THE FUTURE OF SURGICAL TECHNOLOGY

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Surgical interventions have historically required incisions in which a scalpel is used to slice open skin and carve through muscle so that the surgeon can get to a diseased organ to repair or remove it. For centuries, surgical procedures have cured myriad diseases, but not without certain drawbacks: There is often significant discomfort, prolonged recuperation, and alteration in the patient’s appearance.

In an effort to address these issues, the field of minimally invasive surgery was born. Advances in technology have now made it possible for physicians to perform surgery without directly observing or even touching the diseased organ they are working on.

Minimally invasive approaches have become the archetype of modern-day surgery; however, the field is only in its infancy. Today, most surgeries are still open, that is, the patient’s skin, muscle, and sometimes bone are cut and parted, giving the surgeon a full view of the organ involved.

However, things are slowly starting to change, and robotic technology in healthcare is no longer just the stuff of science fiction. Rather, I view it as a giant leap in improving the quality of care. We can see this in the hypermodern surgical suites where robot-assisted and computer-aided surgery is performed. For example, the daVinci robot (Intuitive Surgical, Sunnyvale, California) allows robotic-assisted radical prostatectomies to be performed while the surgeon sits at a control console. Never actually touching the patient, the physician dexterously manipulates robotic arms deep within the patient’s body.

Although it is certainly encouraging that such first-generation surgical robots are now installed in many operating rooms around the world, this is only the
beginning. The current systems are not autonomous robots that can independently perform a given surgery. Rather, these robots assist: They lend a “hand” to surgeons. The ultimate potential of such technologies actually lies far in the future.

Imagine a robot small enough to fit within an MRI machine, right next to a prostate cancer patient. Sitting before a screen at a nearby console, the physician would see a crisp 3-D image of the site to be repaired—an image that could be enlarged or rotated at will. With the push of a button, the location of the tumor could be pinpointed, and an automated algorithm would confirm its boundaries. Targeting the area requiring treatment would be even simpler than playing a typical computer game. The robot would then be moved to eradicate the tumor with infinite precision while preserving normal tissue at the margins.

We are currently working on such a robot in my laboratory at Johns Hopkins.

Modern imaging equipment and the novel image-guided devices we have today provide a provocative insight into our technologically advanced medical future. Components of these advanced imaging, image-processing, and image-controlled systems are being developed for interventional radiology and image-guided surgery. Pioneering research facilities around the country have already merged the capabilities of surgical and radiological suites with the introduction of advanced imagers into the OR. This trend will soon allow patients to undergo diagnostic imaging and receive treatment in a single visit.

What is the ideal surgery for cancer of the prostate and other cancers? As I see it, the goal is a completely noninvasive, incisionless intervention—a procedure that doesn’t require so much as a needle stick. The goal is to make a tumor vanish in the depths of the body, to ablate every tumor cell while preserving all healthy cells. Let’s now look 20 years into the future, and see what happens with Joe and his prostate cancer.

Joe’s Story

Joe, a 59-year-old farmer from Springfield, Nebraska, a small town outside Omaha, is referred by his family physician to undergo a prostate screening. “Just in case, Joe,” says his physician. “You know, we’re all getting older. Now don’t forget, I’ve set you up for 9 a.m. on Wednesday, July 17, 2024, at the new NDT clinic, just across the street from the main gate to the park.”

“NDT? What’s that?” says Joe.
“NDT stands for Noninvasive Diagnostics and Therapy,” replies his doctor. “It’s the standard of care for detecting and eradicating all sorts of tumors. I don’t know how we ever did without it.”

On Wednesday, Joe drives his solar-powered car to the clinic and finds a nice sunny spot to park and recharge his vehicle. As he walks into the building, he is welcomed by a three-wheeled robot waiting for him by the door.

“Welcome Joe, my name is Pam, and I will be your nurse today,” says the machine in a voice pleasantly reminiscent of Audrey Hepburn’s. “Are you ready? Please follow me.”

Pam ushers Joe into an expansive room with a large window facing the park. In the middle of the room is an extra-long operating table. Several flat-screen monitors line the wall opposite the entrance; in front of them sits a control panel that resembles the PlayStation Joe remembers from his childhood.

