BIOMEDICINE

Transcutaneous ultrasound energy harvesting using capacitive triboelectric technology

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A major challenge for implantable medical systems is the inclusion or reliable delivery of electrical power. We use ultrasound to deliver mechanical energy through skin and liquids and demonstrate a thin implantable vibrating triboelectric generator able to effectively harvest it. The ultrasound can induce micrometer-scale displacement of a polymer thin membrane to generate electrical energy through contact electrification. We recharge a lithium-ion battery at a rate of 166 microcoulombs per second in water. The voltage and current generated ex vivo by ultrasound energy transfer reached 2.4 volts and 156 microamps under porcine tissue. These findings show that a capacitive triboelectric electret is the first technology able to compete with piezoelectricity to harvest ultrasound in vivo and to power medical implants.

Medical implants, offering many benefits, have become commonplace. Because they demand a level of power (e.g., ~1 to 10 μW for pacemakers, ~10 to 100 μW for neurostimulators), they are generally powered by batteries that may need to be replaced through surgery, resulting in non-negligible risks and costs (*1*). External recharging technology based on radiofrequencies has led to attenuation through the tissue, which limits the level of power transmitted. Tissue damage in humans can occur upon exposure from boosted transmitted power. Inductive coupling technology is highly sensitive to alignments and distance between coils, and it generates excessive heat in tissues, affecting metabolisms and immune systems. In this regard, both technologies raise efficiency and safety concerns (*2*).

In vivo movements, assumed to be internal energy sources, have a low frequency and an acceleration that is difficult to harvest (*3*). Nevertheless, piezoelectric biomechanical energy harvesters have been developed to sense and monitor vital functions. $Pb[Zr_xTi_{1-x}]O_3$ (PZT) ribbons (*4*), nanoribbons (*5*), and ZnO nanowires (*6*) have been used on the heart to harvest its mechanical energy. Energy harvesting based on piezoelectricity is possible as long as there is a cycling of the stress (squeezing or bending). Triboelectric generators (TEGs) have been studied for energy harvesting, because they can generate electricity if there is a physical contact and separation sufficient for powering implants with low-power consumption (*7*, *8*). TEGs have been implanted in rat thorax (*9*) and under rat chest skin (*10*), and larger and stronger TEGs have been implanted on porcine heart (*11*). Despite a big and strong animal with large power capacity, the power converted (~1 to 10 μW) remained too weak and was far from sufficient to power implants.

Acoustic waves and portable ultrasound (US) generators (*12*, *13*) can transfer energy in vivo independently of environment conductivity or transparency. They are safe at low power and are used to sense, diagnose, and monitor a wide range of diseases and physical conditions and also to transmit energy to power implants in vivo (*14*, *15*). Piezoelectric US energy receivers for powering implants using US have been demonstrated (*16*). However, these receivers used PZT, which is questionable for biomedical use because of its serious toxicity in the human body. In addition, they require complicated fabrication and good resonance to harvest US efficiently. Moreover, they are too thick to be added to implants in the human body. Smaller devices have been tested using micro-PZT diaphragm arrays (*17*), but the power generated is too low to recharge batteries.

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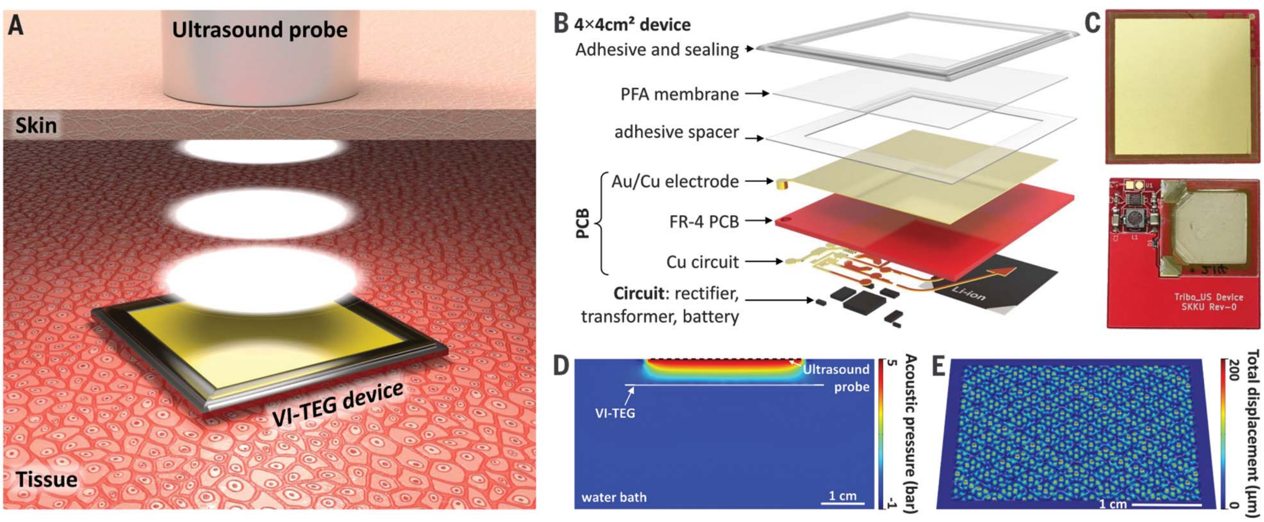

