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Development of an electrostatic generator for a cardiac pacemaker that harnesses the ventricular wall motion

Abstract A variable-capacitance-type electrostatic (VCES) generator that harnesses ventricular motion was developed with the aim of driving a cardiac pacemaker permanently without a battery. The developed model of the VCES generator was handmade, but it was too large to implant into the thoracic cavity of a laboratory animal. For this reason, to demonstrate its feasibility, a somewhat complicated method that measured the left ventricular wall motion by means of the accelerometer module put on the free wall and reproduced the motion in real time with a vibration mode simulator was used. The VCES generator was vibrated on the simulator, and its generated power was supplied to the cardiac pacemaker, which then stimulated the heart. A mean power of approximately 36μW was generated, which was enough to drive the cardiac pacemaker. Continuous electric generation and cardiac pacing were performed successfully for more than 2h in the animal experiment.

Key words Electrostatic generator · Electric generator · Bioenergy · Cardiac motion · Resonance · Cardiac pacemaker

Introduction

To date hundreds of thousands of cardiac pacemakers have been implanted. Today, although cardiac pacemakers can function for a long time on lithium batteries, the batteries must be changed surgically before they become flat. This procedure may cause patients mental and physical pain. Ideally, there would be no need for aftercare and cardiac pacemakers would work permanently by electrical generation using bioenergy. Physical or chemical methods of generating electric power to drive in vivo systems were proposed in the 1960s.[1–6] In those days, implantable electric generators for practical use had not been developed because the generated electric power was much to low to drive artificial organs. Remarkable progress in electric and electronics engineering has made it possible to drive a cardiac pacemaker with as little as 50μW power. This fact may give us an opportunity to consider electric power generation that converts bioenergy to electrical energy.

We have been developing a variable-capacitance-type electrostatic (VCES) generator that harnesses the motion of the living body to supply electric power to an implantable cardiac pacemaker.[7] Although electromagnetic generators are popular in general, the reason why the electrostatic generator was chosen is as follows. Energy density of a variable capacitor, which is a component of the electrostatic generator, can be raised by enlarging the surface area of electrodes per unit volume and shortening the gap between electrodes. Moreover, the variable capacitor can convert mechanical work done by linear motion into electrical energy directly. Such motion is obtained easily in the living body. These facts allow miniaturization of the VCES generator. The most suitable vibrating source in the living body is the ventricular wall because its rather large motion persists all day long, which is not the case with other organs. However, vibration of the ventricular wall for electrical generation is relatively slow, only 1 to 2Hz. Therefore, to realize a high driving rate for the generator, the generator should be resonated with a harmonic component of the vibration. To verify the feasibility of VCES generators, we developed a VCES generator that was driven in real time by simulating the vibration of the left ventricular (LV) free wall with a vibration mode simulator. Moreover, a canine heart was paced by the cardiac pacemaker driven by the VCES generator.

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Materials and methods

VCES generating system

The VCES generator converts in vivo mechanical energy into electrical energy based on the following principle. The VCES generator has a variable capacitor (VC), which is a key device for energy conversion and has a capacitance change of between C_{min} and C_{max}. At first, applying a DC voltage of V_0 across a VC at C_{max}, the VC has an electric charge of $Q = C_{max}V_0$ and an electrostatic energy of $E_{before} = C_{max}V_0^2/2$. Next, when the capacitance is decreased to C_{min} by an external force while preserving the electric charge Q, the voltage V increases according to the equation

$$V = \frac{C_{max}}{C_{min}} V_0 \tag{1}$$

and then the VC has the electrostatic energy

$$E_{after} = \frac{1}{2} C_{min} V^2 = \frac{C_{max}}{C_{min}} \cdot \frac{1}{2} C_{max} V_0^2 = \frac{C_{max}}{C_{min}} E_{before} \tag{2}$$

This means that the stored electrostatic energy becomes C_{max}/C_{min} times as large as before. That is, the energy increment of $(C_{max}/C_{min} - 1)C_{max}V_0^2/2$ is equal to the mechanical work done by the external force.

