Numerical Modeling of Electromagnetic Field in the Biological Cell

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Abstract— This work demonstrates how a stochastic model can be implemented to obtain a realistic description of the interaction of a biological cell with an external magnetic or electrical fields. In our model formulation, the stochasticity is adopted by introducing various levels of forcing intensities in model parameters. The presence of noise in nuclear membrane capacitance has the most significant effect on the current flow through a biological cell. The increasing amount of data reporting on the biological effects of magnetic and electric fields is leading researchers to understanding of how important it is to fully understand the mode of action of magnetic or electric fields to living organisms. Indeed, even if the perturbations of biological systems by magnetic or electric fields are sublethal at shorter times of exposure, these perturbations could, especially at longer times of exposure, evolve into a progressive accumulation of modifications, whose ultimate effects still need to be clarified.

1. INTRODUCTION

The influence of static magnetic fields (SMFs) or modulated magnetic fields (MFs) on biological systems has been a topic of considerable interest for many years [1, 2]. At the current state of knowledge, the biological effects, both in vivo and in vitro, of SMFs have yet to be unequivocally interpreted. Induced electric currents, unlike time-varying (electromagnetic) fields, are not associated with these fields except during activation and deactivation or when there is movement within the field. The increasing production of electric (EMFs) and magnetic fields (MFs) due to the expanding use of electronic devices in normal life, is encouraging studies on the effects of EMFs and MFs on living organisms, with a view to better protecting human health against their probable unfavorable effects [3]. The recent growing interest in the influence of MFs on life process derives from the concern about their possible harmful effects on human health. Although the data reported in the literature are quite heterogeneous in terms of MF intensity (from 10^{-7} to $10\,\mathrm{T}$), type of field (static or oscillatory), and subjects exposed to MFs (from in vitro cultured cells to humans), a link between MFs and tumor genesis has been suggested [4]. Since the cell fate process under the external stimulation involve the interaction of external field with biological cells dispersed in extracellular matrix (ECM) is important to initially understand such interaction for a single cell. Also, the evaluation of the time scale for such fundamental interactions requires careful theoretical analysis, as precise experimental measurements can be difficult. At a much finer scale, one has to consider how the electric current path will be influenced by the electric transport properties of cell membrane, cytoplasm, nuclear membrane, nucleoplasm, etc.. Typically, a biological cell contains various ions such as K^+, Na^+, Cl^-, Ca^{+2}, etc.. All such ions are also present in ECM, however, with different concentration. As ECM and cytoplasm have different chemical composition, the conductivity of the two medium will also different and hence, the mobilities of the ions. A dielectric membrane surrounds the cellular organelles as well as all the inorganic ions and organic compounds. As a potential difference is maintained due to the presence of the ions across the dielectric cell membrane, the interaction of the cellular field with the external electric fields is to be expected. If the membrane potential difference reached in the range of 0.7–1 V in response to externally applied E-field, structural changes in the membrane occur with the transient pore formation across the membrane, a process known as electroporation. Electroporation is important for many cellular processes. The effect of electric field depends on the pulse duration, field strength and cell type [5]. Although the influence of electric field on various biophysical and biochemical process is known or clinically realized, the fundamental understanding of interaction is still missing.

2. MODEL ASSUMPTIONS

In order to develop a model of electrical analog for a biological cell, a number of assumption are made.

Table 1: Basic model parameters for various cell sizes.

Parameters	Standard value	Lower limit	Upper limit	Used
Extracellular conductivity (σ_0, S/m)	1.2	-	-	1.2
Cell membrane conductivity (σ_1, S/m)	3e-7	1.0e-8	1.0e-6	3e-7
Cytoplasmic conductivity (σ_2, S/m)	0.3	0.1	1.0	0.3
Extracellular dielectric permittivity (ε_0, As/Vm)	6.4e-10	-	-	6.4e-10
Cell membrane dielectric permittivity (ε_1, As/Vm)	4.4e-11	1.8e-11	8.8e-11	4.4e-11
Cytoplasmc dielectric permittivity (ε_2, As/Vm)	6.4e-10	3.5e-10	7.0e-10	6.4e-10
Cell radius (R, μm)	10	5	100	20
Cell membrane thickness (D, nm)	5	3	7	5
Magnetic flux density (B_0, Tesla)	2	-	-	2
Electrical voltage (V)	200	-	-	200
Field frequency (f, kHz)	10	2	200	1 k–100 M

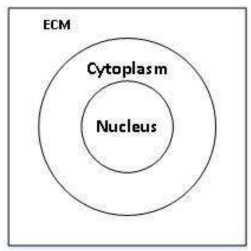


Figure 1: Schematic representation of the cross section of an ideal spherical shaped biological cell embedded in ECM.

