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Simulation of Cell Dielectric Properties Based on COMSOL

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Abstract

The dielectric properties of cells can be observed by injecting a low amplitude current at different frequencies (1MHz~100MHz). The simulation research is taken on the software platform named COMSOL Multiphysics. The electric field and the cell model is created with prior information. By simulation, it's verified that at low frequencies, the region of interest (ROI) behaves the conductivity characteristic while the electrical signal cannot pass through the cell membrane due to its capacitor properties. With the excitation frequency increasing, the ROI behaves more permittivity characteristic that the current flowing through the cell membrane becomes more and the current density increases. The research of the cell dielectric properties provides an auxiliary method to diagnose the status of the cell.

Keywords: dielectric properties, cell model, excitation frequency, finite element method (FEM), auxiliary method

1. Introduction

1.1 Cell structure

From the biological point, cells are the smallest units that constitute the biological tissues. Most biological cells consist of cell fluid and membrane. The cell fluid can be divided into intracellular fluid and extracellular fluid as shown in Fig.1. Intracellular fluid can be regard as saline solution which consists of water mainly, inorganic salt and other metabolites. Extracellular fluid provides the living environment for cells with appropriate PH value and saline concentration. Both intracellular and extracellular fluid have good electrical conductivity [1].

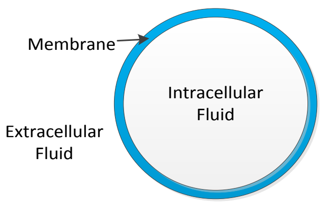


Fig.1. Simplified single cell structure model

The cell membranes are composed of insulating bilayer phospholipid and proteins. The membranes separate the intracellular and extracellular fluid. However, water and some micro-molecular proteins can exchange between intracellular and extracellular fluid, due to the permeable selective characteristic and the structure of the membranes.

1.2 Cell dielectric properties

The specified structure of a cell determines its special electrical characteristics. When a direct current or a low frequency alternating current is injected into the cell, a little or even none current can flow into the cell because of the insulated membrane. This behavior is called low-frequency dielectric property. When the excitation frequency gradually increasing, the membrane becomes electrically invisible and the current can inject into the cell by passing through the membrane. This performance is called high-frequency dielectric property[2]. The current lines flow as shown in Fig.2.

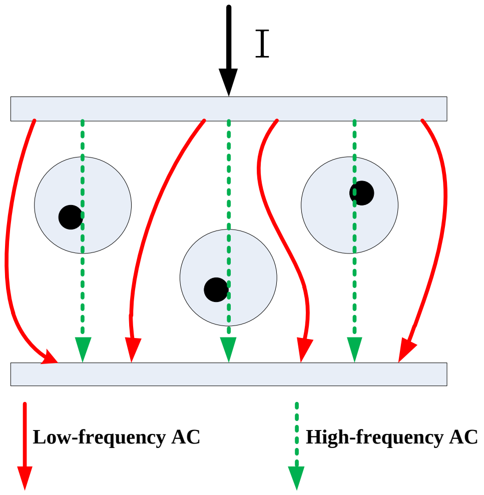


Fig.2. Current flows through the cell

According to the theory of cell dielectric properties, cell membrane has the characteristic of capacitance and the two cell fluids has the characteristic of resistance[3]. The electrical characteristics of single cell can be equaled to an electrical circuit as shown in Fig.3(a), where the parameters represent different parts of the cell.

R_m: equivalent resistance of membrane
C_m: equivalent capacitance of membrane
R_i: equivalent resistance of intracellular fluid
C_i: equivalent capacitance of intracellular fluid
R_e:equivalent resistance of extracellular fluid
C_e: equivalent capacitance of extracellular fluid

While R_m, C_i and C_e are much larger than C_m, R_i and R_e, less current would go through them, so these can be neglected to achieve a simplified equivalent electrical model as shown in Fig.3(b).

