The virtual surgeon
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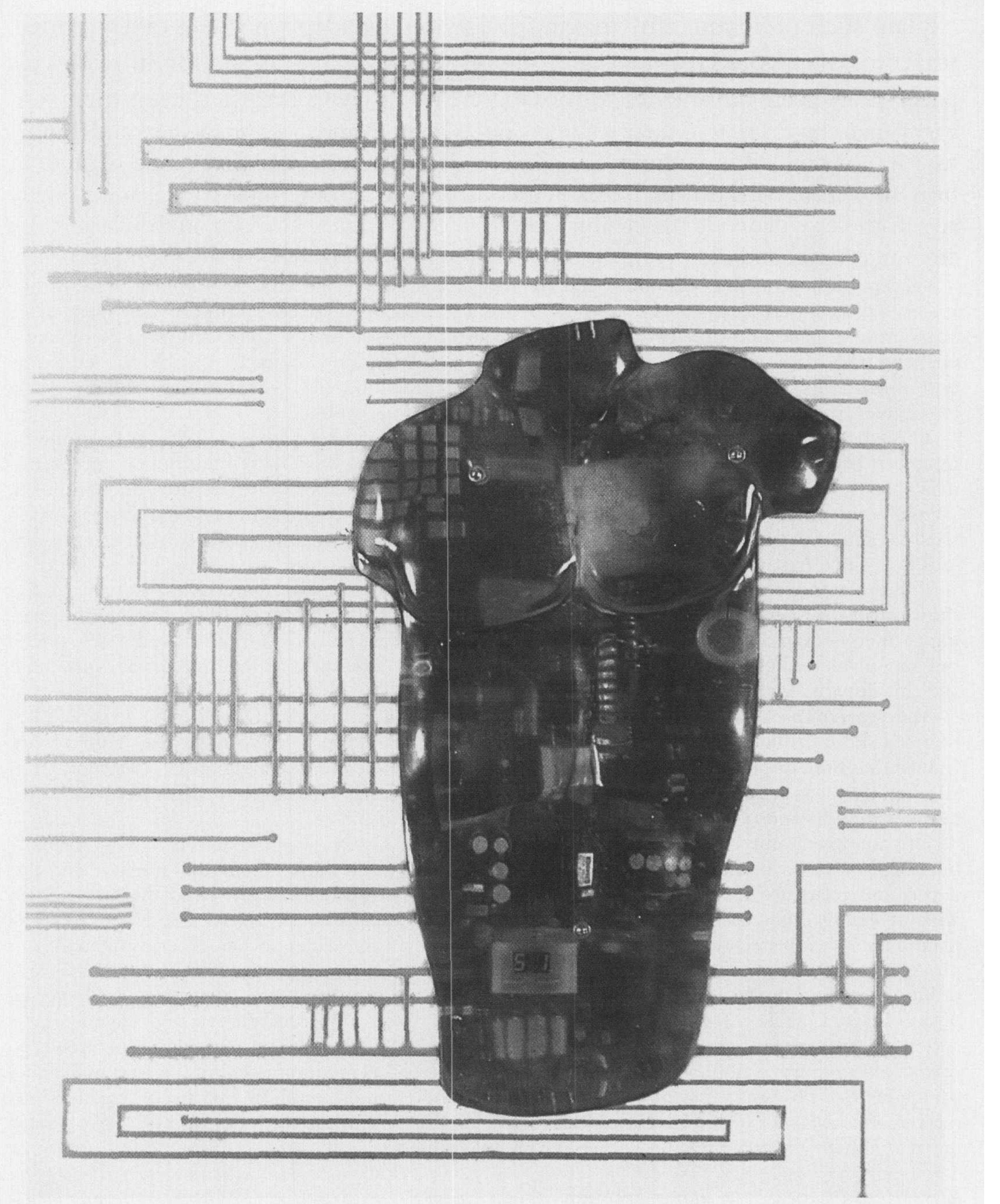
THE VIRTUAL SURGEON

Robotics, 3-D imaging and computer simulation portend a sweeping change in surgical practice and education

