DETERMINATION OF THE BIOIMPEDANCE OF THE HUMAN BODY BASED ON THE MULTI-FREQUENCY MEASUREMENT METHOD

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Abstract

Bioimpedance analysis is based on measuring the electrical conductivity of various body tissues. The integrated multi-frequency method is performed by the integrated single-frequency method with the same position of the electrodes, but measurements are made at several frequencies. The beginning of the practical application of bioimpedance analysis to characterize human body composition is usually associated with the work completed in the early 1960s by anesthesiologist Henri Tomasset to assess first the water sectors of the body and then other components of body composition. To measure the impedance of a specific body segment, the current and measuring electrodes must be positioned accordingly. The main structural element of the biological system is the cell, which consists of the cytoplasm and the membrane surrounding it. The cell membrane acts as a barrier between the intracellular fluid and the extracellular fluid. In our proposed method, the frequency ratio is in the range of 3:4:5.

This means that if we take the high frequency as 500kHz then 3 other frequencies should be taken 166kHz, 41kHz and 8kHz. It can be concluded that the 4-frequency method with measurements at 8 kHz, 41 kHz, 166 kHz and 500 kHz and the Cole-Cole model provide better accuracy than the other methods.

This means that if we take the high frequency as 500kHz, then the other 3 frequencies should be taken as 166kHz, 41kHz and 8kHz. It can be concluded that the 4-frequency method with measurements at 8 kHz, 41 kHz, 166 kHz and 500 kHz provides better accuracy.

Keywords: Bioimpedance analysis, body mass index, electrical conductivity, body segment impedance, multifrequency method, bioimpedance spectroscopy.

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1. Introduction

In bioimpedance analysis, the active and reactive impedances of the human body or its segments are measured at different frequencies. Based on them, body structure characteristics such as fat, cellular and skeletal muscle mass, volume and distribution of body water are calculated.

One of the main conditions for the development of body composition study methods was formed in the first half of the 19th century due to the emergence of demographic statistics and biometrics. In 1835, for the general characterization of human populations, Quetelet introduced the concept of the average person and proposed the use of weight-height indices, which express different ratios of dimensional anthropometric characteristics, to assess individual physical development. Several dozen such indices were later proposed. The most popular is the Quetelet index or body mass index, which is calculated as the ratio of body weight in kilograms to the square of body length in meters: BKI = Body weight, kg / (body length, m^2).

The widespread use of body mass index (BMI) is due to the simplicity and availability of measurements. Numerous studies have shown that deviation of BMI from normal values is associated with increased risk of morbidity and mortality. A relationship between relative mortality risk and BMI has been established. With normal index values (20-25 kg/m^2), the relative risk of death is minimal, with an increase in the index, mortality from cardiovascular diseases, cancer and other causes increases, and with low BMI values, death occurs primarily due to chronic lung diseases.

Bioimpedance Analysis

Bioimpedance analysis is based on measuring the electrical conductivity of various body tissues. The beginning of the practical application of bioimpedance analysis to characterize the composition of the human body is usually associated with the work completed in the early 1960s by the French anesthesiologist Henri Tomasset to assess first the water sectors of the body and then other components of body composition. The history of Russian research and development in the field of bioimpedance analysis is more than 70 years. The first works on this topic were published in the 1930s, and in the same years, bioimpedance equipment was produced in small batches to assess the survival rate of grafts based on data on their electrical conductivity. The method is based on measuring the Z impedance of the whole body or individual segments of the body using special devices - bioimpedance analyzers. The electrical impedance of biological tissues consists of two components: active R and reactive resistance X_c.

The material substrate of active resistance R in a biological object is fluids (cellular and extracellular) with an ion-conducting mechanism. The substrate of X_c reactivity (dielectric component of impedance) is cell membranes. With the value of active resistance, the volume of water in the body (WBO) is calculated, its low resistance is due to the presence of electrolytes.

The electrical resistance of adipose tissue is about 5-20 times higher than the main components of fat-free mass (LBM). High correlations between body impedance and OVO, BMI and fat mass values have been identified.

