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DOI: 10.1515/SBEEF-2016-0014

REVIEW ON ELECTROMAGNETIC STIMULATION OF ALIVE TISSUES

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Abstract. ***The electric, magnetic or electromagnetic phenomena that occur in the biological tissues include: the behavior of excitable tissue (the sources), the electric currents and potentials in the volume conductor, the magnetic field at and beyond the body, the response of excitable cells to electric and magnetic field stimulation (through changes in their electrical activity, changes of chemical transport through cell membrane); the intrinsic electric and magnetic properties of the tissue. This paper presents an overview of fundamental phenomena occurring in the application of stimuli with a future purpose of focusing on several models of external electromagnetic stimulation. The target is to create models of the electroconductive anatomy of some alive tissues will be proposed, in order to investigate the fields and the currents generated by the on-set of an electric field (in the first case) or a time-variant magnetic field (in the second case) or the superposition of the two types of stimuli .***

Keywords: electromagnetic stimulation, biological tissue, stimulation function

I. INTRODUCTION

Among the most important applications of electromagnetic field in medicine are the medical therapeutics (healing processes of bone - fractures, osteoporosis) and soft tissue (reduction of edema, healing burns, tissue regeneration peripheral nervous rheumatic), neurological disorders (Parkinson's, Alzheimer's, epilepsy etc., treatment of drug addiction etc.) and cardiac stimulation. [1-3].

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The anatomical structure will be detailed and it will be assumed to contain linear and isotropic tissues (subdomains). In order to validate the methods and the models, their specific characteristics concerning the proposed field quantities can be computed and analyzed.

Usually, the medical procedures which imply the direct contact between the electromagnetic device and the human body parts (tissues and organs) do not take into consideration several negative effects of field-tissue interaction.

To reduce the harmful side-effects of the applied procedures, some safety factors will be considered, such as the excitation threshold level in the tissues and surrounded subdomains and the maximum values of the activating function in the excitable membranes. The results of the analyzed models will be compared, in order to recommend a highly effective method yielding the safe excitation of the conductive tissue.

Within the stimulation for resuscitation, as well as in the case of therapeutical electromagnetic stimulation it is very important to generate a current density field with optimal distribution with respect to the stimulated tissues; this leads to an inverse problem of the electromagnetic field, poorly conditioned, that needs new models and computation procedures.

It is well known that, in optimization problems, the solution is obtained by testing a large number of direct electromagnetic field problems, solved by numerical methods specific.

The future target is even more complicated because we want to take into account both the stimulus applied electrokinetic (boundary conditions, sources) and the magnetic field lines.

II. STATE OF THE ART

The electric stimulation with an electric or magnetic field and material magnetization includes the effects of these fields applied to biological tissues, using different devices [4].

From the biomedical application, we mention: electrical or magnetic stimulation of the central nervous system, of muscles and motor nerves, the electrical stimulation of the heart, electrotherapy, electro-surgery, electro-magneto-therapy, magneto-therapy, the magnetization of the tissues ferromagnetic contain [5].

Within the biomedical sphere, the last years have brought a tremendous development of the studies and research at international level mainly within the field of electric stimulation, but lately within the magnetic one as well. Therefore, the optimization of the medical existent procedures is wanted, new techniques and models, laboratory experiments and computer simulations are proposed.

A research direction is represented by external stimulation – within this domain, the models have in view the optimization of the external electrodes, regarding their number, position, shape or dimensions and the applied impulse [6]. The efficiency of the procedure takes into consideration minimization of the side-effects on patients (pain, contact tissues injuries) and maximization of the beneficial effects in stimulated tissue.

A novelty is the magnetic cardiac stimulation, more precisely the stimulation with an electric field produced by a time-variable magnetic field. The modeling within this domain has in view the investigation of the induced currents in the body and the characteristics of the defibrillation coil (shape, the number of turns, length) and the applied stimulus [6].

Within the majority of the studies, an indispensable aspect is the numerical modeling of the medical procedures [7]. For this purpose, different models, more or less complex, useful for a certain step of the research, are proposed [8]. The main advantages are: saving time and resources, multiple possibilities of approaching a problem, direct transfer of the results in practice, after pre-established validity criteria. Another advantage is the use of “virtual models” instead of real ones (human or animals), when in certain countries the testing is against the ethical rules.

From the numerical point of view the approach is made using different methods: Finite Element Method (FEM), Finite Difference Method (FDM), Boundary Element Method (BEM); regarding the state, the studies are also diverse, considering stationary or dynamic models, simpler or more complicated anatomic domains, 2D or 3D cases, isotropic or non-isotropic.

