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Bioimpedance analysis of the patient's superficial tissues

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A new method for analyzing physiological conditions of the patient's superficial tissues *in vivo* is proposed. Precision measurements of the complex electrical resistance were performed using the bioimpedance spectroscopy method. The design of a diagnostic module for complex non-invasive diagnostics of the physiological condition and processes in the surface tissues of a patient has been developed. An experimental verification of the developed method of bioimpedance spectroscopy was carried out on reference solutions and patient's superficial tissues *in vivo*. A biophysical interpretation of the obtained results is proposed.

Keywords: bioelectrical impedance analysis, bioimpedance spectroscopy, superficial tissues, diagnostic module, cell membranes, intracellular fluid.

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Bioimpedance analysis is a contact method for measuring the electrical conductivity of biological tissues, which makes it possible to assess a wide range of morphological and physiological parameters of the body [1–5]. The method is based on measuring the impedance Z of the whole body or individual segments of the body using impedance analyzers. Bioimpedance analysis of body composition helps to control the condition of lipid, protein and water metabolism of the body and, therefore, is of interest to physicians of various specialties.

In addition to integral assessments of the bioelectrical parameters of the body, it is possible to study individual segments and local areas of the body. Clinical studies shown that the impedance parameters of body regions are sensitive indicators of the condition of patients and, in particular, make it possible to predict adverse outcomes in patients with critical state [6].

Bioimpedance analysis options are classified according to several criteria: probing frequency, body areas, configuration of measuring electrodes and measurement tactics. Depending on the used set of alternating current frequencies, bioimpedance methods are classified as single-frequency, dual-frequency or multi-frequency. In the latter case, the method is called bioimpedance spectroscopy. Bioimpedance spectroscopy makes it possible to quantify the state of organs and systems of the body in various diseases, and also allows you to monitor and evaluate the effectiveness of physiotherapy and other therapeutic effects.

Bioimpedance measurements of individual segments and local areas, in particular the skin and subcutaneous adipose tissue in arbitrary areas of the patient's body, using standard methods, probes and overhead electrodes [7–11] are difficult due to the large surface area of the body, complex structure, as well as a significant difference in the electrical resistivity of the skin and subcutaneous adipose tissue of the patient. Thus, it is fair to say that novel bioimpedance methods for examination of the state of biological tissues and physiological processes occurring in them in the process of therapeutic treatment of a patient are much needed.

In the present study, we propose a new method and a versatile design of an diagnostic module for non-invasive *in vivo* examination of the state of superficial tissues (skin, subcutaneous adipose tissue) of patient in an arbitrary body region using the bioimpedance spectroscopy.

The novelty of the proposed method lies in the original ring design of the diagnostic module and the method of vacuum fixation of the studied biological tissue, which makes it possible to study and control physiological processes, including during the therapeutic treatment of the patient's surface tissues (vacuum massage, skin tightening, cellulite treatment and lysis of subcutaneous adipose tissue). The developed design, as well as the configuration of the electrodes, is fundamentally compatible and can be used for radiofrequency therapeutic action on the patient's surface tissues with simultaneous bioimpedance control of the process.

Universal diagnostic module was designed so as to provide temporal fixation of the studied superficial tissue (via vacuum suction) and perform simultaneous measurements of the electrical impedance. The measuring probe was a vacuum cup connected to a vacuum system, in the housing of which the central and ring measuring electrodes, as well as connecting cables were mounted (Fig. 1).

Measurements of the electrical impedance of reference solutions and surface tissues of the patient were performed using a measuring stand and a developed diagnostic module. Meter LCR HiTester HIOKI 3532-50 was used to determine the impedance. Data collection and processing were carried out using the PRAP software package [12,13].

Figure 1. *a* — diagnostic module for bioimpedance study of the state of surface tissues, *b* — experimental configuration with tissue vacuum fixation, used in the measurement of electrical impedance *in vivo*.

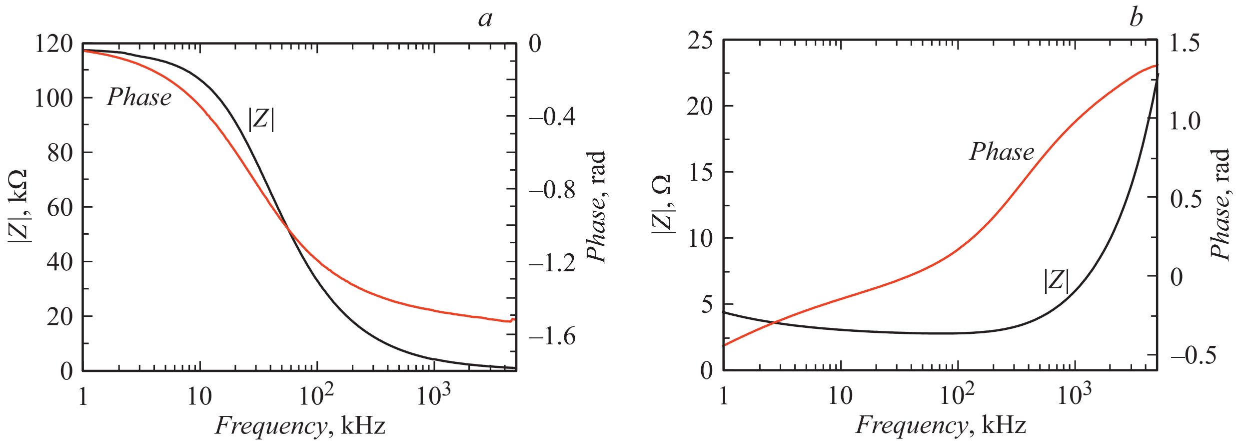

Figure 2. Impedance spectra of reference solutions: *a* — ethyl alcohol, *b* — NaCl aqueous solution (50 g/450 ml).

