Wireless power for tiny medical implants

A new scheme could allow pacemakers, brain stimulators, and more to leave their batteries behind.

With advancing technology, most components of electronic medical implants can be made smaller and smaller. But power sources have lagged behind. An implant needs to last for years to decades without interruption; a battery that can store energy for so long must be centimeters in size. That limitation complicates many practical devices: In deep-brain stimulation, for example, electrodes in the brain are connected by wire to a power source implanted in the chest.

It's possible to wirelessly transfer energy to a device from a source outside the body. But straightforward wireless powering schemes are prohibitively inefficient for powering a millimeter-sized implant more than 1 cm beneath the skin surface, in part because of the way electromagnetic fields interact with biological tissue. Now Ada Poon, John Ho, and colleagues at Stanford University have devised a new method of wireless power transfer that works with tissue's dielectric properties rather than against them.[1] In a theoretical model of a multilayer structure, the researchers found that a pattern of crescent-shaped currents modulated at 1.6 GHz can act as a self-focusing power source, producing propagating waves that converge at the site of a microimplant well below the surface, as shown in figure 1a.

In experiments on a pig cadaver, 0.04% of the source power was transferred to a 2-mm receiver 5 cm beneath the surface. That efficiency sounds low, but it's far more than enough to power a cardiac pacemaker with an external source that emits about as much microwave power as a cell-phone antenna. Teaming up with colleagues in Stanford's medical school, the researchers wirelessly powered miniature pacemakers implanted in live rabbits, and they're preparing their first study on human patients.

The theory

The simplest scheme for wireless power transmission is inductive transfer between two coils. An alternating current through a source coil produces a changing magnetic flux through the receiver coil, which generates an electromotive force and thus an electric current. The efficiency of that transfer depends on the sizes of the coils and the distance between them. It works well when the receiver coil can be made large and placed close to the surface. For example, cochlear implants—which convert sound signals into electrical impulses for patients who are deaf because of damage to the hair cells of the inner ear—are powered by simple inductive transfer.

But as the receiver coil becomes smaller, the magnetic flux through it necessarily decreases. And when the distance between source and receiver becomes large enough, the magnetic field at the receiver is no longer well approximated by the field produced by a static current; instead, it must be treated as a traveling wave. The refractive properties of biological tissues in the microwave regime, it turns out, are nontrivial: Their refractive indices are between 7 and 8.

Most previous research on power transfer through tissue has neglected those refractive effects. But Poon, whose background is in wireless communications, decided to take them into account. "In communications," she says, "you always consider the channel, or the physical medium, that carries the signal." She and her colleagues modeled a layered tissue structure, shown in figure 1a, designed to represent the human chest wall, and calculated the optimum pattern of currents that would deliver the highest magnetic field to an implant deep in the heart.[2] The result is shown in figure 1b. Curiously, those currents don't produce propagating electromagnetic waves in air, but when placed in close proximity to tissue, they do.

Because the ideal current source looks nothing like a simple coil or combination of coils, the next step was to figure out how to realize it. Through trial and error, the researchers devised a 6-cm-square metal plate with curved and radial slots cut in it, as shown in figure 1c. When they applied 1.6-GHz

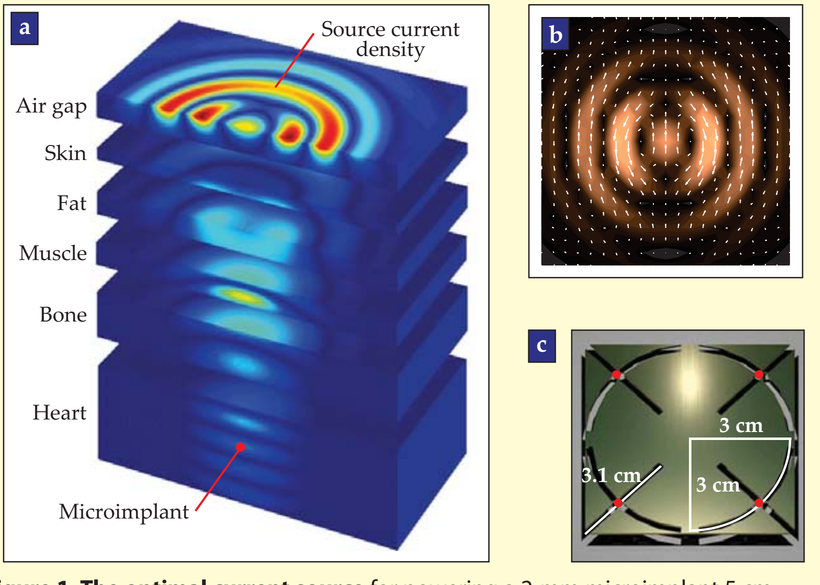

Figure 1. The optimal current source for powering a 2-mm microimplant 5 cm inside the body. **(a)** A theoretical model of a layered tissue structure representing the human chest wall is shown in cross section. The magnetic field, represented by the color scale, weakens at increasing depth, but because of the focusing properties of the source, the implant still receives sufficient power. (Adapted from ref. 1.) **(b)** In the ideal source current pattern, the current direction is shown by the white vectors. **(c)** A 6-cm-square metal plate, with slots cut into it as shown, provides a good approximation to the ideal source. Voltages oscillating at 1.6 GHz are applied to the four ports marked in red. (Panels b and c adapted from ref. 2.)