BY RICHARD M. SATAVA



Babis Vekris, a.k.a. Electrus, The Digital Man II, *1991*

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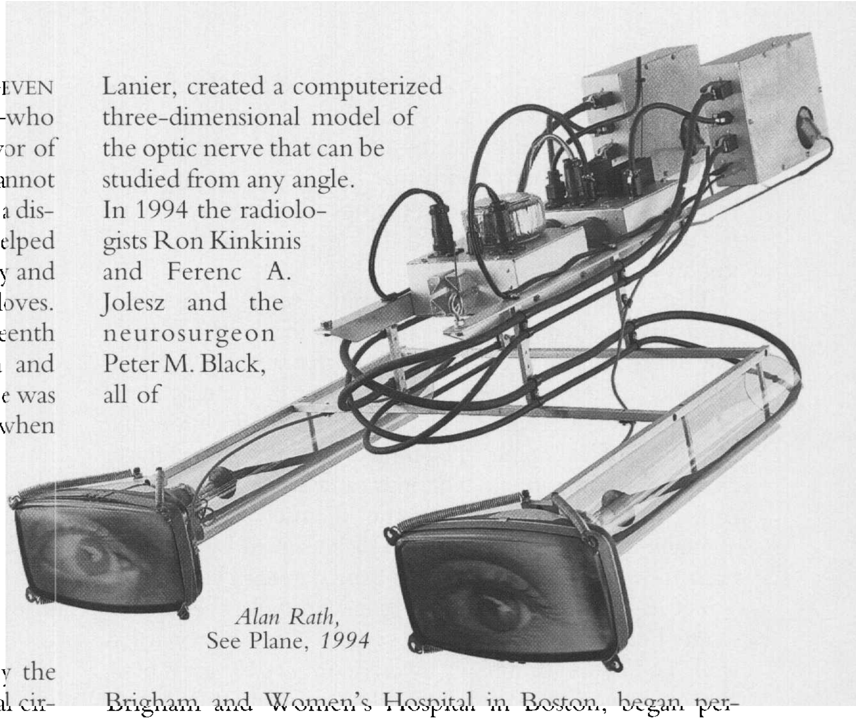
IN EVERY CENTURY, THERE ARE PEOPLE—EVEN those who probably should know better—who insist that their art, their craft, their endeavor of whatever kind, has reached its apex and cannot possibly be improved. Take Berkeley G.A. Moynihan, a distinguished English surgeon born in 1865. Moynihan helped develop the advanced aseptic rituals of modern surgery and was one of the first surgeons to adopt the use of rubber gloves. Thanks to those advances and many others of the nineteenth and early twentieth centuries, including anesthesia and microscopy, the image of surgery as a sawbones practice was fast fading away. But Moynihan was not as sophisticated when it came to predictions about the future of his discipline. Buoyed by the successes of his era, he wrote in 1930: "We can surely never hope to see the craft of surgery made much more perfect than it is today. We are at the end of a chapter."

Moynihan died in 1936. Surgery, of course, continued to develop at a breakneck pace. In 1952 the first open-heart surgery was performed, made possible by the heart-lung machine. The machine maintained artificial circulation within the largest blood vessels while the heart was temporarily stopped for the operation. In the 1960s flexible endoscopes were developed, which incorporated fiber optics to enable the surgeon to see inside a hollow organ, such as the bladder or the colon. Lasers began to function as precise microscopic "knives" for performing eye and internal surgeries. More recently, laparoscopes, aided by video cameras, have enabled the surgeon to make keyhole-size incisions in the abdomen, in order to examine or operate on diseased organs. Many other technological breakthroughs have been made since the 1970s that Moynihan would never have imagined. Innovations such as computerized axial tomography (CT) and magnetic resonance imaging (MRI) scans, for instance, have proved to be major milestones in the noninvasive diagnosis of disease.

