Modelling of Effect of Electromagnetic field on Changes of Plasma Membrane Potential

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***Abstract*—** Non-ionizing electromagnetic radiation has shown a wide spectrum of biological effects on living cells and tissues. The object of present study is via computer simulations to determine how electromagnetic field affects the cell itself, and how its action can change the electrical properties of the cell.

We found out that electric potential on both sides of the membrane varies under the influence of the electromagnetic field, and its value increases with the increasing frequency. Due to the action of the external low-frequency electromagnetic field, eddy currents are formed in the internal environment of the cell as well as on its surface. Induction of eddy currents is not uniform in the cell. The maximum induction occurs at places which are perpendicular to the axis of the Helmholtz coils. Also, the formation of eddy currents is dependent on the type of environment. Inside the cell, it leads to the induction of a greater degree than in the surrounding of cells, which is associated with a higher value of electrical conductivity within the cell. No eddy currents were induced within the membrane.

***Keywords*—**Cancer transformation, computer simulation, electromagnetic field, plasma membrane potential

I. Introduction

NON-ionizing electromagnetic radiation has shown a wide spectrum of biological effects on living cells and tissues. It can influence cellular activity and division especially of nerve, muscle or heart cells [1, 2] also can stimulate bone growth and accelerate fracture healing [3]. However, low and intermediate intensity electromagnetic field was considered as having no visible and adverse biological effect [4]. Henry Lai based on survey of research papers published since 2006/2007 on the genetic effects of nonionizing electromagnetic fields [5] reports that 82% of biological studies show effects and 18% do not show effects. Furthermore, it is evidenced that magnetic fields individually affect chromatin conformation (6); extremely low frequency magnetic fields cause oxidative DNA damage [7], affect transcript levels of genes [8], and also can decrease reproduction [9]. However, mechanism of its action has been unclear. One of possible explanations is induction of changes of membrane potential of cells.

The resting membrane potential varies depending on cell type within the range of -90 mV to -50 mV. Since the voltage value of the resting membrane reflect many physiological processes in the cell. Its value affects the cell cycle, and all the processes associated with it. The change in resting membrane potential can stop the cell division, or on the contrary can activate mitotic division of the cell. Change in membrane voltage can be induced by change of ion concentration on the surface of the cell membrane as well as inside the cell. However, we would like to know if it is possible to influence the resting membrane voltage by external low-frequency electromagnetic fields and, if so, what effect will have this field to the cell membrane itself, to the internal environment of the cell and also to the surrounding external environment.

The object of present study was via simulations and measurements to determine how electromagnetic field affects the cell itself, and how the action can change the electrical properties of the cell.

II. Methods

To simulate the behaviour of the cells in the outer low frequency electromagnetic field, we established its electromagnetic model. Equivalent electric diagram of the cell membrane (Fig. 1) shows that the cell membrane could be compared to the condensator [10], where one layer represents internal environment of the cell, and the other layer represents the external environment of the cell. Between these layers is located the cell membrane, which is non-conductive, and represents a dielectricum.

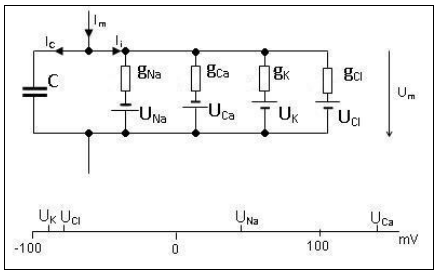

Fig. 1 Electric alternative scheme of cell membrane and typical distribution of balanced voltage [15]

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As parameters for each environment we used parameters *of RC model (Resistor-Capacitor model) of human red cell* described by Gims and Wachner [11] (Table I). Each environment has a defined electrical conductivity g[S/m], which expresses the ability of the environment to conduct electric current I [A]. In any environment is also defined its relative permittivity εr [-].

TABLE I
PARAMETERS OF INDIVIDUAL ENVIRONMENTS OF RC CELL MODEL [11]

	Electric conductivity g [S/m]	Relative permittivity ε_r [-]
External environment	0.12	80
Cell membrane	0.000001	9.04
Internal environment	0.53	50

For the modelling we used spherical shape that is closest to electromagnetic model of the cells. Cross section of the model is presented in Fig. 2. Inner space of the sphere had same parameters as internal environment of the cell, with thickness 0.5 µm in diameter. Inner space was covered by cell membrane that in our model represented dielectricum between two condensator plates. The thickness of the membrane was 0,10µm. Cell membrane was surrounded by plate with external environment parameters with thickness of 0.5µm. This electromagnetic model of the cell we put into homogenic electromagnetic field produced by Helmholtz´s coils.

