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Potential Use of Heart Contractions as a Source of Energy for Implantable Devices

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We present an analysis of possible approaches to transforming heart contractions kinematics into electrical energy to supply implanted devices. Preclinical studies of cardiac kinematics were conducted. We conclude that it is possible to develop generators for microelectromechanical systems (MEMS) to increase the service life of leadless pacemakers.

Bradyarrhythmia is an arrhythmia characterized by a low pulse rate or pauses in cardiac contractions. It accounts for 20-30% of all impairments to cardiac rhythm [1]. Clinically severe bradycardia is apparent as vertigo and presyncopal and syncopal states. Bradyarrhythmia can also cause secondary supraventricular tachyarrhythmias, such as atrial fibrillation and flutter. Critical bradycardia is a life-threatening state, as it can lead to asystole and sudden cardiac death [1]. Thus, the prevention and timely treatment of bradyarrhythmias can decrease the level of disability in patients with bradycardia and provide a warning of undesirable cardiac events.

The only function of the first single-chamber pacemaker (Fig. 1), implanted in 1958 [2, 3], was to impose a rhythm of 70-80 contractions per minute and consisted essentially of an impulse generator based on two transistors and a power supply placed in a sealed epoxy resin casing.

Pacemakers have evolved since then and are now complex hi-tech devices with a wide range of functions: multichamber stimulation, self-testing, setting of stimulation modes to specific pathological manifestations, frequency adaptation, wireless information exchange, etc.

However, current implantable endocardial pacemakers have a number of significant drawbacks associated with the need for a conductive electrode passing within the lumen of the subclavian vein conducting stimulation impulses from the control unit to the electrode heads fixed within the heart chambers. In the long-term postoperative period, patients with implanted endocardial pacemakers are at increased risk of developing so-called electrode complications, with increases in the threshold of stimulation (output block) due to connective tissue encapsulation of the electrode head, perforation of the heart wall by the electrode, breaks and impairment to the integrity of the conductor due to repeated deformation, and purulent complications (generator pocket suppuration, electrode sepsis, generator pocket decubitus). In addition, the conducting part and the electrode heads are in direct contact with the blood, which increases thrombus formation. Perforation of the leaves of the tricuspid valve can also occur, which can lead to the formation of significant regurgitation and, if necessary, implantation of a biological prosthesis, with surgical intervention using extracorporeal circulation. The service life of current pacemakers is 5-7 years.

Thus, pacemakers with minimal risks of electrode complications are currently under active development. The obvious design solution is to exclude the conducting part of the electrode and implant the device epicardially directly onto the surface of the heart.

In 2013, studies at the Bakoulev Scientific Center for Cardiovascular Surgery developed and performed in vivo testing of the first Russian epicardial leadless pacemaker (Fig. 2, a and b).

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A new direction is currently under way – energy harvesting, i.e., collecting and transforming nonelectrical energy into electrical to supply low-power autonomic devices. In the case of pacemakers, this approach involves combined use of galvanic power sources with low capacity and converters of different types of nonelectrical energy to electrical. Electromagnetic irradiation, temperature differences between the body and the surroundings, kinetic energy due to physical activity, and energy from chemical reduction–oxidation reactions in the body – all these phenomena and processes represent an extensive area for the development of efficient converters [3-9].

In relation to epicardial pacemakers, the obvious solution is to convert the mechanical energy of cardiac contractions into electrical energy.

a b

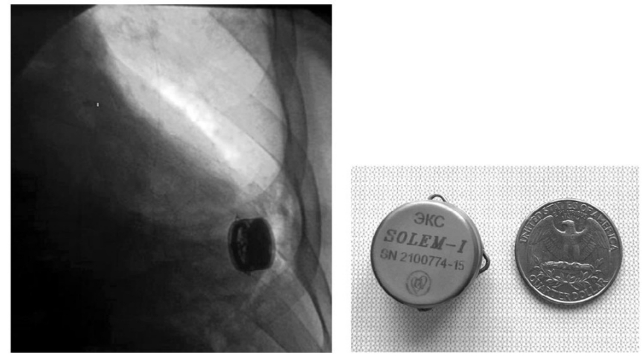

Fig. 2. Leadless epicardial pacemaker: a) view of leadless pacemaker on a patient’s X-ray; b) dimensions of leadless pacemaker.

