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Медицина є прикладом інтеграції багатьох наук. Наукові дослідження у сучасній медицині на основі досягнень фізики, хімії, біології, інформатики та інших наук відкривають нові можливості для вивчення процесів, які відбуваються в живих організмах, та вимагають якісних змін у підготовці медиків. Науково-практична інтернет-конференція «**Розвиток природничих наук як основа новітніх досягнень у медицині**» покликана змінювати свідомость людей, характер їхньої діяльності та стимулювати зміни у підготовці медичних кадрів. Вміле застосування сучасних природничо-наукових досягнень є запорукою подальшого розвитку медицини як галузі знань.

Конференція присвячена висвітленню нових теоретичних і прикладних результатів у галузі природничих наук та інформаційних технологій, що є важливими для розвитку медицини та стимулювання взаємодії між науковцями природничих та медичних наук.

Комп’ютерна верстка:
Марія ІВАНЧУК

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У збірнику подані матеріали науково-практичної інтернет-конференції «Розвиток природничих наук як основа новітніх досягнень у медицині». У статтях та тезах представлені результати теоретичних і експериментальних досліджень.

Матеріали подаються в авторській редакції. Відповідальність за достовірність інформації, правильність фактів, цитат та посилань несуть автори.

Для наукових та науково-педагогічних співробітників, викладачів закладів вищої освіти, аспірантів та студентів.

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Methods of parameters measuring of two equivalent electrical circuits of living tissues

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Abstract. Two equivalent electrical circuits simulating electrical properties of living tissues are analyzed. For each of these circuits expressions for calculation of their parameters on the basis of experimental measurements of frequency dependencies of active and reactive resistance of living tissue are obtained, and it is sufficiently these measurements to made at low frequencies which expand possibilities of measurements and provide the avoidance of frequency dependence of these parameters. For one of these schemes, these are such parameters as the electrical capacity of the intercellular substance – membrane - cytoplasm system (transmembrane capacity) (C), membrane resistance $\mathrm{R_m}$ and intracellular resistance $\mathrm{R_i}$, and for the other, the same parameters C and $\mathrm{R_i}$ and intercellular substance resistance $\mathrm{R_e}$.

Key words: bioelectrical impedance, transmembrane capacity, membrane resistance, intracellular resistance, equivalent circuit

1. Introduction

Various electrical circuits with resistors and capacitors are used to simulate electrical properties of living tissues [1-6]. Inductive elements are absent in such circuits, as there are no elements in living tissues, which could produce a significant magnetic flux [7]. It is known that any living tissue consists of intercellular substance and cells, which in turn consist of an outer shell - a membrane, which has both conductive and dielectric properties, and an inner structure – cytoplasm, be a conductor [7]. The conducting properties of the membrane give us reason to assign it a certain resistance, which we denote by R_m. The cytoplasm inside the cell is an electrolyte, i.e. a conductor, it has a certain resistance, which we denote by R_i. Since the cell membrane is also a dielectric, and there are conductors on both sides of it, this system is a capacitor, the electrical capacitance of which we denote C. Let us denote the resistance of the intercellular substance R_e.

The problem is how all these elements of the circuit section should be connected in order to most correctly interpret the experimental frequency dependences of the total resistance $|Z|(\omega)$ (impedance), active$\mathrm{R}(\omega)$ and reactive $\mathrm{X}(\omega)$ resistances of a particular tissue.

The purpose of this paper is to analyze possible equivalent circuits of living tissue and calculate parameters of these circuits based on measurements of frequency dependence of impedance of living tissue at low frequencies of alternating current. Measurements at low frequencies provide independence (or insignificant dependence) of the parameters themselves, especially the electrical capacitance on frequency (electrical capacitance depends on frequency due to frequency dependence of dielectric permittivity of cell membrane dielectric [8,9]) and to avoid negative effect of high frequency current on the investigated living tissue.

2. Methods of equivalent circuits parameters calculating

Consider certain equivalent circuits.

1. A circuit with a capacitor and a resistor in series (Fig. 1a). This circuit is far from the truth [1]. At low frequencies it gives a very large impedance because the resistance of the capacitor $X_c = \frac{1}{\omega C}$ becomes very large (at $\omega \to 0,\ |Z| \to \infty$) which contradicts numerous experiments [1, 3-6, 9-12] (Fig.2)

2. A circuit with parallel connection of capacitor and resistor (Fig.1b) This scheme gives a contradiction to the experiment for high frequencies. Indeed for $\omega \to \infty$ $X_c = \frac{1}{\omega C} \to 0$ and then $|Z| \to 0$ which is not observed in experiments.

