PRIMER OF ROBOTIC & TELEROBOTIC SURGERY

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CHAPTER 10

Computer-Enhanced Instruments: The Next Generation of Surgical Robots

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Advances in robotics and computer-based technology have enabled complex work in surgery to be automated and/or performed by remote control. Much excitement has been generated about the development of robotic systems in minimally invasive surgery. Successful robotic application in minimally invasive surgery relies on innovative technology and effective integration of this technology into the complex human-machine interactions in the operating room environment.

One objective of this chapter is to present the human factor issues related to the design of surgical robots. The discussion of human factor issues is focused on the interaction of the surgeon with robotic systems and the underlying cognitive processes involved.

Robotics promises to enhance surgical performance by increasing dexterity or automating surgical tasks that are difficult to perform remotely (1,2). Robotics can increase the precision and accuracy of the surgeon's fine motor performance by stabilizing tremor, or by scaling down the motions made by a surgeon's hands. There is also the potential to enhance the surgeon's sense of touch through tactile interfaces (3). Currently, successful robotics application in minimally invasive surgery has been limited to positioning devices for the endoscopic camera or laparoscopic instruments.

Innovative systems that can be integrated seamlessly into the surgical process are under development. The ultimate goal is to make the robotic technology transparent to the user, just as the complex technology of a desktop computer is not apparent to the person typing a letter. Surgeons should not believe that they are using a robotic system but that they are holding an instrument as an extension and enhancement of their hand.

Lack of knowledge about the integration of robots and humans to perform work in a synergistic manner is a critical problem. Until this knowledge becomes available, it will not be possible to design effective robotic technology for surgery or to train surgeons to perform effectively in this complex environment.

Technology can improve the performance of a system with increased reliability and precision. However, it can also create unexpected interactions and new types of errors (4,5). High error rates in surgery, in particular those associated with technology in minimally invasive procedures, have been documented (6–8). There is a great need to improve system performance and patient safety (9,10), but relatively little systematic research is conducted to this end.

The use of robotics and automation in surgery is relatively new. There has been little documentation of the effectiveness of this technology in the complex environment of surgery, but much has been made of the failure to adopt robotics in the operating room. The general misconception is that the robotic devices are technologically sound and functional as designed, but that the human surgeon controlling the robot is incompetent. This notion leads proponents of robotics and automation to strive to incorporate even more automation in an effort to design the error-inducing human out of the loop. It might be more constructive to examine other industries where automation has become an integral part of complex systems, e.g., aviation, nuclear power generation, and process control. A systems approach in the design and analysis of surgical robots would be well advised.

WHAT IS COMPUTER-AIDED SURGERY AND THE ROLE OF ROBOTICS IN CLINICAL MEDICINE?

The revolution in technology and automation ushered in the industrial age in the 19th century. Assembly-lines, the first attempt at automation, were introduced into the manufacturing setting to increase productivity and reduce the cost of goods. Assembly-line workers were forced to perform repetitive, routine, mundane tasks, resulting in the unintended consequence of treating workers as machines, which was a dehumanizing experience. Unlike machines, humans are not well
suited to highly repetitive tasks performed at a rapid pace. Assembly lines in the mid-20th century in Detroit automobile manufacturing facilities, on which manual assembly was the standard practice, produced the notorious “Monday” and “Friday” cars that were poorly constructed and fraught with problems. Human supervisory control over machine action, introduced in Japan in the form of automobile assembly-line robots in the late 20th century, produced a consistently high-quality product and a significant competitive advantage in the marketplace.

The robot may be considered a subset of automation, in which a physical or electronic link is interpolated between the human and machine, and the device has various degrees of autonomy in its tasks. Robots in the manufacturing sector are allowed little autonomy; in contrast, robots in the aerospace industry may act with a high degree of autonomy. This has led to the ability to land aircraft in zero-visibility weather, and it allows pilots to fly military aircraft that is too complex and unstable to be guided under human control alone.

First-generation surgical robots are now appearing in the health care sector. Surgical procedures require both cognitive and motor skills. The appropriate use of automation is to relieve the surgeon of the routine, mechanical aspects of surgery, and to enhance performance by extending the surgeon’s skills. Automation in surgery is already in wide use. An example of automation in routine tasks is the use of the stapler to approximate tissues (Fig. 10.1). Prior to the advent of the stapler, wound closure was achieved by suturing. The first staplers introduced into the surgical setting applied individual clips to approximate tissues. Multifire staple guns are now in common use, further automating the task of wound closure. In this instance, the master end (the surgeon’s hands) and the slave end (the clip-fastening mechanism) are directly connected. The staple gun is a robot, albeit a primitive one, translating a command at the master end to applying a clip at the slave end. The surgeon is able to perform tasks more simply, more quickly, and, in many situations, more safely by using this robot every day in the operating room.