Figure 1 shows a VCES generating system. This system consists of an initial charge supply (ICS), a variable capacitor (VC), whose capacitance can be changed by an external mechanical force, a capacitor for energy storage (storage capacitor, SC), and two rectifying diodes (D_1, D_2). A battery is used only one time to supply electric charge to the capacitor for the ICS at the very beginning of power generation. There are two phases in one operating cycle. At first, when the voltage of the VC is low, the ICS supplies electric charge to the VC in a counterclockwise direction (ICS $\rightarrow$ D_1 $\rightarrow$ VC $\rightarrow$ ICS). After that, as the capacitance C_1 is decreased gradually by the external force, voltage V_1 increases. Then, the electric charge of the VC flows into the storage capacitor in a clockwise direction (ICS $\rightarrow$ VC $\rightarrow$ D_2 $\rightarrow$ SC $\rightarrow$ ICS). At the same time, the electric charge returns to fill up the ICS. The amount of electric charge in the ICS remains constant in one operating cycle. Thus, electrical energy in the storage capacitor increases, that is, mechanical work done by the external force is converted to electrical energy. Therefore, electrical generation is performed.

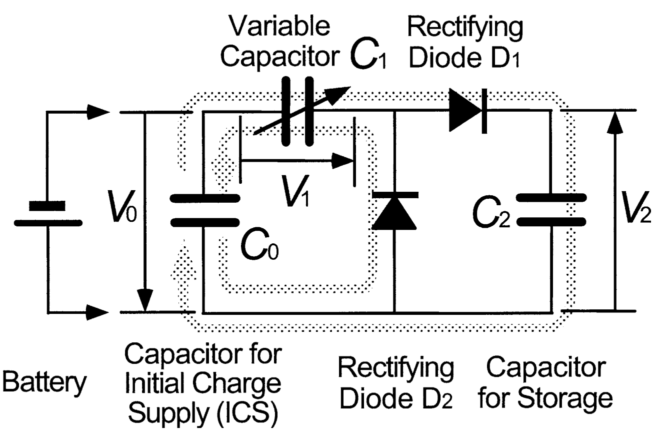

Fig. 1. Variable-capacitance-type electrostatic (*VCES*) generating system

Honeycomb-type variable capacitor

Honeycomb-type variable capacitors (HVC) were designed for simplicity in manufacturing. The fundamental structure is as shown in Fig. 2. Figure 3 shows how its capacitance can be changed; the capacitance becomes small when the HVC is expanded and large when it is compressed. The HVC shown in Fig. 4 was made by repeatedly folding a pair of long electrodes made of aluminum-evaporated polyester film to avoid having many terminals. An aluminum-evaporated polyester film sheet is always used as the material for metal-evaporated-film-type capacitors. First, two sheets of aluminum-evaporated polyester film, 5 μm thick, 30 mm wide, and 5 m long, were mated together by using double-sided adhesive tape at regular 5-mm intervals. Figure 5 shows a unit cell of a honeycomb-type variable capacitor. Second, the mated sheets were repeatedly folded and joined by using double-sided adhesive tape. The variable capacitor has 20 cells per layer and 50 layers; thus, it has 1000 cells. Both the upper and lower sides of the HVC were joined to acrylic boards.

Resonator with honeycomb-type variable capacitors

The lower sides of three HVCs were affixed to an acrylic board, forming a base, as shown in Fig. 6. The upper sides

