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Wearable, Wireless Electronics

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A Q&A with John A. Rogers

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Throughout his career in materials science, John A. Rogers of Northwestern University has worked on projects that range from cameras inspired by insects' compound eyes, to self-folding silicon structures modeled after Japanese kirigami paper cutting, to self-healing polymer materials. His current main focus is developing flexible biomedical structures that integrate with the human body to improve the quality of life for the most vulnerable patients, from premature babies to the elderly with neurological conditions. Some examples include implantable devices that dissolve after their usefulness is completed and flexible, wearable sensors that eliminate the need for wires tethering patients to monitors. For his extensive work, Rogers was awarded Sigma Xi's 2023 William Procter Prize for Scientific Achievement. He spoke about his research with American Scientist*'s editor-in-chief, Fenella Saunders. This interview has been edited for length and clarity.*

Materials science cuts across many areas, so how do you approach its diverse applications?

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Northwestern University

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Our mindset is to think not only about the materials themselves but also about how they can be exploited in devices that can have meaningful impacts on society. This approach not only connects our fundamental science with technologies that benefit people, but this forced exposure to system-level considerations helps us to refine our understanding of key challenges and unanswered scientific questions at the base materials level. Broadly speaking, we are interested in bioinspired and biointegrated technologies and associated enabling materials. If you're thinking about devices that interface with the body, health care applications rise to the top of the priority list, due to their potential to improve the way we care for patients.

How do you establish collaborations with the medical community?

About two-thirds of our projects are requests from physicians who are struggling with an unmet clinical need related to their particular class of patient. Many of the most daunting challenges occur at the earliest stages of life. And thus our research involves a core focus on technologies related to maternal, fetal, neonatal, and pediatric care. But we also have significant programs at the other end of the age spectrum, for end-of-life health challenges. Here, we work with stroke survivors, Alzheimer's patients, Parkinson's patients, and those who live with dementia.

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The remaining one-third of our projects arise from a gut-level intuition that we have as engineers around what might be useful for patient care. One successful example are devices we designed to dissolve away naturally when exposed to biofluids over a well-defined time frame. Here, we thought, resorbable sutures are really useful, so let's try to extend that concept by creating a set of materials to enable a resorbable electronic device to open up applications beyond the simple mechanical function of a suture to something that could offer digital biochemical sensing, electrical stimulation, drug release, that kind of thing. This idea really exploded into a whole set of opportunities around what we're referring to as *engineered medicines*. They operate kind of like a drug in the sense that you take a dose, but then they are eventually resorbed by or expelled from the body. Once the clinical folks became aware that this kind of thing was even possible, they called us and asked to use these dissolvable electronic devices to serve as temporary pacemaker alternatives to what they're using now, but without the need for surgical extraction and the associated costs and patient risks at the end of the device's utility.

How do temporary pacemakers work?

If you have an invasive cardiac procedure, let's say an open-heart surgery, commonly the surgeons will insert a temporary pacemaker built out of permanent materials at the tail end of the surgery. It's basically a pacing lead that comes out from the chest and connects to a power supply that creates the stimulating pulses to pace the heart. But they don't activate the device unless during the recovery period following the surgery, the heart rate drops below a

