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Smart Flesh

Electronics that mold to the human body

Getting Old Gets Easier

DNA Swap Fixes Rare Mutations

Weird Weather No Fluke

Beginnings of BIONIC

Flexible, stretchable electronics could launch cyborg era

By Meghan Rosen

This stamp-on circuit and other new electronic devices are designed to conform to human tissue.

Michael McAlpine's shiny circuit doesn't look like something you would stick in your mouth. It's dashed with gold, has a coiled antenna and is glued to a stiff rectangle. But the antenna flexes, and the rectangle is actually silk, its stiffness melting away under water. And if you paste the device on your tooth, it could keep you healthy.

The electronic gizmo is designed to detect dangerous bacteria and send out warning signals, alerting its bearer to microbes slipping past the lips. Recently, McAlpine, of Princeton University, and his colleagues spotted a single *E. coli* bacterium skittering across the surface of the gadget's sensor. The sensor also picked out ulcer-causing *H. pylori* amid the molecular medley of human saliva, the team reported earlier this year in *Nature Communications*.

At about the size of a standard postage stamp, the dental device is still too big to fit comfortably in a human mouth. "We had to use a cow tooth," McAlpine says, describing test experiments. But his team plans to shrink the gadget so it can nestle against human enamel. McAlpine is convinced that one day, perhaps five to 10 years from now, everyone will wear some sort of electronic device. "It's not just teeth," he says. "People are going to be bionic."

McAlpine belongs to a growing pack of tech-savvy scientists figuring out how to merge the rigid, brittle materials of conventional electronics with the soft, curving surfaces of human tissues. Their goal: To create products that have the high performance of silicon wafers — the crystalline material used in computer chips — while still moving with the body. Beyond detecting bacteria to nip potential illnesses before they begin, such devices could comfortably monitor a person's vital signs and deliver therapeutic treatments.

Unlike Arnold Schwarzenegger's cinematic cyborg, which forced flesh and blood to fuse with a machine base, today's researchers focus on tailoring electronics to fit the human form. One group, led by materials scientist John Rogers of the University of Illinois at Urbana-Champaign, has created flat electronic "temporary tattoos" that stick to skin. This summer, the researchers invented an electronic finger sleeve that detects movement and touch. Now, a similar technology can hug the heart like cling wrap. Such a device could sense erratic beats and zap a spastic organ back into rhythm. Other inventions, implanted into the brain, might send out microshocks to jolt away an epileptic seizure.

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In the last two years, another team, led by Zhenan Bao of Stanford University, has been working toward making stretchy, artificial skins from rubber and carbon nanotubes. The skins will feel like the real thing to the touch — and they will have a sense of touch too, electronically detecting changes in strain and pressure from a stretch or a pinch.

In the short term, flexible, stretchable electronics could help make medical devices smarter, by integrating sensors into sutures, surgical gloves or balloon catheters that feel their way through the passageways of a heart. Incorporating electronics onto (and into) human bodies for everyday use may follow close behind.

"We went from a computer that fit in a room, to a computer that goes on your desk, to a computer that can go in your pocket," McAlpine says. Joining computers to the body, he says, is "the next logical step."

Rogers is one of the scientists pushing the field forward. And last year, he put some skin in the game.

Stuck on skin

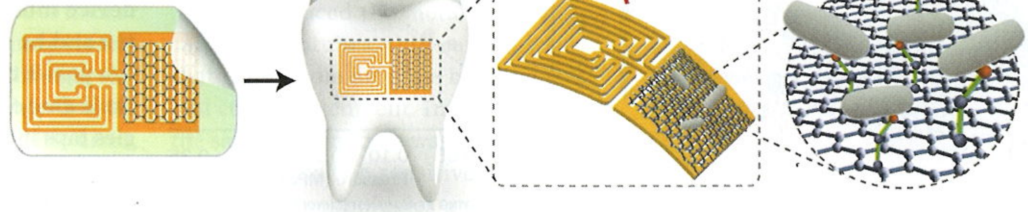
Silicon wafers are lousy for making skin electronics. "In terms of mechanics," Rogers says, "they're basically like a plate of glass." When the body twists and bends, they break.