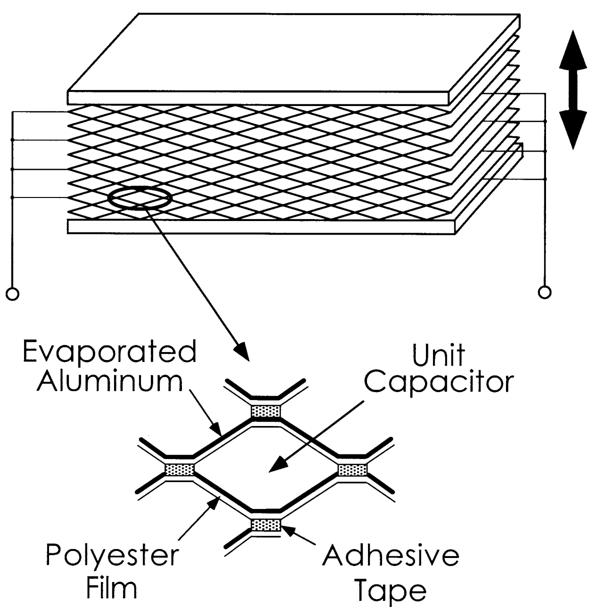

Fig. 2. Fundamental structure of a honeycomb-type variable capacitor

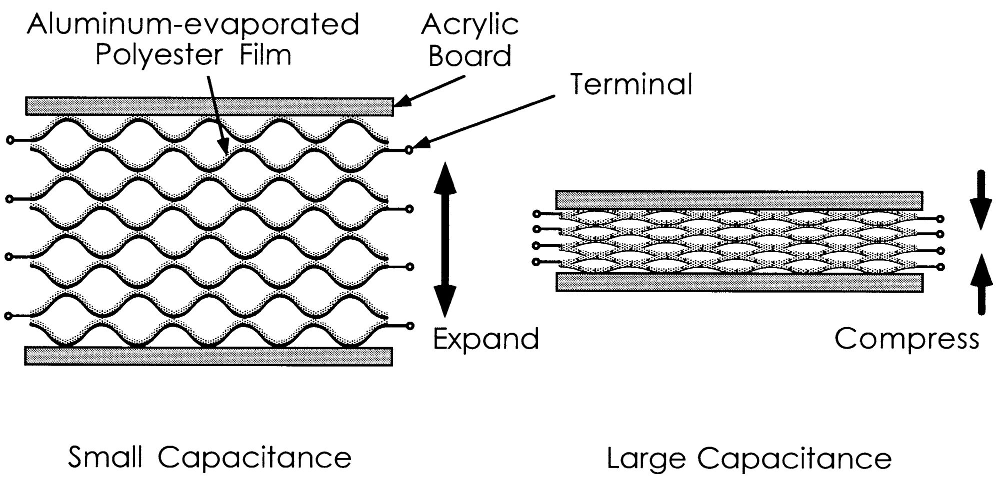

Fig. 3. Capacitance change in a honeycomb-type variable capacitor

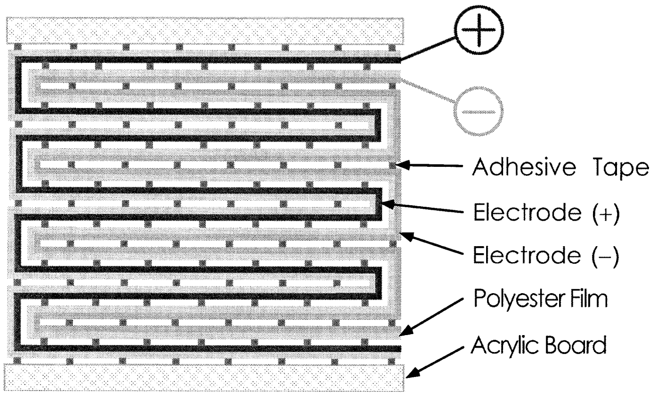

Fig. 4. Practical stacking method for aluminum-evaporated polyester film

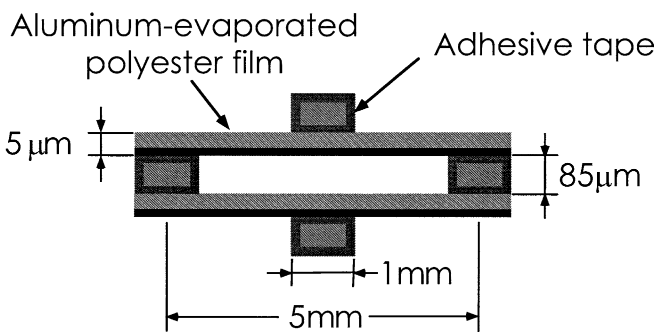

Fig. 5. Unit cell of the honeycomb-type variable capacitor

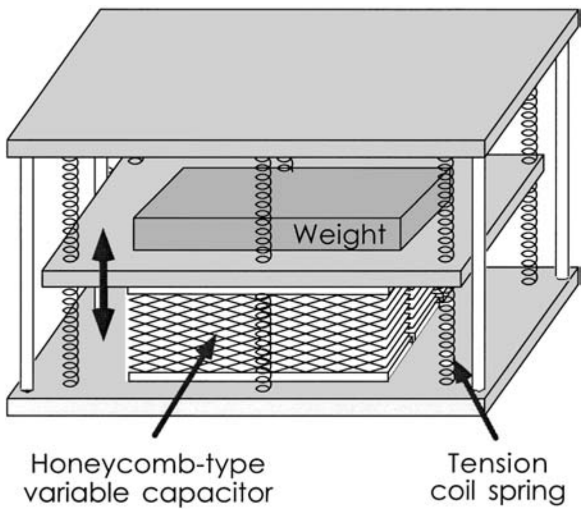

Fig. 6. Honeycomb-type variable capacitor with coil springs

were similarly attached to another acrylic board, which was suspended between the base and a third acrylic board by 12 tension coil springs. A weight was placed on top of the suspended board. We call this device an HVC resonator. The total spring constant of the resonator was approximately 1100 N/m, and the total mass suspended by the coil springs was approximately 780 g. The resonant frequency of the HVC resonator was 6.0 Hz.

Measurement of cardiac motion

A beagle weighing 12 kg was used for the experiment. The LV wall motion was measured by a 3-axis accelerometer module placed directly on the LV free wall as shown in Fig. 7. This accelerometer module weighed 5 g and was composed of a dual-axis accelerometer (ADXL250AQC, Analog Devices, Norwood, MA, USA) and a single-axis accelerometer (ADXL150AQC Analog Devices). In this experiment, the x-, y-, and z-axes represent the direction perpendicular to the LV wall (radial direction), the direction of revolution around the long axis of the heart (circumference direction), and the direction from the apex to the LV wall, respectively.

Cardiac pacemaker