Arguably, the multifire stapler and miniaturized video camera together enabled laparoscopic cholecystectomy to become a commonplace procedure. The benefits of minimally invasive surgery include a smaller incision, shorter recovery time, shorter hospital stay, and lower infection rates. The disadvantages of this type of surgery are increased time required for the procedure and a decrement in feedback and dexterity because the surgeon’s hands are removed from the surgical field, resulting in an increased reliance on the video feedback from the camera. This form of telesurgery forces the surgeon to work more slowly, and necessitates a steep learning curve to become comfortable with the technology (11).

There remain obstacles to the development and implementation of technology for robotic surgery, primarily related to the interfacing of the technology with the human operator. Being removed from the surgical site, a surgeon does not receive the full range of sensory information normally obtained through vision, audition, the vestibular apparatus, haptics, kinesthesetics, and the olfactory senses. Rather, most of the available information is received through the visual channel. Even that modality is based on video images of the remote site, which typically provide a restricted field of view and limited depth information from a vantage point that may not be optimal. The task of performing surgery with limited and altered information is further constrained by physical restrictions such as limited degrees of freedom in manipulation. The use of robotics to facilitate minimally invasive surgery clearly addresses a clinical need, by returning the perception of the surgeon’s hands in the operative field. By doing this, some of the technical benefit of open surgery will be gained while retaining all the benefits of minimally invasive surgery.

Technology has been introduced into the surgical milieu to make the surgeon’s job easier, e.g., stapling versus suturing. The disadvantage associated with technology is its inherent limitation: the stapler can only staple, whereas the surgeon can react to a wide range of circumstances and tissue
dynamics during suturing. Yet, 90\% of surgeons are not comfortable performing complex minimally invasive surgery procedures, possibly because the learning curve to develop the technical skills, with the current instrumentation, is too steep (11) (Fig. 10.1.). As robotics becomes more sophisticated, the technology may be able to overcome these difficulties. In minimally invasive surgery, the robotic system should allow the surgeon to feel that he or she is performing open surgery, with the dexterity, tactile feedback, and all the cues he or she has come to expect in the open environment. Ultimately, robotics can increase the precision and accuracy of the surgeon’s fine motor performance by stabilizing tremor, or by scaling down the motions made by a surgeon’s hands. There is also the potential to enhance the surgeon’s sense of touch through tactile interfaces.

The first generation of robotics in surgery is currently in use: the da Vinci system (Intuitive Surgical, Inc., Menlo Park, Calif.) and ZEUS (Computer Motion, Goleta, Calif.). (These companies have now merged.) These systems illustrate the concept in which the physical connection between the surgeon’s hands and the action in the operative field has been replaced by an electronic link. Some of the skill enhancements offered include scaling of motions and reduction of tremor, allowing finer movements and actions than are possible by the human hand. Why, then, are these systems not in much greater use?

WHAT IS WRONG WITH SURGICAL ROBOTS?

Why has the use of robots not been accepted more rapidly in surgery? Again, let us consider the automobile. When automobiles were first introduced, they were not generally accepted. There were several reasons for this: the infrastructure to support the use of automobiles (good roads, gas stations, etc.) did not exist; automobiles were very expensive, relative to the horse and carriage; the automobile broke down often and mechanics were not available; and the horse provided familiar and reliable transportation. All systems available to the traveler at the time were established to support the use of the horse. The automobile was purchased by a very few wealthy people as a status symbol rather than as a practical method of transportation. Later, because Henry Ford could manufacture inexpensive, reliable cars, a market was created. Roads were improved, gasoline became commonly available, and automobiles and trucks quickly replaced the horse and carriage as the preferred method of transportation.

The current generation of surgical robots is comparable with early automobiles. They do not add much to the manual method of surgery, and they are very expensive. Furthermore, they require refitting of the operating room and a change in the operating room culture. For robots to become sufficiently useful in the operating room to be generally adopted, they must overcome these problems. Robots must provide a quantum leap, not a marginal improvement, in benefit. Until this occurs, they will not be worth the cost and extra difficulty introduced by their use.

