Self-powered biomedical devices tap into the body's movements

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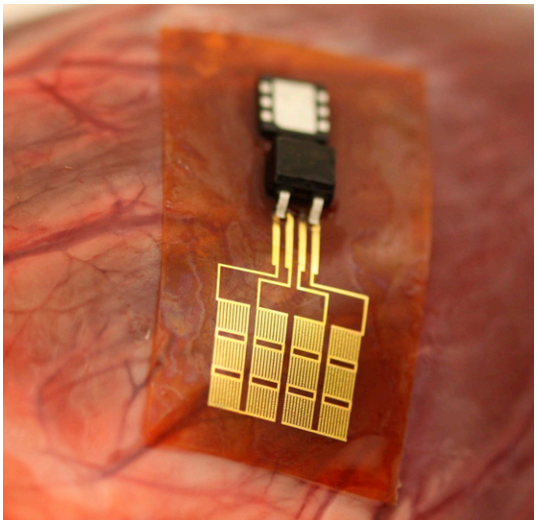
In early 2017, researchers managed to slip a flexible sliver of polymer next to a pig's heart. The device—placed between the heart and the fibrous wall that encases it, called the pericardium—squished and expanded with each contraction. It also converted the physical strain of its movement into electrical energy stashed into a capacitor. When hooked up to a commercial pacemaker, the device produced a steady pulse of 130 beats per minute—effectively using the heart's own mechanical motions to power an implanted pacemaker.

The study, led by materials scientist Zhong Lin Wang of the Georgia Institute of Technology in Atlanta, demonstrated how self-powered electronics could lead to a new generation of smaller pacemakers and other implanted devices that improve safety and performance, last longer, and obviate the need for invasive battery-replacement surgeries (1). Wang and several other researchers envision a world in which batteries are a thing of the past: deep-brain implants powered by electric impulses, cochlear implants fueled by inner ear vibrations, bone implants that stimulate tissue repair, and shoes and clothes that turn every bodily movement into a source of power.

Crystal Clear

When solid materials, such as some ceramics, crystals, proteins, or bone, are pulled or stretched, charged particles in their crystal structure are dislodged, creating a flow of ions—and thus, an electric current known as piezoelectricity. This ability to convert mechanical energy to electricity has been known for centuries; one of its most famous applications was in developing piezoelectric sonar transducers to detect submarines during World War I. Piezoelectric materials are now widely used in cigarette lighters, quartz watches, and more.

But while studying the potential of these materials for self-powered biomedical devices, Wang's team ran into a problem. Some of the devices they'd engineered delivered a power output several-fold higher than others—as it turned out, because of a tiny air bubble squished between polymer layers within the devices. That air resulted in an accumulation of electric charge as the layers rubbed against each other, a



Devices such as this one, being tested here on a bovine heart, could harvest the body's own energy to work like a pacemaker. Image credit: Canan Dagdeviren (Massachusetts Institute of Technology, Cambridge, MA).

phenomenon known as the triboelectric effect. The discovery led Wang and his colleagues to shift their focus to triboelectric power, eventually leading to the recently published study.

Both triboelectric and piezoelectric systems rely on converting mechanical energy that's abundant—and goes wasted in the human body—into electrical energy to power pacemakers and other devices. Such implants currently rely on batteries, which only last a few years before needing replacement. A pacemaker, for example, is replaced every 7 to 12 years via an invasive, complex surgery.

Self-powered devices also promise to be smaller, so they can be used in tight spaces, such as for implants within the brain. And unlike batteries, these devices can be made with flexible, biocompatible materials.