A simple cardiac pacemaker, shown in Fig. 8, was made to generate a constant-rate pacing pulse. The pacemaker can generate a stimulating pulse of arbitrary rate and width.

Experimental apparatus

Figure 9 is a schematic drawing of the animal experiment. The prototype of the HVC resonator was handmade, but it was too large to put on the LV free wall. For this reason, a somewhat complicated method was chosen to demonstrate the feasibility of the VCES generator. The experimental apparatus consisted of the HVC resonator, the cardiac pacemaker, a vibration mode simulator, a 3-axis accelerometer module weighing 5 g, two single-axis accelerometer modules, each weighing 4 g, and two personal computers with analog to digital and digital to analog converters. The HVC resonator was placed on top of the vibration mode simulator. Acceleration signals of the LV free wall from the accelerometer module were processed by a personal computer, and the simulator, which was driven by the processed signal, reproduced the LV free wall motion. Therefore, the HVC resonator was forced to move as if it were attached to the LV free wall. The VCES generator with the HVC resonator supplied electric power to the cardiac pacemaker. The canine heart was paced by the cardiac pacemaker after a sinoatrial (SA) block was induced. The pacing rate was set at 180 bpm during the experiment.

Experiment

Myocardial electrodes were installed in the right atrium (RA). The SA block was induced by crushing the myocardium in the vicinity of an SA node. The output voltage and output current of the VCES generator were measured and recorded by a personal computer. At first, the cardiac pacemaker was driven by a DC power supply. The canine heart was paced with an amplitude of 2 V and a pulse width of