Bioimpedance and its Measurement. Resistance and Impedance

Figure 1b plots the frequency dependences of R, X_c, Z and φ calculated for the case of $R_e = R_i = 400\ \Omega$, $C_m = 4$ nF. The values of X_c and φ are shown without considering the negative sign. The effect of capacitance, characterized by the values of X_C and φ, tends to zero at both low and high frequencies. The frequency at which X_c reaches its maximum value f_c is called the characteristic frequency. Noticeable changes in impedance parameters occur in the frequency range of about 10^3 to 10^6 Hz. This range is called impedance dispersion region. Let's also note that the pair graphs of Z(f) and φ(f) are called Bode diagrams. Another visual tool for showing the frequency properties of an impedance is a hodograph called a Nyquist plot, Wessel diagram, or impedance locus. The hodograph shows R, X_c pairs obtained at different frequencies. For the circuit in Fig. 1a, when the frequency varies from zero to infinity, the hodograph has a semicircular shape (Fig. 1, c). X_c values are shown as positive.

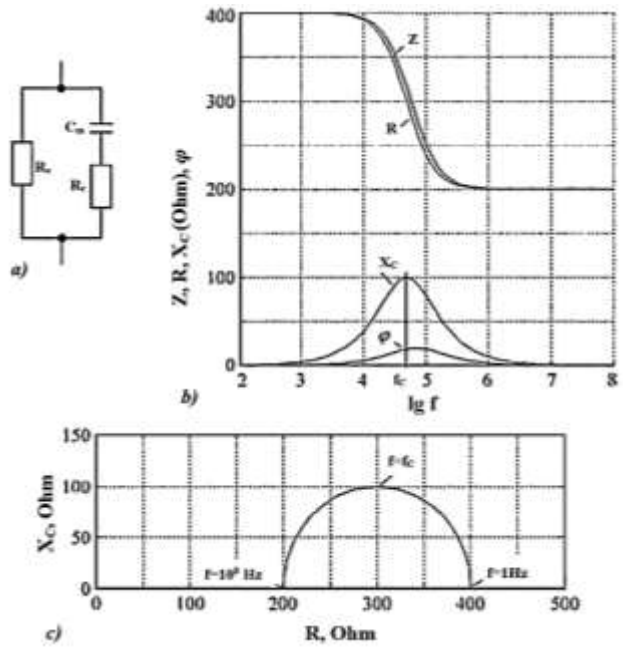
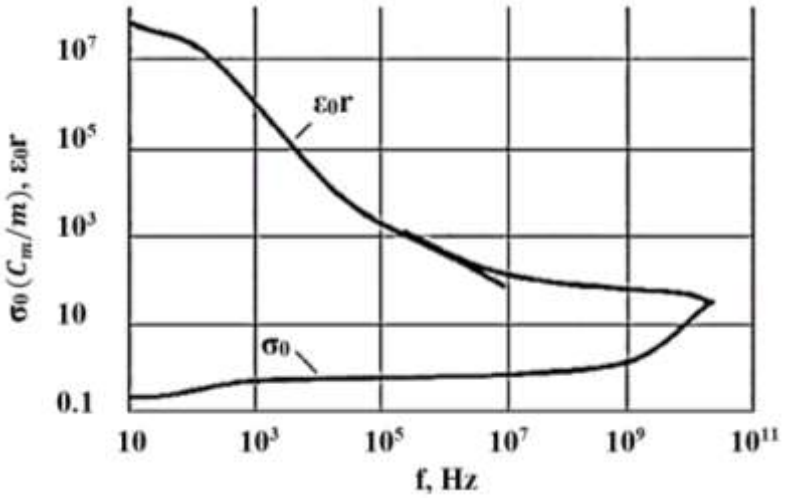


Figure 1. a) Simplified equivalent scheme of a biological object, b) frequency characteristics, c) hodograph

Frequency Dependence of Biological Tissue Resistance

The resistance and conductivity of biological tissues mainly depend on the alternating current frequency. As an example, let's consider the frequency dependences of specific permeability σ_0 and relative permeability $\varepsilon_0 r$ of muscle tissue (Fig. 2). At frequencies from 100 kHz to 10 MHz, a double line of the $\varepsilon_0 r$ graph appears, which is due to the use of two different measurement methods in this frequency range. Active conductivity soon increases. At relatively low frequencies, this is due to the decrease in the reactivity of the dielectric partitions and the increased penetration of the current into the intracellular space. The increase in permeability at frequencies above 1 GHz is related to other mechanisms, but this range is not used for body composition analysis. When the dielectric constant increases, the frequency decreases.

Figure 2.



