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Development of an automated system for measuring bioimpedance for the study of body composition

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Abstract. Bioimpedance analyzers are non-invasive instruments that practitioners use to measure physiological parameters of body composition. The existing technology for measuring bioimpedance is constantly being improved, and more and more commercially available analyzers that do not solve the problems with measurement errors and the information content of the obtained data appear on the market. This article proposes an automated bioimpedance measurement system for studying body composition with a reduced impedance measurement error up to 1% and an increase in the information content of the human body composition due to the expansion of the impedance frequency measurement from 0.3 kHz to 2000 kHz.

Keywords: bioimpedance, current source, circuit, model, object

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Разработка автоматизированной системы измерения биоимпеданса для изучения состава тела

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Аннотация. Биоимпедансные анализаторы относятся к неинвазивным инструментам, которые практикующие врачи используют для измерения физиологических параметров состава тела. Существующая технология измерения биоимпеданса постоянно совершенствуется и на рынке появляется все больше коммерческих доступных анализаторов, которые не решают проблемы с погрешностью измерений и информативностью полученных данных. В данной статье предлагается автоматизированная система измерения биоимпеданса для исследования состава тела с уменьшенной погрешностью измерений импеданса до 1% и повышением информативности состава тела человека, благодаря расширению измерения частотного диапазона импеданса от 0,3 кГц до 2000 кГц.

Ключевые слова: биоимпеданс, источник тока, схема, модель, объект

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Introduction

The development of new approaches to both hardware and software for bioimpedance analysis in recent years has significantly increased its capabilities and expanded the list of both already implemented and promising applications [1]. In the modern world, the introduction of diagnostic devices is receiving great development, which makes it possible to save money and effectively influence the patient [2]. Although the technology has been improved, it is currently difficult to obtain high-quality measurements of physiological parameters with most commercially available bioimpedance analyzers because they do not detect large amounts of fat under the skin [3].

The creation of an automated system is based on the idea of measuring human bioimpedance, with improved measurement accuracy (impedance measurement error up to 1%) and an increase in the information content of the human body composition, due to the expansion of the measurement of the impedance frequency range from 0.3 kHz to 2000 kHz [3].

When measuring the impedance of biological objects, there are instrumental and methodological errors. Instrumental errors are caused by the presence of errors of electronic components that are part of the developed automated system. A detailed analysis of methodological measurement errors is presented by the authors in [4]. Thanks to the calibration of the digital automated bioimpedance meter, it was established that the total methodological and instrumental accuracy of bioimpedance measurement in relative form does not exceed 1%.

Structural diagram of the automated bioimpedance measurement system

The automated bioimpedance measurement system includes a measurement object, a measuring unit (highlighted by a dotted line in Fig. 1) and a personal computer. The object of measurement can be either a person or a calibration device. In the case of measuring human parameters, the measuring unit is connected to the object through measuring electrodes (not shown in the diagram). The calibration device is connected to the measuring unit through a connector and it is necessary for calibrating the measuring unit before operation.

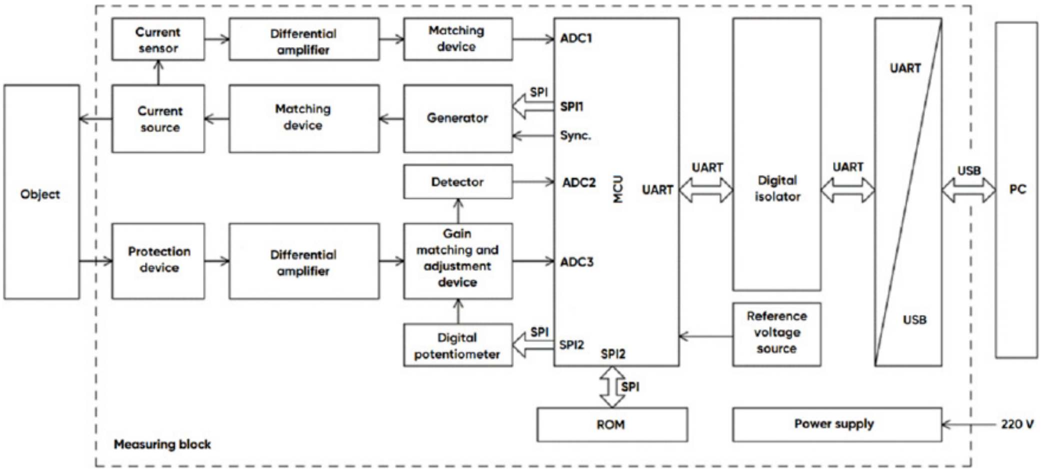


Fig. 1. Structural diagram of an automated system for measuring bioimpedance

The calibration device imitates the parameters of the electrode-human cell transition. The personal computer is intended for processing, displaying and storing the measurement results. The measuring unit operates under the control of a microcontroller, to which a ROM (read-only memory) is connected to store calibration coefficients, the number of the measuring unit, and other service information. The voltage reference source generates the voltage with high accuracy and temperature stability for the ADC (analog-to-digital converter) operation. The microcontroller is connected to a personal computer through a digital isolator and an interface converter. The digital isolator prevents leakage current from flowing into the personal computer, and also additionally protects a person from electric shock (in the grounding absence of the personal computer case).