Fig. 1. Concept and design of the VI-TEG. (**A**) Illustration of US energy harvesting under skin using the VI-TEG. (**B**) Exploded view of the VI-TEG structure. (**C**) Front and back photo of the VI-TEG. (**D**) Finite element method (FEM) simulation of US acoustic pressure propagation through water and the VI-TEG. (**E**) FEM simulation of the VI-TEG's vibrations in water at 5 mm under the 20-kHz US probe (*20*).

We investigated the use of a high-frequency vibrating and implantable triboelectric generator (VI-TEG) for harvesting US in vivo. The VI-TEG is designed to be implanted underneath the skin (~10 mm) (Fig. 1A). We designed a thin (~50-µm-thick) and large membrane of perfluoroalkoxy (PFA), which is a copolymer of tetrafluoroethylene and perfluoroethers, with the aim of vibrating the membrane (*18*, *19*) under the pressure of US (fig. S1). Such a generator ensures easy and constant operation despite variations of the environment and usage conditions. The membrane was suspended on a thin 3.6-cm by 3.6-cm Cu electrode made on flexible printed circuit board (PCB) and covered with Au [Fig. 1B; see materials and methods in the supplementary material (*20*)]. The air gap was 80 µm (fig. S2). We sealed the membrane with melt adhesive (*20*). The VI-TEG (Fig. 1C) is less than 1 mm thick. Finally, we integrated on the backside a rectifier, transformer, voltage regulator, and battery. Preliminary acoustic and mechanical simulations showed that US cannot go through the VI-TEG because of its reflection (Fig. 1D and figs. S3 and S4). Under 20-kHz US excitation, the membrane vibrates in a multimode (Fig. 1E and fig. S5), generating multiple nodes and antinodes moving up and down.

The VI-TEG operates in single-electrode mode (*21*) using the Cu/Au electrode as primary electrode, a small backside Cu electrode as reference electrode, and the PFA membrane as triboelectric layer. When vibrating, the PFA membrane contacts the electrode and the triboelectric phenomenon generates negative charges on the inner surface of the membrane. These charges decrease the electrical potential of the electrode compared to the reference, attracting holes in the electrode and generating a current pulse in the circuit (Fig. 2A). When separating, the electrode's potential increases, releasing holes in the circuit and generating a reverse pulse (*22*). For characterization, VI-TEGs were submerged into grounded water at 5 mm under a 3-cm-diameter US probe (Fig. 2B) setup (fig. S6) at 20 kHz and 3 W/cm^2 for human body safety (*23*, *24*). The VI-TEG was able to generate 25-V voltage peaks at 40-megohm impedance (Fig. 2C) and 1.3-mA current peaks at 1-ohm impedance (Fig. 2D). These results correspond to a root mean square (RMS) voltage of 9.71 V and RMS current of 427 µA.

The VI-TEG generated 450 µA at 33 kilohms, supplying a maximum output power of 6.74 mW (Fig. 2E), which is equal to 0.872 mW of constant average power and a power density of 5.2 W/m^2. As expected, at a lower US power of 1 W/cm^2, the voltage decreased but the current remained high, and we generated 3.84 mW at 10 kilohms (Fig. 2F).