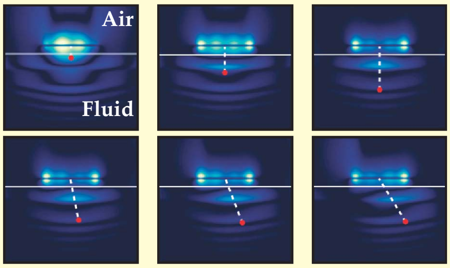

Figure 2. A moving implant can be powered by dynamically refocusing the magnetic field. In experiments on a receiver coil (red) moving in a liquid solution with the refractive properties of muscle tissue, the receiver could move several centimeters and still receive power. (Adapted from ref. 1.)

oscillating voltages at the four ports marked in red, they generated a current pattern close to the ideal one. (They've since developed new ideas for using metamaterials to better reproduce the current pattern.)

The lab

Poon and company's theoretical model assumed each layer of tissue to be uniform, flat, and homogeneous, so they sought to test their scheme's robustness to the inhomogeneities of real tissue by measuring the power transfer through the skull or chest wall of a pig cadaver. But to do so, they needed a way to measure the power received by a 2-mm coil representing a microimplant. Connecting the coil to a standard power meter requires attaching wires, and those wires themselves would affect the whole system's inductance and thus the power it received. Instead, the researchers connected the coil to an LED, with circuitry designed so the LED would flash at a rate proportional to the power received by the coil. They fed the LED output through an optical fiber and into a photodiode, which counted the flash rate and thus measured the power.

In the experiments on pig tissue, when the receiver was placed 5 cm from the surface in either the chest or the head, a 500-mW source transferred about 200 μW to the receiver. Even when the depth was increased to 10 cm, the power received was still about 10 μW. A typical cardiac pacemaker uses just 8 μW.

The 500-mW source emits about as much microwave power as most cell phones. But the safety of cell phones offers no guarantee that the source is similarly safe, because the source's power is concentrated in one direction. The IEEE has established standards for safe levels of exposure to radio and microwave radiation: The power dissipated by any 10-g portion of tissue must not exceed 100 mW. Poon and colleagues' source met that standard with almost a factor of 10 to spare. Increasing the source power to the maximum safe level would allow even more power to be coupled to the receiver.

As the model in figure 1a shows, the regions of relatively strong magnetic field are much larger than a microimplant, but they're still localized—and an implant placed in heart or muscle tissue will, by necessity, move around. Fortunately, the researchers found that simple tweaks to their source current pattern could shift the focus up and down and from side to side. Even with the source shown in figure 1c, they could achieve a great deal of spatial flexibility simply by shifting the relative phases of the signals into the four ports, as shown in figure 2. Furthermore, they could do that refocusing dynamically: As the receiver coil was moved through a liquid solution designed to mimic the properties of muscle tissue, it signaled back to the source to show how much power it was receiving. (In the researchers' experiments, that signal was carried by an optical fiber, but it could be conveyed wirelessly.) The source then implemented a search algorithm to maximize the power transmitted to the receiver. The receiver could move laterally by several centimeters and still receive power.

The clinic

The 2-mm pacemakers that Poon and colleagues tested on live rabbits are about an order of magnitude smaller than the cardiac pacemakers in use today. The pacemaker is an ideal device to use for such a test—it's easy to measure an animal's heart rhythm to see if it's being regulated by the electronic implant—but it's not a representative example of how the wireless powering scheme might eventually find clinical application. Pacemakers require constant power, and it's not feasible for patients to carry the 6-cm source around with them at all times. As Ho points out, "Imagine what would happen when you took a shower."

Instead, they envision that their method would be most useful on implants that require only intermittent power. Those can include devices to stimulate nerve-cell clusters called ganglia to relieve pain (their first human trial will be on ganglion stimulation) and sensors to monitor various biological functions. Miniature pacemakers are a possibility, too, though they'd need to include an onboard rechargeable battery. But because that battery need only carry enough power to last weeks, rather than years, it can be made small.

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References

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2. S. Kim, J. S. Ho, A. S. Y. Poon, *Phys. Rev. Lett.* **110**, 203905 (2013).

Model dynamo may solve Mercury mystery

Simulations suggest that the planet's top-heavy magnetic field derives from the unusual chemistry of its core.