To form a sinusoidal signal, a generator, which is controlled via the SPI interface (serial peripheral interface) is provided. The current source generates a sinusoidal current on the measurement object. The voltage drop across the object is measured by a differential amplifier with an input ESD protection (electrostatic discharge protection) circuit. The matching and gain control device is controlled by a digital potentiometer, which makes it possible to change the gain of the entire receiving path. From the output of the matching and gain control device, the signal is fed to the input of the ADC3 of the microcontroller, as well as to the detector, which extracts the signal amplitude and feeds it to the input of the ADC2 of the microcontroller. To assess the shape of the flowing current, a current sensor is provided, the voltage from which is measured by a second differential amplifier, after which the signal is fed to the matching device and to the input of the ADC1 of the microcontroller.

The microcontroller is designed to implement the control of all nodes of the bioimpedance meter, measurement, digitization and output of values on a personal computer. The microcontroller contains two ADCs, the signals to the inputs of which are received through internal demultiplexers. The ADC1 channel in the block diagram is connected to the first ADC inside the microcontroller. The ADC2 and ADC3 channels are connected to the second ADC of the microcontroller through a demultiplexer. The range of voltages applied to the ADC inputs is from 0 V to 3.3 V. The reference voltage value is 3.3 V. The microcontroller has two SPI interfaces to control peripherals. The first SPI interface controls the oscillator, the other one controls the digital potentiometer and ROM. The digital potentiometer and ROM have different signals for selecting slave devices (chip select) [5, 6].

The generator is designed to form a sinusoidal signal at the output with a constant amplitude. The microcontroller, via the SPI interface, sets only the signal frequency from the generator output. To synchronize the signal from the generator output, from the microcontroller output, a pulse signal sync 'sync.' with the frequency of 2 MHz, with a duty cycle of 2 is provided. The frequency of 2 MHz corresponds to the maximum operating frequency of the sinusoidal signal on the sample. The rest of the output frequencies are set by dividing the frequency 2 MHz.

The current source is designed to form a sinusoidal current in the range from −1 mA to +1 mA with a frequency set by the generator. The current source is controlled by voltage. The signal from the generator output through the matching device is fed to the input of the current source. The matching device removes the DC (direct current) component of the signal, and also amplifies it. The output stage of the current source is made according to the bridge circuit.

The differential amplifier is designed to measure the voltage on the sample. It has a high input impedance to eliminate the influence on measurements. An ESD protection device, which 'drains' excess voltage in the power circuit is provided at the input of the differential amplifier.

Before starting the measurement, the microcontroller must set the measurement limit to 1000 ohms and send a command to the generator to generate a signal with a frequency of 1 MHz. Depending on the resistance of the object, the voltage amplitude on it will change, and its value will be fixed by the detector for a period of 10 ms. Depending on the voltage level at the output of the detector, the microcontroller decides how to set the measurement limit.

The measurement limit is set by a digital potentiometer, which is controlled via the SPI interface by a microcontroller. In total, the digital potentiometer has 256 positions, the resistance ratio is given by the number Dn (position) placed in the register.

At the time of measurements, two channels ADC1 and ADC3 are involved (Fig. 1). The signal to ADC1 is proportional to the current flowing through the sample, and the signal to ADC3 is proportional to the voltage across the sample. According to the voltage on the sample, one can judge the resistance according to Ohm’s law. The dependence of the voltage on ADC1 on the current flowing through the sample is shown in Table 1.

Table 1

Dependence of voltage on ADC1 on current flowing through sample

Current, mA	Voltage at ADC1, V
+1	+3
0	+1.65
–1	+0.3

The dependence of the voltage on the ADC3 on the resistance at a constant current through a sample of 1 mA is shown in Table 2.

At all measurement limits, zero voltage on the sample corresponds to 1.65 V at ADC3 (middle point). The dependence of the voltage on the ADC3 on the resistance at a constant current through the 1mA sample is shown in Table 3.

