Development of an automated bioimpedance analyzer for monitoring the clinical condition and diagnosis of human body diseases

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Abstract. Bioimpedance analysis allows to identify various pathologies, diagnose diseases in the early stages and determine the tactics of outpatient treatment for patients. It is most widely used in clinical practice. The article presents a structural diagram of the developed automated bioimpedance analyzer. The functional and metrological analysis of the hardware allowed to identify and systematize the causes of the methodological and subjective errors of the measurement results. To reduce the measurement error, a current source circuit, which allows the hardware to reduce leakage currents, is proposed. Bioimpedance measurement using an automated bioimpedance analyzer is performed at a frequency of 100 Hz to 2.5 MHz with a basic relative error of 0.1%.

1. Introduction
In the middle of the 20th century, at the intersection of biology and medicine, a new field of research—the study of body composition was born and separated in a detached direction. It includes computed tomography, x-ray densitometry, anthropometric and other methods. These methods allow to determine the body tissues composition, as well as diagnose various diseases.

Anthropometric parameters, such as body mass index (BMI), are among the most common indicators for assessing the physical health of patients around the world. Hundreds of scientific articles and decades of practical research have proved the high accuracy of such epidemiological diagnostics, but low enough sensitivity for individual studies [1].

Bioimpedance research allows to more accurately measure the composition the individual body due to which it is used for individual characteristics of a person.

Bioimpedance analysis (BIA) refers to contact methods for measuring a wide range of physiological parameters of biological tissues, by evaluating their electrical conductivity. The test site can be of various sizes: small segments, parts of the body or the whole organism. It is known that all body tissues, due to their biological characteristics, have certain values of electrical resistance. Due to this fact, it is possible to calculate the volumes of water, fat, cell and musculoskeletal components.

The value of bioimpedance includes two components: active and reactive resistance. Active resistance is formed due to the ionic mechanism of extracellular and intracellular electrical resistance, and reactive resistance is the resistance of cell membranes [2].
The active BIA use began with the diagnosis of physical indicators in athletes. The high values of the BIA correlation and total body water have given rise to the serial production of bioanalyzers and their application in medicine, science, military and space fields [3].

2. Development of an automated bioimpedance analyzer hardware

The aim of this work is to create an automated bioimpedance analyzer, with a relative error in measuring the bioimpedance of the human body not more than ± 0.1%. According to the technical specifications, it is necessary that the measurements take place in the frequency range from 100 Hz to 2.5 MHz. The bioimpedance analyzer includes hardware and software based on a personal computer. To determine the bioimpedance, a tetrapolar measurement scheme is used. The measuring unit of the hardware implements a method for measuring the half-sum of the incoming and outgoing current, which allows to reduce the measurement error.

Technical characteristics of the bioimpedance analyzer hardware are given in table 1.

Table 1. Technical characteristics of the bioimpedance analyzer.

| Parameter                                          | Value         |
|----------------------------------------------------|---------------|
| Limits of measurement (Ohm)                        | 1000 and 100  |
| The maximum current flowing through the human body (mA) | 1             |
| Range of current values (mA)                       | 0,1 – 1       |
| Frequency range of the flowing current (kHz)       | 0,1 – 2500    |
| Total measurement time (s)                         | 15            |

When measuring, the following sources of methodological errors should be taken into account. The human body, from an electrical point of view for bioimpedance research, is a system of circuits of resistors and capacitances connected in a parallel-serial manner. The current flowing through the entire system and the voltage are recorded incorrectly due to spurious current leaks to the common wire, because the measuring electrodes are connected to the extreme points.

The power transformer of the power supply in its peculiarity has a capacitive coupling between the primary and secondary windings, as a result of which leakage currents can flow through it to the neutral wire. When conducting measurements at an object at a low frequency, the capacitive coupling resistance is large, and the error introduced by it is small. At high frequencies from 1 to 2.5 MHz, the resistance becomes low. Consequently, the current flowing through the capacitive coupling will be significant to the measured current. The value of such a parasitic capacitance can reach tens of picofarads.

To reduce the influence of leakage currents on the measurement error, in this paper we use a current source circuit in which both the incoming and outgoing currents relative to the measurement object are subject to measurement. The use of such a circuit allows the hardware to reduce the influence of leakage currents inside the measuring unit on the final result. Simulation of the measurement mode of an object, consisting of many RC circuits and having capacitive coupling with a zero potential point, showed that leakage currents are compensated to the ground inside the object when summing the incoming and outgoing current.

The measurement error is also affected by the position of the research body in space relative to other objects [4 - 7].

Figure 1 shows a block diagram of an automated bioimpedance analyzer. This device is structurally a measuring unit with an electrode system connected to it.

The measuring unit consists of two parts: hardware and software. The software part provides the interaction of the measuring unit with a personal computer, obtaining frequency characteristics of bioimpedance, displaying current and voltage waveforms in real time on the monitor screen, automatically generating a report of the measurement results, calibrating the device using a calibration...
device at each frequency and recording the protocol of correction coefficients, representing complex quantities.