What the latest developments all have in common is their link to the information age. The growth of information technology has swept through everyday life, deeply touching everything from telecommunications to banking to automotive fuel efficiency. But the promise it holds for the practice of surgery is only beginning to be realized. Moreover, just as the birth of modern surgery in Moynihan's era came about through a happy convergence of separate discoveries, so surgery in the information age will advance primarily through the integration of several recent technologies. Innovations in the sensory-rich computer interface best known by the generic name virtual reality will enable surgeons to manipulate complex, three-dimensional images, and will even provide the sensation of touching those images. Stereo imaging systems, computers and robotic manipulators will combine to create a new framework for carrying out surgical procedures. And the benefits of that framework will be felt beyond the operating room. Escaping the confines of geography, the surgeon of the future will routinely use two-way audiovisual systems to guide students or consult with colleagues.

Such advances already exist outside the realm of mere imagination. For example, in 1991 VPL Research, Inc., a company founded by the virtual-reality pioneer Jaron Lanier, created a computerized three-dimensional model of the optic nerve that can be studied from any angle. In 1994 the radiologists Ron Kinkinis and Ferenc A. Jolesz and the neurosurgeon Peter M. Black, all of Brigham and Women's Hospital in Boston, began performing neurosurgeries in which a 3-D representation of the brain, formed by continually updated images from MRI scans, is superposed on a live video image. With that technology the surgeons can pinpoint the position of a brain tumor to within 0.5 millimeter—an unprecedented precision. And in 1997 the surgeons Jacques Himpens and Guy-Bernard Cadière of Saint Blasius Hospital near Brussels performed the first human gallbladder operation via telesurgery, or surgery performed from a remote location.



Alan Rath,
See Plane, *1994*

Many components of surgery in the information age—what many people call cybersurgery—are already in place, such as artificial intelligence and high-performance computing. Much of the technology is still being refined, however, and cost remains a formidable barrier to clinical applications. But for observers who can see beyond the present—and particularly for the younger generations of surgeons, for whom computer skills are a native language—it is clear that surgery is headed for yet another revolution. The future of surgery—and medicine in general—is not in blood and guts, but in bits and bytes.

NO PROCEDURE NOW IN USE BETTER SHOWS the way to the coming revolution in surgery than laparoscopy. It could well turn out that laparoscopic surgery will one day be seen as a transitional form of surgery, a way station on the road to full telesurgery. The basic laparoscope is a stainless steel tube, about a foot long and a half inch in diameter, with an eyepiece on one end. The surgeon inserts the tube through a small abdominal incision, usually in the belly button. (Several more small incisions are made in the abdomen to admit the laparoscopic instruments, which typically have a handle on one end and tongs or scissors on the other.) Optical fibers guide light through the laparoscope. Until a few years ago, though, the surgeon had to put an eye directly to the end of the laparoscope in order to see inside the body. That meant the surgeon had to hold the laparoscope with one hand, leaving only one hand free to take a biopsy or make a repair.

That problem was solved recently when miniature video

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cameras were incorporated into laparoscopes. In spite of the low light inside organs, the cameras can display an image of good quality on a video monitor, thereby enabling the surgeon to keep both hands free. An important ancillary benefit is that other people in the operating room, including the scrub nurse, can watch the operation on the monitor and be ready to assist.

That revolution in minimally invasive surgery arose from the marriage of a number of technologies that had been available for years. The fiber-optic light source was derived from the fiber-optic boroscope, an instrument in the tool kit of every aviation mechanic as early as the 1950s, for inspecting the insides of jet engines. The miniature video camera traces its origins to the cameras built into camcorders in the 1970s. And the laparoscopic instruments themselves are fundamentally the same ones used and diagrammed by the great French surgeon Ambroise Paré in the sixteenth century.

Yet in spite of the advances it has brought, the laparoscopic breakthrough has taken surgery a step backward as well. To be sure, minimally invasive surgery has great benefits over open surgery: it causes less pain, and it leads to a shorter hospital stay and faster recuperation. But minimally invasive surgery has also created new problems: the surgeon has lost three-dimensional vision, the sense of touch, some dexterity, and natural eye-hand coordination.

THE VIDEO MONITOR REALISTICALLY REPRESENTS the interior of the patient, but it provides only a flat, two-dimensional image that limits the surgeon's perceptual understanding. Moreover, the laparoscopic instruments are awkward and counterintuitive. Imagine trying to eat without bending your wrist, or think about how limited your dexterity is when you are pulling a corncob from a pot of boiling water with a pair of tongs. The surgeon feels the same kind of frustration working with the long, straight instruments of laparoscopy.