But the appeal of silicon is its history. "There's been a half a century of global research and development to understand how to purify it, dope it, make devices out of it and manufacture with it," he says.

A typical computer chip has metal wires that carry a current along a rigid silicon base. Components etched into the base control the flow. Rogers' team is working with the brittle silicon to make it flexible and stretchable enough to ride atop skin. By creating ultrathin silicon ribbons instead of etching into a silicon block, the researchers have produced parts that bend without breaking. Think of how you can roll up a piece of paper but not a wooden board, Rogers says. The paper's thinness makes it supple.

In his team's epidermal electronic devices, squiggles of silicon ribbons snake across rubbery support surfaces. The squiggles join with gold to form the devices' sensors — for detecting temperature or pressure or strain — and link up in a mesh that puckers and flexes along with the sheet it is mounted to.

Toothy circuit
When transferred to a tooth, a graphene-based sensor printed on biodegradable silk could help fight disease. Such a device can detect the presence of bacterial intruders in the mouth and communicate its findings via wireless readout.



FACING PAGE: J. ROGERS/UNIV. OF ILLINOIS; THIS PAGE: M.S. MANNOOR *ET AL*/*NATURE COMMUNICATIONS* 2012

One day, a slim skin sticker designed by the team could be used to a track a person's health (*SN: 9/10/11, p. 10*). It would even be gentle enough for premature babies. The electronic gadget might also be tapped for nonmedical uses: Secret agents with an electronic sticker hidden under a shirt collar could pick up and send out conversations, an extra-covert way to "wear a wire."

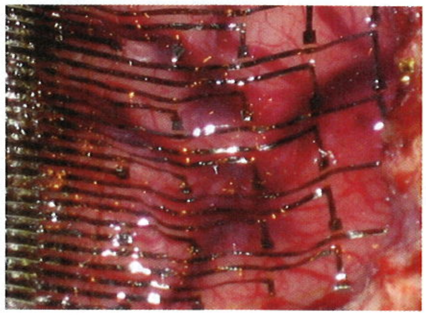
Already, Reebok is working with Rogers to develop a skin-mounted sports monitor designed to move with the body while tracking an athlete's health. Reebok's flexible device straps on instead of stamping on, "but it's a great first step in that direction," says Rogers.

While gadget lovers wait for the device to debut sometime later this year, Rogers and collaborators have moved beyond flat electronics into a third dimension. In August they reported inventing an electronic "finger tube" — a molded polymer sheath with built-in sensor disks of silicon and gold. For a snug fit, Rogers' team used a 3-D scanner to map a finger's form. He envisions the stretchy tubes will one day top the fingers of smart surgical gloves, to enhance the sense of touch for delicate operations.

Rogers is also teaming up with other researchers to apply the new technology to bigger body parts — such as hearts.

Keep the beat alive

When St. Louis surgeons remove a failing heart from a transplant patient, biomedical engineer Igor Efimov and his colleagues are among the first to know. They take advantage of the heart's last



This flexible brain sensor can monitor activity more gently and accurately than current technologies.

moments of life to test prototypes of a cardiac technology that might one day have the power to heal.

Efimov and his team have joined with Rogers' group to develop the device, which slips around the heart and uses a low-energy method to gently calm spastic tremors. Jittery flutters called atrial fibrillations afflict millions of people worldwide and can bump up stroke risk.

A safe, effective atrial defibrillator exists, but it is bulky, with rigid electrodes and wires that eventually wear out, short-circuit or leak. What's more, "nobody wants to use it because it's too painful," Efimov says. The defibrillator uses so much energy to jump-start a heart that patients describe it as a mule kick to the chest. His team's method is more like a love tap; it's pain-free.

Inside the "heart sock" are printed sensors that monitor activity across the surface and stimulators that deliver tiny shocks when needed. And because the sock is light and floppy, it could outlast today's clunky cardiac equipment.

Recently, Efimov and colleagues have begun testing prototypes on donated human hearts. A partnership between Barnes Jewish Hospital and Efimov's lab at Washington University, both in St. Louis, delivers sick hearts from patients to scientists. When transplant patients get new hearts, researchers get to experiment on the old ones.