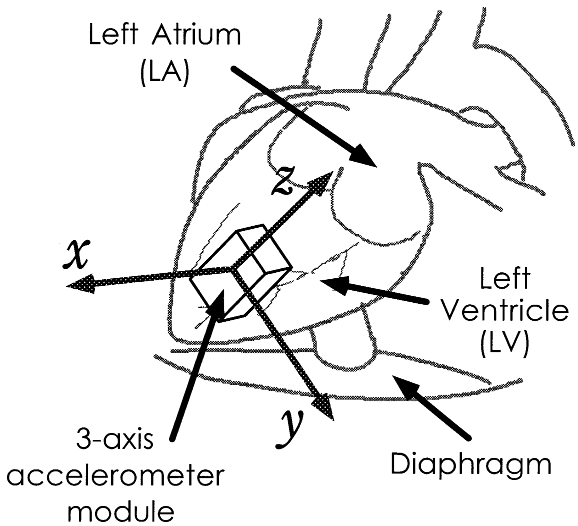

Fig. 7. Measurement of motion of the canine heart

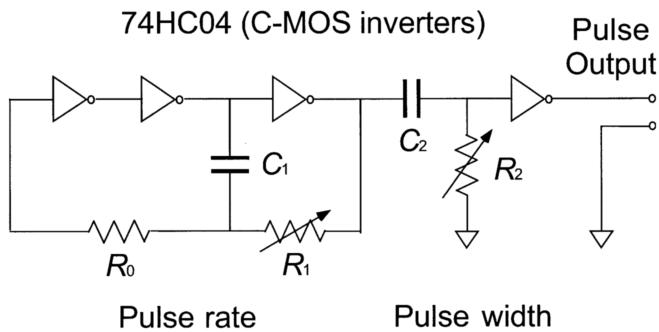

Fig. 8. Simple circuit of the cardiac pacemaker used for the animal experiment

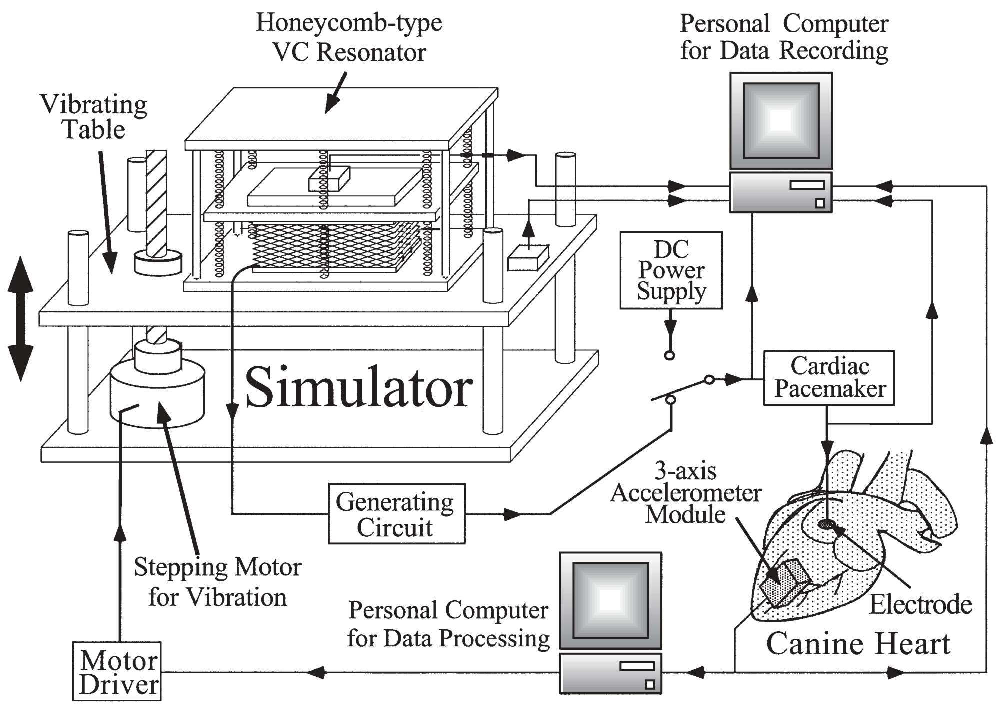

Fig. 9. Experimental apparatus for electrostatic generation and cardiac pacing

0.5 ms. The pacing rate was set at 180 bpm because the heart rate was 160 bpm before the SA block was induced, and the VCES generator was expected to resonate with the second harmonic component of the canine heartbeat because the resonant frequency of the HVC resonator was 6 Hz. Next, the VCES generator was operated for a few minutes by the vibrator, and then the DC power supply was replaced by the VCES generator when a sufficient amount of generated energy had been stored in its storage capacitor. Finally, continuous electrical generation and cardiac pacing was performed.