Specific conductivity of muscle tissue σ_0 and frequency dependence of relative permeability ε_{0r}

Measurement of Impedance of Body Segments

To measure the impedance of a specific body segment, the current and measuring electrodes must be positioned accordingly. Consider a simplified equivalent diagram of the human body (Figure 3).

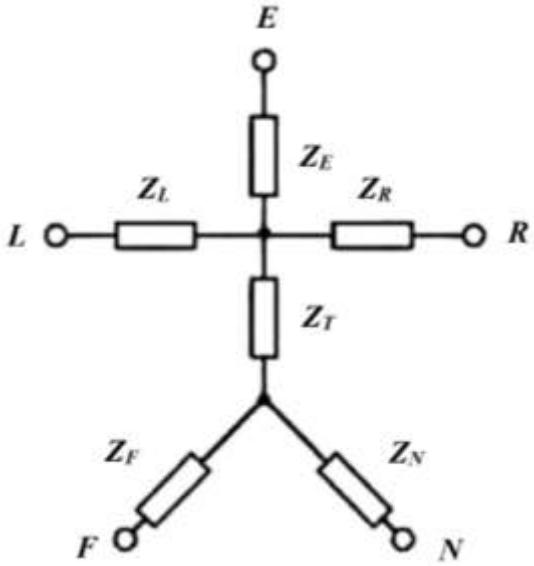
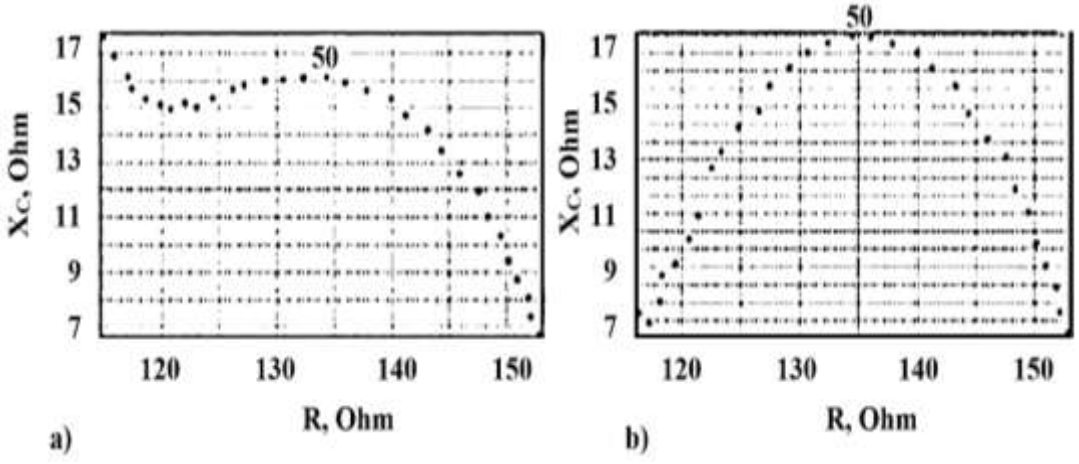


Figure 3. Simplified equivalent diagram of body segments

Let's introduce the designation: E - head, R - right arm, L - left arm, F - left leg, N - right leg, T - trunk. A measurement in which a current source is connected to the left and right hands and the voltage is measured between the left hand and the left leg will be abbreviated as LR/LF. In this case, the measured voltage is proportional to the modulus of the impedance ZL, since no current flows through ZT and ZF. Same impedance EL/LR, LR/LE, LF/LR etc. can be determined by measuring. Torso impedance LF/RN, EF/RN, LN/RF, etc. obtained by measuring Similarly, there may be options to measure the impedances of other segments.

Measurement error is the difference between the measured value of a physical quantity and the true value. The true value of the impedance of a biological object is unknown, so the errors of bioimpedance analyzers must be



evaluated by measuring equivalents of biological objects, as well as by comparing the results of measurements of the same biological object. Another possible source of error information is the difference between measured frequency responses of bioimpedance parameters and those predicted based on validated theoretical models [12].

Instrument errors are related to the characteristics of the equipment used. These errors occur for the following reasons:

- errors of reference impedances used during calibration;
- temperature and time instability of generator current values and measurement path parameters;
- errors related to non-linearity and inertia of detectors;
- analog-to-digital conversion and calculation errors.

