ESSAY

TRANSLATIONAL MEDICINE

The future of bionic dynamos

Internal organs have the potential to power implantable devices

By **Canan Dagdeviren**[1,2]

Millions of lives rely on implantable medical devices. At present, the power sources (typically batteries) for such devices are rigid and bulky and must be changed frequently. Users are often forced to undergo a surgical procedure each time the battery needs to be changed, which are accompanied by health risks and high costs.

One compelling solution to this problem would be batteries that could be recharged or replaced by harvesting energy from the natural mechanical movements of organs. Most existing harvesters resemble conventional batteries and depend on rigid electronics. They are, therefore, less than ideal for intimate contact with soft tissue.

Piezoelectric ceramics can serve as energy harvesters, sensors, and actuators because they can convert mechanical energy into electrical energy and vice versa. The brittle nature of such materials, however, limits their applications in biomedical areas.

As a graduate student in John A. Rogers' laboratory at the University of Illinois, Urbana-Champaign, I was intrigued with the idea of creating conformable piezoelectric devices, which would have the shape and mechanical properties that match those of soft tissues. Thus, I focused my dissertation research on flexible-stretchable piezoelectric systems that could transform the available energy from natural movement into useable signals (*1*–*4*).

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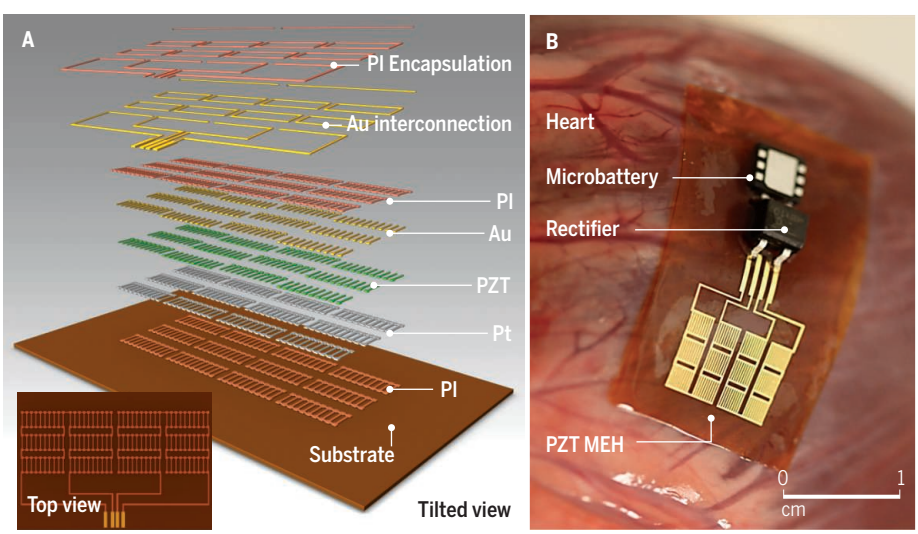
Cardiac and respiratory motions are nearly inexhaustible sources of mechanical energy, as both persist through the duration of an individual's life span. Such energy can be utilized as a power source via mechanically adaptive piezoelectric systems, which allow intimate integration with any region of the body. To create a flexible piezoelectric mechanical energy harvester (MEH) (*4*), I formed piezoelectric ceramics (lead zirconate titanate, PZT) into a thin capacitor unit [see the figure (A)]. In this configuration, the midpoint of the PZT layer lies at a distance (*h*) from the neutral mechanical plane where the bending strain is zero. The goal was to maximize the electrical response and the degree of bendability while maintaining the strain below the fracture thresholds of the piezoelectric ceramics. The fabrication process entailed situating the capacitor unit on a silicon (Si) wafer, chemically etching the unit, lifting it off of the wafer and transfer printing it onto a flexible substrate (polyimide). Finally, the device was encapsulated within a biocompatible layer of polyimide to isolate it from the bodily fluids and tissues and to minimize the risks of electrical failure or negative immune responses.