Materials and Methods

Studies were carried out at the Bakoulev National Medical Research Center for Cardiovascular Surgery, Ministry of Health of the Russian Federation.

Studies were carried out on the epicardium of intact left ventricles from domestic pigs. A total of 15 animals aged 6-9 months were studied; mean weight was 56 ± 5 kg. All animals underwent ECG traces and standard echocardiography (EchoCG) to exclude cardiac valve pathology, congenital anomalies, and signs of myocardial ischemia.

Animal keeping and surgical manipulations were performed in compliance with sanitary standards – the requirements for studies with laboratory animals of the Russian Academy of Sciences and Russian Ministry of Health. Animals were kept on a diet (State Standard GOST R 50258-92) in compliance with the international recommendations of the European Convention for the Protection of Vertebrates Used for Experimental Purposes (1986). Animals were harvested from experiments in compliance with the “Regulations for Studies Using Experimental Animals” (USSR Ministry of Health Order No. 755 of August 12, 1972) and the “Regulations for Conducting Studies Using Experimental Animals” (Ministry of Higher Education Order No. 724 of November 13, 1984).

Fig. 1. The first implantable pacemaker – Siemens-Elema (Germany).

Experimental Conditions

The test object – the experiment animal – was prepared for study by i.m. administration of Zoletil (2%, 1.5 mL) and Xylazine (20%, 3 mL) (premedication). After 15 min, the animal was placed on the operating table on the right side ready for the study procedures.

The study was divided into two stages: the invasive and the noninvasive. The invasive study was performed using two sensors sutured to the epicardium (Fig. 3), each consisting of a triaxial MEMS gyroscope and an accelerometer. Measurements were made with the sternum approximated. Data from the sensors were passed through the control block of a USB interface to a personal computer to reconstruct the displacement trajectory from acceleration and angular velocity measurements.

The noninvasive study consisted of echocardiography (EchoCG). The kinematic activity of the epicardium was evaluated by velocity vector analysis of 2D images (VVI) using a Siemens (Germany) workstation and Syngo US Workplace Software 3.5 (version 3.5.6.34).

Fig. 3. Device for contact measurement of acceleration and radial velocity (in vivo experiment).

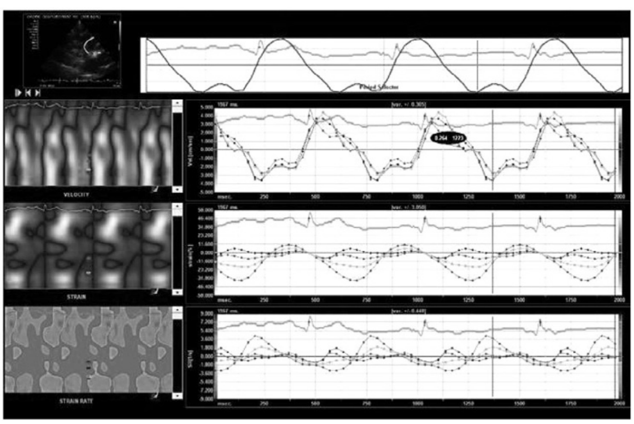

Fig. 4. Data on epicardial movement at different levels and left ventricular walls obtained using the noninvasive method. From above: movements of the basal segment of the lateral wall; velocity of motion of left ventricular wall at different levels; deformation of the left ventricular myocardium at different levels; frequency of deformations of the left ventricular myocardium at different levels.