3. A circuit with a capacitor and a resistor connected in parallel to which one resistor is connected in series (Fig. 3). Obviously, in this circuit, the resistor R_m models the resistance of the membrane, and the R_i - cytoplasm resistance [1].

a b

Fig. 1. The simplest equivalent electrical fabrics: (a) - section of the circuit with a series connection of resistor and capacitor, (b) - section of circuit with parallel connection of resistor and capacitor R- resistance of cells and intercellular substance, C- capacity of the system intercellular substance - cell membrane - cytoplasm

This circuit reflects the experimental results in the limiting cases much better. Indeed, if $\omega \to 0$ current flows only through the resistors and the total resistance will be $R_m + R_i$, i.e. will have a constant value, and if $\omega \to \infty$ current flows through the capacitor and the resistor R_i and the total resistance will be equal to R_i, that is, it will also have a constant value, which is quite consistent with the schematic experimental curve in Fig. 2.

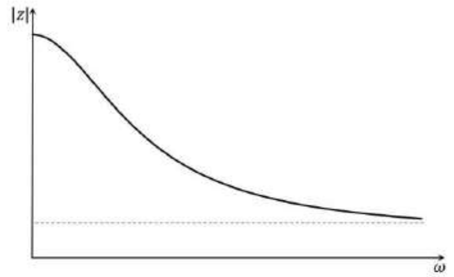

Fig. 2. Schematic experimental dependence of the impedance of living tissue on the frequency of alternating current

To investigate$|Z|(\omega)$, $R(\omega)$, and $X(\omega)$ throughout the all frequency range let us find their theoretical expressions. For this purpose we will find the complex resistance

$$Z(\omega) = R(\omega) + jX(\omega)$$

Where $j = \sqrt{-1}$ is imaginary unit.

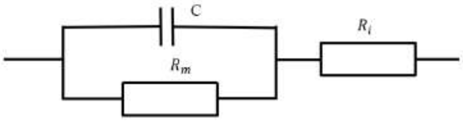

Fig. 3. Equivalent electrical circuit of living tissue. C - electrical capacity associated with the system of intercellular substance - membrane - cytoplasm, R_m- resistance, which simulates the resistance of the membrane, R_i- resistance, which simulates the resistance of the cytoplasm

According to the diagram in Fig. 3, the complex impedance is

$$Z(\omega) = R_i + \frac{-jR_m X}{R_m + X}$$

After algebraic transformations and considering $X = \frac{1}{\omega C}$, we obtain

$$Z(\omega) = R_i + \frac{R_m}{(R_m \omega C)^2 + 1} - \frac{jR_m^2 \omega C}{(R_m \omega C)^2 + 1}$$

The real part of this complex resistance is the active resistance $R(\omega)$, and the imaginary part is the reactive resistance $X(\omega)$:

$$R(\omega) \equiv Re(Z) = R_i + \frac{R_m}{(R_m \omega C)^2 + 1} \tag{1}$$

$$X(\omega) \equiv Im(Z) = \frac{-R_m^2 \omega c}{(R_m \omega C)^2 + 1} \tag{2}$$

Find also the impedance

$$|Z|(\omega) = \sqrt{R^2(\omega) + X^2(\omega)} = \sqrt{\frac{(R_i + R_m)^2 + (R_i R_m \omega C)^2}{(R_m \omega C)^2 + 1}} \tag{3}$$

Find the flex point ω_f of the curve R(ω). To do this we differentiate (1) twice and equate the derivative to zero ($\frac{\partial^2 R(\omega)}{\partial \omega^2} = 0$). As a result we obtain:

$$\omega_f = \frac{1}{\sqrt{3}R_m \mathrm{C}} \tag{4}$$

Substituting the last equation into (1) and denoting R(ω_f) ≡ $\mathrm{R_f}$ we obtain the expression for the active resistance at the flex point

$$R_f = R_i + \frac{3}{4}R_m \tag{5}$$

According to (1), $\mathrm{R}(0) = R_i + R_m$. Let us denote this value by R_0. Then, given (5)

$$R_m = 4(R_0 - R_f) \tag{6}$$

The value R_m can already be calculated because the right side of (6) contains quantities that can be measured. Then by (4) we can calculate the membrane capacity:

$$\mathrm{C} = \frac{1}{\sqrt{3}R_m \omega_f} \tag{7}$$

as well as cytoplasm resistance

$$R_i = R_0 - R_m \tag{8}$$

So, by equations (6) - (8) we can unambiguously calculate the parameters of the equivalent circuit in Fig. 3. and all measurements are carried out at low frequencies, which has great advantages over measurements in a wide range of frequencies, because it guarantees independence of the parameters from frequency and also makes it possible to avoid the harmful effects of such frequencies on living tissues.