The third difficulty is that the sense of touch is nearly absent; the surgeon feels little pressure from the handle of a laparoscopic instrument as it touches or manipulates an organ. Finally, the arrangement of the instruments relative to the video monitor, patient and surgeon is awkward. Because monitors are bulky, they are often placed off to the side instead of in front of the surgeon. That means the surgeon is not looking in the direction of his or her hands while performing the operation. The natural coordination of visual perception with hand motions that the surgeon has known ever since playing with toys in a sandbox must be unlearned, and new, counterintuitive motions must be practiced.

In all four of those difficulties virtual reality can play a corrective role, and several new systems for telesurgery have already been designed to address the problems. Such systems promise to retain the benefits of minimally invasive surgery while restoring to the surgeon the intuitive, 3-D experience of open surgery.

Among those systems are ones designed by Philip S. Green of SRI International in Menlo Park, California; by Yulun Wang of Computer Motion, Inc., in Goleta, California; by Gerhard Buess of the University of Tübingen in Germany and investigators at the Forschungszentrum in Karlsruhe, Germany; and by Ian W. Hunter of the Massachusetts Institute of Technology. Each system takes a somewhat different approach to improving laparoscopic surgery; what they all have in common is a computer-enhanced interface connected both to input and output devices.

What does that mean? In telesurgery, the surgeon sits at a central control console—which could be in the same room as the patient or in a different city. The idea is to give the surgeon enough sensory input so that he or she has the feeling of directly performing surgery on the patient. In the SRI and Computer Motion systems, the surgeon at the console holds instrument handles that look and feel like the real surgical instruments. An image from the patient is projected in such a way that the surgeon can look downward (as if looking into the abdomen) and reach under the screen to feel the instrument handles, whose tips appear in the image display. When the surgeon moves the handles, the tips move as well; the surgeon "feels" the resistance of the tissues—except that there are no tissues at the surgical console. Instead, the surgery is actually being performed by a remote, usually laparoscopic, manipulator, assisted by a nurse at the site. The perception of doing open surgery—of actually touching, grasping and cutting organs with one's own hands—is thereby returned to the surgeon without exposing the patient to the risks of traditional surgery.

The SRI system (now licensed to Intuitive Surgical, Inc., of Mountain View, California) was the one used by the Belgian surgeons who performed the successful human gallbladder operation I mentioned earlier. In initial animal studies, that system has also proved capable of performing numerous other common surgical procedures, including gastric resection (removal of part of the stomach), splenectomy (removal of the spleen) and aortic graft placement (replacement of the diseased main blood vessel of the lower body with a synthetic tube).

FURTHERMORE, TELESURGERY is not limited to abdominal surgery. This past June the French heart surgeons Alain Carpentier and Didier Loulmet performed the first closed-chest human telesurgery heart operation, at Broussais Hospital in Paris. Using the SRI/Intuitive Surgical system, the surgeons were able to open a blocked artery by snipping out the diseased part and grafting on a replacement section, without opening up the patient's chest. In short, they performed a coronary bypass operation using minimally invasive techniques.

In the Karlsruhe system the surgeon sits in a cockpitlike console, with a bank of video screens in front and two sur-

