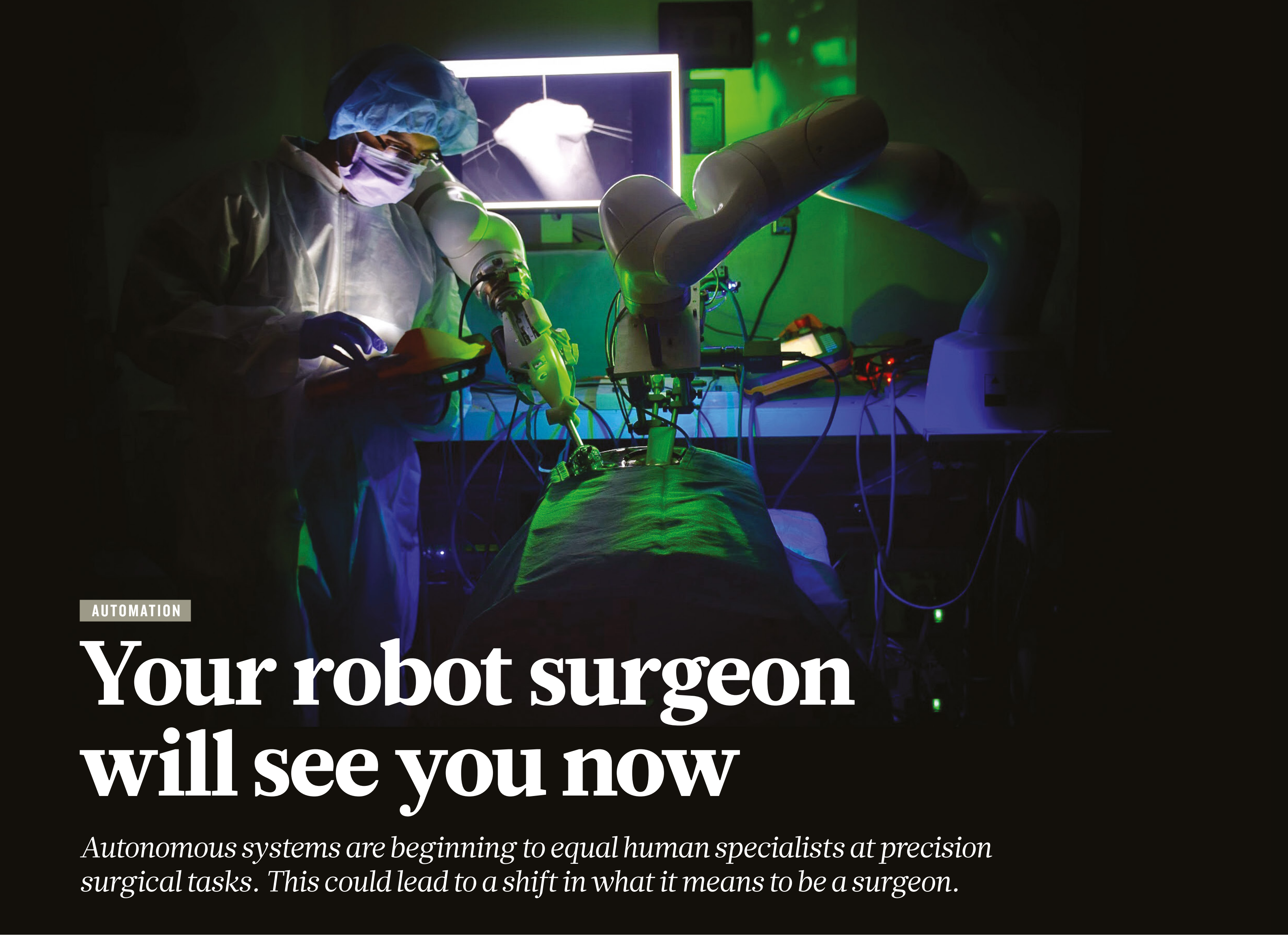


MICHAEL KAM, UNIV. MARYLAND

AUTOMATION

Your robot surgeon will see you now

Autonomous systems are beginning to equal human specialists at precision surgical tasks. This could lead to a shift in what it means to be a surgeon.

BY ELIZABETH SVOBODA

One of the most potentially disruptive innovations in medicine is a faceless white robotic cylinder about the size of a breath mint, attached to the end of a catheter. On an operating table at Boston Children's Hospital in Massachusetts, researchers are showing how it can navigate to a patient's leaking heart valve better than some surgeons can with years of training. First, the assembly is inserted into the base of the heart. From there, it propels itself using a motorized drive system along the pulsating ventricular wall to a damaged valve near the top of the ventricle, guided by vision and touch sensors. The robot wedges itself into position near the leaking valve. A surgeon then takes over to launch an occluder — a minuscule stopper — from the robot that plugs the leak.