III. STIMULATION FUNCTION

The stimulation function used in the numerical models shows what electric quantity is active during the stimulation process. Assuming the coaxial cable model for the cylindrical fiber (the cell), under the action of an activation stimuli, its behavior is emphasized, resulting the space-time variation of the membrane voltage:

$$\lambda^2 \frac{\partial^2 V_m^{'}}{\partial' x^2} - \tau \frac{\partial V_m^{'}}{\partial t} - V_m^{'} = r_0 i_s \lambda^2 \qquad (1)$$

where

$V_{\cdot}^{'} = V_m - V_r$ represents the trans-membrane voltage variation V_m function of its steady-state value V_r

$\lambda = r_{m/}(r_i + r_0)$ - is the space constant

$\tau = r_m c_m$ - represents the time constant

To highlight the stimulation function, the equation 1 can be written as:

$$\lambda^2 \frac{\partial^2 V_m^{'}}{\partial' x^2} - \tau \frac{\partial V_m^{'}}{\partial t} - V_m^{'} = \lambda^2 f_s \qquad (2)$$

The free term of equation 2 represents the growth to be registered by the membrane voltage with respect to the steady-state when subjected to a stimulus to produce depolarization.

The physical significance of the stimulation function can be described both for electric and magnetic stimulation case. For electrical stimulation case, by using an electrodes system connected to a voltage source, a stimulating current is being produced, the corresponding function being in this case: $f_s = r_0 i_s$

For the magnetic stimulation, a time variable electric field is being produced, generated outside the body, the stimulation function being, in this case, the derivative of the electric field strength along the fiber's longitudinal direction $f_s = \frac{\partial E_x}{\partial x}$.

The equivalence of the two stimulation functions can be demonstrated using the cylindrical fiber wiring diagram of the pattern [13].

The positive values of this function give a raise of the membrane voltage to the depolarization threshold, and if they are big enough leading to activation. On the other hand, the negative values produce hyperpolarization. To determine the distribution of this function, one should estimate the induced electric field strength in the area subjected to stimulation.

There are mathematical models [14-15] that allow the optimization of the stimulation procedures, taking into account certain criteria such as efficiency maximization by distributing the stimulation function with maximum values in the targeted area and with values close to zero in the neighboring areas.

IV. MAGNETIC AND ELECTRIC STIMULATION

A. Magnetic stimulation

The magnetic stimulation is a method to stimulate excitable tissue through an electric current produced by a time-varying magnetic field.

The reason for using time-varying magnetic field to produce the stimulation current is its different distribution (as compared to the electrical stimulation case), and the fact that it penetrates more easily regions with increased electrical resistance (such as the skull or other bone), avoiding also the high current density in certain areas of sensory receptors (such as the scalp), and therefore the sensations of pain, being basically a non-invasive method, due to the lack of physical contact between the coil and tissue stimulation concerned.

In magnetic stimulation, one of the key assumptions is that the magnetic permeability of biologic tissue is that of vacuum and has no significant effect on the magnetic field.

Past experiments in this area are trying to prove the effectiveness of this technique and the stimulation of the heart, using the same type of coils as in neuromuscular diseases case.

The magnetic pacemaker includes a coil placed near the skin. To induce a current in the inner tissues, the coil should generate a powerful magnetic field that varies very fast.

In practice, this is generated by charging a capacitor at high-voltage charging a capacitor and then discharge it (with a thyristor) coil. Typical models used in the magnetic stimulation coils are: the multi-layered cylindrical coil, the coil disk type multi-layered coil and the layer cylindrical coil.

Today's magnetic pacemakers generate an energy of 500 J and use 3 ÷ 5 kV for coil operation. Peak values are about 2 T and the maximum of dB/dt is of 5x104 T/s. The energy W required to stimulate the tissue is proportional to the square of the magnetic induction and therefore the square of the product of the electric field strength and pulse duration.

The stimulation of excitable tissue results from the flux of the induced current through the membrane, without which the depolarization and excitation would not be possible.

B. Model of the electric stimulation of the heart

The external electric stimulation of the heart involves two electrodes applied on the thorax in order to defibrillate the cardiac tissue. The purpose is to have fewer side effects on the surrounding tissues, especially on the thorax wall which is in direct contact with the defibrillator paddles.

The heart caption and cardiac function restoring should be made in good conditions that suppose a minimization of the quality factor represented by the ratio R of the maximum current density in the thorax with respect to the maximum value in the myocardium.