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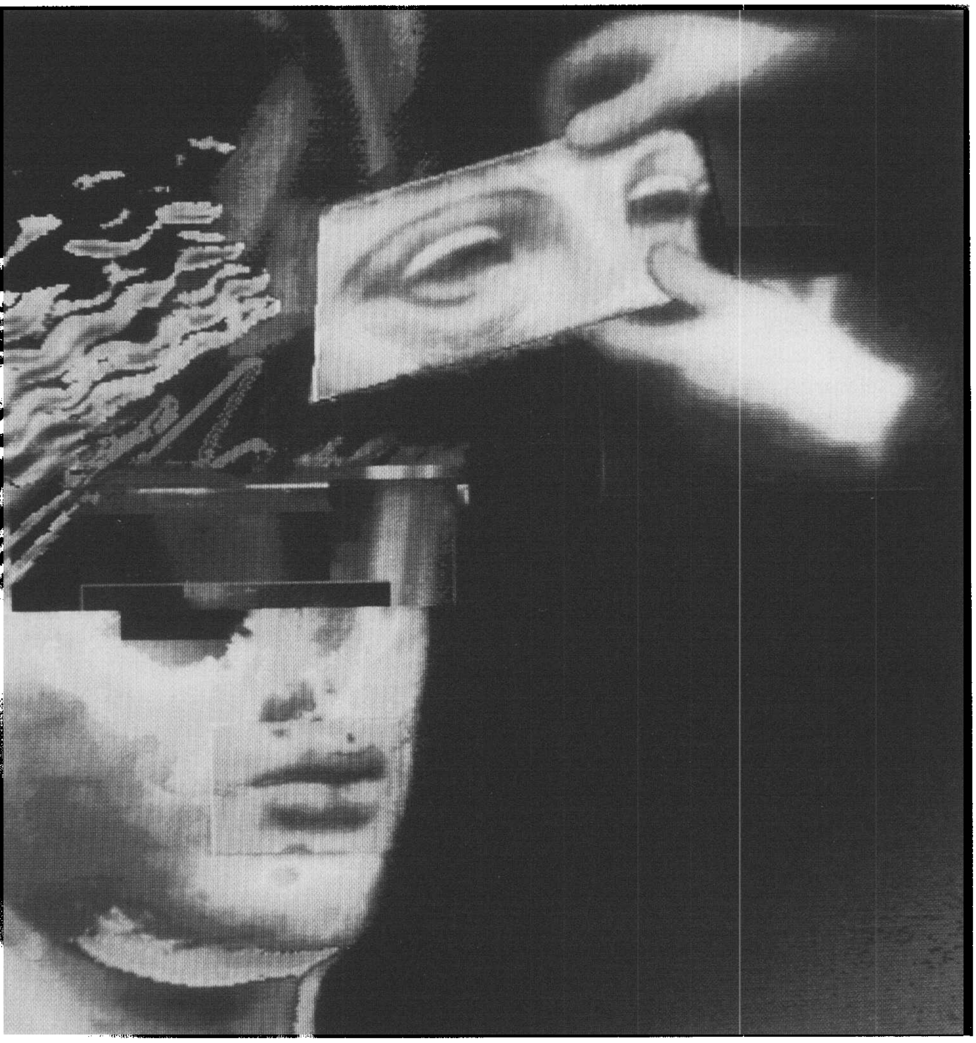
gical input handles suspended over the shoulders from behind. The handles reach over the surgeon in much the same way a golf instructor stands behind a student and helps hold the golf club. Such a position permits precise tracking of the surgeon's natural forearm, shoulder and hand motions. That naturalistic result is enhanced by the bank of monitors, which shows the surgeon different internal images of the patient as well as a panoramic view of the operating room. Thus, rather than giving the surgeon the feeling that he or she is standing outside the patient and looking down into the abdomen, the system gives the perception that the surgeon is holding the handles of the instruments while positioned practically *inside* the abdomen.



Susan Felter, Eyes, *1989*

Indeed, several of the telesurgery systems are being developed to enhance the surgeon's experience beyond normal human capabilities. Hunter, for instance, has designed a system to improve dexterity in ophthalmologic surgery. One of the difficulties of modern retinal surgery is that it requires extremely precise positioning of the laser, to within at least twenty-five microns, because of the close spacing of the retinal blood vessels. If the laser were to hit a vessel, the impact could cause a blood clot in the retina and, ultimately, blindness. The unaided human hand, however, cannot reliably position a surgical instrument to within less than a hundred microns of its target. Furthermore, muscle fatigue in the hand rapidly creates a tremor, at a frequency of eight to fourteen cycles a second. To complicate matters further, the patient's eye itself is not stationary, but instead has a natural motion of 200 cycles a second.