Table 2

Dependence of voltage on ADC3 on resistance at constant current voltage through 1mA sample

Measurement limit, Ohm	Sample resistance, Ohm	ADC3 voltage, V
50	50	2.96
100	100	2.97
200	200	3
500	500	3
1000	1000	3

Table 3

Dependence of voltage on ADC3 on resistance at constant current through -1mA sample

Measurement limit, Ohm	Sample resistance, Ohm	ADC3 voltage, V
50	50	0.34
100	100	0.33
200	200	0.3
500	500	0.3
1000	1000	0.3

As it can be seen from the tables, the measurements do not use the full range of voltage measurements at the ADC input (from zero to 3.3 V). Such a voltage margin is necessary in order to increase the overload capacity, as well as to carry out correct operation at all measurement limits. On some samples, more frequency response drops, which, if the limit is chosen erroneously, can lead to saturation of the ADC input can be observed. A sufficient voltage margin eliminates this disadvantage. It is not necessary to programmatically limit the measured resistance to the value of the selected limit, if the system measures, for example, at the limit of 1000 ohms a value of more than 1000 ohms, then these values must be reflected in the frequency response.

Automated Bioimpedance Measurement System

The automated bioimpedance measurement system (Fig. 2) in its design has a device and measuring electrodes. The device is connected to a personal computer.

The input action is created on the patient's body in the form of a weak electric current of a given frequency using electrodes. A reaction to an impact in the form of a potential difference in a certain part of the body is perceived. The following patient data are used to perform calculations: measured data (active and reactance), sex, height, weight, age.

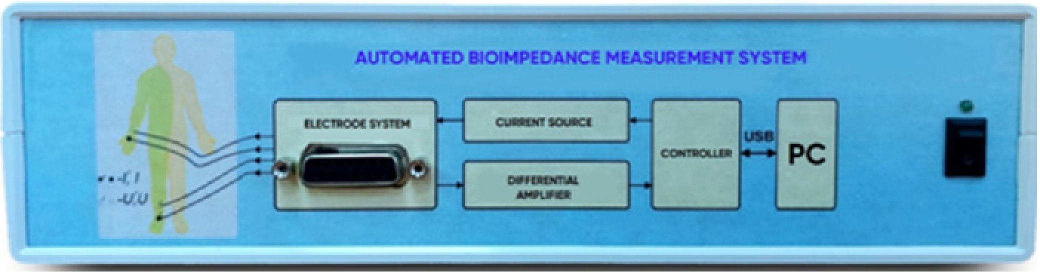
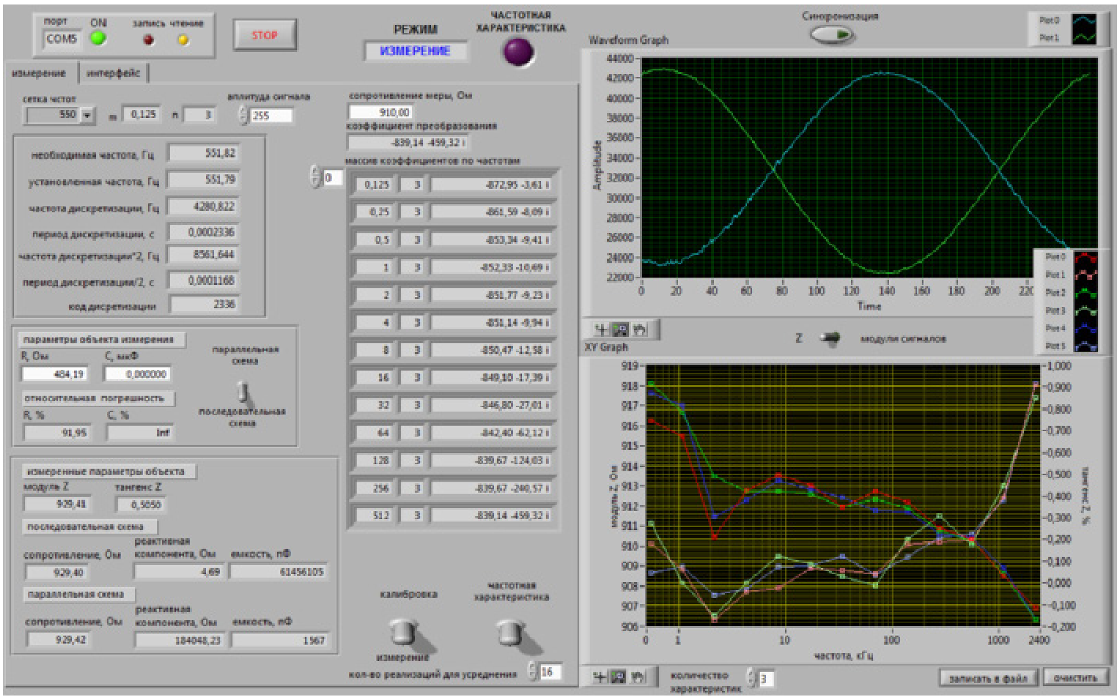


Fig. 2. Automated Bioimpedance Measurement System

Based on bioimpedance measurements and input data, a set of physiological parameters of the body is determined. Measurement data, calculations and experimental conditions are stored in the database. The report can be displayed on a PC (personal computer) screen, saved as a file and printed (Fig. 3). The dynamics of changes in indicators is recorded and visualized and a preliminary medical report is formed.