3. MODEL DESCRIPTION

The cross section of a spherical cell, embedded in ECM, is shown in Fig. 1. The simple model of the cell is consisted only of the extracellular matrix, the cell cytoplasm and the cell nucleus. Other cellular structures are in this model neglected because their life cycle is very complex and does not exist the easy way to model their behavior. Parameters of the model and used material characteristics are shown in Table 1. The model was developed with the use a rotational symmetry as a two dimensional (2D). Analysis of the electromagnetic field has been divided on the analysis of the magnetic and electric field. For the analysis of the magnetic field has been used element PLANE53 where has been identifying the magnetic vector potential created by the magnetic field of size $B = 2\,\mathrm{T}$. For the analysis of the electric field has been used the element PLANE121. On the top and bottom sites has been specified the electric potential $V = 200\,\mathrm{V}$. In both cases was made a harmonic analysis of which was adjusted by the frequency $f = 1\,\mathrm{kHz}$, 100 kHz, 200 kHz, 400 kHz, 800 kHz, 1 MHz and 100 MHz. The finite element mesh was created by 7778 elements and 23609 nodes.

4. RESULTS OF THE MODELING AND DISCUSSION

The analysis was divided into a few steps. In the first step were analyzed changes in the influence of the magnetic field in the cell and ECM for all frequencies. Material properties that were applied in the magnetic analysis, especially relative permeability which is for all materials differ from one with very small changes, causes changes the magnetic induction ΔB in the ranging $\pm 10\,\mu\mathrm{T}$. To displaying of this small changes were deducted the basic magnetic field of 2 T. To displaying the magnetic field intensity was subtracted value of 1.59 MA/m. The distribution of magnetic flux density and magnetic field intensity is shown in Fig. 2. The changing of the magnetic field are reflected in the cell membrane. The distribution of the magnetic field is not changing with a frequency.

In the next step was analyzed the electric field in the model. There were performed analysis for all of the selected frequencies. In the model were evaluated distribution of the electric potential, the electric field strength, the overall capacity of the model and the capacity of the cell membrane and the ICM. The evaluation of the frequency depending on the capacity is of the Fig. 3. The figure shows that the capacity of ECM is frequency independent and in the entire frequency band takes

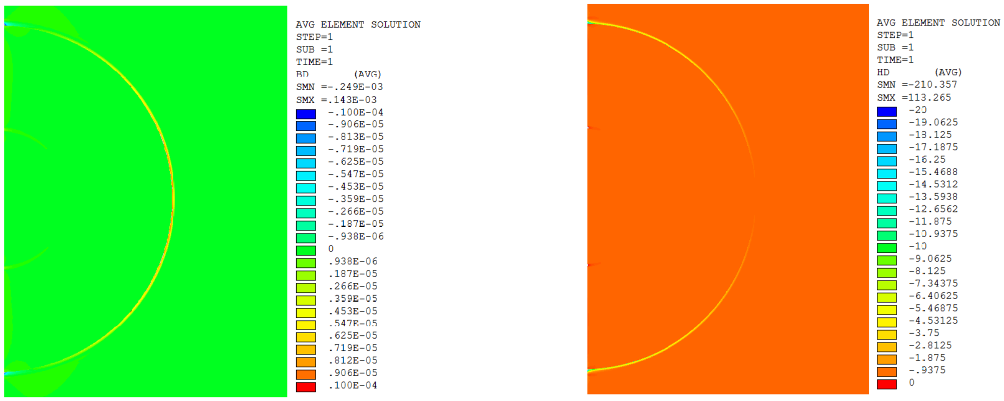


Figure 2: Magnetic flux density **B** and magnetic field intensity **H** distribution in the model.

a value of 11.8 fF. The capacity of the membrane is approximatly constant between values of 1 kHz to 100 kHz. After crossing the frequency $f = 100$ kHz begins the capacity to decline sharply until to frequency $f = 1$ MHz. The capacity drops from 1.61e-13F to 9.8e-18F. After crossing frequency of 1 MHz starts gradual decrease in capacity. The capacity of the membrane contributes of the largest part to the total capacity of the entire model. Due to the decline in the capacity of the membrane start to operate capacities in the ICM. Due this capacity represents the cell membrane a high impedance for frequencies up to 100 kHz and prevents the penetration of the electric field into the ICM. We can say that the membrane behaves as a high-pass filter. In the next step of the modeling we are examined the analysis of the electrostatic field and the change in frequency due to electrostatic field. It was evaluated the overall capacity of the model and other partial capacity of the cell membrane, ICM and ECM. The capacity in the ICM is constant with a value bout 1.18e-14F. The capacity inside the cell varies only little and with increasing of the frequency it increases too. The most interesting result is the change of the capacity of the cell membrane or the reactance. This value decline steeply after crossing the value of frequency 100 kHz to 1 MHz and then is decline finer. The cell membrane has the largest share of the total capacity of the model. The cell membrane can act as a capacitor. It is a high impedance (or resistance) at lower frequencies and at high frequencies is like a little resistance. This property may be likened to a highpass in electrical circuits.

