BIOPHYSICS AND BIOCHEMISTRY

Bioelectric Impedancemetry of the Myocardium during Cardiac Surgery with Artificial Circulation

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We analyzed changes in bioelectric impedance of the myocardium during cardiac surgery under conditions of cardioplegy. The results suggest the possibility of using bioelectric impedancemetry for evaluation of the state of the myocardium during surgery. Bioelectric impedancemetry allows evaluation of interstitium filling during infusion of the cardioplegic solution and reperfusion damage to cardiomyocytes.

Key Words: *bioimpedance; bioelectric impedance; interstitial space; cardioplegy; reperfusion*

The development of a reliable diagnostic method for online monitoring of the state of cardiomyocytes and interstitial space of the myocardium during cardiovascular surgery enabling evaluation of the degree of ischemic and reperfusion damage to the myocardium and the level of myocardial perfusion during infusion of the cardioplegic solution is an urgent problem of modern cardiology.

Bioimpedance measurements are used in various spheres of medicine for evaluation of cell homeostasis and measuring of extracellular water content [3,7]. There are published data on the possibility of using bioimpedance measurements in organs and tissues stimulated with currents of different frequencies. This method is used for monitoring of the state of biomembranes and interstitial space [2,4-6].

Direct current passing through a biological system induces an opposite electromotive force (EMF), which increases to a certain value. EMF can be measured by switching the electrodes from the generator to a galvanometer and by recording fading oppositely directed current. The quantity of electricity accumulated in the living system after current flow is determined by not only static, but also relatively high polarization capacitance. Electrical resistance of tissues is determined by their ohmic and capacitance resistance. For alternating current both ohmic and capacitance resistance should be taken into account [1].

Electrical conductance of living cells and tissues can be evaluated using equivalent schemes, *i.e.* certain combinations of ohmic and capacitance resistances allowing modeling of electrical parameters of cells and tissues. For instance, electric impedance for a series of ohmic and capacitance resistance the is calculated by the formula:

$$Z=\sqrt{R^2+\frac{1}{\omega^2 c^2}},$$

where R is ohmic resistance and $1/\omega c$ is capacitance resistance. For parallel connection, the impedance is calculated by the formula:

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$$Z = \frac{1}{\sqrt{\frac{1}{R^2} + \omega^2 c^2}}.$$

Living cells are characterized by more intricate combination of series and parallel connections.

It is difficult to determine the absolute value of tissue resistance, because it depends on measuring conditions (electrode area, distance between electrodes, tightness of the electrode-tissue contact, thickness of the object, *etc*.) [1].

The slope of electroconductivity dispersion (S_c) more reliably characterizes the physiological state of the biological tissue. Some properties of the dispersion can be expressed by the ratio of resistances measured at low and high frequencies; when two resistance are measured at different frequencies under the same conditions, their ratio is a constant for normal state of the given tissue [5]:

$$R_{LF} = \rho_{LF}\frac{l}{S},\ R_{HF} = \rho_{HF}\frac{l}{S},$$

where ρ_{LF} and ρ_{HF} are specific resistance of the biological tissue at the applied frequency, l is a distance, and S is the area of the measuring electrode. Thus,

$$S_C = \frac{R_{LF}}{R_{HF}} = \frac{\rho_{LF}}{\rho_{HF}}.$$

As is seen from this formula, S_C does not depends on parameters of the measuring electrode, but is determined only by tissue properties.

After biological death of the tissue S_C approaches 1. In normal intact cells and tissues with parameter depends on the evolutionar position of the organism. For instance, for mammals S_C varies from 2.5 to 10.0, while for frogs it is equal to 1.5-3.0. This coefficient depends also on the structure, function, and state of the tissue. In organs with intensive metabolism (liver, spleen) it is higher than in muscles [7].

Thus, alternating current with a frequency below 40 kHz flows along the vessels and extracellular matrix, but not through cells, because their specific resistance (due to high ohmic resistance of cell membranes) far surpasses the specific resistance of liquid media. At frequencies of hundreds and thousands kHz the capacitance resistance of cell membranes just little impedes current flow through cells and the current densities inside and outside the cells become comparable. At these frequencies electric current easily passes through both extracellular and intracellular medium. In contrast to low-frequency measurement, the electroconductivity increases and, consequently, tissue resistance (bioimpedance) decreases.