The central and ring metal electrodes of the measuring probe were connected to the input connectors of the impedance analyzer. Impedance scanning was carried out in the frequency range from 1 kHz to 5 MHz. Before performing measurements on the surface tissues of the patient *in vivo*, the diagnostic transducer was calibrated using reference solutions of ethyl alcohol and aqueous NaCl solutions. To do this, the diagnostic probe was placed in a chemical vessel filled with reference solutions. Fig. 2 shows the impedance spectra of reference solutions.

The difference between the impedance spectra of ethyl alcohol and NaCl aqueous solutions is due to different mechanisms of ionic conductivity and electrode/solution contact capacitance. Ethyl alcohol, like distilled water, is close to a classical dielectric solution, while electrolyte solutions have an ionic type of conductivity, which leads to increase in impedance with frequency as a result of a decrease in ion mobility.

Fig. 3 shows the impedance and dielectric (frequency dependences of permittivity ε and dielectric loss tangent $\tan\delta$) spectra of the patient's surface tissues (abdominal region) *in vivo*. The active resistance of the surface tissue decreases with frequency increasing. At relatively low frequencies, this is due to decrease in the reactance of the dielectric partitions and penetration increasing of current into the intracellular space. Parallel capacitance also decreases with frequency increasing. At different frequencies different relaxation mechanisms operate, i. e. decrease in the polarization of dielectrics with frequency increasing of the alternating electric field. At frequencies from fractions of hertz to a few kilohertz, the decrease in the permittivity ε is due to various effects occurring on the surface and in the channels of cell membranes and in intracellular structures. In the range from tens of kilohertz to 5 MHz, the Maxwell–Wagner effect occurs, which means decrease in the effective permittivity of multilayer dielectric with different permittivities of the layers with frequency increasing. Also at these frequencies, the polarization capacity of large protein molecules gradually decreases.

When analyzing the dependences obtained, note that the electrical impedance of biological tissues Z has two components: active R and reactive X resistances, being in the relation $Z^2 = R^2 + X^2$. The material substrate of

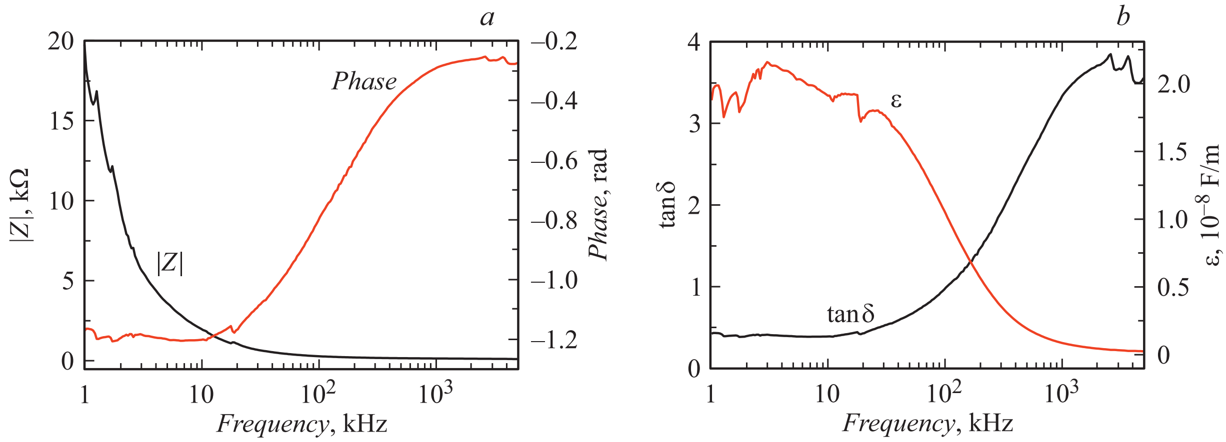

Figure 3. Impedance (a) and dielectric (frequency dependences of permittivity ε and dielectric loss tangent $\tan\delta$) (b) spectra of surface patient tissues (abdominal region) *in vivo.*

the active resistance R in the biological object is liquids (cellular and extracellular), which have ionic mechanism of conduction. The substrate of reactance X (the dielectric component of the impedance) is cell membranes. Also note that there is a capacitive component of the impedance associated with the contact of the electrodes and the structure of the surface tissue.

Since vacuum fixation of surface tissues is used in measurements of impedance spectra *in vivo* (Fig. 1), it is of interest to study transient processes in the studied tissues under the action of vacuum suction. It was found that the impedance of the surface tissue, measured at a frequency of 1 kHz, decreases from 6 to 1 kΩ within 60 s, and the dependence is exponential. The impedance change in this case is due to the gradual influx of blood and lymph to the area of the surface tissue under study, caused by vacuum suction.

Thus, it can be stated that the complex impedance of biological tissues determined for a given current frequency can change significantly under the influence of physiological and pathophysiological factors. Besides, the impedance spectrum of biological tissue changes dramatically during therapeutic treatment, reflecting the modification of the structure and composition of the tissue (lysis of adipose tissue, necrosis, coagulation, blood filling, changes in the content of intercellular and intracellular fluid) [14]. This makes it possible to use the developed method of bioimpedance spectroscopy and the diagnostic module for quantitative assessment of the condition of the patient's surface tissues in various diseases, as well as to monitor and evaluate the effectiveness of physiotherapy and other therapeutic interventions.

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Compliance with ethical standards

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and National Research Committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Informed voluntary consent was obtained from all participants involved in the study.

Conflict of interest

The authors declare that they have no conflict of interest.

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