The Hunter telesurgery system offers a solution to those problems. First, it tracks the motion of the patient's eye with a platform-mounted camera, so that the eye appears stationary on the video display. The system can also scale down the motion of the surgeon's hand by a hundredfold: if the surgeon's hand moves a centimeter, a laser would move only a hundred microns. At the same time, the video image of each retinal vessel can be magnified to the size of a finger. Finally, through sophisticated digital signal processing and filtering techniques, the computer interface can remove the normal tremor of the surgeon's hand. By combining all those techniques, the system can enable the surgeon to position a laser to within ten microns of its target—making it ten times more accurate than the unaided hand.

All the new telesurgery systems incorporate simple sensors that can convey to the surgeon a sense of pressure, or resistance to touch. And numerous investigators, including Buess and David L. Brock of MIT, are embedding miniature tactile devices into the tips of the grasping instruments to add the perception of the texture and shape of the object being grasped to the gross sensation of pressure. Although vision is still by far the most well-developed sense in telesurgery, the sense of touch will eventually come to play a larger role in creating the virtual experience.

TELESURGERY SYSTEMS were initially developed to enhance the surgeon's dexterity. The surgeon was to sit near the patient, only a few feet away. (That is how the heart operation in Paris and the gallbladder operation in Belgium were done.) But the use of computers and other electronic systems to improve dexterity created an unintended consequence: the possibility of remote surgery. Once motion is converted into electronic signals by the computer, the possibility exists to transmit those signals to distant sites.

That said, all the systems under development use either a direct connection, via electronic cable, or a wireless link over a very short distance. It remains for the future to realize the dream of providing remote expert surgical capabilities worldwide, particularly to third-world countries that lack such care.

For now, any remote surgery will take place only over

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fairly short distances. The reason is that long-distance transmission via satellite communication creates a lag in the signals. Geosynchronous satellites hover about 22,000 miles above the earth; at that height, it takes longer than 1.5 seconds for them to receive, process and bounce back signals. Such a lag time creates a barrier for telesurgery, because the human operator is not equipped to compensate for the delays.

Data from astronaut training, for instance, show how delays between a hand motion and the resultant movement of a servomechanism (in this case, the space-shuttle arm) affect a person's ability to control the mechanism. Delays of less than twenty-five milliseconds are imperceptible. If the delay is as long as fifty milliseconds, the operator knows that something feels wrong, but automatically and intuitively compensates for it. When the lag reaches a hundred milliseconds, the operator clearly perceives the delay but can be trained to accommodate it. At 200 milliseconds, however, it is nearly impossible for anyone to compensate, even with extensive training.

In addition, when lags of 200 milliseconds or more come into play, telesurgical systems become unstable and tend to crash. Hence, at least for the immediate future, telesurgical systems will probably be usable only where the lag time is less than 200 milliseconds. That translates into wireless transmission across thirty miles or less, or cable transmission across 200 miles or less.

THE TECHNIQUES OF VIRTUAL REALITY IN SURgical practice have applications beyond surgery itself: they have great potential for use in medical education and surgical planning. In spite of formidable advances in knowledge, medical education has changed little in the past thirty years. Most medical schools still stress rote learning, and students have little context to help them organize all the facts they must retain.

Computer-generated images can provide the intuitive learning framework students need. In 1994 the National Library of Medicine released the first phase of its landmark Visible Human Project, directed by the biomedical engineer Michael J. Ackerman. The Visible Human Project, accessible at <http://www.nlm.nih.gov/research/visible/visible_human.html>, has created a digital image data set of two humans, one male, the other female. Cross sections, ranging in thickness from one-third to five millimeters, have been prepared from MRI and CT scans of the bodies, as well as from digital photographs of frozen body slices. Properties such as texture and vital signs remain to be added. But once the project is complete, students will be able to link the names of organs to images, thereby gaining a fuller understanding of body parts and their interrelations.

Several other virtual worlds have been developed to demonstrate basic anatomy and to serve as rudimentary models in surgical training simulators. For example, in 1991 Lanier and I created the first training simulator for abdominal surgery. The images of the organs were created with a simple computer-graphics drawing program, and the simulator enabled the student to "fly" around and through the various organs to get a feel for their physical interrelations. The simulator also incorporated several virtual laparoscopic tools, which enabled the student or surgeon to practice endoscopic surgical techniques.