A device for measurement of bioelectric impedance of the myocardium was designed at A. N. Bakulev Research Center of Cardiovascular Surgery under the supervision of L. A. Bokeriya, Academician of the Russian Academy of Medical Sciences.

We analyzed changes in bioelectric impedance of the myocardium during cardiac surgery under conditions of cardioplegy.

MATERIALS AND METHODS

The study included 30 patients operated at A. N. Bakulev Research Center of Cardiovascular Surgery, Russian Academy of Medical Sciences, in 2003-2004 for heart valve disease. In all patients, antegrade and retrograde (via the coronary sinus) cold blood cardioplegia after Buckberg was used for protection of the myocardium.

Bioelectric impedancemetry was performed as follows. Immediately before the onset of extracorporeal circulation, two myocardial electrodes were stitched to the anterior wall of the right ventricle for quadrupolar measurements of bioelectric impedance. The myocardial electrodes were fixed is such a way as to ensure maximum coverage of the studied myocardial segment. The distance between the electrodes was 3 cm.

The electrodes were connected to a bioimpedancemeter, a general-purpose device, and bioimpedance (Z) was measured at 110 and 9.4 kHz. The values of high-frequency (Z_{HF}) and low-frequency (Z_{LF}) impedance and their ratio Z_{HF}/Z_{LF}, dispersion slope (S_C) after primary processing were continuously input into a computer. After final processing the data were displayed on a monitor in digital and graphic regimens. The temperature of the studied myocardial segment was measured for standardization of Z_{HF} and Z_{LF} curves to 37°C.

RESULTS

All impedance values were compared with the initial values (Table 1) measured on warm heart at 36.7°C.

In all patients initial S_C was on average 2.14± 0.03 and does not depend on the volume of the studied myocardial segment.

Analysis of experimental data revealed some general regularities in changes of bioelectric impedance of the myocardium (Fig. 1).

Before clamping of the aorta, the electric resistance of the myocardium remained practically un-

TABLE 1. Initial impedance and IDM, (Ω; *M*±*m*)

Parameter	Initial	IDM
Z_{LF}	850.8±9.7	1003.3±11.3
Z_{HF}	395.8±3.7	434.9±4.3
S_C	2.15±0.02	2.31±0.03

changed, which reflected stable state of the intra- and extracellular spaces. A few seconds after aorta clamping, the impedance sharply increased at the expense of Z_{LF}, as was seen from S_C increase. This change can be explained by emptying of small blood vessels and dehydration of the interstitial space (Fig. 1). This process takes 1.8±0.1 min on average and the electric resistance of the myocardium stabilizes, if infusion of the cardioplegic solution is not started by this time.

The first cardioplegia session (induction) was performed 1.2±0.1 min after aorta clamping for inducing asystole. Immediately after infusion of the solution, impedance sharply decreased to the initial value primarily at the expense Z_{LF}, which attested to filling of the vascular bed and interstitial space with the cardioplegic solution. The impedance decreased to a certain value and remained at this level until the end of infusion. After cardioplegia, the impedance increased again and attained a maximum, so-called "impedance of dry myocardium" (IDM). Similar changes were seen during the subsequent cardioplegia sessions (reinfusion, Fig. 1).

During infusion of the cardioplegic solution we observed a visual relationship between changes in volume rate of cardioplegic solution infusion and bioelectric impedance of the myocardium. In order to describe the relationship between the volume rate of cardioplegic solution infusion and Z_{LF} decrease we determined the degree of proportionality for these variables using Pierson linear correlation (Fig. 2). Calculations showed that the higher was the volume rate of cargioplegic solution infusion, the more pronounced was the decrease in Z_{LF}. The correlation coefficient between these parameters was 0.84 (p<0.001).

After declamping and resumption of the coronary blood flow, the electric resistance of the myocardium decreased to the initial values. In 9 patients, the high-frequency impedance continued to decrease below the initial value, the maximum decrease was observed 19.2±1.5 min after the start of reperfusion (Fig. 1).