"It's a good deal," Efimov says. After the heart is pulled from the body and unhooked from its blood supply, the researchers have a short window of time before the heart shuts down. They shuttle it to the lab and conduct their experiments, laying pieces of prototype heart sock material on the organ to measure electrical activity and other properties. In the team's sensing tests so far, he says, it is "working really wonderfully."

Efimov has also stimulated rabbit hearts with a more complete version of the sock, and is planning to try it on the hearts of living dogs — the best animal model for human atrial fibrillation, according to Efimov. With so many people worldwide relying on defibrillators and other implanted heart devices, Efimov sees an obvious market.

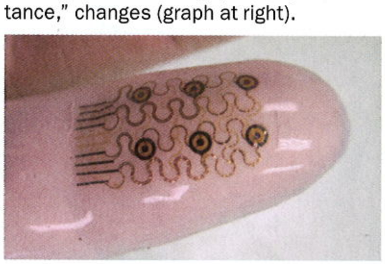
Though Efimov focuses on cardiac therapy, he has ideas for other uses for the technology. Scientists could use related devices on muscles or bones, he says, or to hook up human brains to the Internet. "There are so many applications," he says. "It's just amazing."

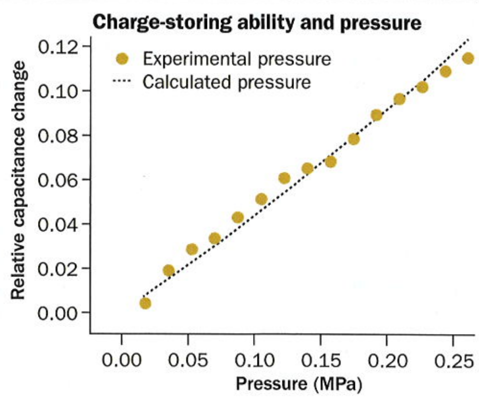
Handle with silk

A Web-browsing brain may sound like science fiction, but researchers have already figured out how to implant flat chips into the human brain to pick up neural signals and turn them into actions (*SN: 7/2/11, p. 26*).

But forcing flat electronics to lay against the soft, sloping surface of the brain is a delicate and tricky task. The device must physically touch the cortex and be stiff enough that surgeons can pass it through tiny openings in the skull. One of the best current technologies taps into neural activity by jabbing sharp pins into the brain where they contact clumps of brain cells. The pins

Touch sensitive Electronic finger sleeves (one below) might pave the way for human-machine interactions or find their way into smart surgical gloves. When squeezed, a sensor's ability to store an electric charge, its "capacitance," changes (graph at right).





SOURCE: M. YING *ET AL/NANOTECHNOLOGY* 2012

BOTH: J. ROGERS/UNIV. OF ILLINOIS, TOP: D.-H. KIM *ET AL/NATURE MATERIALS* 2010 mount to a rigid silicon chip.

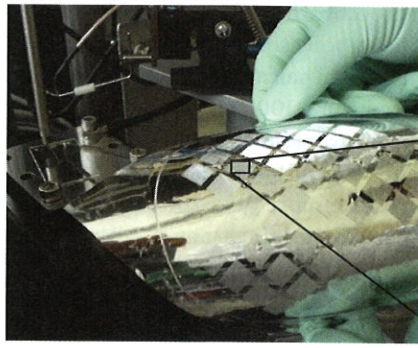
Though easy to handle, today's approaches irritate the tissue and can trigger long-term inflammation. Low-profile devices that instead sink into the brain's crevices and work with its micro-movements — bulges, contractions and pulses — could be less traumatic and longer lasting. If scientists can figure out how to work with them.

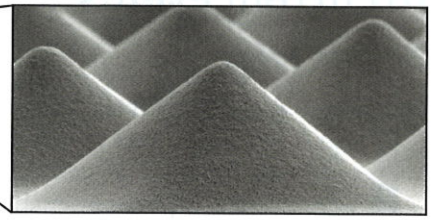
"You can't really hold or manipulate the device very well because it's so thin and flexible and sloppy that it's not even self-supporting," Rogers says. "So how do you move it around?"

