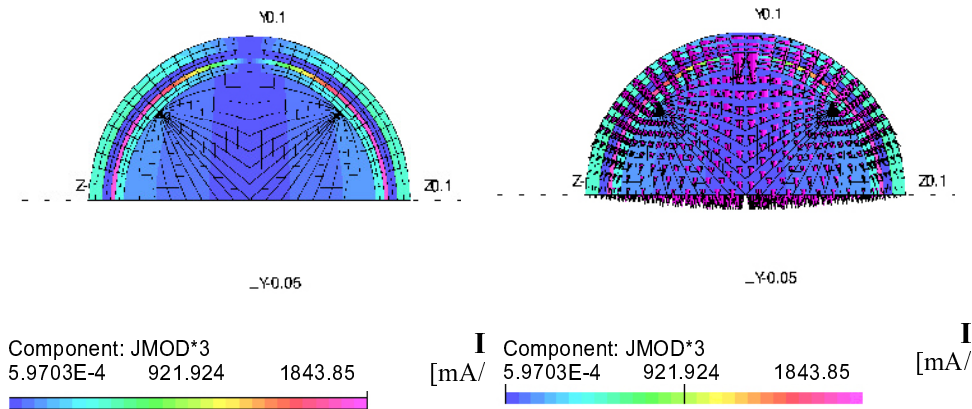


Fig. 6. Density of current and current vectors in the head submitted to magnetic stimulation

form. The distribution of current density in the brain tissue is interesting but requires further study. Current density in the cortex layer was 0.1-1 mA/mm², which actually suggests a lesser current load than that observed during electric stimulation (ECT technique). On the other hand, it is difficult to explain the phenomenon of extremely low density of current in the deeper layers of the brain. Our earlier calculations [38, 41] as well as reports by other authors [1] indicated that a magnetic field could penetrate to deeper layers of the brain and deeper from the head surface than subconvulsive electric stimulation, i.e., that, which does not evoke a convulsive attack. Although at

present therapeutic effectiveness of TMS is not connected with stimulation of deep structures of the brain but with stimulation of the cortical layer of frontal lobes, the results obtained in our model investigations require further explanation and study, or clinical interpretation.

The presented results of the study confirm usefulness of numerical methods for modeling of biological phenomena. Computer modeling allows us to investigate physical conditions of current flow both during electroconvulsive therapy and transcranial magnetic stimulation of the brain. When magnetic stimulation is applied, however, the current charge seems to be much lesser. Nevertheless, even during ECT, the stimulating current did not exceed limiting values. The issue of magnetic stimulation effectiveness in irritating deep structures of the brain requires further study.

Further investigations require a precise selection of optimal, i.e., both effective and safe, parameters of magnetic stimulation. In the future, we expect to create a three-dimensional multi-layer model of the human head, which will correspond with the real conditions, that is, with anatomic and biophysical properties of particular layers of the head better than that used hitherto. We expect to work out limiting values for both kinds of stimulation, i.e., electric and magnetic type (current safety, thermal capacity, etc.). Due to structural and functional anisotropy of the head, we intend to perform modeling in dynamic conditions. Using the so-called genetic algorithms the authors will strive to work out the optimal geometry of the coil and to determine the area of the head best suited for physically effective magnetic stimulation of the brain.

Conclusions

1. Computed techniques are useful in modeling of various biological phenomena like, e.g., current flow in the head of a person subjected to electroconvulsive therapy (ECT) or transcranial magnetic stimulation (TMS).
2. The magnetic field applied in TMS seems fully effective in irritating the surface structures of the brain. Moreover, current charge is markedly lesser as compared with that in ECT.
3. The problem of TMS effectiveness in irritating deep structures of the brain requires further study.

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