Figure 4.
(a) and (b) bioimpedance hodographs before error correction

An Integrated Frequency Method for Estimating Body Composition

The integrated single-frequency method for assessing body composition has been used in medicine for more than 20 years and is applied in dozens of device types produced by manufacturers in many countries. It has been tested many times using different reference methods and has been the subject of debate with many authors pointing out its inherent limitations and shortcomings. Nevertheless, to date, this method can be considered the only actual standard in the field of bioimpedance analysis of body composition and, like any standard, it is the basis for wide practical application of the technology corresponding to it. The considered method is called integral because it estimates the composition of the whole body. For this, it is necessary to measure the impedance of the whole body. For this purpose, electrodes are placed on the wrist of the right hand and the ankle of the right foot, as shown in figure 5.

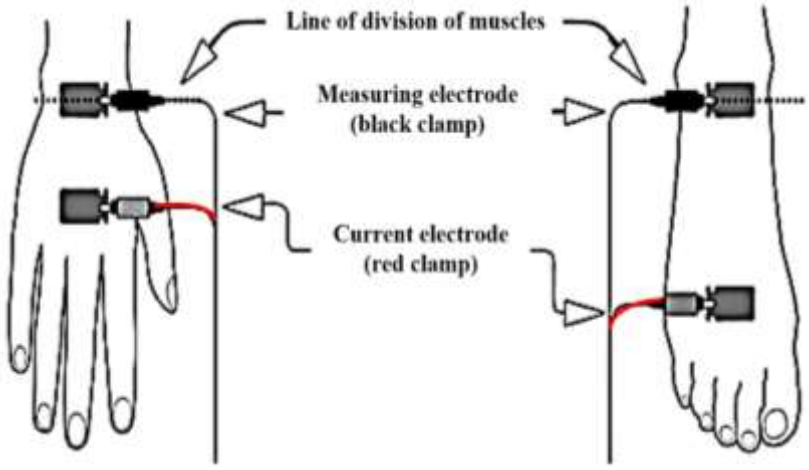


Figure 5. Standard electrode arrangement

The colors of the wires or clamps connected to the current and measurement electrodes shown in the figure are traditional for many manufacturers of bioimpedance analyzers. The positions of the measuring electrodes on the articulation lines of the joints are determined quite precisely, which helps to repeat the measurement results. The current passes through the right arm and right leg and occupies a significant part of the trunk. In this case, the measured impedance is mainly determined by the resistances of the arm and leg, as shown in figure 5.

An Integrated Multifrequency Method for Estimating Body Composition

The integrated multi-frequency method is performed by the integrated single-frequency method with the same position of the electrodes, but measurements are made at several frequencies. The main purpose of the multi-frequency method is to estimate the volume of water (VOW) and the composition of extra-tissue fluid (ETF) in the human body more reliably than the single-frequency method allows. At the moment, it is not possible to specify VOW and ETF measurement frequencies that can be called generally accepted. To assess VOW, the probing current must freely enter the cells through the membranes. For this, the frequency should be as high as possible. At the same time, with increasing frequency, errors caused by parasitic capacitances increase, radiation of electromagnetic waves into the surrounding space increases, and the solution of some other technical issues becomes complicated. A frequency of 500 kHz is used in many commercial and research instruments. However, even at this frequency, the effect of cell membrane capacitance is not completely eliminated. ETF volume estimation should be performed at the lowest possible frequency so that alternating current does not penetrate cells through cell membrane capacitances and therefore intracellular fluid does not contribute to overall conductance. Many bioimpedance analyzers use a frequency of 5 kHz. With a further decrease in frequency, the impedances of the skin contacts of the electrodes increase rapidly, which complicates the measurements and leads to an increase in errors. Recall that in an ideal situation, to estimate the volume of VOW, it is necessary to measure the impedance at an infinitely high frequency, and to estimate the volume of ETF, it is necessary to measure the impedance at a frequency equal to zero. Such measurements are not possible. Estimates of object resistance at zero and infinitely high frequencies are obtained using the bioimpedance spectroscopy (BIS) method. In a standard device, the active and reactive components of the impedance are measured at multiple frequencies in the range of 5-

500 kHz. The number of different frequencies should be at least 15–20 [14], and their sequence should be described by at least approximately a logarithmic law. In this example, the number of frequencies is 31. Measurement results are shown in square form. Then, based on these results, an approximation of the Cole model described by the formula is found [4, 7, 8, 15].