Pam instructs Joe to place his index finger in a cradle located on her hand, an identification procedure that allows instant access to his records. Within a fraction of a second his entire medical record, including 3-D anatomic, physiologic, and pathologic data, are retrieved from a national biomedical database. The i.d. process also provides insurance information. “Authorization for procedure approved,” announces Pam, who then asks Joe to lie on the table. A large C-shaped frame, supported by a rigid titanium arm attached to the ceiling, quickly and silently swings over Joe’s body. “Please relax and hold your breath for one second,” Pam tells him. “The image is ready, and I will now have the doctor come and speak with you.”

A few minutes later the doctor, a young woman in a crisp white jumpsuit, enters the room and introduces herself as Dr. Olivia Johnson. After examining the gleaming globe screen at the top of the console, she projects the image to a screen that swivels into place in front of Joe. “I’m afraid the imager has found an occult tumor in the left lobe of the prostate,” Dr. Johnson tells him. She aims her index finger at the hot-red spot in the 3-D image. “Unfortunately, spectroscopic pathology has already confirmed that this is malignant. However, there’s good news. With our new system, I can have you treated in no time.”

“But I’m a Jehovah’s Witness,” Joe interrupts, his forehead creased with concern. “I cannot have surgery that may require a blood transfusion.”

“Don’t worry, Joe,” says Dr. Johnson. “What we do here is bloodless surgery, a new type of noninvasive procedure. There are no transfusions, no scalpel, and
no incision will be made. In fact, we won’t touch you at all. In addition, there’s no need for anesthesia. There will just be some energy that I’ll beam over you. You may feel a little warmth, but it won’t hurt. I don’t even have to scrub for the procedure, and the only gloves I’ll use are these,” she adds, pulling on a pair of black gloves studded with LEDs. “I’ll be right here with you the whole time.”

“But Doctor, where’s the control room? And what about the lead chest shield?” Joe asks, sounding a bit scared now.

“You’re thinking of old-fashioned radiation treatment; with NDT, we don’t need those anymore,” replies Dr. Johnson. “This new equipment is safer, and the treatment has no side effects. It has been proved to work in many other fields, and no recurrence of prostate cancer has ever been reported in the national biomedical database. Your post-op quality of life should not be affected, and your erection quality and urinary bladder continence will be fine, too,” she assures him.

“Where do I change?” asks Joe.

“You can keep your undershorts on, and leave your shirt on, too,” replies the doctor. Pam, on standby mode since the doctor’s arrival, shuttles over to the table as Dr. Johnson sits down at the controls. In response to her commands a mechanical arm, lowered from the ceiling, sweeps back and forth above Joe’s pelvis for about 60 seconds, emitting a low-pitched buzz.

“That’s it, Joe—the prostate cancer is all gone. It’s completely vaporized and the margins are confirmed negative,” says Dr. Johnson a few minutes later. She shakes Joe’s hand. “Not bad at all, was it? You can get ready to go home, and Pam will follow up through your cure.”

**It’s Not Science Fiction**

Is Joe’s story a futuristic tableau out of Hollywood? Not at all. This is a future scientific opportunity, based on minimally invasive therapies and technology that are already available. The diagnostic tools and treatment devices Dr. Johnson described are now in development, with the goal of increased efficacy and significant reduction of the trauma of a major medical procedure; the patient will be able to go home sooner and will recover more quickly. Some of these new devices are already in use at major hospitals; others are years away.

We already have laparoscopy, which is used to perform radical prostatectomy procedures. Pioneered in the 1980s for the repair of arthritic knees and other
damaged joints, minimally invasive laparoscopic techniques are already in regular use for treating a variety of urological conditions, including prostate cancer, by Li-Ming Su, M.D., Director of Laparoscopic and Robotic Urological Surgery at Johns Hopkins, and Christian P. Pavlovich, M.D., Director of Urologic Oncology at Johns Hopkins Bayview Medical Center.

Laparoscopy (from the Greek words lapara, or flank, and skopion, a means of viewing something) is a type of surgical procedure in which small (1–2 cm) incisions are made, through which plastic tubes (trocars) are inserted to keep the channel open so that tools—including surgical instruments and the viewing telescope (laparoscope) with its mini-camera—can be inserted. When the abdomen is inflated with carbon dioxide, organs can be pushed out of the way for access and better vision, allowing the surgeon to work while watching an external video monitor. The tools can be manipulated to make necessary repairs, just as if the abdomen had been cut open the old-fashioned way, but without the surgeon’s hands ever entering the patient’s body.