To assess the biocompatibility of the MEH, I grew rat smooth muscle cells (SMCs) on the MEH and then measured their adherence and viability. The SMCs readily adhered to fibronectin-coated structures, with evident spreading and intact, detectable cytoskeletal structures. Using the LIVE/DEAD viability kit and a lactate dehydrogenase assay, I found that after 9 days of culturing, there was no detectable cytotoxicity, with more than 96% of cells deemed viable.

Next, I incorporated a bending stage to mimic organ movements, which provided insights into the device performance under mechanical loads. The results indicated that the MEH could achieve a peak output voltage of 3.7 V under peak strains of 0.35% with a system efficiency of ~1.2%. Additionally, the generated electrical energy could be simultaneously stored with a chip-scale rechargeable battery and a Schottky bridge rectifier integrated on the same flexible substrate with the MEH.

I then conducted in vivo studies in both ovine and bovine animal models, whose organ sizes approximate those found in humans. To determine which part of the heart would generate the maximum amount of electrical power, I sutured the MEH to a right ventricle (RV), left ventricle (LV), and the free wall of the heart [see the figure (B)].

The RV yielded the highest output voltage, likely as a result of its shape and function. The chamber of the RV has a box or wedge shape with a thin concave free wall (*5*), whereas the LV has a cylindrical shape with a thick wall structure (*6*). The LV ejects the blood by a twisting contraction, whereas the RV shortens the free wall. The MEH, therefore, experiences more bending when it is affixed to the RV rather than to the LV.



The PZT MEH. Flexible piezoelectric harvester to generate electrical power from internal organs' movements. (**A**) The schematic illustration of the device layers of a PZT MEH (area of 2 × 2.5 cm^2), consisting of 12 groups that are connected in series to the neighboring group in order to increase the output voltage. Each group contains 10 PZT capacitors with top (chromium-gold) and bottom electrodes (titanium-platinum), which are electrically connected in parallel. (**B**) The photograph of a PZT MEH, integrated with a chip-scale rechargeable battery and a Schottky bridge rectifier, on a bovine heart. Scale bar, 1 cm.

[1]*Society of Fellows, Harvard University, Cambridge, MA 02138, USA,* [2]*David H. Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. Email: canand@mit.edu*

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CATEGORY WINNER: TRANSLATIONAL MEDICINE

Canan Dagdeviren

Canan Dagdeviren was born in 1985 in Istanbul, Turkey. As a Fulbright Doctoral Fellow, she received her Ph.D. degree in Material Science and Engineering at the University of Illinois at Urbana-Champaign. Dagdeviren developed a conformable, piezoelectric, energy harvester that converts mechanical energy from internal organ movements into electric energy to power medical devices. It is soft and flexible and conforms to the heart as well as other soft tissues. This technology could extend the battery life of implanted electronics or eliminate the need of battery replacement, sparing patients from repeated operations and the risk of surgical complications. Beginning in January 2017, she will assume the role of assistant professor at the MIT Media Lab, where she will direct the Conformable Decoders research group.

As the myocardial tissue of the heart is anisotropic (*7*), I hypothesized that the orientation of the MEH on the heart would influence the voltage generation. Indeed, the MEH oriented in the 0° and 45° directions, with respect to the apex of the heart, generated higher output voltages than the MEH oriented in the 90° direction. These results were consistent with what we expected to see, as the 0° and 45° orientations are within the known range of the cardiac fiber alignments (+60° on the endocardium and −60° on the epicardium) (*7*).

Next, I modulated the heart rate through electrical and chemical stimulations to mimic running. In both tests, the increase in heart rate yielded a rise in the voltage generation, which demonstrated that the MEH is capable of functioning during extreme conditions while maintaining intimate integrations with soft tissue. We further determined that a stack of five MEHs generated power of 1.2 $\mu W/cm^2$, which is sufficient to operate a cardiac pacemaker (*8*). There were no mechanical alterations observed in the heart.

My research produced a first-of-its-kind, flexible microgenerator that can harvest energy from the natural contractile and relaxation motions of organs. I demonstrated that this MEH has the capacity to power implantable devices. At the intersection of piezoelectric materials and novel microfabrication techniques, my MEH offers boundless possibilities to benefit human health and well-being. ■

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