From (6) and (8) we obtain the relationship between the measurable quantities

$$R_0 - R_\infty = 4(R_0 - R_f) \tag{9}$$

Let us prove that the frequencies at which the experiment should be performed to calculate the parameters R_m R_i and *C* using this method, are really quite low. The highest frequency at which the resistance should be measured for this purpose is the flex frequency ω_f. The resistance at the flex frequency is given by the relation (5) from where it can be seen that it is not very different from the resistance at zero frequency with (8): $R_0 = R_i + R_m$ that is, the value of R_f is from 75% to 100% of the value R_0. This is also confirmed by experiments. Fig. 4 shows the frequency dependence of the resistance of human muscle tissue from [12]. One can see that R(ω) has a curvature change in the frequency of about 8 kHz.

To find the same parameters we can also use the experimental dependence of the reactance. To do this, find the first derivative of its expression (2) and equate it to zero $\left(\frac{dX(\omega)}{d\omega}=0\right)$. As a result we obtain the frequency at which the reactance reaches its maximum

$$\omega_m = \frac{1}{R_m C} \tag{10}$$

and the value of the reactance at this frequency

$$X_m = -\frac{1}{2} R_m \tag{11}$$

From the last two formulas we find:

$$R_m = -2X_m \tag{12}$$

and

$$\mathrm{C} = \frac{1}{2\mathrm{X_m}\omega_\mathrm{m}} \tag{13}$$

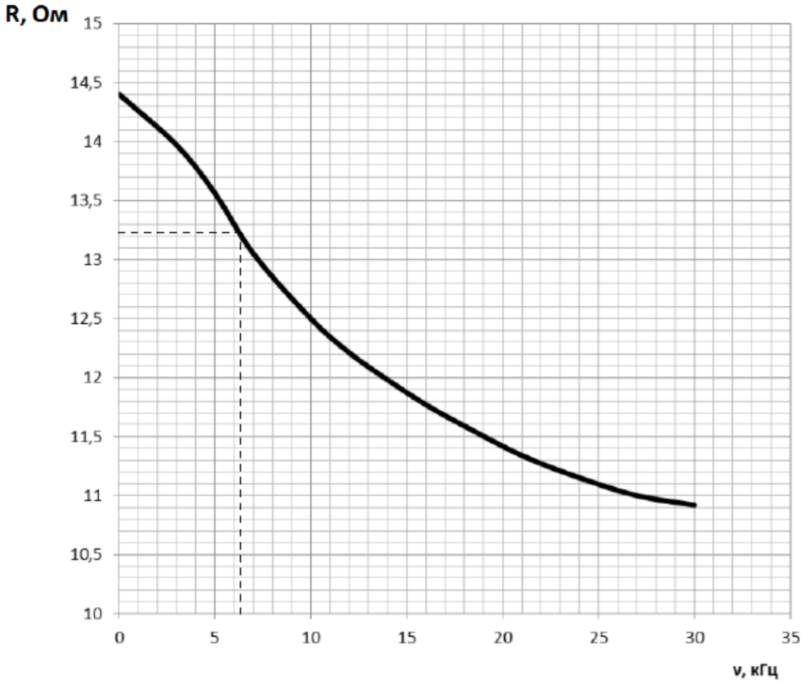

Fig. 4. The frequency dependence of the active resistance of human muscle tissue is based on data from [12]. The dashed lines show the frequency of inflection of this curve and the value of active resistance at this frequency

A schematic experimental curve with all its special points is shown in Fig. 5

Note that in the role of the second equation instead of (11) we can take the equation for $X(\omega)$ at small frequencies. For this purpose, in (2) we neglect the small value $(R_m \omega C)^2$ compared to 1 and we obtain:

$$X = -{R_m}^2 C\omega \tag{14}$$

From this equality we have that the tangent of the slope angle α of the line $X(\omega)$ in the small frequency region is equal to $R_m^2 C$:

$$\mathrm{tg}\alpha = -R_m^2 C \tag{15}$$

Finding the second derivative of $X(\omega)$ over ω and equating it to zero, we obtain other equations for finding R_m и C:

$$R_m = \frac{4}{\sqrt{3}} X_f \tag{16}$$

$$C = \frac{\sqrt{3}}{\omega_f R_m}, \tag{17}$$

where ω_f, X_f - frequency and the corresponding reactance of the flex point of the curve $X(\omega)$

