On measurement errors of the impedance spectrum of human body in vivo

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Abstract. Deviations of the impedance spectrum of human body segments from that predicted by the Cole model are explained by the properties of biological objects and measurement errors. Our analysis of the measurement’s equivalent scheme shows an importance of contact impedances and allows for explaining positive reactance of low-resistance body segments. Representation of the measured impedance as a connection of the Cole model impedance and capacity in parallel gives better fitting of measured impedance spectrum. The results of analysis show that said capacity is determined mainly by the properties of body tissues rather than stray capacitance between the body and surrounding objects.

1. Introduction
The frequency dependence of biological objects’ complex impedance is usually approximated by the Cole model [1, 2]. This model is used for the description of biological tissues’ properties in in vitro measurements [3]. However, in in vivo measurements, deviations of the impedance spectrum from the circular arc predicted by the Cole model usually occur. Such deviations were explained previously by various factors, such as stray capacity between the body and surrounding objects, contact impedances, cable capacities, and other [4–6]. The aim of our study was to analyze quantitatively various factors influencing the results of impedance measurements and discriminate between biological tissues’ effects and that of measurement errors.

2. Device and methods
BIA measurements were conducted by the analyzer ABC-01 ‘Medass’ (Moscow, Russia) that measures complex impedance according to the conventional tetrapolar scheme using multiple (31) frequencies ranged from 5 to 500 kHz [7]. Two kinds of electrodes were used: the disposable bioadhesive electrodes with contact area 2.4×2.4 cm, and reusable AgCl electrodes with contact area 2.5×3.6 cm, denoted as E1 and E2, respectively. E2 electrodes were used with the conductive gel. Patient’s cable was 1.8 m in length. The measurement was conducted in standing position distantly enough from the conductive objects with legs and arms moved apart.

The results of measurements were processed using device-supplemented software that allows for best approximation of the impedance spectrum in an operating frequency range as the impedance $Z_{\text{Cole}}$ corresponding to the Cole model with the capacity $C_p$ taken in parallel. This capacity may be influenced by biological object’s own capacity, stray capacity, and measurement errors.
BIA measurement errors were analyzed both theoretically, i.e. using equivalent scheme calculations, and experimentally, i.e. by measuring the impedances of reference circuits. Two kinds of errors were considered: calibration errors as well as extra errors due to differences between the parameters of equivalent scheme during measurement compared to those during calibration procedure. Much attention was paid to extra errors as calibration errors are systematic in nature and, hence, their influence can be minimized.

Equivalent measurement circuit is shown on Fig. 1, where 1–4 – electrodes’ clamps, CG – current generator, Z_B – biological object impedance, Z_C1, Z_C2, Z_C3, Z_C4 – contact impedances, C_{12}, C_{13}, C_{24}, C_{34} – interelectrode capacities. Each of impedances Z_{c1}–Z_{c4} consists of electrode’s own impedance, impedance of electrode to body contact, and impedance of body part between current and voltage electrodes. Capacities C_{12}–C_{34} are influenced by the device and cables capacities. It can be shown that the influence of the capacitance C_s is equivalent to that of distributed stray capacitance between the subject and surrounding objects.

We simulated calibration and measurement procedures. For this, U_m values were calculated using equivalent circuit by the node potentials method. We utilized the same values of C_{12}–C_{34} on calibration and measurements because of using the same cable. For contact impedances Z_{c1}–Z_{c4}, similar assumption is not reasonable because of dependence on the types of electrodes, their positioning, and the properties of skin. The measurements using analyzer ABC-01 “Medass” includes registration of the impedances Z_{c1} and Z_{c3} between 1-3 and 2-4 clamps. These impedances give an approximation of Z_C1 and Z_C2 impedances used in calculation of measured impedance. Such a correction was also implemented during simulation of measurements. The data on interelectrode capacities and contact impedances Z_{c3} and Z_{c4} were obtained from auxiliary experiments.

Verification of the measurement model present in Fig. 1 was carried out by the comparison of calculated and experimentally derived error values. Then, using the obtained error values, possible deviations of impedance spectrum under corresponding measurement conditions were analyzed.

3. Results

The results of segmental BIA measurements of the impedance spectrum for healthy volunteer are presented in Fig. 2. Similar spectrums were obtained for other volunteers. Fig. 3 shows estimates of contact impedances for electrode types E1 and E2.

Eq. 4 shows the results of theoretical and experimental analysis of extra errors. Calculations of expected values of measurement errors of the resistance R and reactance X were performed for a frequency of 500 kHz in the range of R between 50 and 400 Ohms at X/R = 0.1. The following real values of interelectrode capacities were used: C_{12} = 40 pF, C_{34} = 60 pF, C_{13} = C_{24} = 70 pF. The values of impedances that simulated contacts at calibration were Z_{c1} = Z_{c2} = 100 Ohms, Z_{c3} = Z_{c4} = 10 Ohms. The values of contact impedances during measurement (based on Fig. 3b) were Z_{c1} = Z_{c2} = 170 Ohms, Z_{c3} = Z_{c4} = 120 Ohms for E1 electrode type, and Z_{c1} = Z_{c2} = 70 Ohms, Z_{c3} = Z_{c4} = 40 Ohms for E2 electrode type. Calculations with other parameters show that, in first approximation, the magnitude of errors is proportional to the frequency value and interelectrode capacities. Experimental estimates of measurement errors, denoted as E1exp and E2exp, were obtained using reference circuits that simulated biological object and contacts of E1 and E2 electrodes. Calibration errors were excluded by measurement of reference circuits corresponding to calibration conditions.