In the aerospace industry, robots have been developed that provide this quantum leap. With increasingly crowded skies in commercial aviation, the autopilot, which can respond to neighboring aircraft position and airport controllers, is in general use, leading to safer air travel. Current technology in aeronautics also allows aircraft to be landed in zero-visibility weather. This increases the utility of the aircraft and extends the pilot’s abilities beyond that which he or she would be able to accomplish without technological aid.

In the US Air Force, the F22 Raptor aircraft is an example of the use of robotics to augment human capabilities. This aircraft is inherently unstable and cannot be flown under direct human control. The pilot still “flies” it using the joystick and rudder pedals, the human–machine interface on which he or she trained, but that interface is removed from the mechanisms that control the movement of the aircraft. The linkage between pilot and controlled mechanisms is entirely electronic and a simple movement of the joystick causes many (100 to 200) subtle, and often nonintuitive, actions (thrust, attitude, flaps, etc.) controlled by the computer. No human pilot would be able to fly this aircraft without the aid of the computer interface. The computer, interpreting the actions at the human–machine interface (controls), allows all pilots to be able to efficiently fly the sortie. The computer is granted semiautonomy, in which it understands what the pilot wants to do (e.g., turn left), and performs all activities necessary to complete the action without specific instructions for each activity from the human, and indeed, without the human even being aware of what those activities may be. This might be compared with the situation in which a human is riding a horse and pulls on the reins to indicate to the horse to turn left. The horse’s brain tells the appropriate nerves and muscles to perform the appropriate actions. Thus, the horse’s heart rate may increase, the right legs take longer strides, and the breathing rate may increase, all without the direction from the rider.

In the case of the F22 aircraft, robotics are allowing humans to perform in an arena that is beyond their natural capabilities because the computer has been granted semiautonomy to make the critical adjustments necessary to carry out the pilot’s higher level command.

The success of technological development and use in aviation is due in large part to a great deal of human factors research and the design of effective human–machine interfaces. In the case of technology used in surgery, similar efforts are needed. The coupling between the user and the machine can greatly affect the usefulness of the enabling technology. Much can be learned from the work already done in the aviation industry and adapted to the complex surgical domain. In the next section, the relationship between the human and machine will be discussed in detail.

HUMAN–MACHINE INTERFACE

A good human–machine interface for robotic surgery can address both the cognitive and physical constraints of the system. These constraints are a result of information-processing
limitations of the human, such as limited cognitive resources and limited information available. To begin, one needs to adopt a multiprong approach to tackle this multifaceted problem. In order to design a new system that will be usable, or to improve on an existing design, the system must be identified and described at the physical level (what the system contains), functional level (what the system does), and operational level (how the system is used). Requirements and constraints also need to be determined so that the new design can adequately address them.

Several researchers have taken a human-centered systems approach to analyze the complex environment of minimally invasive surgery. Compared with traditional open surgery, minimally invasive procedures impose additional safety concerns and precision requirements, as well as greater physical and visual-motor constraints on the surgeon (12–14). These additional safety issues are due to restricted access to the operative site within the respective body cavities, with respect to visual, tactile, and motor skills. In other words, the very tools that allow surgical procedures to be performed with minimal invasiveness present both major physical and perceptual barriers. Visually, information regarding the surgical site is altered. The lack of stereoscopic view and adequate depth cues results in longer performance times (15–17) and more wasteful movements with the surgical instruments (18). In addition to a restricted view of the operative site, and loss of depth perception, other visual-motor constraints include displaced visual space; image magnification, coupled with a separation of hand space from work space (operative site); and, frequently, a rotation of the display space relative to the operative site. To use an analogy with familiar technology, this might be compared with driving a car using only a periscope that is extended through the roof and with all the windows blacked out. Further, the periscope would have a telephoto lens attached to it, magnifying a small region of the road and minifying the surrounding area.