Results

LV free wall motion

The canine heart rate was approximately 160 bpm in the anesthetized condition without pacing. Figures 10 and 11 show 3-axis accelerations of the LV wall and their spectra after fast Fourier transform (FFT), respectively, with a constant pacing rate of 180 bpm. The displacement of the LV wall shown in Fig. 12 was computed after filtering out the effects of breathing, the frequency of which was under 1.0 Hz. Stroke length in the direction of revolution around the long axis of the canine heart (circumference direction, *y*-axis) was largest of all, between 9 and 10 mm. Stroke length in the direction from the apex to the LV wall (*z*-axis) was approximately 4 mm, and that in the direction perpendicular to the LV wall (radial direction) was hardly detectable. As shown in Fig. 11, acceleration of the LV wall contained harmonic components under approximately 15 Hz, and the second harmonic component of 6.0 Hz was largest.

Electric generation

When cardiac pacing was performed at 180 bpm, an acceleration component of 6.0 Hz in the direction of revolution

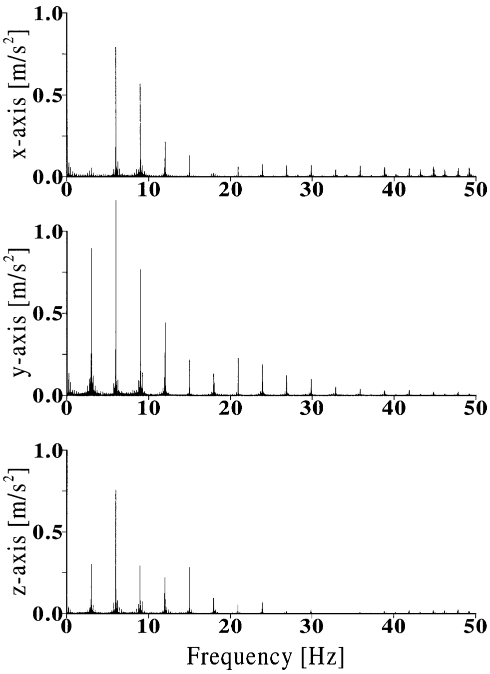

Fig. 11. Fast Fourier transform (*FFT*) of the acceleration

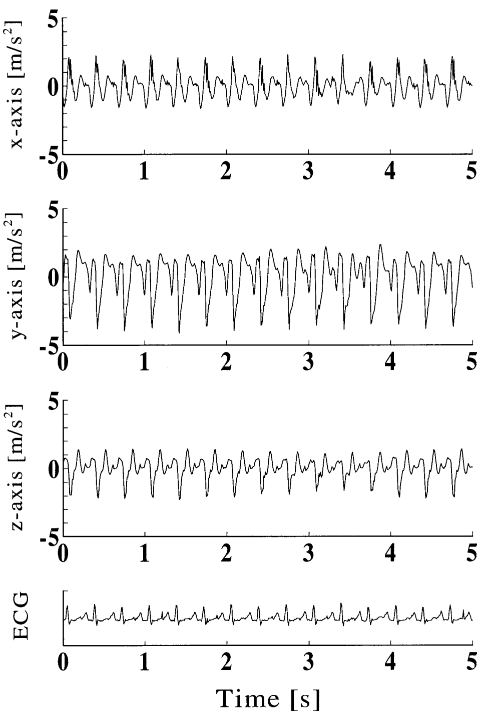

Fig. 10. Acceleration of the left ventricular free wall

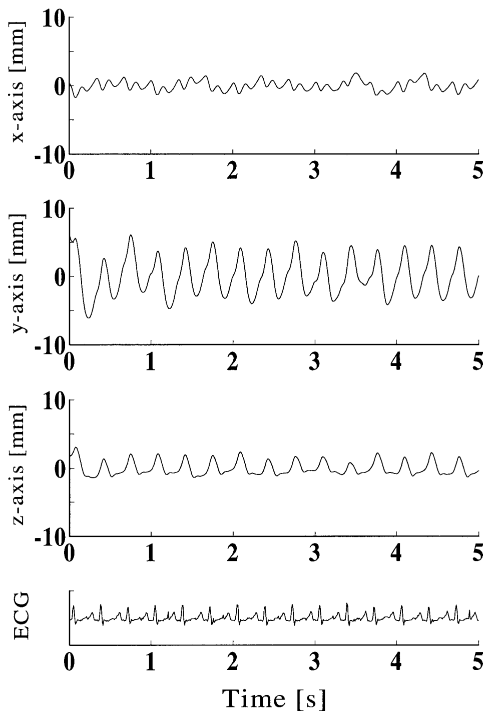

Fig. 12. Displacement of the left ventricular free wall

around the long axis of the heart (circumference direction, y-axis) was largest, and vibration in that direction was employed for the VCES generation. The pacing pulse width was set at 0.4 ms. The voltage of the ICS was chosen to be 45 V because generated power was insufficient at 30 V. Figure 13 shows the transient generated power synchronized with each heartbeat at 180 bpm. The mean generated power was approximately 36 μW. Output voltage smoothed by the 100-μF smoothing capacitor was almost constant at approximately 2.4 V. Mean current consumption of the pacemaker was approximately 15 μA. Required capacitance change to generate enough power was between 100 and 300 nF. The electrical energy of the cardiac pacing was approximately 6 μJ/pulse; thus, the mean electric power of the stimulating pulse was approximately 18 μW.