The simplest, most basic parallel to Joe’s treatment that we can draw today is ESWL, extracorporeal shock wave lithotripsy, which is used to shatter kidney stones and gallstones. ESWL falls into the category of transcutaneous (though the skin) energy delivery, which is the ultimate noninvasive therapy tool, an elegant and efficient form of minimally invasive surgery. The lithotripsy (the word means “stone-pounding”) device uses shock waves that penetrate the skin and go directly to the stones, pulverizing them.

Following on the heels of ESWL is another amazing example of transcutaneous energy delivery that is now in clinical trials: HIFU, or high-intensity focused ultrasound. Ultrasound is a vibration with a frequency higher than the human ear can hear. By increasing the intensity of the waves and focusing them on a single area, large amounts of energy can be deposited into tissue. When focused on a tumor, the ultrasound beam heats up the malignant cells, leading to their eventual death and eradication of the cancer.

Although HIFU was first used in 1944, it has taken decades (and the introduction of MRI) for researchers to come up with surgical applications for it. HIFU is an incredibly promising technology for noninvasive tumor ablation, and its potential clinical impact is indeed significant. Image-guided HIFU procedures could permit the ablation of tumors not only in the prostate, but also in the liver and lung, each procedure carried out without the need for an incision. This high-energy procedure could also eliminate radical mastectomy, the breast cancer operation that women fear most.
Using image guidance from MRI, biomedical scientists can guide the energy focus precisely to the target. The high-frequency ultrasound beam passes through the skin without trauma and zeroes in precisely on the tumor; there is no burning, irritation, or swelling after treatment with HIFU.

At present, a Phase III trial is being conducted with Sonablate (Focus Surgery, Inc., Indianapolis Indiana), a HIFU device. Men suffering from organ-confined Stage 1 or 2 prostate cancers have volunteered for the study.

Robots In Your Future

As you can see from my story about Joe, I envision robots performing many surgical tasks in the future. Robots—from a word derived from the Czech word *robota*, meaning “forced labor”—became a subject of great interest in this country after WW II. By the early 1960s, General Motors had installed robots in its automobile plants to relieve human workers of hazardous jobs such as lifting heavy automobile bodies, unloading equipment, and spray-painting cars. More than 30 years later, AESOP (Automated Endoscope System for Optimal Positioning), developed by Computer Motion, Inc. (Goleta, Georgia), became the first surgical robot to receive FDA approval. This six-foot robotic arm helps position an endoscope, moving it into position during surgery in response to a voice command, hand control, or foot pedal.

The 21st century saw the advent of the daVinci Surgical System, which has taken prostate surgery to its current level in robotics. Although “robotic surgery” conjures up images of a futuristic world in which a machine replaces the human being who once did the operating, the reality is not nearly as startling. In robot-assisted radical prostatectomy, the robotic machinery (remotely controlled by the surgeon’s hands) drives laparoscopic instruments to perform the operation. Robot-assisted prostatectomy is no longer a rarity: It now accounts for about 15% of the prostatectomies performed in the United States. At Johns Hopkins, the daVinci robot is used by Dr. Su and Dr. Pavlovich to perform minimally invasive removal of the prostate through multiple tiny “key-hole” incisions.

The system consists of four main components: the surgeon console (typically located several feet away from the operating table), a patient-side cart (which contains up to four robotic arms), cutting and suturing tools that are attached to the robotic arms and connected by cables to the surgeon controls, and an endoscopic camera unit that provides real-time magnified images of the surgical field and the movement of the instruments.
Seated at the console, the surgeon looks through a viewfinder at magnified three-dimensional images sent from the endoscopic viewing device positioned within the patient’s body. To manipulate the surgical tools, the surgeon slides his or her fingers into the instrument controls inside the console. Foot pedals are used to reposition the images as needed.

The surgeon controls the amount of force applied to the surgical tools, which can rotate a full 360 degrees. The robotic system translates the larger movement of the surgeon’s hands on the controls into smaller, precise movements of the instruments. Moreover, it filters out hand tremors, steadying the surgical instruments to a degree not possible in human hands.

Performing radical prostatectomy through a robotics system has been shown to involve less blood loss but not lower blood transfusion rates, less postoperative pain, shorter hospital stays, or faster return to physical activity, when compared with standard open surgery performed by experienced surgeons. Some downsides of robot-assisted surgery are the cost of the equipment, which runs about $1.5 million and limits its availability, and the small number of surgeons who are experienced in performing the procedure.