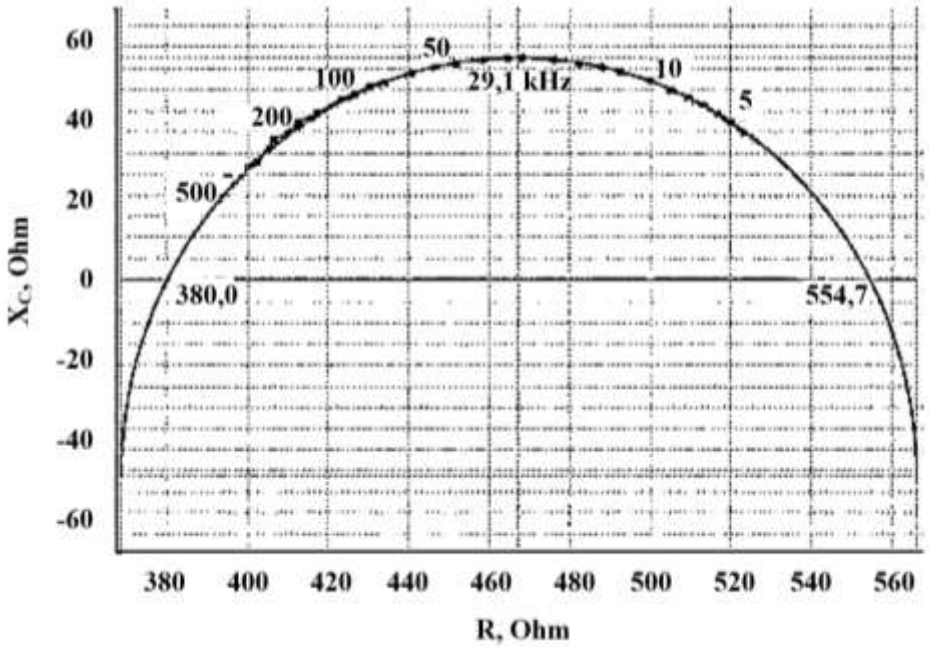


Figure 6. Approximation of the impedance spectrum according to the Cole model

The hodograph plot for the Cole model appears as a semicircle. The crosses on the hodograph indicate the positions of the points for the same frequencies at which the measurements were made. The resistances R_0 and R_∞ correspond to the points of intersection with the axis of the active resistance R of the approximate hodograph, since the reactance of any passive circuit at zero and infinitely high frequencies is zero (Fig. 6).

Calculations with series and parallel equivalent circuits and measurement at 50 kHz with measurements at 50 kHz or 5 kHz or 500 kHz estimated from approximate resistance values at zero and infinitely high frequencies, including the mixture model, were investigated. For VOW and ETF, regression equations in their simplest form (kDT2/R) + const were used for each of the compared methods. The equations for VOW had the same form, but at 50 kHz, reactance was used instead of active resistance, when measuring at 500 kHz, the combination of active resistances at 5 kHz and 500 kHz was taken as resistance.

Measurements were performed on volunteers using the same Xitron Technologies bioimpedance spectrometer. Deuterium dilution was used as the reference method for VOW, NaBr dilution was used for ETF, and the tissue fluid (TIF) value was determined as the difference between VOW and ETF.

In our proposed method, the frequency values should be in the range of 3:4:5. This means that if we take the high frequency as 500kHz then 3 other frequencies should be taken 166kHz, 41kHz and 8kHz. It can be concluded that the 4-frequency method with measurements at 8kHz, 41kHz, 166kHz and 500kHz and the Cole fit method provide better accuracy than the other methods. The deterioration of the reliability of the estimates obtained at a frequency of 50 kHz is explained by the violation of the VOW / ETF ratio during impacts.

The main structural element of the biological system is the cell, which consists of the cytoplasm and the membrane surrounding it. The cell membrane acts as a barrier between the intracellular fluid and the extracellular fluid. From a technical point of view, it can be said that the electrical resistance of the biological system changes depending on the cell structure, that is, the physical-chemical exchange between the internal environment of the cell and its external environment. Depending on the research methodology (determination of body mass index, fat ratio, dry muscle ratio in the bioimpedance analyzer), the resistance of biological system elements is determined. Apparently, electrical resistance is a diagnostic information carrier for a biological system [2, 9, 10].