More recent studies have been conducted to investigate perceptual motor coordination in endoscopic surgery. Holden et al. (19) have shown that, in a pick-and-place task, changing the camera position or the surgeon’s position with respect to the task space disrupted performance, but when the position of the camera and surgeon changed together, while retaining relative orientation, skill performance was maintained. Their findings are consistent with those reported by Cunningham and Welch (20), and suggest that surgical skill depends on a consistent mapping between the virtual hands (displayed tool end-effectors) and the eyes, but not the particular visual or motor orientations. To continue the analogy of the car with the periscope, the periscope would be programmed to point in the direction the car is moving, i.e., pointing to the right when the driver turns the steering wheel to the right, and to adjust the telephoto mechanism to focus at the appropriate distance. This has implications for the design of user interfaces and surgical skill trainers. In motor-learning literature, skill training in consistent mapping conditions has been shown to increase performance. For a more detailed discussion of this topic, see examples in Flach et al. (21).

Tactile sensation from the tissues and surgical tools is reduced in minimally invasive surgery, while manipulation of the endoscopic tool is usually restricted to four degrees of freedom. The control of the surgical tools is further complicated by the fact that the tools rest on a fulcrum at the entry port into the body cavity. Therefore, hand movement direction and tool end-effector directions are reversed. This opposition in directions must be taken into account when viewing and coordinating hand motion with the endoscopic image on the video monitor. Furthermore, because the camera is controlled by an assistant, it often requires some adjustments, guided verbally by the operating surgeon. This also requires experience on the part of the assistant, who ideally should understand the intentions of the operating surgeon, and even anticipate them where possible. In the car and periscope analogy, the periscope would be controlled by the passenger, and the driver would be required to verbally instruct the passenger in the movement and focus of the periscope. This could be the ultimate manifestation of the backseat driver.

The combination of the physical, precision, safety, and visual-motor constraints make minimally invasive surgery a very difficult task to learn and to master. This is evidenced by the large number of medical errors associated with this technology (7,22–24). Some of these medical errors have been directly related to poor design of technology and rapidly changing technology (5,16,25), as well as insufficient knowledge or training of surgeons (8,11,25–27). Some of these injury-causing errors do not exist in open surgery (12). For example, insertion of the Veress needle and trocar in laparoscopic surgery can cause injury from a lack of direct visual guidance. Another serious error occurs when clips on the cystic artery are not put in place in a cholecystectomy procedure. Other errors are associated with the use, or misuse, of unfamiliar instruments, such as applying too much force with the graspers, tearing the gallbladder, or leaving the hook knife activated between steps. Correlation with the car-periscope analogy is obvious, with the outcome being a very crumpled car.

In the operating room where minimally invasive procedures are performed, the surgical team often consists of at least two nurses, and an anesthesiologist, the operating surgeon, and an assisting surgeon or resident physician. Throughout the operation, the operating surgeon orchestrates the surgical team by issuing orders while attending to his or her own task of performing the surgery. The surgeon’s task is to manipulate tissue states remotely and recognize the changes effected, with minimum error and maximum control, although not at any particular speed (28). This requires a combination of highly complex cognitive processes, including attention, knowledge, recognition, decision-making, and motor execution, all contributing to continuous, on-line, closed-loop control. The model of human information processing proposed by Wickens and Hollands (29) can be modified to describe the cognitive processes that underlie the
decisions for motor responses in minimally invasive surgery (Fig. 10.2.). The increased information-processing demands on the surgeon are imposed primarily by visual-motor constraints in laparoscopic surgery.

Visual-motor constraints are due to the restricted view of the operative site, loss of depth perception, and magnified and displaced visual space coupled with a separation of hand space from work space (operative site). Other increased information-processing demands arise from the necessity to transform the visual field to map onto the operative site, while controlling the tool end-effectors at the operative site with the hands, based on the surgeon’s mental representation of the tool end-effectors from the video image.

Studies of surgical procedures with stereoscopic versus traditional monoscopic endoscopes have shown that the lack of stereoscopic and other adequate depth cues results in longer performance times (15,30) because surgeons must grope forward and backward with the instrument to gauge the relative depths of objects by touching them slowly, so as not to damage the tissue in contact. According to Patkin and Isabel (28), 5 of 16 cues for depth perception are absent with traditional monoscopic endoscopes: stereopsis, motion parallax, convergence, accommodation, and eye dominance. The cues for depth perception that are still available include touch-confirm, linear perspective, relative size, relative brightness, detail perspective, aerial perspective, interposition/occlusion, shadows, plane height, and structure through motion (28). However, these cues are susceptible to deterioration and conflict when the operator’s perceptual capacities are exceeded.