Researchers working in this niche field see the potential for electric power in every bodily movement: heartbeats, the breathing movements of the diaphragm, or the pounding of footsteps on pavement. Both theoretical and experimental studies have found that the energy from these motions can easily power

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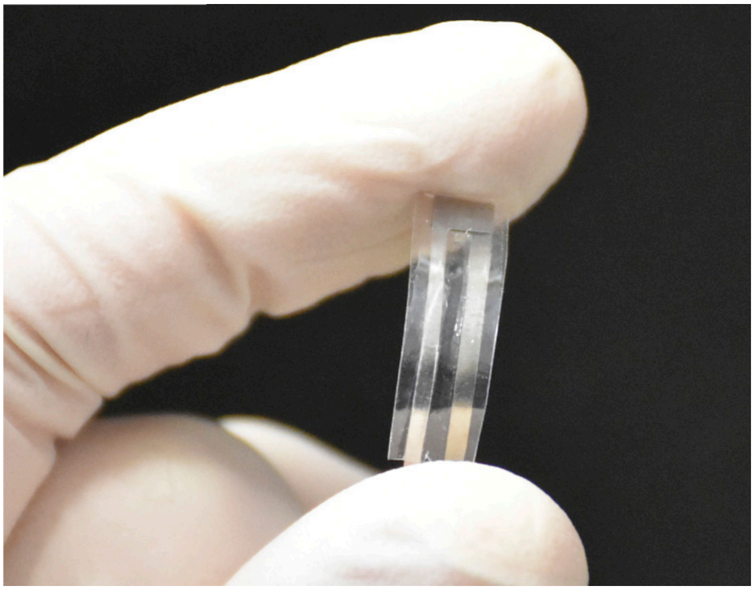

A sensor made from a biodegradable polymer detects the force of breathing movements when placed on a mouse's diaphragm. Less invasive than a catheter-based sensor, it dissolves on its own and doesn't need to be removed—making it potentially useful for monitoring patients who undergo anesthesia. Image credit: Thanh Nguyen (University of Connecticut, Storrs, CT).

implanted devices. For example, theoretical studies have found that simply breathing can generate 0.83 watts of power, whereas a cardiac pacemaker only needs 50 microwatts to work for 7 years (2, 3).

Inner Driving Force

In 2010, then-doctoral student Amin Karami was researching ways to harvest energy from the mechanical motions of airplane wings when his father passed away suddenly after a heart attack. He began to wonder: could he adapt his research to improve cardiac pacemakers? The work relied on a ceramic-based piezoelectric material. "But I hadn't seen anything really fundamental about human energy harvesting," recalls Karami, who's now an assistant professor of mechanical engineering at the State University of New York in Buffalo. "I started thinking about where we see sustained motion in the human body both in healthy and sick people and that led me to the heartbeat itself."

Although piezoelectric materials have a long history in other fields, adapting the technology for biomedical uses was not easy, Karami says. For starters, the heartbeat is wildly variable depending on a person's activities. Second, technical details, such as optimizing power requirements for different working conditions of commercial pacemakers, are proprietary industrial knowledge—Karami and Wang say that to do their experiments, they had to do take a commercial pacemaker and dissect it in the lab to figure out the requirements. Any device that fits into the body would also need to be extremely reliable. "With energy harvesting for non-biomedical uses, it's mostly cost that matters, not size," Karami explains. "But this is a totally different world—if a pacemaker doesn't work the person could die." Karami, his doctoral advisor Daniel Inman, and their colleagues designed a slim, ceramic-based device that could, in principle, replace a pacemaker's battery (4).

Like Karami, Canan Dagdeviren, assistant professor of media arts and sciences at the Massachusetts Institute of Technology (MIT) in Cambridge, also began by adapting technologies from other fields. While she was a graduate student, Dagdeviren found that many of her labmates worked on stretchable devices to generate piezoelectricity but not on harvesting biological energy. In 2014, Dagdeviren and her colleagues demonstrated how a tattoo-like, polymer-based device could be used to generate piezoelectricity and power a pacemaker placed in a mouse (5) (see Science and Culture: Wearable tech meets tattoo art in a bid to revolutionize both, https://www.pnas.org/content/115/14/3504). "Our paper was one of the first to show that such a device works even when the chest is closed, and that the average power generation is even higher than a modern pacemaker needs," she says.

Ceramic-based materials work best to generate power, but they're also brittle, Dagdeviren says. Polymer-based implants that are flexible and stretchable are sturdier and, thus, better suited to biomedical uses.