The 'patient' on the table is not human but a pig — the researchers behind the device say it'll be years before their robot creation is masterminding valve repairs in people. But its abilities hint at the dawning of a new era of surgery. Intelligent surgical robots with varying degrees of autonomy are proving in early tests to be the equals of surgeons at some technical tasks, such as locating wounds, suturing and removing tumours. These tiny, precise operators promise clean results and broader access to specialized procedures — and the robots are prompting some surgeons to think what their role will be in an increasingly automated landscape.

CRUISE CONTROL

Robotic surgery is already with us. Instruments such as the Da Vinci by Intuitive Surgical in Sunnyvale, California, and the Senhance by TransEnterix in Morrisville, North Carolina, allow surgeons to take control of multiple robotic arms through a hand-operated console, and give them greater dexterity and vision when operating in hard-to-reach areas. But devices like the capsule robot at Boston Children's Hospital go one step further: they can operate independently, at least for part of the procedure.

That next level of assistance allows intricate surgical feats to be performed without the surgeon worrying that their hands might slip or their grip falter — a positive development, given that mistakes by clinicians lead to more than 200,000 US deaths each year[1]. "A surgeon can go click, click, click, these are the places I want a suture to happen," says Animesh Garg, a computer scientist at the University of Toronto in Canada who has worked on surgical automation for the best part of a decade. "We wanted this to be like cruise control of surgery."

Not every surgical manoeuvre is a good candidate for robotic automation, according to Lennox Hoyte, an engineer and urogynaecological surgeon at the Pelvic Floor Institute in Tampa, Florida. Those that are, such as suturing and valve repair, tend to be the tasks that surgeons consider boring and repetitive, he says. The simpler a procedure is to break down into basic, specific commands, the easier it is for a smart robot to learn and execute. "The mindset is often more complex tools, but simpler motions," says Pierre Dupont, an engineer in Boston Children's Hospital's robotic research team.

ONE STEP AT A TIME

Suturing can be broken down into simple, easily defined movements, and so is an ideal task for independent surgical robots. A team including engineer Axel Krieger, then at Children's National Health System in Washington DC, developed a system that uses a lightweight robotic arm to place a line of specialized sutures all by itself[2]. Krieger and his colleagues wanted to automate a surgical task called intestinal anastomosis, in which two segments of the intestine are stitched together after a portion of the organ is removed. The procedure typically requires awkward and intricate hand movements that even the best

PIERRE DUPONT

An assistant readies the Smart Tissue Autonomous Robot to perform intestinal anastomosis — an awkward surgical procedure involving intricate movements.

surgeons struggle to do perfectly. "You have to apply 20 sutures very precisely, and if you miss one, you have a leak," says Krieger, now at the University of Maryland in College Park.

Krieger knew that for a robot to pull off the procedure, it would have to be adept at pushing a needle through soft tissue — a challenging task because tissue can shift unpredictably as the needle pokes through it. So the team fitted their surgical robot, dubbed Smart Tissue Autonomous Robot or STAR, with a force sensor to ensure the needle does not push too hard and deform the tissue.

The robot is guided to where to suture by dots of infrared bioglue that the researchers put on the colon tissue. These markers, Krieger says, allow the robot to "track the tissue when it moves and adjust every stitch" — even in an environment as dark and cramped as is the abdominal cavity. In a trial in living pigs, STAR placed sutures that were more evenly spaced and leak-proof than those made by specialists[2]. The researchers supervised the automated procedure to make sure each stitch was performed correctly, sometimes making small adjustments to the thread's position.

As well as refining STAR's suturing technique, Krieger is teaching the robot another skill: tumour removal[3]. As before, Krieger and his colleagues use infrared markers, but this time to flag areas of cancerous tissue. The robot then selectively excises these parts with a heated electrode tip. Early testing in pig tissue has shown that STAR can remove tumours and cut tissue as precisely as surgeons can — a crucial skill because leaving even a few tumour cells behind could allow the cancer to return. "You have to be incredibly precise so you don't leave any tumour behind [or] cut out any of the healthy tissue," Krieger says.

Heart-valve repair also tests the mettle of even experienced surgeons, owing in part to the challenge of positioning surgical instruments correctly in a confined space. It was that difficulty that prompted Dupont and his team to develop an autonomous robot for the task. The learning curve for the project's engineers was steep, Dupont says. To minimize surgical risk, the team's small robot would need to complete its precise journey from the base of the heart to the defective valve while the person's heart was beating, which means navigating an environment that is in constant, vigorous motion.