Using a small integrated circuit, we were able to charge a capacitance (fig. S7) of 4.7 mF (Fig. 3A) at an average charging rate of 155 µC/s. For practical applications, we recharge a 700-µA hour thin-film Li-ion battery (Fig. 3B) that could supply commercial implants like pacemakers, neurostimulators and nerve stimulators, or drug delivery implants. We recharged the battery to 4.1 V

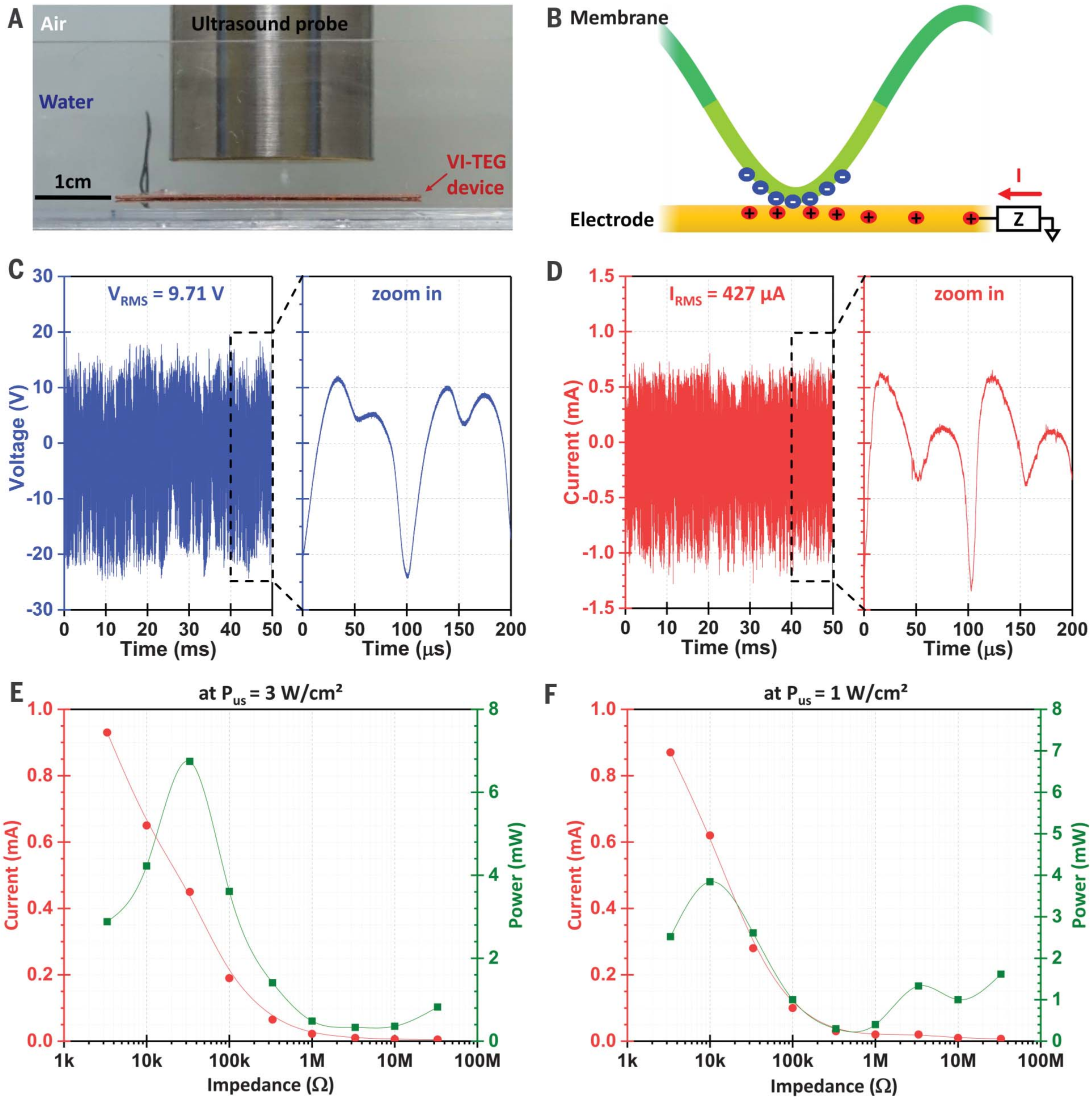

Fig. 2. Electrical characterization of the VI-TEG. (**A**) Side view of the experimental characterization setup. (**B**) Schematic of the VI-TEG operation mechanism. (**C** and **D**) Triboelectric voltage at 40-megohm impedance (C) and current at 1-megohm impedance measured in water at 5 mm from the US probe setup at 20 kHz and 3 W/cm^2 (*20*) (D). (**E** and **F**) Maximum current and power depending on the electrical impedance at 5 mm from the US probe set at a power density of 3 and 1 W/cm^2, respectively.

in 4 hours 30 min, at an average charging rate of 166 μC/s. For comparison, for the commercial pacemaker KSR701, the typical daily consumption is 289 μA hour.