In addition to shortcomings of the physical properties of the visual input, the motion represented on the monitor and that of the hand-controlling the tools are frequently mirror images. In other words, as the hand moves the tool handle to the right, the image of the tool end-effector moves to the left on the video monitor. This mirror reflection is further affected by magnification, which may be either excessive or inadequate, and the orientation and viewing perspective of the endoscope with respect to the endoscopic tool, which may add to the mismatch in mapping between the position of the tool handle and the observed position of the end-effector. The camera, which is controlled by an assistant to the surgeon, often requires some/adjustments guided verbally by the operating surgeon; this function requires considerable experience on the part of the assistant. The orientation of the endoscope is also restricted by the fixed port of entry so the only possible positions for the camera are within a conical volume described by rotation of the proximal end of the endoscope. A scope with a 30-degree field of view lens is sometimes used, depending on surgical site and preference of the surgeon. Movement within this cone provides yet another viewing perspective that the surgeon must mentally rotate.

Telesurgery is a visually guided manual task where a congruent mapping between visual and motor directions of movement is important. Under normal circumstances (i.e., direct vision and direct manipulation), this mapping is fast and accurate (31). When the correspondence between these two spaces is disrupted, as in minimally invasive surgery, errors occur (20,32). Although humans are adaptive to inversion of the visual world (18,32), it takes time for the adaptation to
take place and it is resistant to conscious effort. Therefore, it is difficult for surgeons to orient themselves within a short
time at the start of a surgical procedure, and reorient quickly
with each change of the endoscope’s position.

The result of information-processing limitations inherent
in performing motor tasks in general is not knowing what to
expect from one’s own action, insensitivity to sensory/
perceptual discrimination, and lack of proficiency in performing
appropriate actions (33). In minimally invasive surgery,
these limitations manifest themselves because of the filtered
stimuli on which the surgeon relies to make decisions for
subsequent actions. Schueneeman and Pickleman (34) suggest
that, in addition to manual dexterity, the surgeon’s ability to
"see" the relevant anatomy of the operative site is important.
The expert surgeon quickly identifies important landmarks
in the incision and mentally organizes multisensory data and
actions during the course of the surgical procedure so as to
produce smooth and efficient sequences of responses. There-
fore, perceptually based cognition about complex spatial and
anatomical relationships is important for surgical success.
When these relationships change frequently during the course
of a surgical procedure, it is difficult to continually adapt and
keep pace.

For the surgeon, most of the global decisions for the pro-
cedure have been made prior to entering the operating room.
Consequently, the surgeon’s cognitive task during surgery
consists of two parallel goals: to execute a planned sequence
of actions based on knowledge of the surgical procedure and
to detect and correct deviations from the preplanned course
of action, as the operation proceeds, based on new informa-
tion from the environment and on declarative knowledge of
anatomy and case-specific details. As the surgeon is operat-
ing under uncertainty and risks, as well as time and energy
pressures, these two goals may conflict, so that surgical plans
are modified as the operation progresses, much like reactive
problem-solving in a dynamic control system. Each decision
to select a particular response is based on the previous re-
sponse and perception of its feedback, which is filtered by a
two-dimensional display of the surgical field.

In many respects, this is prototypical navigation behavior.
Navigation in general implies following a path to a prede-
termined destination using knowledge or information of and
from the environment. As outlined by Wickens and Hollands
(35), when navigating through our physical world we acquire
landmark knowledge by initial exposure to each new area. Af-
fter more experience traveling through that area, we develop
route knowledge, followed by survey knowledge with still
more experience. Survey knowledge is a cognitive map that
integrates both landmarks and routes with their spatial rela-
tions (29). Once the cognitive map is acquired, it guides
travel by laying down a travel plan. Then, at each decision
juncture, decisions for action are made based on route and
landmark information available from the environment.

In this respect, the surgeon’s on-line decision-making at
each stage of performing minimally invasive surgery is evi-
dence of cognitive control from different levels. The surgeon
exhibits features of rule- and knowledge-based behavior, in
addition to skill-based behavior. Even with expert surgeons,
surgical manipulations are slow, methodical, and sometimes
hesitant, suggesting increased information processing such as
decision-making, accessing stored rules from memory, and
mental rotations. This may be due to the visual-motor con-
straints in the task. The model proposed by Rasmussen (36)
for multiple levels of cognitive control over human behavior
can be applied to each step of the surgical procedure to de-
scribe the surgeon’s behavior. Thus, the surgeon’s cognitive
processes can be inferred by analyzing the behavior during
various stages of the procedure.