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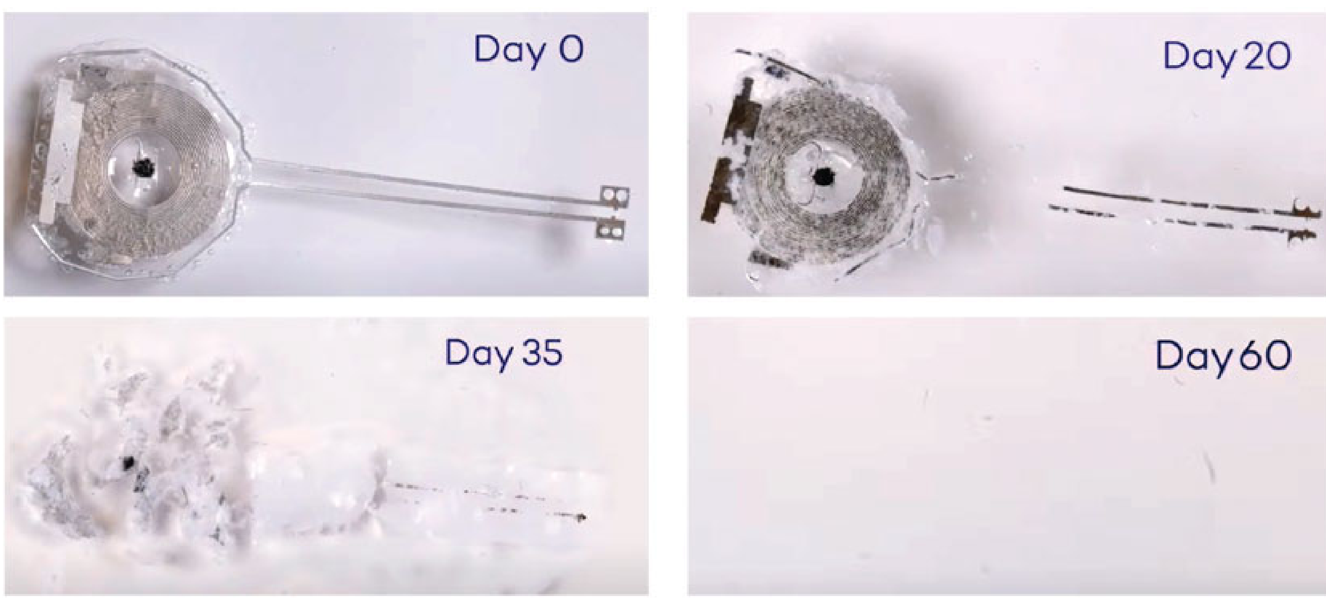
safe threshold—something that can happen following the trauma associated with the surgery and any complications that might occur after. Once the patient has recovered, the pacemaker must be removed. Typically it's just pulled out. The pacing lead is often encapsulated in scar tissue that tears away during this process, and that's usually fine. But in certain cases, tearing of the scar tissue is accompanied by tearing of the healthy cardiac tissue, which can lead to internal bleeding that can have serious implications for the patient's health. It turns out that Neil Armstrong passed away due to complications associated with removal of his temporary pacemaker; it caused an internal bleed that wasn't immediately recognized. This type of event is still relatively rare, but it does happen frequently enough that cardiac surgeons asked us to develop a temporary pacemaker that does not require that extraction process, but would naturally dissolve away and disappear after it is no longer needed.



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(/) Our bioresorbable pacemaker is wirelessly powered and activated, so we can pair it with one of our wireless skin-interfaced devices to monitor the heart rate, compute when the heart rate drops below that threshold value, and then activate a transmission coil to power up the pacemaker and pace the heart. The vision is that the technology could allow patients to leave the hospital earlier than they would otherwise if they're tethered to an external power supply and electrocardiogram leads. Our latest version has the power supply built in; essentially it has a bioresorbable battery, a really tiny one, that is a pair of dissimilar metals and acts like a galvanic cell, which is activated by exposure to biofluids. The whole thing is about the size of a grain of rice, and you can actually inject it with a syringe and then optically trigger its operation.

What makes the device resorbable?

Most of the materials are soluble in water by a chemical reaction known as *hydrolysis*, without any required metabolic action or enzymatic activity. For our pacemaker, we chose materials that naturally dissolve away in the water content associated with the surrounding biofluids.

For any kind of electronic circuit, you need three classes of materials: one that provides that semiconductor functionality needed for switching a transistor on and off; some kind of metal to form the wiring that carries the current; and a material that's an electrical insulator to insulate those wires from one another. We have a number of choices for each type of electronic material, the key ones

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of which turn out to be minerals that are needed for healthy metabolism, such as iron, zinc, and magnesium—things that you would find in a vitamin tablet. We can make conducting wires out of those materials.