As we mentioned, depending on the research methodology (measurement of the electrical

conductivity of the biological system), both constant and alternating current can be used as a stable source in the measurement circuit. Each form of current will produce unique biophysical effects in a biological system [1, 2, 9]. It is appropriate to use those biophysical effects in the study of the properties of the biological system. It is preferable to use an alternating current source as a stable source, especially if the phenomenon of polarization is taken into account. When applied from a low-frequency alternating current source, the probe current does not enter the cell membrane and flows through the circuit in proportion to the resistance of the extracellular fluid. When a high-frequency current source is used, the probe current will flow through the circuit depending on the resistance of the cell membrane and extracellular fluid. Electrical modeling is used to calculate the probe current and electrical conductivity of the seed based on the structure of the biological system. When a low-frequency current flows through the tissue, this process is modeled by a resistor, and when a high-frequency current flows, the cell membrane is modeled by capacitance, and the intracellular and extracellular fluid are modeled by resistors. The mentioned model is shown in the figure below (figure 7).

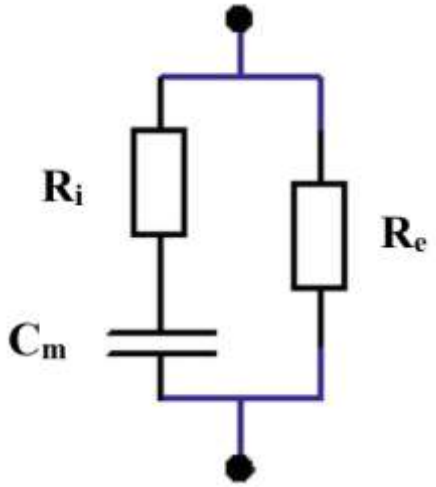


Figure 7. RC circuit model for determining the electrical resistance of a biological system

Here, R_x is the extracellular fluid resistance, R_d is the intracellular fluid resistance, C_m is the membrane capacitance, and Z is the complex resistance [4].
As is known, the impedance of the biological tissue changes depending on the probe current of different frequencies. The law of variation of working voltage with angular frequency and small amplitude is as follows.

$$\Delta V = V_m \sin \omega t = V_m \sin(2\pi f t) \quad (1)$$

Under the influence of internal voltage, the current will be expelled from the circuit with a certain phase shift. The law of variation of the probing current will be as follows.

$$\Delta I = I_m \sin(2\pi f t - \theta) \quad (2)$$

Equations (1) and (2) can be used to determine the complex resistance expression of a biological object.

$$Z = {V_m}/{I_m}\, e^{j\theta} \quad (3)$$

Equation (4) can be obtained using the Euler equations of equation (3).

$$Z = \frac{V_m e^{j\omega t}}{I_m e^{j(\omega t-\theta)}} = e^{j\omega t - j(\omega t-\theta)} = e^{j0} = cos\theta + isin\theta \quad (4)$$

$z_0 = {V_m}/{I_m}$ if we accept, we can write as follows.

$$z(\omega) = z_0 cos\theta + isin\theta \quad (5)$$

If we look at the model in Figure 1, we can see that by determining the voltages V_z and V_a and the ratio of the current flowing through the circuit, the complex resistance can be calculated. Assume that the current flowing through Z_x and R_a is equal to each other ($I_x = I_a$). Then we can determine the ratio of voltages V_z and V_a with the following expression.

$$\frac{V_z}{V_a} = \frac{IZ_x}{IR_a} = \frac{Z_x}{R_a} \quad (6)$$

Based on expression (6), we can define the following expression.

$$Z_x = R_a \frac{V_z}{V_a} = R_a \frac{|V_z|\angle\varphi_1}{|V_a|\angle\varphi_2} = R_a \frac{V_z}{V_a}\angle\theta \qquad (7)$$

With the help of this equation, the bioimpedance of the biological tissue can be determined [5,6].