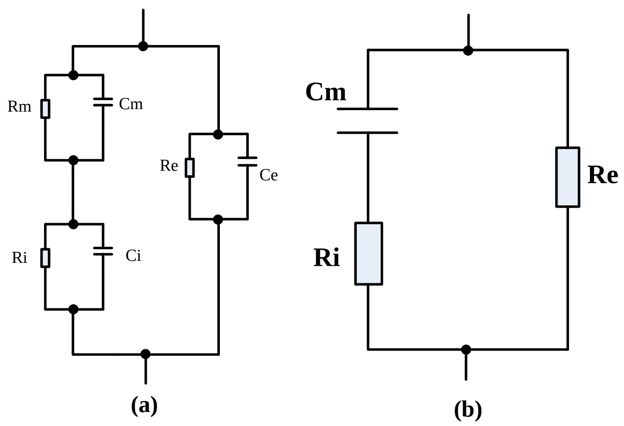


Fig.3(a). A equivalent circuit model of single cell
(b). Simplified equivalent circuit model of single cell

1.3 Finite element method

The finite element method (FEM) was defined and published by Clough in 1960. With the development of computer, the numerical solution of differential equations has been developed and applied a lot. The main idea of FEM is to approach an entire continuous domain by finite discrete domains. The unknown function on the entire domain is represented by functions on each discrete domain approximately[4]. A commercial software named COMSOL Multiphysics is a powerful solution engine.

2. Method

This section uses the software COMSOL Multiphysics to build the model of single cell. The geometric shape of model and the value of dielectric properties of cell are selected referring to blood cells[5].

2.1. Single cell model

2.1.1 Modeling and parameter settings

The parameters of the single cell model is shown in Fig.4. The meaning of the parameters is as follows:

ε_e: permittivity of extracellular fluid
σ_e: conductivity of extracellular fluid
ε_i: permittivity of intracellular fluid
σ_i: conductivity of intracellular fluid
ε_m: permittivity of membrane
σ_m: conductivity of membrane
R: radius of single cell
T_m: thickness of membrane

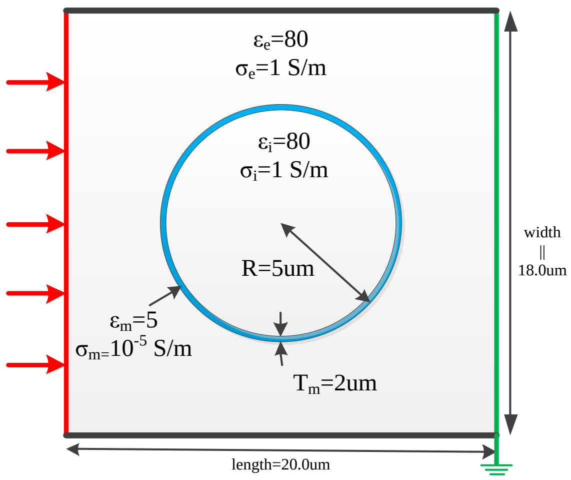


Fig.4. Geometric and electrical parameters of single cell model

As shown in Fig.4, the excitation current with current density of $1A/m^2$ enters the region of interest (ROI) from the left boundary and flows out from the right boundary. The above and bottom boundaries are electrical insulation.

2.1.2 Meshing grid

Meshing is the process by which the active geometrical space (domain) of a model is sub-divided into a collection of sufficiently smaller spaces so that linear or higher order polynomial approximations can be used as a reasonable analog of the functional physical behavior being modeled, which is the core of finite element method.

The software COMSOL is used to generate the grid. If using coarse mesh size (CMS) to structure the grid, the accuracy of calculation results is not enough because of the less grids. But too refined meshing grid takes a lot of memory which leads to long time calculation. All things considered, this paper used normal mesh size (NMS) that the number of generated elements is between coarse mesh size (CMS) and fine mesh size (FMS) to create the meshing grid as shown in Fig.5 and Fig.7.

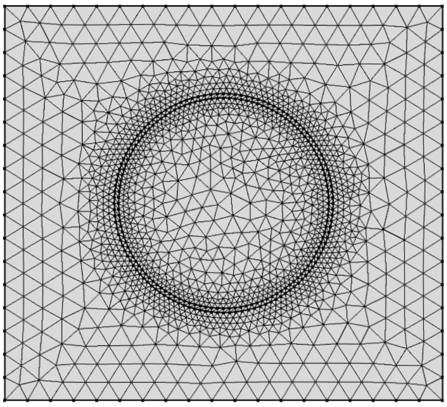
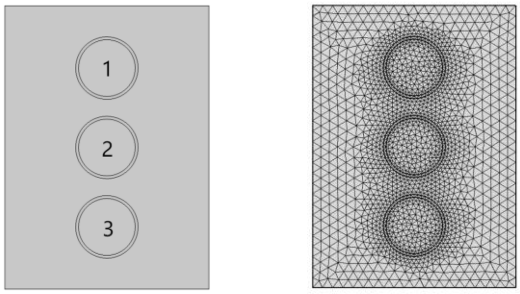


Fig.5. Meshing grid of single cell model
(3014 elements)

2.2. Multi-cell model

Because of the special electrical properties of cell membranes, cells show different characteristics in the electric field with different frequencies and the changes of cell membrane's electrical properties lead to changes on physiological state of cells.