An useful example is the 2D stationary model of a real cross-section of the human thorax, a non-homogenous domain containing eight regions (tissues and organs), each of them being considered continuous, linear, time-invariant, homogenous, isotropic (excepting the muscles), with an average value of the conductivity.

The domain can be analyzed using Finite Element Method (FEM), focusing on the efficacy of the transcutaneous cardiac defibrillation that depends on different optimization factors such electrode position, the strength of the stimuli etc.

The paddles can be considered as a superconductive media and the exterior as a perfect insulator.

The resistivities of the organs and tissue were assigned based on values found in the specialized literature.

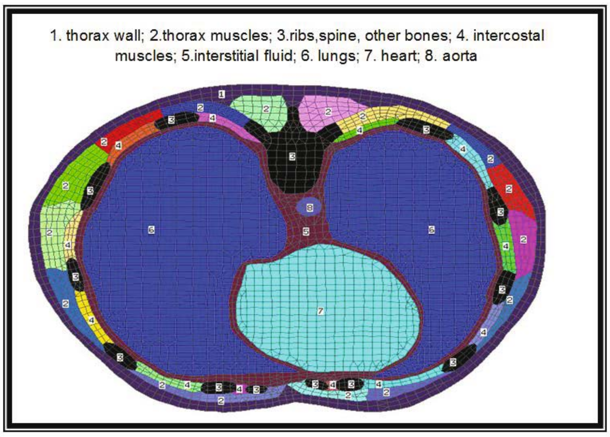

Fig. 1. FEM bidimensional model of the thorax

In order to simulate the anisotropy of the thoracic muscles and predicting the direction of the current density in the vicinity of the electrode, isotropic values of the resistivities can be assigned as follows: the transverse resistivity for the muscles underneath the electrodes and the longitudinal resistivity for the muscles far apart from the electrodes.

The equation to be solved on each subdomain:

$$\Delta V = 0 \tag{3}$$

This equation will be completed by the boundary conditions:

- Dirichlet (the positive electrode $V_+ = 120V$, the negative one $V_- = 0V$)

and

- Neumann $\partial V/\partial n = 0$.

For this basic model the maximum values of the current density have been detected in the interstitial fluid (close to the cardiac apex and the back bone and all around the lungs) and the minimum values inside the lungs and the bones.

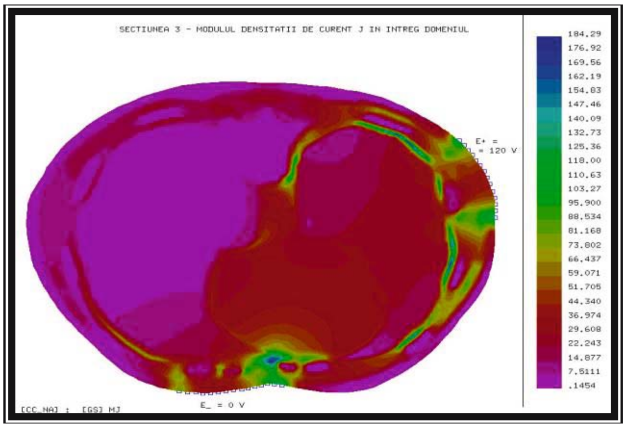

Fig. 2. The current density distribution

V. CONCLUSIONS

Starting from the basic model, the efficacy of the medical procedure can be increased and the negative effects on the patient's thorax can be reduced at the same time with the descent of the transthorax level from the top to the bottom of the sternum.

The numerical modeling in electromagnetic stimulation represents an indispensable aspect of the studies within this research area, not only for the advantage of the time and resources sparing but for the multiple possibilities of the problems approach and the direct transfer of the results.

All the models can be improved, using better approximations of the real situation, as regards all their aspects (geometry, electrical characteristics, regimes, optimization functions etc.).

The paper will be continued as a research on an interdisciplinary field of great interest in the world, biomedical engineering, more precisely the numerical modeling of electromagnetic stimulation of living tissues, based on modern concepts that substantiates similar concerns in the advanced countries in terms of scientific and technological, by creating the prospect of subsequent realization of experimental models that can be tested in vitro and in situ tissue. New models of the electric, magnetic and mixed stimulation and techniques for determining the current density field will be further developed.

VI. ACKNOWLEDGMENT

This work has been funded by University Politehnica of Bucharest, through the "Excellence Research Grants" Program, UPB – GEX. Identifier: UPB–EXCELENȚĂ–2016 Research project title "Stimuli electromagnetici pentru tesuturile vii" (Electromagnetic Stimuli for alive tissues), Contract number 73 (acronym: SEMBIO).

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