Results of approximation of the impedances of measured body segments using the impedance Z_{Cole} and capacitance C_p taken in parallel are given in Table 1.
Figure 2. Impedance plots of body segments: wrist-to-ankle (a), elbow-to-knee (b), knee-to-knee (c), proximal forearm (d).

Figure 3. $Z_{c1}$ and $Z_{c2}$ impedance plots (a), frequency dependences of modules of $Z_{c3}$ and $Z_{c4}$ (b).

Figure 4. Resistance (a) and reactance (b) measurement errors dependences on resistance value.

Table 1. The results of BIA segmental measurements

| Body segment          | SEE Cole, Ω | Cp, pF | SEE Cp, Ω | $R_{500}$, Ω | $X_{500}$, Ω | $ΔR_{500}$, Ω | $ΔX_{500}$, Ω | $ΔR_{50}$, Ω | $ΔX_{50}$, Ω |
|-----------------------|-------------|--------|-----------|--------------|--------------|---------------|---------------|--------------|---------------|
| Wrist-to-ankle        | 2.43        | 60     | 0.54      | 297          | -27.5        | 2.2           | 16.7          | 0.6          | 2.2           |
| Wrist-to-wrist        | 1.03        | 40     | 0.51      | 327          | -27.8        | 1.7           | 13.5          | 0.5          | 1.7           |
| Elbow-to-knee         | 1.59        | 180    | 0.71      | 135          | -12.8        | 1.1           | 10.3          | 0.5          | 1.5           |
| Knee-to-knee          | 0.82        | 320    | 0.22      | 76           | -7.4         | 0.7           | 5.8           | 0.3          | 0.8           |

Results in the Table 1 were obtained using E2 electrode type. Here, SEE Cole and SEE with $C_p$ are standard errors of the impedance approximation as $Z_{Cole}$ only and $Z_{Cole}$ with $C_p$ capacitance taken in.
parallel; $R_{500}$ and $X_{500}$ are measured values of resistance and reactance at a frequency of 500 kHz; $\Delta R_{500}$ and $\Delta X_{500}$ are changes in resistance and reactance at a frequency of 500 kHz after elimination of the capacitance $C_p$ influence on measured impedance; $\Delta R_{50}$, $\Delta X_{50}$ are similar changes at a frequency of 50 kHz.

4. Discussion and conclusions

The impedance plots shown in Fig. 2 for body segments of various resistances are similar to those published by other authors [4, 5, 8]. The results of error analysis (Fig. 4) provide an opportunity to explain the differences of impedance spectrum of different body segments. Satisfactory agreement between calculated and experimental error values suggests that such an explanation is correct.

In case of body segments with the resistances over 200 Ohms an effect is prevalent of the low-pass filter of the impedances $Z_{c3}, Z_{c4}$ and capacitance $C_{34}$ (Fig. 2a). In the resistance range 100–200 Ohms, change of polarity of the reactance measurement error takes place for the E1 electrodes caused by the predominant effect of $C_{13}$ and $C_{24}$ capacitances that transmit voltage from the current generator output directly to the voltage gauge. This leads to the shift of the high-frequency end of an impedance plot in positive direction (Fig. 2b,c). In both ranges effects strongly depend on the contacts impedance. Other values of interelectrode capacities entail changes in the boundaries range.

If absolute value of the impedance is less than 100 Ohms, then the positive error of the reactance measurement with electrodes E1 becomes so large that the measured value of the reactance $X$ reverses its sign (Fig. 2d). The error of resistance $R$ also reverses sign (Fig. 4a). The observed form of the impedance locus is sometimes interpreted as the presence of an inductive component. But this effect is formed by joint action of the interelectrode capacities and contacts impedances. So, when measured low-resistant body segments, the electrodes contact impedance may produce unreliable results.

For sufficiently large object resistances and small contact impedances the measurement provides reliable information on the object impedance. Table 1 shows that the values of $\Delta X_{500}$ are significantly higher than the absolute value of the expected error of the reactance when measured using E2 electrodes (Fig. 4b). So, the capacitance $C_p$ is really present in measured impedance, and is not the result of measurement errors. Representation of measured impedance as the parallel connection of $Z_{cole}$ and $C_p$ significantly improves an accuracy of approximation. Note also, that excluding of the $C_p$ capacitance exerts little effect on the results of measurements at the frequency 50 kHz.

Since the value of $C_p$ increases with the decrease of resistance of measured segment, one can draw conclusions about the nature of this capacity. Stray capacitance $C_s$ must increase with length and, hence, with the resistance of segment. Yet, the resistance and own capacity of a homogeneous object are linked by obvious relation $RC = \rho \varepsilon$, where $\rho$ is the resistivity, and $\varepsilon$ the dielectric constant. Thus, the value of $C_p$ is determined primarily by the capacitive component of the biological object impedance $Z_{bh}$ rather than by the stray capacitance $C_s$.

In conclusion, understanding the nature and properties of errors caused by contact impedances and interelectrode capacitances gives a possibility to improve methods of calibration and measurements by the correction of the influence of these elements.

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