The triboelectric signal varies with the acoustic radiation pressure. It decreases when the distance from the US probe is increased (Fig. 3C and fig. S8) and increases when the US power is increased (Fig. 3D). Depending on conditions, we observed two different electrical signal shapes, indicating two different vibration types of the PFA membrane [movie S1 and supplementary text (*20*)]. The radiation pressure forces the membrane against the electrode and modifies the contact between them, which changes the membrane vibration and the resulting electrical signal. At higher US power, the radiation pressure is high and the membrane moves and comes into contact with the electrode at the US excitation frequency of 20 kHz, generating a 20-kHz sinusoidal electrical signal (Fig. 3C, inset i). At a greater distance from the probe or lower US power, the radiation pressure decreases. The membrane is thus able to rebound on the electrode, generating a different 10-kHz electrical signal with a 20-kHz harmonic (Fig. 3C, inset ii). Indeed, triboelectric voltage is proportional to the distance between the membrane and the electrode, which shows that the membrane rebounds on the electrode every two US oscillations (figs. S9 and S10, respectively). The rebound of the membrane on the electrode allows the membrane to separate further from the electrode, which maximizes the triboelectric voltage generated. The rebound amplitude decreases as the acoustic radiation pressure decreases with the distance or the US power. As a result, there is an optimal configuration (fig. S11) where, despite occurring at lower US power or at a greater distance than in the forced vibration mode, the free vibration mode can generate higher voltage and current peaks (fig. S12).

To simulate conditions closer to those for medical applications, we first characterized VI-TEGs in bovine serum (BS), which is a more representative fluid inside the body than water [figs. S14 and S16 (*20*)]. In addition to water, BS contains some proteins, ions, and hormones that can affect its acoustic properties. The slight decrease in performance of the VI-TEG could be related to the relatively higher acoustic impedance of BS, due to its larger mass density and sound velocity compared to water, resulting in less transmitted US to the VI-TEG (*25*). Indeed, to accurately assess the performance of the implants, the medium through which the US is transmitted should be similar to biological tissue. We characterized the VI-TEG under the skin of a rat [figs. S13, S15, and S17 (*20*)], a more realistic condition. Our findings under the skin of the rat demonstrated that the VI-TEG performs less well than in BS, although the VI-TEG was at a 1-mm depth (equivalent to the thickness of the skin of the rat). The skin is a complex medium consisting of not only water and serum but also blood and tissue; these differences affect acoustic properties and result in even less US power transmission to the VI-TEG. However, the electric power generated by the VI-TEG was on the order of 100 μW, which is enough to recharge some implants.

Because the aim of this study was to develop an external charging system for electronic transcutaneous implants, we characterized the VI-TEG under porcine tissue, which is comparatively similar to human skin in terms of anatomy and composition (Fig. 4, A to D, and fig. S18), and we performed ex vivo characterizations. Transcutaneous electronic implants are generally located at ~5 to 10 mm depth. In this regard, our device was characterized at 5- and 10-mm depths. At 0.5 cm, the VI-TEG generated output signals of more than 2.4 V and 156 μA (Fig. 4E). The decreases in voltage and current are due to the attenuation of the US. The VI-TEG, at 1.0 cm under layered tissues including skin and fat, generated output signals of more than 1.93 V and 98.6 μA (Fig. 4F). Power-generating performance of the VI-TEG under the porcine tissue was about 4.78 and 2.81 times lower than in water and BS, respectively, because of the increased acoustic impedance and attenuation in the different media and layered structure. Reflection and absorption at the interface (skin and fat) also decreased US acoustic power. However, the power generated, approximately 98.6 μW, was