порт: COM5

РЕЖИМ: ИЗМЕРЕНИЕ

сетка частот: 550 m: 0,125 n: 3

амплитуда сигнала: 255

необходимая частота, Гц	551,82
установленная частота, Гц	551,79
частота дискретизации, Гц	4280,822
период дискретизации, с	0,0002336
частота дискретизации*2, Гц	8561,644
период дискретизации/2, с	0,0001168
код дискретизации	2336

параметры объекта измерения

R, Ом: 484,19 C, мкФ: 0,000000

относительная погрешность

R, %: 91,95 C, %: Inf

измеренные параметры объекта

модуль Z: 929,41 тангенс Z: 0,5050

последовательная схема

сопротивление, Ом: 929,40 реактивная компонента, Ом: 4,69 емкость, пФ: 61456105

параллельная схема

сопротивление, Ом: 929,42 реактивная компонента, Ом: 184048,23 емкость, пФ: 1567

сопротивление меры, Ом: 910,00

коэффициент преобразования: -839,14 -459,32 i

массив коэффициентов по частотам: 0

0,125	3	-872,95 -3,61 i
0,25	3	-861,59 -8,09 i
0,5	3	-853,34 -9,41 i
1	3	-852,33 -10,69 i
2	3	-851,77 -9,23 i
4	3	-851,14 -9,94 i
8	3	-850,47 -12,58 i
16	3	-849,10 -17,39 i
32	3	-846,80 -27,01 i
64	3	-842,40 -62,12 i
128	3	-839,67 -124,03 i
256	3	-839,67 -240,57 i
512	3	-839,14 -459,32 i

кол-во реализаций для усреднения: 16

количество характеристик: 3

Fig. 3. Main application menu of the automated bioimpedance measurement system

A circuitry part of the measuring apparatus, which will allow measurements of bioimpedance in a wide frequency range from 300 Hz to 2 MHz has been developed. Thanks to the obtained frequency response, the selectivity of measurements, which allows increasing the influence of some tissues or organs on the measuring signal and at the same time reducing the influence of others will become possible.

The accuracy of body composition data has been improved by developing a current source that measures both currents flowing into the object and currents flowing out of the object. It will allow hardware to minimize the influence of leakage currents inside the measuring apparatus on the final result.

Calibration is performed using a 910 ohm resistor. As a result of calibration, a table of complex coefficients is formed at each of the thirteen frequencies in the range from 300 Hz to 2 MHz (Fig. 3). Then, using the correction coefficients obtained, the resistance of the resistor with a nominal value of 910 ohms is measured. The resulting frequency response is shown in Fig. 3.

The ordinate axis on the left shows the module of the complex resistance, measured in ohms. The tangent of the phase angle tgφ, expressed as a percentage, is displayed on the ordinate axis on the right. The frequency in Hz is deposited along the abscissa axis. The abscissa axis has a logarithmic scale. Bright colors of red, blue and green (in the upper part of Fig. 3) the module of the complex resistance Z is indicated, and the tangent of the phase angle tgφ is indicated in pale colors (in the lower part of Fig. 3)

It can be seen from the graph that the maximum absolute deviation of the resistance:

$$\Delta R = 918 \text{ ohms} - 910 \text{ ohms} = 8 \text{ ohms}. \quad (1)$$

The maximum relative deviation is determined as follows:

$$\delta_{\Delta Z} = \frac{918 \text{ ohms} - 910 \text{ ohms}}{910 \text{ ohms}} \cdot 100\% \approx 0.87\%. \quad (2)$$

In turn, the maximum absolute deviation:

$$\Delta R = -0.9 - 0 = -0.9\%. \quad (3)$$

As a result, the relative error of the impedance measurements will not exceed 1%.

Conclusion

An automated bioimpedance measurement system has been developed, in which the total instrumental and methodological error of bioimpedance measurements has been reduced to 1%, which is confirmed by the calibration results. The proposed bioimpedance meter has an extended frequency range from 0.3 kHz to 2000 kHz. A distinctive feature of the proposed automated system is the use of a current source in the system for bioimpedance measurements, which minimizes the influence of a parasitic leakage current from the measuring object to the ground, which positively affects the accuracy of measurements.

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