Another virtual world is the limb trauma simulator, developed in 1994 by the biomedical engineer Scott L. Delp of MusculoGraphics, Inc., in Evanston, Illinois. Delp began with the leg from the male in the Visible Human Project and simplified the model to provide the high-speed computations needed for the trauma simulator. Although not as realistic looking as the Visible Human leg, the simulator can recreate tissue properties, bleeding, wounding and the interaction of surgical instruments with the wound. It even permits the virtual debridement (cleansing and trimming) of the wound, the removal of bone fragments and the stanching of a virtual hemorrhage.

Medical educators are beginning to appreciate the powers and possibilities of virtual reality. At the University of California, San Diego, for instance, the instructional developer Helene M. Hoffman has created a software application to teach anatomy that combines virtual reality with two-dimensional multimedia educational resources. The hybrid system enables students to learn anatomy and also to see related studies in pathology, histology and radiology. For example, a student can learn the anatomy of the gastrointestinal tract in 3-D, and also see images of an ulcer and videos of a biopsy being performed on the ulcer.

When such anatomical simulators are augmented with information from a real patient, they can help the surgeon plan and practice for surgery. As I noted earlier, the team at Brigham and Women's Hospital relied on MRI scans of the brain, overlaid on a video image of the area of the patient's brain to be operated on, to position their surgical instruments. To plan a procedure, the surgeon views a 3-D representation of the patient's anatomy, which can be rotated, made transparent or cross-sectioned in any imaginable way. Other sophisticated visualization algorithms can also be applied, algorithms originally developed for planning and tracking the flights of cruise missiles. With such software the surgeon can "fly" through the patient's virtual organs.

The outlook for such surgical training and planning systems is promising. Preliminary studies suggest that an hour of training on a surgical simulator is worth three hours with an animal or human cadaver. An added benefit of the virtual systems could be to reduce the number of animals needed for the education of a surgeon.

WHY ARE THE TECHNOLOGIES OF CYBERsurgery not already being used? In fact, some have been implemented, but they are not widespread. The technologies need further refinement: for example, the resolution of the images must be improved to make them less cartoonlike, and relevant physiological data about the patient must be added to the

FOR NOW, REMOTE SURGERY *is limited by cable-transmission speed*

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basic anatomy. In my view those refinements will come sooner rather than later, as computing power continues to grow.

Cost is another barrier. Although information technologies, in general, are dramatically cheaper than industrial technologies (think of the cost of a pocket calculator compared with the cost of an old-style mechanical adding machine), realizing those savings will require a massive infusion of the technologies into the marketplace. Laparoscopic surgery systems in common use today, for instance, generally cost between $40,000 and $60,000. But a 3-D telesurgery system still costs at least twice that much.

What is needed are explicit cost-benefit analyses for the latest forms of surgery. Here at my own institution, Yale University, as well as at Pennsylvania State University at Hershey and at the University of Chicago, surgical simulation and training centers are being set up to evaluate the new technologies for cost-effectiveness. For cybersurgery to gain widespread acceptance, many convincing demonstrations will be necessary.

to 200 miles or less.

THE ISSUES OF LICENSING, LIABILITY AND social acceptance must also be sorted out if cybersurgery, particularly remote telesurgery, is to be adopted. Under current law, surgeons must be licensed separately by every state in which they want to practice. Telesurgery across state lines obviously raises the question of which state licenses the surgeon would have to hold. Likewise, if a mishap should occur, which state law would govern the inevitable litigation? And, as with all new technologies, both surgeon and patient must overcome the natural resistance to change. But as a new generation, raised on video games and the Internet, comes into its own, I think such resistance will disappear. What seems like sweeping change in surgical practice to the present generation could well become the norm and the expectation to the next.