For the semiconductor, we really got lucky in the sense that we discovered something that I think very few materials chemists had previously appreciated, which is that silicon itself is water soluble, it just dissolves in water at extremely slow rates, so slow that this process went unnoticed in the past. We have a history of working with silicon in very, very thin, nanoscale forms because this thin geometry makes the material mechanically flexible. One of the postdocs who built these flexible circuits out of these silicon nanostructures noticed that if he left the devices in water overnight, or for a few days, the material just disappeared. He was alert enough to take notice of this observation, and to then dig in and investigate. It turned out that silicon in this nanoscale form, even though the rate of dissolution is very slow, doesn't take very long, only a few days, to dissolve without a trace.

We can thus take silicon as our semiconductor, with iron or magnesium or other bioresorbable metals as our conductor, and then use polymeric materials, in some cases biopolymers such as silk fibroin or other biologically occurring materials in the natural world, as the insulators. We put them all together, pattern them into appropriate geometries, and then make circuits that will eventually dissolve completely if left in the body long enough. From a

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medical standpoint, we typically design them to last a few weeks and then to dissolve completely over three months, or six months, or nine months, as long as they eventually go away to eliminate potential risk to the patient.

What are some other uses of these bio-resorbable materials?

As soon as the temporary, dissolvable pacemakers became well-known in the medical community, we got a call from a lung transplant surgeon, and evidently in those instances you have to pace the diaphragm. So we're now way down the path on developing a resorbable diaphragm pacer. A lot of the engineering and stimulation parameters are pretty similar to those for cardiac pacing, but now you're pacing the respiratory cycles.

Another use of these kinds of stimulators is in the context of neurosurgeries that are performed to treat crush or transection injuries of peripheral nerves. Surgeries to repair a nerve involve suturing together the severed ends of the nerve, and at the end of that surgery, many surgeons use a handheld electrical stimulator to stimulate a proximal site relative to the position of the transection. That stimulation is known to cause the release of neurotrophic factors that accelerate the rate of healing. But this procedure is currently only possible in an intraoperative setting, when the surgeon has physical access to the nerve. So their concept was to take one of our wireless resorbable stimulators, drop it in at the end of that surgery, and then wirelessly activate the stimulation—not just for that brief intraoperative period when they have access, but at various time points during the healing process. It's again the notion of dosing out an engineered form of medicine to accelerate healing. The key advantage of our device, which is enabling this vision for patient care, is that no secondary surgical extraction procedure is needed.

We’re also interested in engineering approaches to treat pain, specifically acute pain in that postsurgical setting, when there are natural opportunities to place devices in the patient’s body during a surgery that needs to happen anyway. Pain mitigation is often done with various kinds of highly addictive drugs. We’d like to be able to replace those drugs with devices that can be turned on and off as necessary, then eventually resorb and disappear in the body after the patient is no longer in need.

We have two forms of devices, one that’s built out of resorbable materials and implanted deep in the body, directly interfaced to the peripheral nerve that’s carrying the pain signals. This device provides high-voltage, high-frequency electrical stimulation of a nerve to block pain signals. The other approach is more novel and relies not only on resorbable electronics, but on resorbable microfluidic devices as well. In this case it’s a long, stretchable microfluidic tubing that interfaces through a cuff-like structure around the surface of a nerve that’s carrying a pain signal that you’d like to block, and we can inject fluids down the length of that microfluidic channel. We use targeted evaporative cooling to decrease the temperature of the nerve, to create a kind of numbing effect. The electronics provide an ability to track the temperature at the nerve site, so we can understand how fast coolant needs to be flowed into

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the device to hold the temperature of the nerve at a level that's below the threshold at which you need to block pain signals, but not too low to cause permanent damage to the nerve.

Also, implantable drug-release vehicles represent a concept that's been pursued by a variety of different companies over the past decade or so. The difficulty with those devices is that once all of the drug has been depleted from the reservoirs, there remains a piece of hardware in the body that needs to be extracted. It's a pretty simple opportunity to exploit this resorbable electronics platform to allow for that wirelessly programmed drug-release functionality, but in a device that naturally resorbs.

Can these devices be used as sensors?