In March 2011, nearly seven years after its launch, NASA's *MESSENGER* probe became the first manmade object to orbit Mercury, where it began a detailed survey of the planet's geochemistry, topography, and space environment. (See the article by Sean Solomon, PHYSICS TODAY, January 2011, page 50.) Within a few months, the spacecraft delivered a surprise: Mercury's magnetic field is top heavy—three times as strong at the north pole as it is at the south pole.[1]

Of the planets in our solar system that possess a global, dipolar magnetic field, only Mercury exhibits the north–south asymmetry. The finding is all the more puzzling because by most every other measure, including gravitational field strength and surface temperature, Mercury's northern and southern halves are essentially identical. Now, with new insights from simulations of the planet's dynamo—the turbulent, magnetic-field-inducing flow of molten material in the planet's core—Hao Cao, Christopher Russell (both at UCLA), and coworkers think they've uncovered the recipe for the symmetry breaking that gave Mercury its unique magnetic field.[2]

Uncommon core

Planetary dynamos feed on motion. As molten metal churns in the core, it stretches and bends existing magnetic field lines, thereby inducing additional magnetic field. If the motion were to stop, the planet's field would decay and vanish. (See the article by Daniel Lathrop and Cary Forest, PHYSICS TODAY, July 2011, page 40.)

In Earth's dynamo, core flows are thought to be sustained partly with energy supplied by phase changes at the interface between the solid inner core and the fluid outer core (see figure 1a). As the planet cools, the inner core grows; it incorporates iron and other heavy elements from the outer core and leaves behind a fluid rich in low-density elements such as sulfur. That hot, buoyant fluid rises to the overlying mantle and generates the convective motion that powers the dynamo. (See the article by Peter Olson, PHYSICS TODAY, November 2013, page 30.)

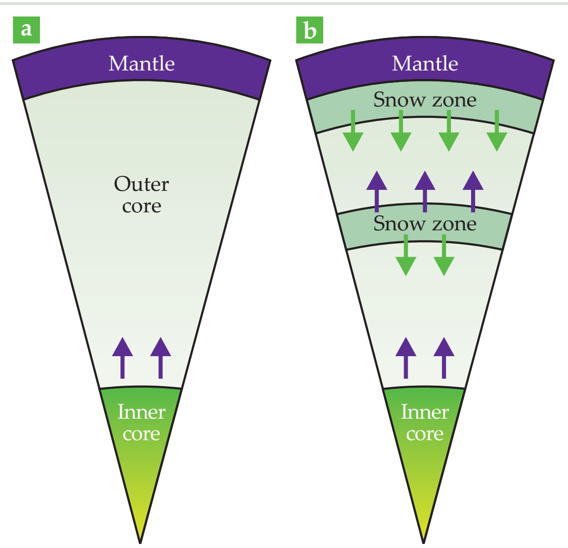

Figure 1. Planetary dynamos are driven in part by convective circulation resulting from phase changes in the planet's interior. **(a)** In Earth, for example, light elements (purple arrows) are expelled into the molten outer core as the solid inner core grows. Those light elements stir the core as they rise to the mantle. **(b)** In Mercury, light elements (purple arrows) and heavy solids (green arrows) can also originate in localized regions of precipitation known as snow zones. (Adapted from ref. 3.)

Traditionally, Mercury's dynamo has been assumed to operate in similar fashion. But there are reasons to suspect that convective forcing in Mercury's core may be significantly more complex than it is in Earth's. For starters, Mercury's core is thought to contain a much higher concentration of light elements; their depression of the core's freezing point is currently the only viable explanation for why the relatively small core hasn't already frozen completely solid. (See PHYSICS TODAY, July 2007, page 22.)

In 2008 Bin Chen, Jie Li (both then at the University of Illinois at Urbana-Champaign), and Steven Hauck II (Case Western Reserve University, Cleveland, Ohio) showed that when molten iron contains a sufficiently large admixture of sulfur and is compressed to Mercury-like pressures, iron can spontaneously precipitate—even when there's no solid–liquid interface to seed the phase change.[3] They predicted that precipitation could potentially occur in two layers, so-called snow zones, inside Mercury's core. Sources of heavy precipitates and buoyant light elements, the snow zones (depicted in figure 1b) would further stir the dynamo.

Newer assessments of Mercury's geochemistry hint at still more complicated forcing patterns. Spectroscopic measurements indicate that Mercury's silicate surface is poor in iron and rich in sulfur, which suggests that the planet formed under highly reducing chemical conditions. Laboratory experiments mimicking those conditions demonstrate that Mercury's core likely acquired substantial admixtures of both sulfur and silicon as it formed. If so, the liquid part of the core could consist of two immiscible layers—an iron–sulfur phase and an iron–silicon phase—each of which could spawn snow zones and potentially give rise to other exotic phase behavior.

To see how different forcing patterns influence dynamo-generated magnetic fields, Cao and his coworkers teamed with a numerical modelling group led by Johannes Wicht (Max Planck Institute for Solar System Research, Göttingen, Germany). The researchers didn't attempt to simulate every possible scenario, just two extreme cases: An Earth-like scenario in which the dynamo is stirred from below and a so-called vol-