Bioimpedance Values in Biological Objects

Figures 8a and 8b show age-dependent graphs of active and reactive resistances in men and women. In classic integral wrist-ankle abduction, according to the conditions of the bioimpedance study, the values of active resistance (R) at a frequency of 50 kHz in healthy people vary widely depending on age and gender: 350-800 Ohms, and reactive resistance (X_c) 45-90 Ohms. The ratio of these values is usually in the range of 5-11. Deviation from the specified ranges may indicate a violation of the measurement procedure. Active resistance decreases with age. It is ≈750 Ohm in 4-year-old children and decreases to an average of 400 and 550 Ohm in men and women, respectively, by the age of 35-40. The response also decreases with age. This is due to an increase in the cross-sectional area of conductive tissues (mainly the muscles of the limbs). Stabilization of the average values of X_c up to 30-35 years of age is observed, and after 60 years, a decrease is observed. The average value of the phase angle increases in children, adolescents and adults, reaches a maximum until 30-40 years of age, and then gradually decreases. It can be seen that, compared to the general population, the phase angle increases significantly in professional athletes, in workers of special purposes, and in patients of a therapeutic nutrition clinic, it is equal to the age norm. is appropriate. The age-related decrease in phase angle values in special forces personnel is probably associated with a decrease in the frequency and intensity of physical activity. In clinical studies, phase angle is used to assess the severity of patients' conditions and to predict survival in patients with severe chronic diseases [9, 10]

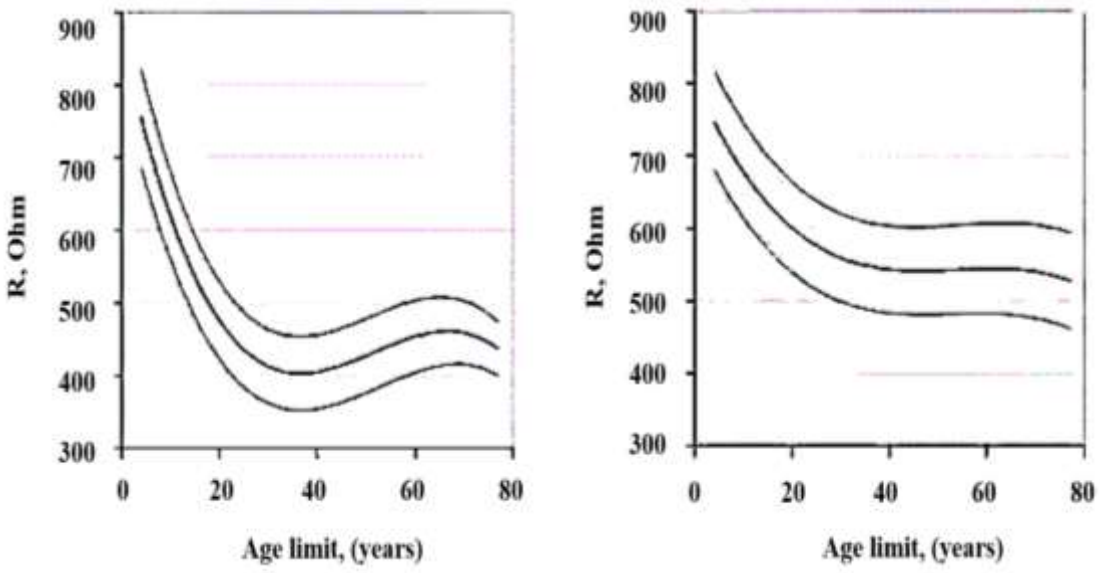


Figure 8. Age dependence of active resistance values for standard wrist and ankle abduction. Left - data for men, right - data for women

Table 1. Resistance and dielectric parameters of tissues of the human body

Tissue	**Average value, Ohm·m**	**Confidence interval, Ohm·m**
Lumbar (cortical)	4,64	3,6 – 5,97
Lumbar (cancellous)	176	123 – 252
Oil	38,5	30,5 – 48,7
Leather	3,29	2,55 – 4,24
Bone	$1.24\text{-}10^6$	$(0{,}91 – 1{,}69)\text{-}10^6$
Blood	1,51	1,20 – 1,91
Lungs	1,57	1,22 – 2,02
Childhood way	2,19	1,70 – 2,82
Breast	3,39	2,49 – 4,63

Bladder	4,47	2,88 – 6,93
Muscles (along fibers)	2,40	1,55 – 3,72
Muscles (on the surface of fibers)	6,75	4,35 – 10,5
Liver	3,42	2,96 – 3,96
Kidney	2,11	1,6 – 2,78
Spleen	4,05	3,07 – 5,35
Heart	1,75	1,33 – 2,31
Thyroid	1,83	1,18 – 2,83
Language	3,33	2,15 – 5,17
Ovum	1,45	0,93 – 2,24
Ovary	2,24	1,44 – 3,47