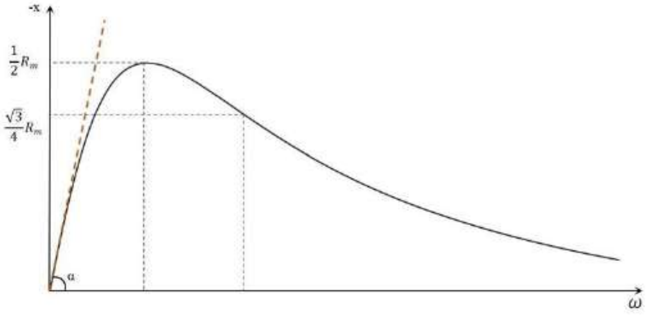

Fig. 5. Schematic experimental frequency dependence of reactive resistance of living tissue. ω_m and ω_f- the frequency of maximum and inflection of the reactance,R_m the same as in Fig.3, α- the angle of inclination of the tangent to the reactance at the point where it is zero

From (12), (13) and (15) we find the relationship between the three quantities being measured:

$$\mathrm{tg}\alpha = \frac{2X_m}{\omega_m} \tag{18}$$

This means that if the experimental curve $X(\omega)$ obeys this equality then it is described by the theoretical curve (1) and therefore the parameters R_m, R_i and C determined from it will be correct. Equation (18) is also advantageous by the fact that it includes only the quantities that are measured at low frequencies.

Obviously, this scheme can be applied to such living tissues in which the intercellular substance can be modeled by a conductor with insignificant cross section, i.e. a conductor with very high resistance (muscle tissues, internal organ tissues, etc.)

4. A circuit with two parallel branches, one of which includes a resistor, and the other - a capacitor and a resistor connected in series (Fig. 6).

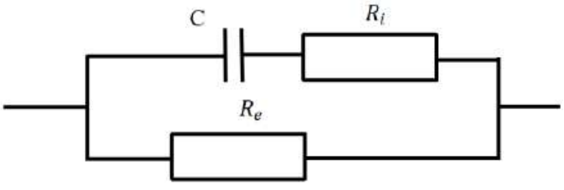

Fig. 6. Equivalent electrical circuit of living tissue. C and R_i is the same as in Fig.3. R_e- resistance of intercellular substance

Obviously, this circuit is applicable to tissues with a significant cross section of intercellular substance (e.g. blood).

Acting similarly to the previous case, we find the resistance of this circuit:

$$Z = \frac{R_e(R_i(R_e + R_i)(\omega C)^2 + 1)}{(R_e + R_i)^2(\omega C)^2 + 1} - j\frac{{R_e}^2\omega C}{(R_e + R_i)^2(\omega C)^2 + 1} \tag{19}$$

and its parameters based on the experimental dependence R(ω):

$$R_e = R_0 \tag{20}$$

$$R_i = \frac{R_f - \frac{3}{4}R_0}{R_0 - R_f} \tag{21}$$

$$C = \frac{1}{\sqrt{3}(R_e + R_i)\omega_f} \tag{22}$$

or based on experimental dependence X(ω):

$$R_i = \frac{R_0^2}{2X_m} - R_0 \tag{23}$$

$$C = \frac{1}{(R_e - R_i)\omega_m} \tag{24}$$

Substituting (20) into (23), we obtain the relationship between the experimental quantities is the same as for the previous circuit:

$$\mathrm{tg}\alpha = \frac{2X_m}{\omega_m} \tag{25}$$

which similarly to (18) for the preliminary circuit, serves as a test equation for fitting the experiment to equation (19).

Conclusion

To interpret electrical properties of different living tissues different equivalent circuits can be used, but in each of these circuits there is a capacitor representing capacitance of the system: intercellular substance – membrane - cytoplasm. By measuring special points of frequency dependence of active or reactive resistance of living tissue, it is possible to calculate this capacitance as well as other parameters of a certain equivalent electrical circuit of this tissue. The methods described above, based on measuring the frequency dependence of bioelectrical impedance, make it possible to calculate this capacitance as well as the appropriate resistances that are present in these circuits. These parameters, in the presence of appropriate and statistically wide experimental data, can serve for estimation of viability of living tissues.

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