The final test for any surgery, of course, is to what degree it benefits the patient. New technologies and concepts must always prove themselves in rigorous evaluations. Yet it is important not to summarily dismiss new ideas because of old preconceptions. To do so would be to squash our visions for the future into a two-dimensional flatland, and to cheat our society out of technology that is ripe with possibility. ●

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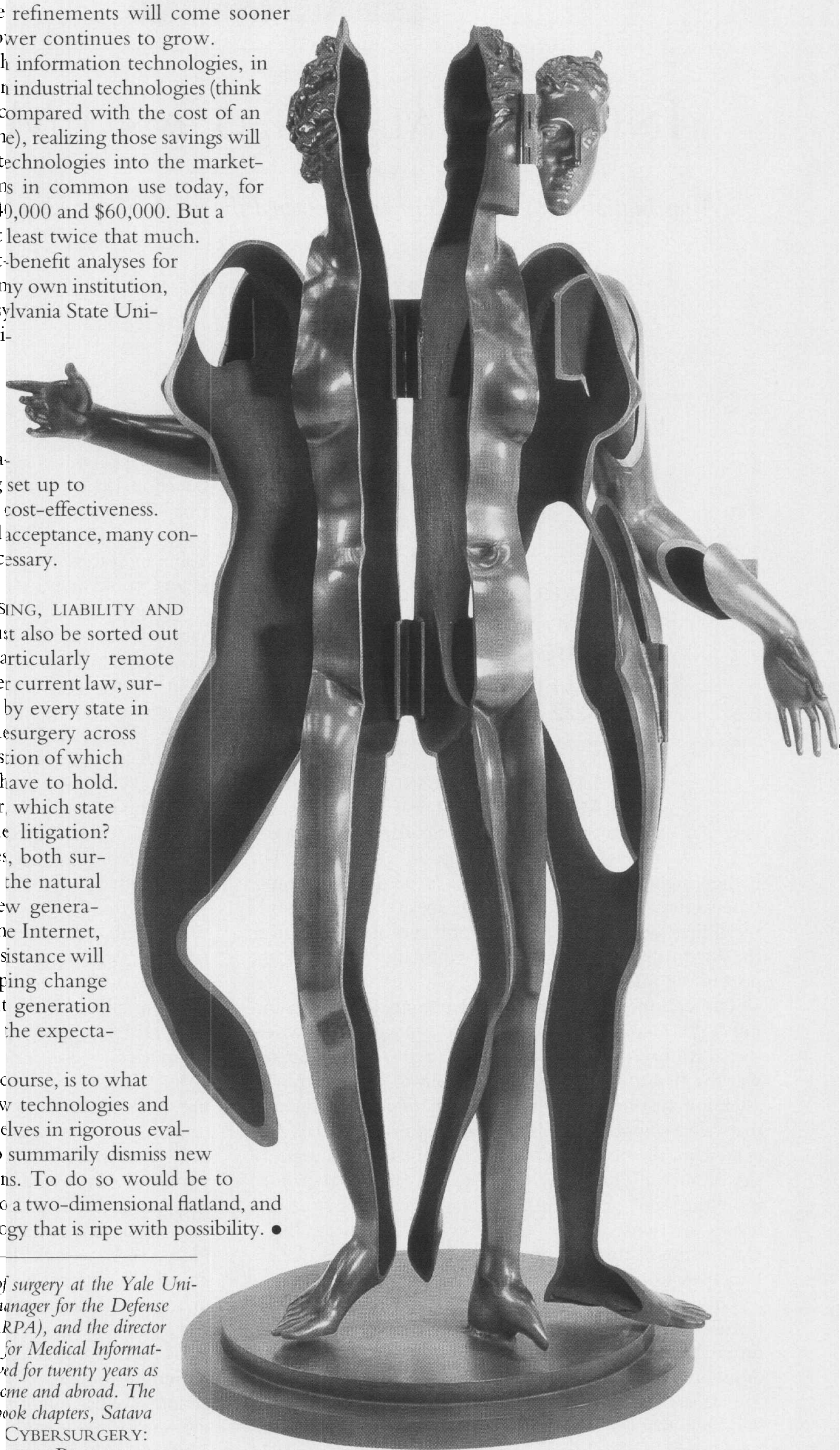

Arman, Grande Venus *(open version), 1995*

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