Experienced surgeons performing either type of surgery (robot-assisted radical prostatectomy or open radical prostatectomy) appear to achieve excellent results with respect to urinary control and sexual function. However, there is still concern about complete excision of cancer and removal of the entire prostate with robot-assisted laparoscopic surgery.

The manufacturer asserts that robotic surgery allows surgeons an exceptionally clear, magnified view of the prostate and surrounding structures, and spares the surgeon much of the fatigue involved in standard surgery. On the other hand, some experts believe that robotic surgery is actually more invasive than standard open surgery because the robotic approach involves entering the intestinal cavity, whereas the open approach does not.

At a recent international meeting in Atlanta where a panel of experienced surgeons compared robot-assisted laparoscopic radical prostatectomy and standard open radical prostatectomy, they agreed that when complications occur they are more serious with robotic surgery, because they often go unrecognized at the time of the procedure. Robot-assisted prostatectomies have not been performed long enough for us to compare their long-term success rates with those of traditional surgeries, but available data have not raised any red flags.
Whatever the approach, the surgeon’s experience and skill are still the most important determinants of a successful surgery. With that in mind, anyone who opts for robot-assisted prostatectomy should ask how many procedures the surgeon has performed and how many have been performed at the hospital. Surgeons who do robotic surgery say that it takes at least 30 procedures to become comfortable with the technique. One hundred or more operations may be required to master nerve-sparing robotic prostatectomy.

Robotic technology will doubtless continue to improve. The U.S. military has valuable technology related to artificial intelligence and miniaturization that could become available for future medical robotic development. Granted, robot technology still has a long way to go before it is universally adopted in most hospital surgical theaters. However, there are currently 36 robotic systems under clinical investigation or already in routine use around the world. This gives an indication of the breadth of current robotic interest.

**Other Technologies In Development**

Delivery of diagnostic and therapeutic modalities through natural orifices is an emerging area of interest. Novel energy sources are being developed to deliver therapies through endoscopes, which are illuminated instruments inserted into the body. Non-ionizing radiation, such as local hyperthermia and photoradiation, can be delivered through these thin catheters directly into a cancerous tumor to kill malignant cells.

Other innovative diagnostic and surgical approaches are being tried. We already have devices small enough to be swallowed, such as the Video Capsule Endoscope (Given Imaging Ltd., Yoqneam, Israel). First approved by the FDA in 2001, this device provides a glimpse of the potential of video capsule endoscopy. After the patient swallows a capsule containing a miniature high-resolution color camera, the device is propelled by the natural peristalsis (wave-like movement) of the gut. The tiny capsule records images throughout the small intestine, which is often the source of obscure gastrointestinal bleeding. These images are transmitted to sensors placed on the patient’s chest and stored in a data recorder worn on the patient’s waist. The device is disposed of once it is excreted.

The MrBot robot, designed to access the prostate under MRI guidance, has been developed in our Urology Robotics lab and is expected to go into clinical trials soon. This is an entirely non-metallic, electricity-free robot, making it the first “MRI Stealth” system. During biopsy, surgery, or other treatment of prostate disease, misplaced probes and needles can create recurrences or side effects. With
the aid of the robot, these instruments will be more precisely guided, using the MRI image as a roadmap for the procedure. MrBot operates alongside the patient inside the MRI scanner and is remotely controlled based on the images the physician sees on a screen. Its invention is a major technology breakthrough because until now no instrument could precisely, safely, and remotely operate in the high magnetic field of the MRI without interfering with the image. Preclinical tests in mockup, cadaver, and animal experiments show promising results. Work continues, under a Patrick C. Walsh Foundation Award, for the refinement of the instrument and fulfillment of the regulatory protocols in preparation for clinical trials.

Significant progress has also been achieved with MEMS, or microelectronic mechanical systems. MEMS technology, which promises to speed up medical and scientific discoveries, combines sensors, electronics, and mechanical elements on a tiny silicon chip. Advances in microchip and wireless technology may allow for the development of ingestible self-propelled micro-robots capable of completing self-guided surgical procedures within the gastrointestinal tract. In time, the technology may be used in the lower urinary tract, and eventually for prostate procedures.

These new tools allow physicians to carry out innovative interventions at locations and with a degree of precision not possible today. We should remember, though, that evolution is a marathon, not a sprint. Significant incremental improvements have already been made, with many more expected in the years to come. Some, I am certain, will bring about quantum leaps in surgical technology.

Biomedical technology in any form will never be a cure-all, but it has played—and will continue to play—a significant role in how well and how long we live.