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PHYSIOLOGY

Non-invasive Evaluation of the Kinematic Activity of the Intact Left Ventricle of the Heart

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Abstract—Vector analysis of the movement of the epicardium has been used to calculate the energy efficiency of different parts of the left cardiac ventricle. The protocol based on the results of these calculations would allow the calculation of the potential power of myocardial contraction.

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The use of generators based on microelectromechanical systems (MEMS generators) is among the priority directions in fundamental and applied science. The creation and development of methods for non-invasive assessment of kinematic activity of the heart and collection of the pilot data will allow the identification of the location of energy-efficient MEMS devices for the conversion of kinematic activity into electrical energy.

Implantable devices that correct the functional disorders of certain organs are increasingly used in medicine; e.g., pacemakers are used to improve the functioning of the heart. The size and the lifetime of these devices are largely determined by the capacity of the power source used. These parameters are especially important in the case of implantable devices located on the surface of the heart, since the weight of such a device should not exceed 15 g. The search for new approaches for the production of power sources (batteries) with a lifetime exceeding 10–15 years is a key direction of research in this field [1–3]. The methods and devices that convert the energy of alternate movements, oscillation, or vibration into electrical energy are currently paid much attention [4]. The development of devices for microelectromechanical conversion of contractions of the heart into electricity is a promising trend in modern medicine [5].

MEMS devices used in biomedicine include microsensors, such as micromechanical pressure and vibration sensors and high-precision chemical sensors. Micromechanical pressure sensors are used in cardiac surgery to measure blood pressure [6, 7]. Micromechanical pressure sensors are also widely used in medicinal infusion pumps, in sensors of blood flow volume and rate, and in other areas [8, 9].

MEMS converters can be used in epicardial pacemakers (EPMs) implanted into the wall of the left ventricle. The kinematic energy of the heart is sufficient to extend the lifetime of the battery of the pacemaker at least twice. The use of EPMs with MEMS converters revealed the necessity of noninvasive measurement of the amounts of kinematic energy produced by specific parts of the LV.

Measurements of kinematic activity of different parts of the myocardium have been performed in rather many studies, but all these reports have a common drawback, namely, the invasive character of the measurements [10]. The use of invasive procedures for the measurement of kinematic energy on the surface of the epicardium in clinical studies is apparently unacceptable, since it requires surgery for access to the heart. Analysis of all non-invasive research methods currently available enabled us to put forward a non-invasive approach for the assessment of kinematic activity of the myocardium. The approach is based on echocardiography with subsequent vector analysis of the movement of different parts of the epicardium.

Analysis of myocardial movements and deformation provides information on both global and local contractility of the myocardium.

The present experimental study employed the method of moving particle analysis to determine the amplitude and the speed of the movement of the left ventricular wall at different levels. The approach developed by the authors involved the selection of the epicardium for vector analysis during the post-processing of data and thus differed from the standard method.

The goal of the present study was to analyze the topology of energy-efficient areas on the epicardial surface using non-invasive procedures. The results obtained will enable the identification of the optimal

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Parameters of epicardial movement and myocardial deformation according to Echo CG

Parameter	Basal level, $n = 15$	Medial level, $n = 15$	Level of the apex of the heart, $n = 15$
Radial displacement, mm	4.01 ± 0.26	3.69 ± 0.17	1.3 ± 0.18
Longitudinal displacement, mm	6.81 ± 0.27	5.7 ± 0.16	1.8 ± 0.21
Deformation of the myocardium	5.61 ± 0.25	3.99 ± 0.21	1.26 ± 0.3

$M \pm SD$, the number of animals in each group was 15; *$p < 0.05$ for the comparison with the medial level and the level of the apex of the heart.

sites for the implantation of MEMS, including the devices used for electrotherapy of the heart.

The study involved experimental animals (domestic pigs). The plan and design of the experimental study was coordinated and approved by the Ethics Committee of the Bakulev Research Center of Cardiovascular Surgery, Ministry of Health of the Russian Federation, on September 6, 2014 (Protocol 325). Fifteen animals 6–9 months of age (average body weight, 56 ± 5 kg) were used for the study. Echocardiography (Echo-CG) was performed in all animals to exclude valvular heart disease, congenital abnormalities, and signs of myocardial ischemia.

Kinematic activity of the epicardium was assessed using vector analysis of the speed of movement of certain points in 2D images (VVI). A workstation produced by Siemens (Germany) and the Syngo US Workplace Software 3.5, Version 3.5.6.34, were used for the assessment. The parameters evaluated included the radial displacement of the epicardium, the longitudinal displacement of the epicardium, and deformation of the myocardium. Each parameter was recorded at three levels (basal, medial, and apical). The analysis was performed on the QRS loop of standard projections at three levels along the short axis (basal, the level of the mitral valve; medial, the level of the papillary muscles; and apical; the apical projections were recorded at the positions corresponding to a two-, four-, and five-chamber image). Two parameters were recorded for each of the anterior, lateral, and posterior walls at each level. The movement parameters were assessed in the epicardial region. The radial displacement of the epicardium, the longitudinal displacement of the epicardium, and deformation of the myocardium were analyzed.

Statistical analysis was performed using the Statistica 10.0 software (StatSoft, United States).

Correspondence of the distribution of the values to a normal distribution was tested using the Shapiro–Wilk test. Data that followed the normal distribution were presented as $M \pm SD$.

The nonparametric Wilcoxon–Mann–Whitney test U test and the parametric two-way Student's t test (for normal distribution) were used to compare two independent samples. The nonparametric Wilcoxon test was used to compare two dependent samples. The comparison of several independent samples was performed using the nonparametric Kruskal–Wallis test with Bonferroni's correction.

The differences were considered statistically significant at $p < 0.05$.

Echo-CG did not reveal congenital anomalies of the heart structure, valve pathology, or local and/or diffuse reduction of the contractility of the left ventricle in any of the experimental animals.

Vector analysis was applied to the data obtained.

The values of radial and longitudinal displacement of the epicardium and the deformation of the myocardium at various levels are presented in the table.

Statistically significant differences in the values of radial displacement at three different levels were observed: $\chi^2 = 30.1$, $p < 0.0001$ (Kruskal–Wallis test with Bonferroni's correction). Pairwise comparison showed that the radial displacement parameters at the level of the apex of the heart differed significantly from the values recorded for the basal and medial levels, whereas there were no significant differences between the values recorded for the basal and medial levels.

Thus, the present study resulted in the development and validation of a procedure for non-invasive assessment of the amplitude of the movement of the left ventricular wall. The first results indicative of the sufficiency of the energy potential of the heart for the support of EPM functioning have been obtained. Moreover, the lateral wall of the LV at the basal level was characterized as the most movable portion of the left ventricle on the epicardial side (in experimental animals).

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