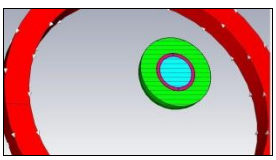

Fig. 2 Cross section of electromagnetic model of the cell

We also focused on determination of electric potentials values on the inner and the outer sides of the cell membrane. We created four connections, each of which connected two different points on both side of the cell membrane. The length of each connection was 0.10 microns, which is equal to cell membrane thickness. The connections are shown in Fig. 3. In all simulations the signal, which energizes the coil was constant.

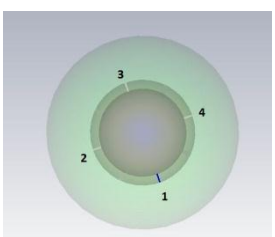

Fig. 3 Connections for evaluation of electric potentials values at both sides of membrane

Electric potential was calculated according to formula:

$$V(r) = \int_{r0}^{r1} E\, dr \quad ,$$

while its values in points r_0 and r_1 we assessed as values on the internal resp. external side of the membrane and at various frequencies.

All simulations we carried out at the different frequencies, ranged from 50 Hz to 500 Hz.

III. RESULTS AND DISCUSSION

Measurements of density of eddy currents and density of power dissipation.

In the model were clearly seen changes of electric properties of internal as well as external environments of cell. In both environments, induction of eddy-currents happened. Their size and direction are shown in Fig 4. The eddy currents induction has occurred mainly at inner side of the cell membrane. In the cell membrane itself, there was no change (Fig. 5).

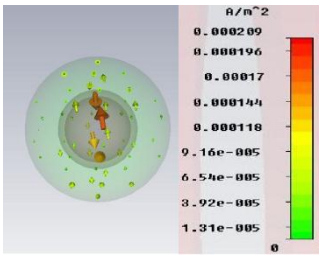

Fig. 4 Electromagnetic model of the cell – current density of eddy currents

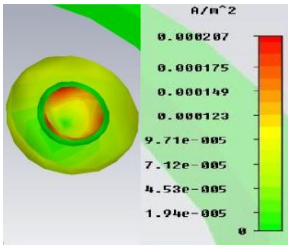

Fig. 5 Absolute value of current density of eddy current at the cross section of electromagnetic model of the cell

In places where eddy currents were induced, we could also see a change in the density of power dissipation. These changes are shown in Fig. 6 on the surface of the cell model, and in Fig. 7 at cross-section of this model. We also observed that in the layer, which represents the cell membrane, there is no change. The greatest changes occurred in the locations, where was also the largest induction of eddy currents. The value of the current density of eddy current and the power loss density are shown in Table II.

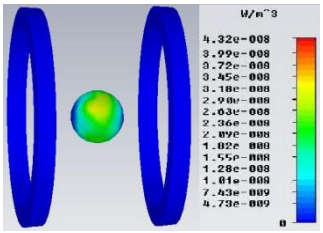

Fig. 6 Density of power dissipation in the electromagnetic model of the cell

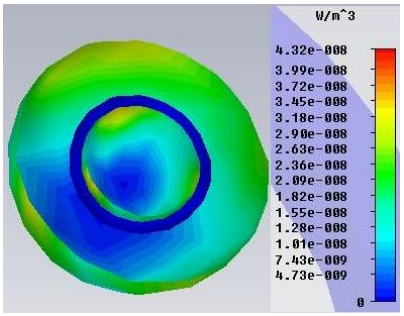

Fig. 7 Density of power dissipation at the cross section of electromagnetic model of the cell

TABLE II
THE MAXIMUM VALUE OF THE CURRENT DENSITY OF EDDY CURRENTS AND DENSITY OF POWER DISSIPATIONIN IN ELECTROMAGNETIC MODEL OF THE CELL

Frequency [Hz]	Current density of eddy currents [Am^{-2}]	Density of power dissipation[Wm^{-3}]
50	2,09307e-005	4,32354e-010
100	4,18614e-005	1,72942e-009
150	6,27921e-005	3,89119e-009
200	8,37228e-005	6,91766e-009
250	0,000104653	1,08088e-008
300	0,000125584	1,55647e-008
350	0,000146515	2,11853e-008
400	0,000167446	2,76707e-008
450	0,000188376	3,50207e-008
500	0,000209307	4,32354e-008

Measurements of electric field at connections

Intensity of electric field distribution along first connection at a frequency of 500 Hz is present in Fig. 8. The x axis expresses the length of a connection, which was 0.10 microns and the y-axis value of the size of the electric field. The upper curve represents the absolute value of the size of the electric field along the connection; lower curve represents the tangential component.

Electrical potentials measured at different frequencies are shown in Tables III- VI. Data presented in tables show that the electric potential on both sides of the membrane varies under the influence of the electromagnetic field and its value increases with the increasing frequency.

