The calculation of the impedance of biological tissue on the model of Yamamoto in the process of galvanic effects

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Abstract. The purpose of this work is to improve the accuracy of research related to the work in the field of modeling and measurement of galvanic processes in biological tissues under the influence of electric current. For this purpose, we propose a refined equivalent electrical model of biotissue and an algorithm for numerical determination of its components.

1. Actuality

Studies of biological materials by the influence of electric current on them are conducted, at least, since 1791, when Galvani published "Treatise on the forces of electricity in muscle movement", which describes the presence of electric current in the muscles of animals. But only now these studies have been widely used in the practice of biological and medical research, which is primarily due to technological progress in this field of science. Such studies include, for example, electrodermal activity (EDA), rheological studies in medicine, galvanization, electrophoresis and others. Such studies are especially important in organ transplantation, where they determine the suitability of donor tissues for transplantation during their storage. With the development of information technology there is a need for adequate equivalent electrical models to improve the accuracy of research.

2. Galvanic properties of biological tissues

Tissues of the body by electrical properties are very heterogeneous environment. Organic substances (proteins, fats, carbohydrates, etc.), which make up the dense parts of tissues, are essentially dielectrics. However, all tissues and cells in the body contain or are washed by liquids (blood, lymph, various tissue fluids) [1, 2]. The composition of these liquids in addition to organic colloids includes electrolyte solutions, so they are relatively good conductors. Thus, biological fluids are electrolytes, i.e. being electrically neutral systems, they consist of positive and negative ions and therefore conduct an electric current, and therefore have an active electrical resistance.

The active electrical resistance of electrolytes depends on the concentration of free ions, their charge, mobility, and temperature. In contrast to metals, the electrical conductivity of electrolyte solutions increases with increasing temperature, as this increases the mobility of ions.
In addition, the tissues of the body consist of structural elements - cells that are washed by a well-conducting electric current tissue fluid. The cytoplasm inside the cell is also a good conductor. They are separated by a poorly conductive layer of the cell membrane. Thus, the biological membrane can be considered as an electric capacitor, the conductor plates of which form the electrolytes of the outer and internal solutions (extracellular and cytoplasm). In biological tissues there are also macroscopic formations consisting of various connective membranes and partitions, which are poor conductors, on both sides of which there are tissues abundantly supplied with tissue fluid. Such a system has electric capacity and, consequently, reactive resistance [3].

When an external electric field is applied in the cells, ions of the opposite sign move and accumulate on both sides of the membrane. This internal field is called polarization, and the phenomenon of formation of the polarization field - polarization of the cell. The phenomenon of polarization is observed not only in cells, but also in macroscopic tissue formations due to the presence of connective tissue membranes and partitions, poorly conducting electric current. Under the influence of an external electric field there is a redistribution of the usual concentration of ions due to different mobility, delay and accumulation of their semipermeable partitions. Thus, the primary action of direct current on the tissues of the body is mainly based on polarization phenomena associated with the movement of ions, their separation and changes in the concentration in different elements of tissues [4].

3. Methods and problems

For biological objects, taking into account the phenomenon of polarization Ohm's law has the form:

$$I = \frac{(U - \varepsilon(t))}{R}$$

where $U$ is the voltage applied to a biological object; $\varepsilon(t)$ is the polarization e. d., $R$ – the resistance of the biological tissue.

Given the above, biotissues have an impedance, the value of which is an important indicator of their properties. Biotissue impedance can be modeled using equivalent electrical circuits [5]. Until recently, the model shown in figure 1 was widely used [6].

![Figure 1](image)

**Figure 1.** Equivalent circuit model of biological tissue:
- $R$ – active resistance of the biological tissue
- $r$ - the resistance of electrolytes
- $C$ – the capacitance of the biological tissue.

Currently, the model shown in Figure 1 is considered to be more adequate in figure 2:
Figure 2. Equivalent circuit model of biological tissue:
R – active resistance of the biological tissue
r - the resistance of electrolytes
C – the capacitance of the biological tissue.

According to this scheme, its impedance $Z$ will be equal To:

$$Z = \frac{r + R\sqrt{1 + r^2\omega^2C^2}}{\sqrt{1 + r^2\omega^2C^2}}$$

(1)

where $\omega$ is the cyclic frequency of the external electric field applied to the biotissue.

However, as mentioned earlier, when an external electric field is applied to biotissues, electrolytes are polarized and, therefore, $r$ is a time function, which is not reflected in the figure 2, none in (1).

4. Proposed solution
4.1 Equivalent model
We propose a method for calculating the impedance of the numerical values of the components found in the supply of stepwise action (Heaviside function) [5] on biotissue on the equivalent Yamamoto model [3, 7], shown on figure 3.

Figure 3. Equivalent electrical model of biological tissue:
R – active resistance of the biological tissue
r - the resistance of electrolytes
C – the capacitance of the biological tissue
Ri-resistor with known nominal value
E-source of stabilized DC voltage
K - device for creating a step impact
A-voltage measurement point relative to " - " E.

4.2. Algorithm
When a step effect is applied to the biotissue [8], the process is shown in figure 4:
Figure 4. Step-by-step Voltages relative to " - " $E$

$E$-stabilized DC power supply voltage  

$U(\pm 0)$ – voltage at point A (Figure 3) at the initial moment of step action  

$U(t)$ - voltage at point A at time $t$.  

At the initial moment of time when the flow speed of the impact of capacity $C$ is discharged, so the voltage $U(\pm 0)$ at point A (figure 3) is equal to  

$$U(\pm 0) = E - U_{Ri}$$

where $E$ is the known stabilized voltage of the power supply and $U_{Ri}$ is the known resistance. Thus, the current at the initial time will be equal to  

$$i(\pm 0) = \frac{E - U(\pm 0)}{R_i}$$

and, therefore, you can calculate the value of $R$  

$$R = \frac{U(\pm 0)}{i(\pm 0)}$$

At time $t$ during the charge of the capacitance $C$, the voltage at point A is equal to $U(t)$, and the current through the resistor $R_i$ is equal to  

$$i(t) = \frac{E - U(t)}{R_i}$$

Thus, the resistance of electrolytes at time $t$ with regard to polarization will be equal to  

$$r = \frac{U(t)}{i(t)} - R = \frac{U(t) \cdot R_i}{E - U(t)} - R$$

herewith  

$$r \cdot C = \frac{t}{\ln \left(\frac{U(\pm 0)}{U(t)}\right)}$$

and therefore,
\[ C = \frac{t}{r \cdot \ln \frac{U(+0)}{U(t)}} \]

5. Practical result

The peculiarity of this method is that its practical implementation requires a high-speed device for the formation of a single impact with a low output resistance. And the need for a synchronized high-speed device for measuring and registering the voltage, but this is currently not technically impossible, and its application allows us to estimate not only the numerical values of the desired values, but also their dynamic characteristics. When conducting comparative experiments, the greatest discrepancy between the results was no more than 11.6%.

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