The following parameters were evaluated: the radial displacement of the epicardium, the longitudinal displacement of the epicardium, and deformation of the myocardium. These values were recorded at three levels: basal, medial, and apical. Analyses were run using QRS complexes in standard projections: the short axis at three levels – the level of the mitral valve (basal), the level of the papillary muscles (medial), and the apical level, in positions giving two-, four- and five-chamber images. Two values were determined for the anterior, lateral, and posterior walls at each level. Measures of movement were assessed in the region of the epicardium (Fig. 4).

Results

Invasive measurements yielded the following results: the mean displacement in the basal part was 8.8 mm, compared with 7.0 mm in the medial part, and 2.5 mm in the apical part.

The results of noninvasive measurements demonstrated the following mean values: the longitudinal displacement of the lateral wall of the left ventricle at the basal level was 6.8 mm, compared with 5.7 mm at the level of the papillary muscles and 2.4 mm at the apex. The mean radial displacement of the lateral wall of the left ventricle was 4.0 mm at the basal level, 3.7 mm at the level of the papillary muscles, and 2.3 mm at the apex.

Analysis of the data obtained during the invasive and noninvasive experiments using 15 model animals showed:

– the mean acceleration along each of the three axes of displacement of the epicardium was 0.35-0.4 m/s^2;

– at the moment of onset of acceleration of the heart, acceleration transiently reached 1.3-1.4 mm/s^2;

– the mean angular velocity of the epicardium was 35-45°/s;

– at the moment of onset of cardiac contraction, the angular velocity transiently reached 150-320°/s;

– the mean displacement of the surface of the epicardium was 7-8 mm.

Data were obtained at a mean heart rate of 70 bpm.

Summary

Analysis of published sources and patent databases shows that the approach with the greatest potential for constructing MEMS generators consists of using electromechanical converters. The electromechanical means of obtaining electrical energy has the greatest specific power among all the approaches considered. Data from preclinical studies provide evidence of the fundamental possibility that heart contractions can be used to obtain electrical energy for devices. Development and studies using a simulation of cardiac kinematics and electromechanical converters able to supply the required electrical power of 30 μW at currents of up to 10 μA and voltages of up to 3 V are continuing.

Conclusions

Increases in the service life of implantable devices can be attained by decreasing the current consumed and by increasing the electrical capacity of the current source. Studies decreasing pacemaker power consumption are being pursued actively, with reductions in leakage currents, improvements in control algorithms, use of energy-saving modes, etc. At the same time, the specific energy density (the ratio of electrical capacity to mass or volume) in current sources has shown little change in recent years, so the volumes and weights of contemporary implantable devices depend mainly on the dimensions of the current source, which is of fundamental importance for epicardial pacemakers. The challenge of increasing the service life of the batteries was partly met in the first epicardial pacemakers: lithium carbon fluoride batteries were developed with capacities of up to 210 mA/h, diameter 18 mm, and thickness 1 mm. Use of batteries with greater capacity would undoubtedly increase the interval between planned pacemaker replacements due to battery depletion. However, there is need not only to increase the pacemaker replacement interval, but also to decrease pacemaker weight and size. Decreases in pacemaker dimensions come about mainly because of changes in the overall layout of the device or decreases in the dimensions of the power supply, i.e., use of batteries with lower capacity. Thus, use of MEMS converters lengthens the service life of pacemaker without increasing weight or size.

Our study using both invasive and noninvasive methods included measurement of the amplitudes of heart wall movements. Initial calculations using the experimental data demonstrated that power at levels of 50-70 μW could be obtained using a pacemaker with an epicardial contact area. Zurbuchen et al. presented experimental results on the conversion of mechanical energy from the contracting epicardium into electrical energy using the principle and mechanism of automatic winding of a watch. In vivo experiments using an animal model in sheep weighing 65 kg at a heart rate of 90 bpm demonstrated a maximum power of 30 μW when attached to the basal part and 23.2 μW when attached to the apex [10].

Considering the requirements of contemporary leadless pacemakers for power at a level of 30 μW, the human heart is evidently able to provide enough power at least to cover the needs of pacemakers. Studies creating MEMS need to continue, to provide increases in service lives of implantable devices.

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