Table 2. Resistivity: modules and phase angles

Tissue	**ρ, Om·m 1 Hz- 10 kHz**	**ρ, Om·m 1 MHz**	**φ_{max}degree**	**Anizotropia**
Dry Skin	10^7	10^4	80	?
Moist Skin	10^5	10^4	30	?
Bone	100		20	?
Oil	20-50	20-50	3	Not a big one
Agred	2,5-20	1,6-10	15	Local
Brain	10	6,7	15	?
Black state	5	3,3	5	?
Muscles	2,5-20	1,67	30	Showing off violently
Blood	1,42	1,42	20	Dependent on motion
Urine	0,4-2,0	0,4-2,0	0	no

Table 3. Dielectric parameters

Tissue	ε_∞	$\Delta\varepsilon_1$	τ_1, ps	a_1	$\Delta\varepsilon_2$	τ_1, ns	a_2
Aorta	4,00	40,0	8,842	0,10	50	3.183	0,10
Stomach	4,00	60,0	7,958	0,10	2000	79,58	0,10
Oil	2,50	9,00	7,958	0,20	35	15,92	0,10
Colon	4,00	50,0	7,958	0,10	300	159,2	0,20
Moist skin	4,00	39,0	7,958	0,10	280	79,58	0,00
Dry skin	4,00	32,0	14,47	0,00	1100	32,48	0,20
Bone Marrow	2,50	9,00	13,26	0,20	80	15,92	0,10
Bone	2,50	10,0	8,377	0,20	180	79,58	0,20
Blood	4,00	56,0	7,958	0,10	5200	132,6	0,10
Lungs	4,00	45,0	7,958	0,10	1000	159,2	0,10
Childhood way	4,00	55,0	7,958	0,10	800	31,83	0,10
Brain	4,00	45,0	7,234	0,10	400	15,92	0,15
Muscles	4,00	50,0	7,958	0,10	7000	353,7	0,10
The nerve	4,00	26,0	8,842	0,10	500	106,1	0,15
Liver	4,00	39,0	7,958	0,10	6000	530,5	0,20
Kidney	4,00	47,0	7,958	0,10	3500	159,2	0,22
The cornea	4,00	48,0	7,958	0,10	4000	63,66	0,05
Spleen	4,00	48,0	7,958	0,10	2500	198,8	0,15
Heart	4,00	50,0	7,958	0,10	1200	159,2	0,05
Sclera	4,00	50,0	7,958	0,10	4000	159,2	0,10
Spinal fluid	4,00	65,0	7,958	0,10	40	1,592	0,00
Dry resin	4,00	42,0	12,24	0,10	60	6,366	0,10
Breathing tube	2,50	38,0	7,958	0,10	400	63,66	0,10
Cartilage	4,00	38,0	13,26	0,15	2500	144.7	0,15
Thyroid gland	4,00	55,0	7,958	0,10	2500	159,2	0,10
Language	4,00	50,0	7,958	0,10	4000	159,2	0,10

Ovum	4,00	55,0	7,958	0,10	5000	159,2	0,10
Ovary	4,00	40,0	8,842	0,15	400	15,92	0,25

2. Conclusion

In bioimpedance analysis, the active and reactive impedances of the human body or its segments are measured at different frequencies. Based on them, body structure characteristics such as fat, cellular and skeletal muscle mass, volume and distribution of body water are calculated. The widespread use of body mass index (BMI) is due to the simplicity and availability of measurements. Numerous studies have shown that deviation of BMI from normal values is associated with increased risk of morbidity and mortality. A relationship between relative mortality risk and BMI has been established. Electrical modeling is used to calculate the probe current and electrical conductivity of the seed based on the structure of the biological system. When a low-frequency current flows through the tissue, this process is modeled by a resistor, and when a high-frequency current flows, the cell membrane is modeled by capacitance, and the intracellular and extracellular fluid are modeled by resistors. In our proposed method, the values of the frequency should be in the range of 3:4:5. This means that if we take the high frequency of 500 kHz, then 3 other frequencies should be taken: 166 kHz, 41 kHz and 8 kHz. It can be concluded that 8 kHz, 41 kHz, 166 kHz and 500 kHz. The 4-frequency method with measurements at , and the Cole fit method provide better accuracy than the other methods.

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