The team gave the robot a detailed map of a typical heart, including the locations of specific vessels and valves. The robot uses this information as a rough guide in each procedure. But the device is also highly adaptable, using input from built-in touch and vision sensors to locate valve leaks in each heart. To pinpoint its precise location, the robot makes repeated gentle tapping contact with the heart wall, "like cockroaches tapping with their antennae", Dupont says. In animal trials this year, the robot successfully navigated from its entry point to the damaged valve area 95% of the time[4].

A SLOW, STEADY REVOLUTION

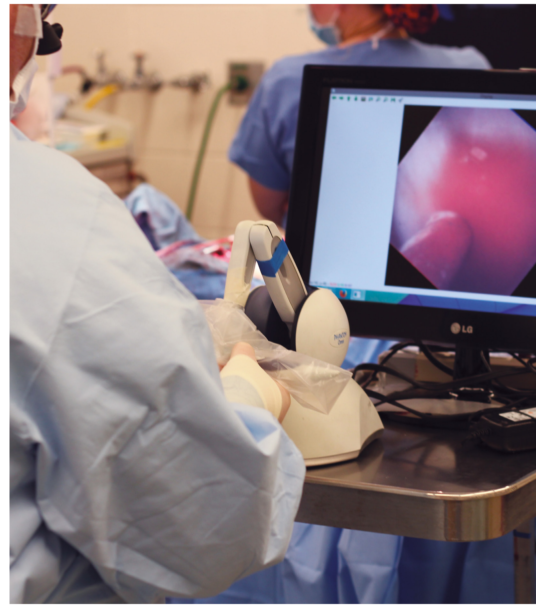
Researchers hope that autonomous surgery will make specialized procedures available to many more people. In the United States, "the distribution of surgeons across the country is not uniform," says urologist Kirsten Greene at the University of California, San Francisco. "There are a lot of areas where people don't have access." The same is true of countries around the world. Autonomous-robot assistance, she notes, could help to fill some of those gaps in surgical expertise. The technology could also reduce the time it takes for aspiring surgeons to learn their trade, says Garg. Robots could allow them to perform complex procedures with fewer years of training.

Robot surgeons cannot yet execute a whole procedure from start to finish. "A decade down the line, certain regular procedures might be automated," Garg says. For example, "surgeries which are very high volume — gall-bladder removal, appendectomy." But that's still some way away, because surgeons are still much better than robots at weighing their past experience to make complex surgical judgments, such as what to do when a blood vessel is in a different place than expected. "When you need contextual understanding, that is where robots start to falter very quickly," Garg says. It is most likely that autonomous surgical devices will enter clinical practice gradually, just as features such as cruise control and, later, lane-keeping systems have made their way into cars ahead of full self-driving capabilities. In addition to well-established robotic assistants such as Da Vinci, Krieger points out that robots are also being used for procedures such as bone cuts and radiation delivery for cancer treatment.

"A decade down the line, certain regular procedures might be automated."

Self-guided robots could be built on surgical tools that some hospital systems already have, which might help to accelerate automation. Some of Garg's designs, for instance, can be attached to the Da Vinci robotic system, which has been used for more than six million human-guided surgeries around the world. "If you have an established robotic platform," Dupont says, "you can slowly add these layers of autonomy." However, at each step, researchers will need to prove that their devices are ready for clinical use. It's one thing to join up pieces of flesh inside a dish, or even in an animal on an operating table, but it's quite another to do the same in people, Garg says — the tolerance of failure is minuscule.

The possibility of greater automation is already raising questions about how the surgeon's role will evolve if intelligent robots take over the trickiest manoeuvres. Most in the field still see a place for surgeons — although they will need to become consummate managers, proving their skill not just at specific procedures, but at using an array of automated tools to best effect. "I don't think you make people obsolete. You move them to the next level where they're acting more like a conductor," Hoyte says. Garg agrees: "For the big picture, you need a human in control."



A heart valve is repaired using a robot that guides itself to the surgery site. Once it arrives, a surgeon takes control with a joystick to do the final repair.

That's their plan for now, at least. But if autonomous robot surgeons are deployed on a large scale, they could start to evolve in unexpected ways. Garg, for instance, is developing self-guided robots that learn from their failures and their successes in much the same way as do people, narrowing the human advantage. Ultimately, robots could share insights gleaned over hundreds of operations with all the other robots in a vast network, supercharging their performance. "You can connect all these systems together, so if there's an unusual anatomy that's treated, that case knowledge would be available elsewhere," Dupont says. But that kind of intelligence sharing is still a long way off. For now, Dupont stresses, autonomous robots are designed to assist human surgeons, not outshine them. "If you have a system that can bring clinicians up that learning curve faster and help them do parts of the procedure, that's going to be the real benefit." ■

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