One example is in treatment of patients who've suffered a traumatic brain injury to the extent that they need brain surgery, and in those cases swelling of the brain and associated increases in the intracranial pressure can be a critical risk factor for the patient during the recovery period. Currently surgeons use intracranial pressure and temperature monitors that track those two parameters. But as with temporary pacemakers, those monitors need to be removed after the patient has recovered. Neurosurgeons asked us for a resorbable wireless pressure and temperature sensor that could be deployed in the intracranial space; we built one out and have demonstrated it in animal models.

Are any of your devices in use now?

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Yes, we have wireless wearable devices approved by the U.S. Food and Drug Administration that provide vital-sign monitoring functionality. They're basically thin, flexible patches that mount on the chest or a limb. The technology is designed primarily for monitoring vital signs in premature babies who are currently monitored with wired systems that are highly inappropriate for these tiny patients. The devices have been deployed globally since 2019 in about 20 different countries. We have partnerships with the Gates Foundation and the Save the Children organization to get these kinds of technologies into lower-income countries where in many cases they don't have any monitoring technology at all, wired or otherwise. Our devices are cost-effective even for these uses, much lower in cost than the standard wired systems. I spent some time in Zambia during an initial deployment, and they're now also used in Kenya, Ghana, Mexico, India, and Pakistan, among other countries. Standard monitors are single use, but we were challenged to build robust devices that can be used a few hundred times, so that the key cost metric is reduced to a few cents per 24 hours of monitoring a patient.

"Pain mitigation is often done with highly addictive drugs. We'd like to replace those with a device that can be turned on and off as necessary, and then eventually disappear after the patient no longer needs it."

(/) Another technology in widespread use involves a totally different type of system. Here, the patch goes on the surface of the skin, like the vital-sign monitoring devices, but instead on the back side are inlet ports that allow sweat from the skin to pass into a network of tiny channels with valves and reservoirs, so that we can quantitatively measure the amount of sweat loss as well as various kinds of biomarkers that are present in sweat by using color-changing chemistries that respond to the concentrations of these markers. Here, we were approached in 2016 by Gatorade to produce a version of this type of skin-interfaced microfluidic device to measure sweat loss and electrolyte loss to guide precision rehydration strategies for serious athletes during training or competitive events. Since launching that product, referred to as the Gx sweat patch, companies in the oil and gas industry are using an advanced version to monitor dehydration in workers operating in extreme environments. And then there are some medical applications as well. It turns out that a sweat chloride test is the gold standard for screening for cystic fibrosis in pediatric patients. Our device provides a great way to do the test because it’s just a soft sticker that you simply place on the surface of the skin, you capture the color change with a smartphone camera, and you thus get the chloride concentration right away, without the need for hospitals or health care technicians, so it’s suitable for use in rural or resource-constrained areas.

Do you take inspiration from nature?

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We’ve recently been thinking about monitoring, not the health of a human body, but the health of a broader environment. Let’s say you want to track a chemical spill as it’s being remediated, with sensors that resorb naturally after they’re no longer needed. But how do you disperse them? We thought about plants dispersing seeds, and with our kirigami-inspired work, we figured out how to add wings to microchips to create helicopter-type flight trajectories, much like maple seeds. It’s still exploratory research, but it’s a fun direction to pursue. But the resorbable part is key because without it, these ideas would represent spectacularly effective mechanisms for distributing electronic waste over large areas, and nobody wants that.

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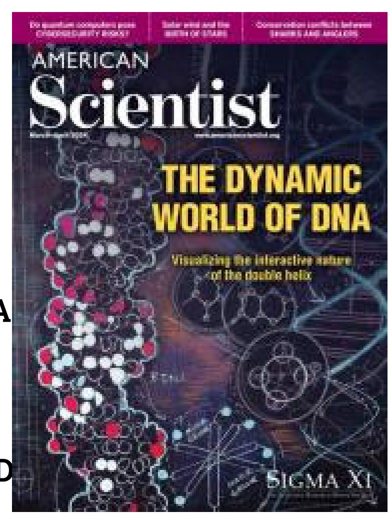

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