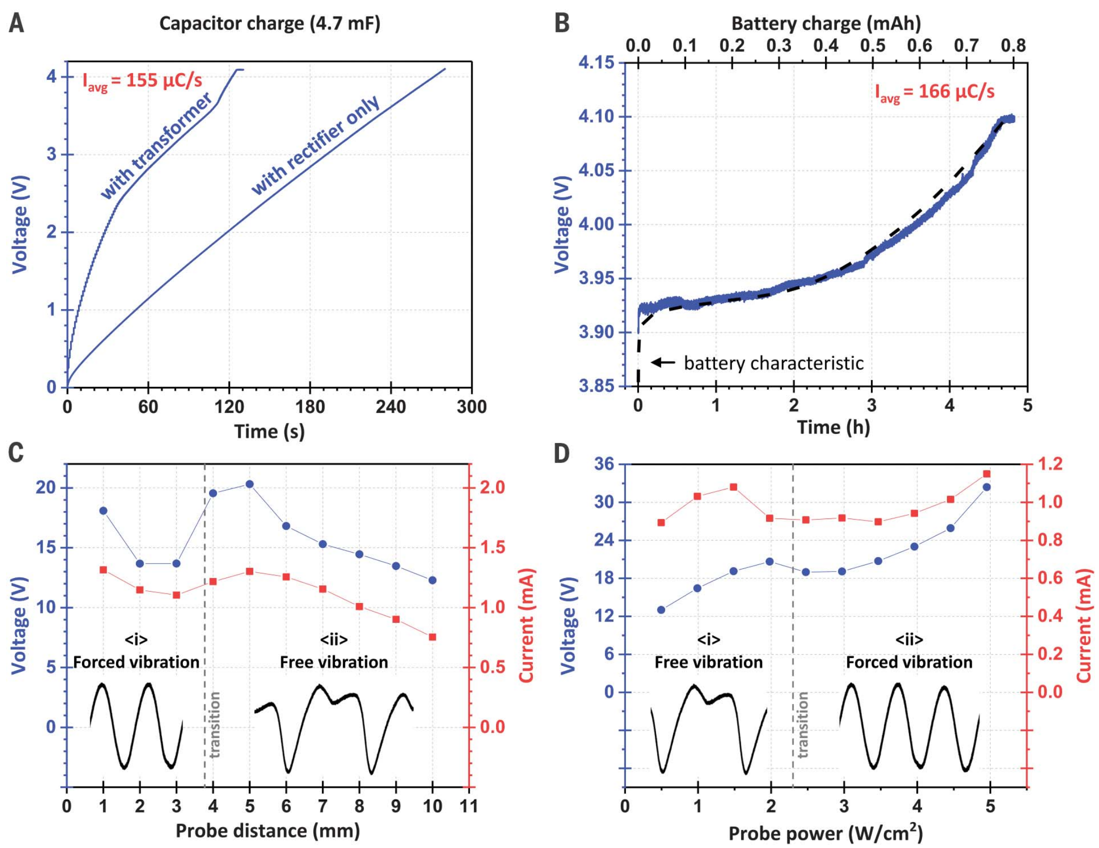

Fig. 3. Power generation and recharging ability of the VI-TEG. (**A** and **B**) Charge of a 4.7-mF capacitor using the integrated transformer (A) and charge of a 700-μA·hour thin-film Li-ion battery in water at 5 mm from the US probe set at 3 W/cm^2 (B). (**C**) Maximum voltage and current depending on the distance from the US probe (at 3 W/cm^2). The insets i and ii show the electric voltage signal shapes at 2 mm and 5 mm from the US probe, respectively. (**D**) Maximum voltage and current depending on the power of the US probe (at 5 mm). The insets i and ii show the electric voltage signal shapes from the US probe power set from 0.5 to 2.0 W/cm^2 and from 2.5 to 5.0 W/cm^2, respectively.