When the heartbeat frequency happened to change, as a result of arrhythmia and so on, the vibrating amplitude of the HVC resonator decreased gradually and the generated power decreased, but, if the storage capacitor of the VCES generator had enough electrostatic energy to drive the cardiac pacemaker until the heartbeat became regular, cardiac pacing and electrical generation could continue. Continuous electrical generation and cardiac pacing were performed successfully for more than 2 h in the animal experiment.

Discussion

It will be necessary to address the following points before in vivo use will be feasible.

- Voltage of the ICS should be less than 30 V.
- The performance level of the variable capacitor, including capacitance change and mechanical durability, should be raised.
- Power consumption of the cardiac pacemaker should be decreased.
- The VCES generator should be covered with a shell made of titanium alloy, which is the same material as that used for implantable cardiac pacemakers.
- The resonant frequency of the VC resonator should be chosen to match the frequency of the harmonic component that appears most frequently in a day.

Another method for harnessing the vibration might be to synchronize the operation of the VC with the stroke change for power generation. However, for the stroke change to be used for electrical generation, one side of the variable capacitor would need to be fixed to the LV free wall and the other side to the chest wall. Fixing one side of the generator to the chest wall would obstruct the motion of the heart, and might cause complications such as ventricular fibrillation. On the other hand, if resonance with the harmonic component of the LV free wall motion is used, the VCES generator can be operated at a high rate, and the generated power will be higher. Moreover, the generator needs to be fixed only to the vibrating source, that is, the LV free wall.

The required capacitance change for VCES generation is between 100 and 300 nF. To make a very small variable capacitor that can realize such a large capacitance change, Micro Electro Mechanical Systems (MEMS) technology must be employed. Comb-type electrostatic actuators have been developed using MEMS technology.[8] Although an electrostatic actuator is a device that converts electrical energy to mechanical energy, its structure is the same as that of a variable capacitor. Therefore, an actuator can be used as a variable capacitor. The principle of operation of a

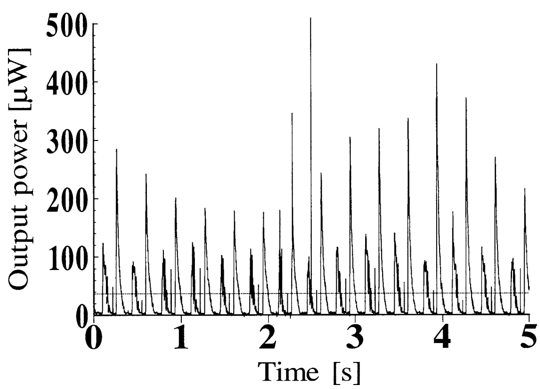

Fig. 13. Output power of the ES generator when the pacemaker was operating. The *horizontal line* shows the mean generated power of approximately 36 μW