In order to observe the dielectric properties of cells under different physiological states, this paper established a multi-cell model based on the single cell model in section 2.1 as shown in Fig.6(a) and the meshing grid using SMM is shown in Fig.6(b).



(a) (b)

Fig.6(a). Geometric model of multi-cell
(b) Meshing grid of multi-cell model (2962 elements)

And three simulation works were implemented to watch the influence on cells that caused by the changes on the membrane electrical parameters. Table.1 shows the parameters setting of three groups of experiments. The parameters are set as the single cell model in Fig.4.

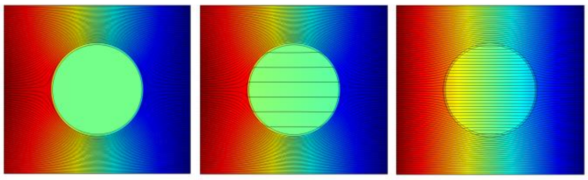
Table.1. Membrane electrical parameters of multi-cell model

	Group A		Group B		Group C	
	ε_m	σ_m (S/m)	ε_m	σ_m (S/m)	ε_m	σ_m (S/m)
1	5	10^{-2}	3	10^{-5}	3	10^{-8}
2		10^{-5}	5		5	10^{-5}
3		10^{-8}	7		7	10^{-2}

3. Simulation result

3.1. Single cell simulation result

The current density distribution at three typical different frequencies (1MHz, 50MHz and 100MHz separately) as shown in Fig.8. It can be observed that there is no current flowing through the cell model at 1MHz. It is because the membrane works as capacitance in parallel with a large resistance. The membrane has high insulation and low conductivity at low frequency. With the frequency gradually increasing, a part of current starts to pass through the membrane at frequency 50MHz. It's apparent that the cell membrane becomes electrically invisible when the frequency reaches 100MHz.The current density in the whole domain is homogeneous.



1MHz 50MHz 100MHz

Fig.8.Current density distribution of single cell at different frequency

3.2. Multi-cell simulation result

Table.2. Multi-cell model simulation results

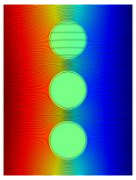
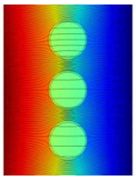
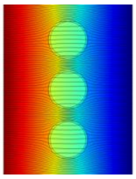
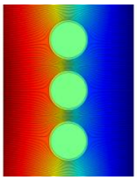
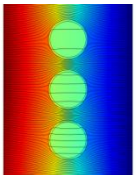
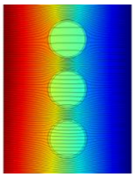
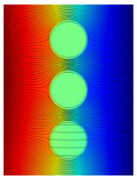
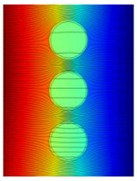
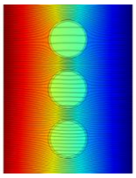
Group A (changes on σ_m)	 1Mhz	 50MHz	 100MHz
Group B (changes on ε_m)	 1Mhz	 50MHz	 100MHz
Group C (changes on ε_m and σ_m)	 1Mhz	 50MHz	 100MHz

Table 2 shows the three sets of simulation results, in the same current field,the three cells with different membrane have respective frequency response. This because the membrane works as a capacitance in parallel with a large resistance, when setting different electrical parameters (permittivity ε and conductivity σ) to the membrane, the value of the capacitance and the resistance changed. The simulation results proves that the change of cell's physiological status can affect its dielectric properties on account of changes on membrane.

4. Discussion

The finite element method has been widely used in mechanics of biological tissue[6]. But at the cell level, there are few papers that introduce the electromagnetic characteristics[7].

This paper preliminarily build a single-cell model and a multi-cell model from microcosmic view and conduct a tentative research at the dielectric properties of the biological cell with finite element method. In view of physiology, most diseases are originated from cell lesion, and the dielectricity of cell is changed earlier than the structural lesion. If the cell dielectricity can be detected by current signal at routine check-up, it's worthwhile for diseases precaution.

The search results of this paper indicate that the different physiology status cells can show up different dielectrical characteristics when is stimulated with different frequencies.

5. Acknowledgements

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