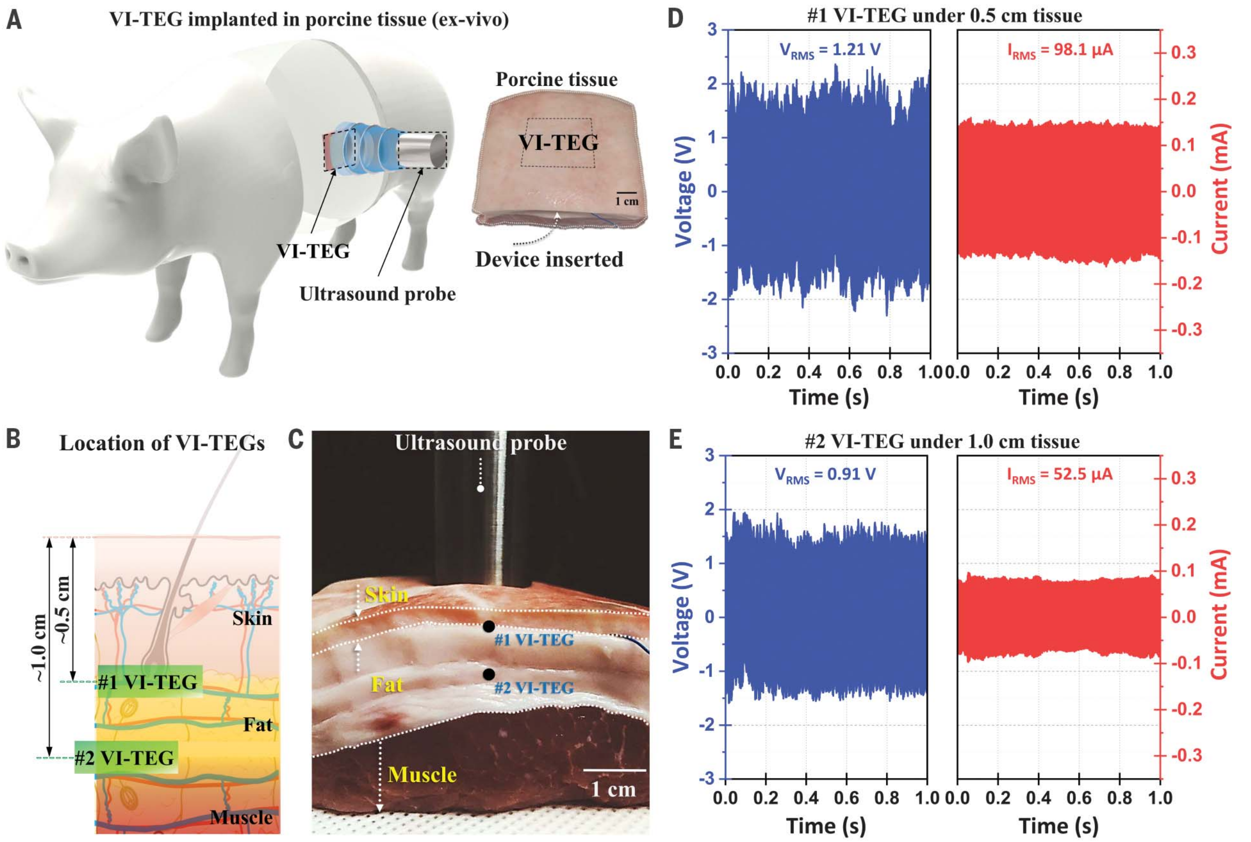

Fig. 4. VI-TEG characterization ex vivo and inside porcine tissue. (**A** and **B**) Schematic of the porcine ex vivo (A) and the tissue (B) showing the location of the implanted VI-TEG. (**C**) Picture of the VI-TEG implanted at 0.5 cm and at 1 cm under the porcine tissue. (**D** and **E**) Voltage at 40-megohm impedance, and current at 1-megohm impedance generated by the VI-TEGs implanted at 0.5 cm (D) and 1 cm (E) under the porcine tissue. The US probe was set at 20 kHz and 1 W/cm^2.

still high enough to recharge the batteries of small implants (e.g., pacemakers or neurostimulators consuming ~1 to 100 μW).

This work investigated triboelectric technology as it receives US energy in liquids and soft tissues. The prototypes can generate power on the order of milliwatts, enabling recharging of capacitors and Li-ion batteries. We noted some performance variations between VI-TEG prototypes and that better controlling the thickness and tension of the membrane, and the air gap, influences the vibrations and could improve performance.

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SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/365/6452/491/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S18
Movie S1
Reference (*27*)

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A sound way to deliver power

Implanted medical devices, such as pacemakers and neurological stimulators, require a source of power, usually in the form of a battery. If a battery is implanted with the device, replacing it would require additional surgery. On the other hand, external power packs are prone to lead to infections where their wires enter the body. Hinchet *et al.* describe a triboelectric generator that can convert externally applied ultrasound into an internal electricity source capable of delivering sufficient energy to recharge a battery on a daily basis.

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