One answer is silk. As with McAlpine's tooth sensor, thin films of silk may help scientists get a grip on flexible electronics. Because the films are stiff when dry, researchers can add a layer of mesh circuits and easily maneuver the films through holes in the skull and onto the brain. Doused with fluid, the film dissolves and the circuit snuggles against the brain's folds. Since the silk doesn't bother the body, film remnants can flush safely into the skull cavity *(SN: 11/3/12, p. 15)*.

"It eventually degrades, and the body has a very low immune response to it," says biomedical engineer Fiorenzo Omenetto. To make the films, Omenetto and his team at Tufts University in Medford, Mass., process silk into its basic protein ingredients. First, they chop up silkworm cocoons, and then they boil the bits in a salt solution to break down the fibers. "It's like making pasta," Omenetto says. At the end of the entire process, what's left is a mixture of water and fibroin — a versatile silk protein that scientists can form into almost anything, including thin sheets.

In 2010, Rogers, Omenetto and colleagues tested a silk-coupled electronic device on a feline brain. They placed the silk-backed mesh circuit onto the visual cortex of an anesthetized cat and monitored brain activity. Compared to thicker devices, the mesh molded more closely to the brain and recorded stronger signals. In people, such flexible devices may one day control prosthetic arms, map brain activity or quell seizures in epileptic patients.





Pyramid boost By adding some texture to a rubber film (magnification below), researchers can increase its sensitivity to pressure. One day this rubber may be combined with other technologies to create artificial skin.

BOTH: BENJAMIN TEE, S. MANNSFELD *ET AL*/*NATURE MATERIALS* 2010

All-in skin

Instead of trying to make traditional electronic materials flexible, Stanford's Bao and colleagues are turning the goal around: They're trying to make flexible materials electronic. By layering thin textured films with carbon nanotubes, Bao and her colleagues are figuring out how to make touch-sensitive artificial skin — no rigid parts required.

Today's ultrasensitive strain sensors are built with a thin layer of silicon film. Pressing on the film changes the amount of current zipping through it, allowing the pressure to be measured. The gadgets are very sensitive, Bao says, but also very fragile. For the applications she is interested in, fragile doesn't work: "A lot of wear and tear will easily damage those kinds of devices."

In 2010, Bao's team made a sensing system that works a little differently by sandwiching a layer of microstructured rubber between two charge-holding metal grids. When pressure is applied to the grids, the amount of charge changes. The pattern of holes carved into the rubber bumped up its sensitivity: Even a butterfly-light touch compressed the cutouts, Bao and colleagues reported in *Nature Materials*.

Of course, metal tends to crack when bent. So last year, the researchers figured out how to give the sandwich's bread layers a little stretch.

They replaced the metal grids with carbon nanotubes, thin carbon wires that can handle extreme bending and still conduct a current. In this version, the sandwich's middle was a flat rubber film that wasn't so sensitive, but combining the technologies and spotting the resulting sandwiches onto another material could yield sensitive, stretchable artificial skin.

Such skin may one day patch areas of real flesh damaged by burns, for example. "Twenty years from now," Bao says, "I can definitely see some flexible sensor sheet that looks just like human skin and can be grafted onto wounds and function like real skin."

In many ways, Bao's artificial skin behaves like the real thing. But it has one big hurdle to clear: It still uses wires to send its messages to a computer. If the skin ever made its way into a prosthetic, it would need to relay signals wirelessly to the wearer's brain. "Ultimately we want the sensors to be talking directly to the neurons," Bao says.

She imagines a future in which a person's electronic skin and other implanted devices link up. A world where a fly lands on the artificial skin of a person's arm, which speaks to an electronic device in the brain, which tells the person to shoo the bug away with a flick of a supersensitive finger.

Today, researchers are buzzing along building bits of electronics that can be integrated into the body. Someday soon, they may cobble the pieces together and get them to converse in a truly bionic being. ■

Explore more

- D.-H. Kim. "Flexible and stretchable electronics for biointegrated devices." *The Annual Reviews of Biomedical Engineering*. August 2012.

Meghan Rosen is a former Science News *writing intern.*