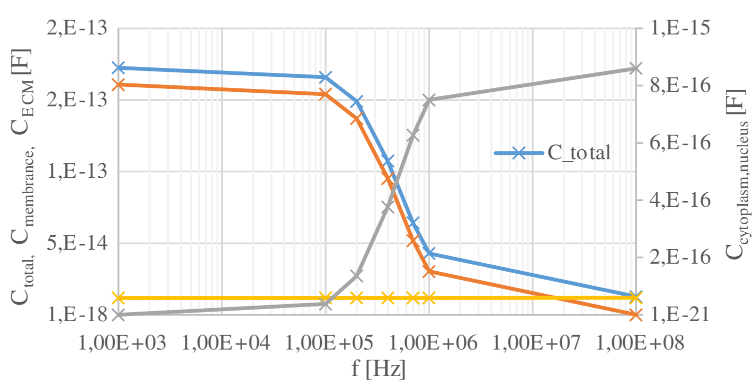
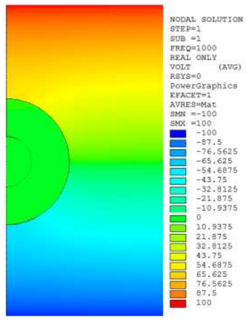
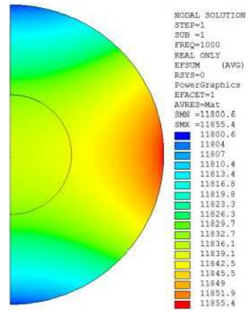


Figure 3: The evaluation of the frequency depending on the capacity.

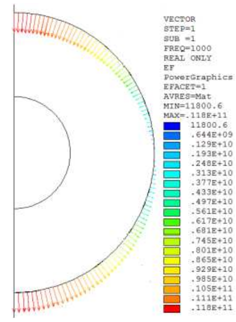
The following figures (Fig. 5) shows the layout of vectors of electrical potential in the throughout of the model and vectors of electrical field intensity in the cell membrane. For low frequencies is inside the cell only little difference of potentials — A few volts and low intensity electric field (intensity difference-gradient). For a frequency of 100 MHz is the potential distribution such the field appears to be with the absence of the cell (the influence of the cell to the field is only minimally) and is evident the big difference intensity of the electric field (Fig. 4).



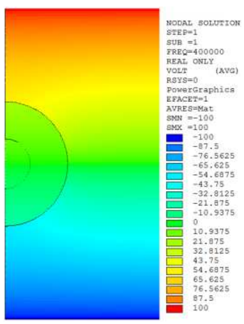
The distribution of electric potential (1kHz)



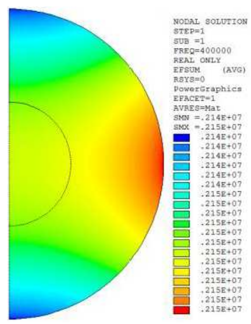
The distribution of **E** (1kHz)



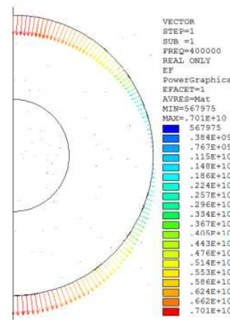
The vector of **E**



The distribution of electric potential (400kHz)

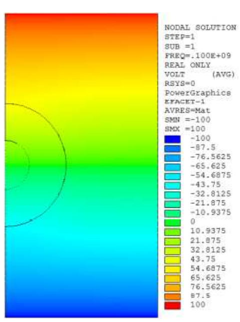


The distribution of **E** (400kHz)

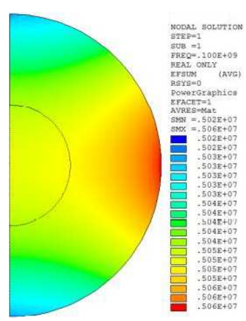


The vector of **E**

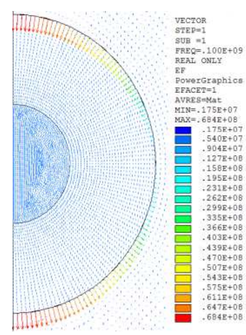
Figure 4: The results of the modeling.



The distribution of electric potential (100MHz)



The distribution of **E** (100MHz)



The vector of **E**

Figure 5: The results of the modeling.

5. CONCLUSION

Information on the cellular effects of magnetic and electromagnetic fields is limited. The results obtained in the present study the first description of the behavior of cell structure exposed to different frequency electric and electromagnetic fields. This fields were created using the program ANSYS and thanks to this the living cells not be used in the experiment. This model could not confirm the influence of magnetic field on the cell structure. This effect could occur in other cell organelles, which can be very difficult analyzed in the numerical model. Electrostatic fields can affect the distribution of the cell charge at very small values of the intensity and could result in a change in certain cellular properties, or change the permeability of the cell membrane to the anions and cations. If are changes in membrane seen at small changes in intensity, the further question of research will be how can be the effect to the cell of the electrostatic field with the large difference of intensity.

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