Figure 1. Block diagram of a bioimpedance analyzer: Σ / 2 - half-adder of the incoming and outgoing current; ADC - analog-to-digital converter; MP - microprocessor; GI - galvanic isolation; PC - personal computer; USB - Universal Serial Bus.

The program part implements the function of repeated measurement of an object from 1 to 20 times, which allows to get rid of random interference arising from accidental movement of the body, heartbeat and breathing.

The hardware of the bioimpedance analyzer (figure 2) is connected to a personal computer using a USB cable, and to the human body using electrodes and wires. The hardware contains three blocks: an interface module, a measuring unit and a voltage source. The interface module provides interconnection with a personal computer via USB. The control is carried out using a microprocessor that controls the generator, receives signals from two analog-to-digital converters (ADCs) that transmit digitized voltage and current information, respectively. The measuring unit is powered by AC power. To ensure the safety of electric shock, a galvanic isolation is created between the microprocessor and the personal computer.

Figure 2. Appearance of a bioimpedance analyzer.

The measuring unit consists of the following units: current source, switch, voltage meter, currents half-adder. The source current does not depend on the resistance of the measured object [8]. It is made on a high-speed operational amplifier of the company Analog Devices AD8056. The voltage meter measures the potential difference formed on the measured object as a result of the passage of current through it and transmits a signal to ADC1. The switch provides switching depending on the microprocessor command either to the object or to the calibration device. The half-adder of the
incoming and outgoing current performs its function of transmitting a signal to the ADC2. A calibration device is a set of precision resistances and capacitors interconnected according to a calibration scheme.

The power source is a device that converts AC voltage of 220 V into a constant stable voltage of ± 5 V and ± 12 V. According to the electrical safety requirements of medical devices, double galvanic isolation is implemented in the information exchange lines and power circuits. In the event of a transformer winding short circuit, this isolation prevents a person from supplying current. It also helps to reduce interference in these circuits.

3. Measurement of the human body bioimpedance

In this experiment, calibration is performed using a 910 Ohm resistor. The obtained frequency response is shown in figure 3.

![Figure 3. Frequency response R = 910 Ohm, after calibration by a 910 Ohm resistor.](image)

On the left, along the ordinate axis, the module of the complex resistance is displayed, the measurement unit is Ohm. The right ordinate shows the tangent of the phase angle \( \text{tg} \phi \), expressed as a percentage. The abscissa axis has a logarithmic scale. The frequency in Hz is laid on it. The bright colors red, blue and green denote the tangent of the phase angle \( \text{tg} \phi \), and the white color is the complex resistance module \( Z \).

The graph shows that the maximum absolute deviation of the resistance \( \Delta R = 918 - 910 = 8 \text{ Ohm} \). The maximum relative deviation is 0.87%. In turn, the maximum absolute deviation \( \Delta \text{tg} \phi = 0.9\% \). It is known that the active resistance does not depend on frequencies, respectively, after calibrating by a resistor of the same rating as the measured resistor, the characteristic should turn in a straight line.

The experimentally obtained frequency response of the resistor \( R = 300 \text{ Ohm} \) after calibration by the 910 Ohm resistor is shown in figure 4.

![Figure 4. Frequency response R = 300 Ohm, after calibration by a 910 Ohm resistor.](image)
The graph shows that the maximum absolute resistance deviation \( \Delta R = 345 - 300 = 45 \text{ Ohm} \). The maximum relative deviation is 13.04%. In this case, the maximum absolute deviation is \( \Delta \tan \phi = 26\% \).

It should be noted that the measurement error is greater, the more significantly the measured resistance differs from the calibration.

Figure 5 shows the frequency response of the resistances 910 Ohm and 300 Ohm.

![Figure 5. Frequency response R = 300 Ohm and R = 910 Ohm, after calibration with a 910 Ohm resistor.](image)

Figure 6 shows the results of measuring the human body using electrodes connected to the left and right hands.

![Figure 6. Frequency response of a human body after calibration with a 910 Ohm resistor.](image)

4. Conclusion

A block diagram of an automated bioimpedance analyzer is proposed, a measuring unit that can measure bioimpedance at frequencies from 100 Hz to 2.5 MHz with a relative measurement error of \( \pm 0.1\% \). is developed. Measurements of bioimpedance at the object are taken. Reducing random error is achieved by multiple measurements with subsequent processing of their results; subjective errors are eliminated due to automation of measurements. The use of modern integrated circuits made it possible to expand the frequency range and reduce the instrumental measurement error. For the purpose of automated bioimpedance measurements, the analysis of electrical models of bioobjects was carried out with guaranteed accuracy, the circuitry of the measuring nodes was modeled, the hardware of the bioimpedance analyzer was developed and manufactured, and the errors of bioimpedance measurements were analyzed.
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