In recent studies, Dagdeviren and others have expanded their work to a range of applications beyond pacemakers, such as pH sensors, cochlear implants, sensors that can be placed in the brain to monitor seizures, and bone graft materials that can accelerate tissue repair. Most are powered by piezoelectric materials rather than other modes of energy harvesting.

For example, biomedical engineer Thanh Nguyen and his team at the University of Connecticut in Storrs used a biodegradable polymer to design a sensor that detects the force of breathing movements when placed on the diaphragm in mice (6). Typically, a device inserted via a catheter is used to track these forces as a way to monitor breathing under anesthesia or in patients who have respiratory disorders. The piezoelectric device was less invasive than the catheter-based sensor, delivered comparable data, and—unlike traditional sensors, which must be surgically removed—simply dissolves on its own several days after the procedure, Nguyen says.

Others have also tried to tap into alternative sources of energy in the body by using thermoelectric or chemo-electric devices. Electrical engineer Patrick Mercier at the University of California, San Diego, studies devices that generate electricity from body fluids—converting chemical to electrical energy—as a way to create wearable sensors to monitor the body's many chemical activities. Such sensors could power themselves and offer a way to unobtrusively monitor blood glucose or other metabolites. In a recent study, Mercier and his colleagues created a wearable biofuel cell that generated electricity from the lactate present in human sweat (7). "If done correctly, such cells can extract quite a bit of power from these fuels," Mercier says. "The potential power output is much larger than many other forms of energy harvesting."

But because such systems are based on enzymes catalyzing electrochemical reactions, they have a short lifespan of just days. Further studies are needed to improve their longevity and shelf stability, Mercier says. "How can we make a sensor well-calibrated, so it can sit on the shelf for 6 months, you put it on and you know the readout is correct?"

Chemo-electric devices could function well as wearables and have the potential to work in parts of the body where relative movement is limited. Because of their short lifespan, they're more likely to be useful in wearables than to power long-term implants such as pacemakers.

Slow Pace

Although these self-powered devices are inching into clinical trials, researchers point out that there's currently no standardized way to evaluate these devices or report data on the design, efficiency, or lifespan of such implants. That makes it difficult to replicate results or performance.

Wang adds that both piezoelectric and triboelectric devices face three major hurdles: devising the right coating to ensure the device is biocompatible, finding ways to implant the device in a noninvasive manner, and ensuring that the implant is durable.

Durability and the lifespan of the device are particularly important considerations for the new generation of leadless pacemakers, Karami notes. Older pacemakers were box-like structures placed near the collarbone with wires leading to the heart. But more modern leadless pacemakers –which are about the size of a grain of rice—are placed directly into heart tissue. Their batteries die after about 7 years, at which point the device is simply silenced and a new one inserted. Because they are covered in scar tissue by that point, there is no way to extricate the old device. This could lead to infections and isn't feasible in younger patients, who would need multiple such implants over the course of a lifetime. "You're practically turning the heart into a little graveyard of all these pacemakers," Karami says. "It's one of the challenges currently and it's far more significant than the previous surgery challenge."

> **"They're marvelous engineering but not always practical."**
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> **—Amin Karami**

The ideal solution, he adds, would be one that simply swaps out the battery in a pacemaker with a self-powered device that ensures the pacemaker doesn't need replacement. But most energy harvesters are still intrusive. "They're marvelous engineering but not always practical." Karami says. "The real challenge is how to simply incorporate the energy harvester into the battery package of the pacemaker."

Nonetheless, these researchers all expect energy-harvesting devices—as wearable sensors rather than implants—will be on the market within the next five years or so because that modality faces fewer regulatory hurdles than implants. These self-powered electronics would constantly monitor a wearer's gait, pulse, blood pressure, or movement. They could benefit athletes, older individuals at risk of falls, or patients with chronic conditions that need constant monitoring.

Mercier says that devices of the future might combine different modalities—thermal, mechanical, or chemical—for the most efficient power generation. Because each kind of human energy varies among bodies and over time, "energy harvesting in humans is going to be stochastic by its very nature," he says. "There's no silver bullet."

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