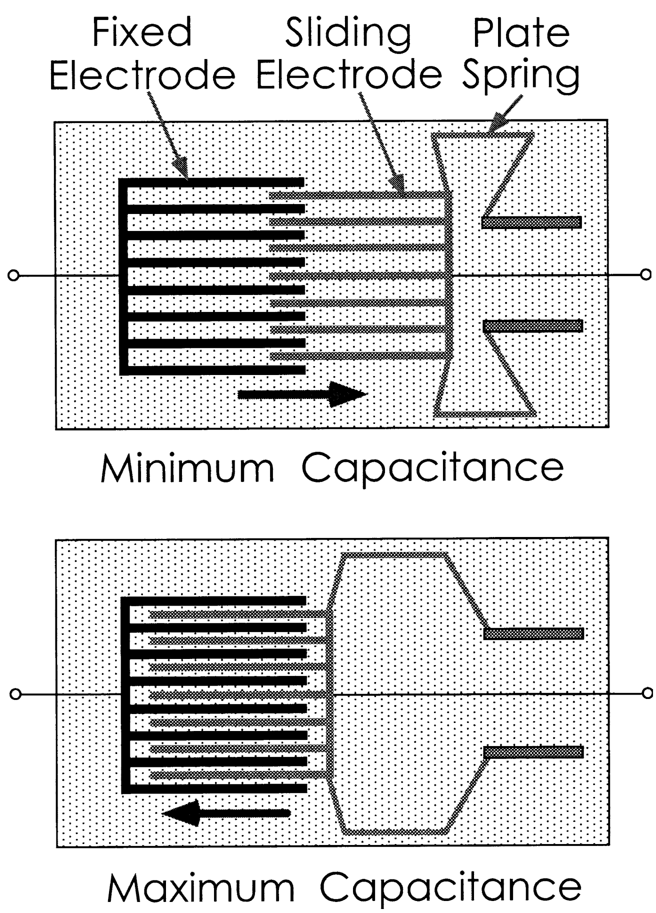

Fig. 14. Comb-type variable capacitor

comb-type VC is shown in Fig. 14. The sliding electrode of the VC is attached to a plate spring so that it can be moved by an external linear vibration. The capacitance is small when the sliding electrode is extracted from the fixed electrode and large when the sliding electrode is inserted into the fixed electrode.

For this study, comb-type variable capacitors could not be made because the MEMS technology was not available. The comb-type VC must be operated within the limit of material fatigue in comb-type electrodes and/or its elements should be made of a single crystal without fatigue. An implantable VCES generator will be realized if materials without any flaw in their crystal structure made by nanotechnology are used for the construction of a comb-type VC. It is estimated that the volume of such a miniaturized comb-type VC would be less than 1 cm^3. Such a miniaturized VCES generator could be implanted during endoscopic surgery without thoracostomy. If a VC operated by intraventricular motion could be integrated into a pacing lead by some method, a minimally invasive implantation of the VC would be accomplished because it would not be necessary to implant the cardiac pacemaker and the VCES generator separately.

Although we have not performed any other experiments on VCES generation and cardiac pacing with animals, our intended objectives will be achieved if mean generated power exceeds the mean power consumption of the cardiac pacemaker, that is, if the HVC resonator is vibrated sufficiently by a harmonic component of the heartbeat at resonant frequency.

Conclusion

In this study, a variable-capacitance-type electrostatic (VCES) generator operated by the left ventricular wall motion was developed. To certify the feasibility of the VCES generator, the left ventricular (LV) free wall motion was reproduced by a vibration mode simulator in real time. Electric power of approximately 36 μW was supplied to the pacemaker. Continuous electrostatic generation and cardiac pacing were performed successfully for more than 2 h in the animal experiment. Therefore, the effectiveness of a VCES generator that harnesses the LV free wall motion was verified. Cardiac pacemakers on the market could be driven sufficiently by such a generator if a comb-type variable capacitor fabricated by MEMS technology were employed as the miniature variable capacitor in the generator.

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