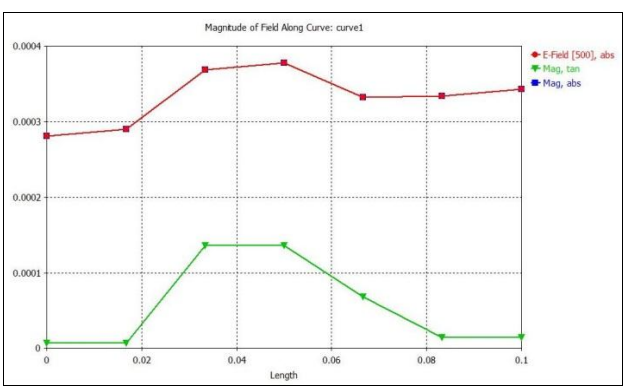

Fig 8 Distribution of electric field intensity along first connection

TABLE III
CONNECTION 1 – VALUES OF ELECTRIC POTENTIAL AT DIFFERENT FREQUENCIES

Frequency [Hz]	Electric potential on inner side of the membrane	Electric potential on outer side of the membrane
50	2,8061e-005	3,4295e-005
100	5,6121e-005	6,8589e-005
150	8,4182e-005	0,00010288
200	0,00011224	0,00013718
250	0,0001403	0,00017147
300	0,00016836	0,00020577
350	0,00019642	0,00024006
400	0,00022448	0,00027436
450	0,00025255	0,00030865
500	0,00028061	0,00034295

TABLE IV
CONNECTION 2 – VALUES OF ELECTRIC POTENTIAL AT DIFFERENT FREQUENCIES

Frequency [Hz]	Electric potential on inner side of the membrane	Electric potential on outer side of the membrane
50	4,0497e-005	3,5848e-005
100	8,0993e-005	7,1696e-005
150	0,00012149	0,00010754
200	0,00016199	0,00014339
250	0,00020248	0,00013184
300	0,00024298	0,00021509
350	0,00028348	0,00025093
400	0,00032397	0,00028678
450	0,00036447	0,00032263
500	0,00040497	0,00035848

TABLE V
CONNECTION 3 – VALUES OF ELECTRIC POTENTIAL AT DIFFERENT FREQUENCIES

Frequency [Hz]	Electric potential on inner side of the membrane	Electric potential on outer side of the membrane
50	2,3083e-005	2,6367e-005
100	4,6166e-005	5,2735e-005
150	6,925e-005	7,9102e-005
200	9,2333e-005	0,00010547
250	0,00011542	0,00013184
300	0,0001385	0,0001582
350	0,00016158	0,00018457
400	0,00018467	0,00021094
450	0,00020775	0,00023731
500	0,00023083	0,00026367

TABLE VI
CONNECTION 4 – VALUES OF ELECTRIC POTENTIAL AT DIFFERENT FREQUENCIES

Frequency [Hz]	Electric potential on inner side of the membrane	Electric potential on outer side of the membrane
50	1,7561e-005	2,1624e-005
100	3,5122e-005	4,3249e-005
150	5,2683e-005	6,4873e-005
200	7,0244e-005	8,6497e-005
250	8,7805e-005	0,00010812
300	0,00010537	0,00012975
350	0,00012293	0,00015137
400	0,00014149	0,00017299
450	0,00015805	0,00019462
500	0,00017561	0,00021624

We can say that due to the action of the external low-frequency electromagnetic field, eddy currents are formed in the internal environment of the cell as well as on its surface, which influences the change of the electric potentials at these points. Induction of eddy current is not uniform in the cell. The maximum induction occurs at places which are perpendicular to the axis of the Helmholtz coils. Also, the formation of eddy currents is dependent on the type of environment. Inside the cell, it leads to the induction of a greater degree than in the surrounding of cells, which is associated with a higher value of electrical conductivity within the cell. Eddy currents are not inducing within the membrane anyway.

This finding enriches current active debate about biological effect of relatively low levels of exposure to non-ionizing electromagnetic radiation produced by radio frequency, microwaves and mobile phones. Some experiments have suggested that they affect alive systems [12 -16], but the evidence for health hazard is contradictory [17]. Our simulation showed that electromagnetic field influences membrane potential. We expect that via this change it could indirectly activate or inactivate biological processes within the cell.

Further research is needed to improve our knowledge in this research area to make clearer the question of effect of low level electromagnetic radiation on the cell.

IV. Conclusions

Based on present simulations we can conclude that electromagnetic fields can influence the electrical potentials on the cell membrane. Change of resting membrane potential thus not depend on the ion concentration on both surfaces of the cell membrane only, also can be influenced by the external electromagnetic field.

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