Resumption of the coronary blood flow after long-term clamping of the aorta can be associated with massive calcium entry into myocytes, which induces sharp osmotic swelling of the sarcoplasmic reticulum and T-system. Utilization of ATP is accelerated due to Ca^{2+}-ATPase activation, mitochondrial production of ATP is suppressed, which leads to exhaustion of the pool of macroergic phosphates. Amphiphilic compounds modifiying physical properties of the phospholipid bilayer are accumulated in cell membranes and impair their integrity. Disturbances in electrolyte and ionic balance lead to burst swelling of cells. These changes ex-

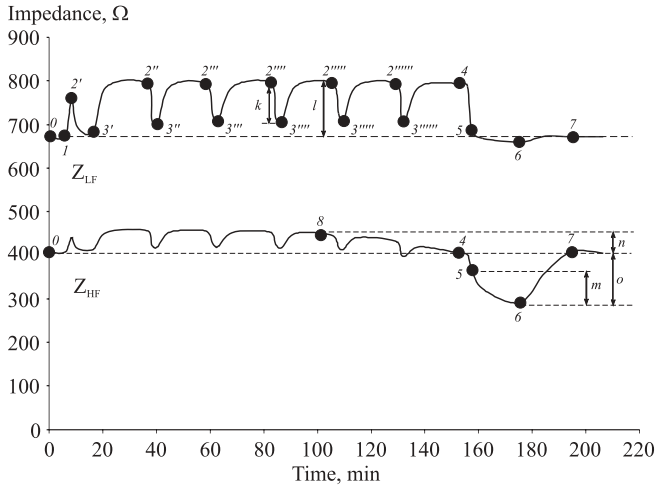

Fig. 1. Bioelectric impedance of the myocardium. 0) initial value; 1) before clamping; 2) before infusion of cardioplegic solution; 3) before the end of infusion; 4) before declamping; 5) first minutes of reperfution; 6) 20 min after resumption of coronary blood flow; 7) recovery of impedance to initial level; 8) start of Z_{HF} drop. Dash: next cardioplegia session; *k*: magnitude of Z_{HF} decrease during cardioplegia; *l*: IDM; *n*: magnitude of Z_{HF} decrease at the peak of ischemia; *m*: magnitude of Z_{HF} decrease during reperfusion; *o*: maximum decrease of Z_{HF}.

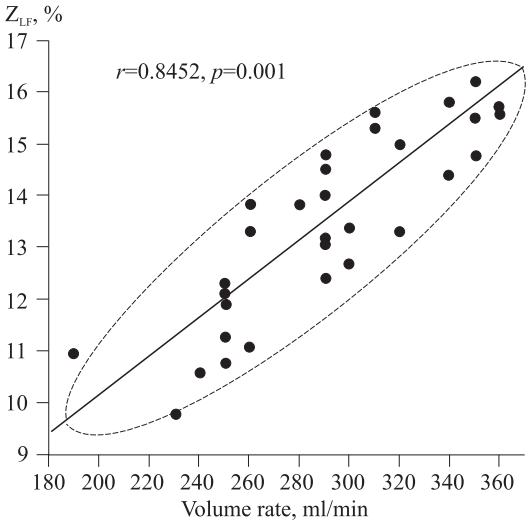

Fig. 2. Correlation between volume rate of myocardial perfusion and Z_{HF} decrease during infusion of the cardioplegic solution. The area of actual values is shown with a dashed line. *r*: correlation; *p*: significance.

tend the total extracellular space of the myocardium and increase its electric conductivity, which manifests in a decrease in bioelectric impedance.

Thus, the strict correlation between the volume rate of cardioplegia and changes in electric impedance of the myocardium makes it possible to use the method of electric impedancemetry for evaluation of the degree of filling of the interstitial space of the myocardium during infusion of the cardioplegic solution. Electric impedance measured during cardioplegic ischemia and after resumption of coronary blood flow allows evaluation of the severity of ischemic and reperfusion damage to cells and myocardial edema.

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