For example, in a Nissen fundoplication consisting of
seven surgical steps, with many task goals within each step,
the surgeon enters the operating room with plans to execute
these steps in sequence (37) (Table 10.1). In an antireflux
procedure, the main goal is to use part of the fundus of the
stomach to form a wrap around the esophagus. The wrap acts
as a sphincter to prevent reflux from the stomach back into
the esophagus. These high-level goals have an impact on the
outcome of behavior at the knowledge-based level. However,
the plan is not so rigid as to contain all requisite surgical tasks
in a specified sequence. Depending on the success of the ac-
tion taken at each step, the surgeon makes adjustments to the
choice of subsequent actions based on his or her judgment
of the state of affairs. With each surgical step in the procedure,
the surgeon, who is highly skilled at performing basic surgical
tasks (e.g., suturing at the skill-based level of cognitive
control), is guided also by rule- and knowledge-based levels
of cognitive control (Fig. 10.3). This is comparable with driv-
ing a car from one place to another. An experienced driver
brings to the task the basic skill of operating the controls in
the car and is guided by rule-based cognitive control in re-
spending to traffic signals, and by knowledge-based cognitive
control in choosing the correct roads to get to the destination.

In a fundoplication, beginning with the second step of
the procedure (Fig. 10.4), all the visual information about
the state of the operation is derived from the video monitor. Therefore, depending on the spatial compatibility between the visual field and the operative field, the surgeon must mentally rotate one field to match the other, as well as transform the mapping into a body-centered coordinate system for some visual-motor integration for successful manipulation. The restricted field of view afforded by the endoscopic camera forces the surgeon to rely on memory and knowledge of the abdominal anatomy for orientation. The camera’s changing point of view, magnification of the image on the monitor with movement of the endoscope, and altered spatial relationship between display space and operative space also require the surgeon to mentally orient and recalibrate the operative field with each change. The surgeon cannot rely solely on skill-based behavior to accomplish task goals. Rules are used to establish orientation before proceeding.

Future efforts in developing endoscopic and telesurgery technology should take into consideration the limitations of human information-processing capabilities and minimize the additional information-processing demands imposed on the surgeon.

**SYSTEM REQUIREMENTS**

In addition to human-centered system design considerations, for robotics to become widely used in surgery, minimum requirements in the following areas must be met: size, cost, culture within the operating room environment, ease of use, and other factors. We will consider each of these separately.

**Size**

Robotic instrumentation currently in use in the operating room setting is large and cumbersome; in most cases, it dwarfs the patient. This creates safety hazards. The surgeon is ultimately responsible for everything that happens in the operating room and, therefore, must have a line of sight to all areas of the operating room in order to observe all activities of the team (Fig. 10.5). In addition, the patient must be easily accessible by all members of the operating room team. To be useful and commonly accepted, robotics must be compatible with the current operating room setting and work flow, and must not obstruct the surgeon–patient interaction (Fig. 10.6).

**Cost**

The health care establishment cannot justify robotic instrumentation that may cost a million dollars without significant improvement in patient care or efficiency of health care provision. For example, the heart bypass pump was a technological advance that, despite its high cost, enabled life-saving open heart surgery to be performed. The current generation of surgical robots in use today adds considerable expense with an unclear advantage in providing patient care. The high cost impedes adoption of the technology and the opportunity for innovative physicians to use the device in new and potentially useful applications.
FIG. 10.4. Hierarchical decomposition of the Nissen fundoplication procedure (39).

FIG. 10.5. The surgeon is ultimately responsible for everything that happens in the operating room; therefore, line of sight is critical. The surgeon’s console, analogous to the aircraft cockpit, must have the human–machine interface optimized for comfort and efficiency. (Courtesy of endoVia Medical, Inc., Norwood, Mass.)

Culture Within the Operating Room Environment

The operating room is a hierarchical environment with conventions that have evolved over a long time. For robotics to be accepted, the instrumentation must fit into this environment without disrupting familiar routines. The surgeon and the assistants must have direct access to the patient and must be able to view each other, the patient, and the anesthesiologist during the procedure. Change in the operating room environment must be gradual, with new technology incorporated relatively seamlessly into current routine processes. Consider the example of the use of new technology in aeronautics: new aircraft, especially military aircraft, are controlled by new technological advances that function entirely differently from traditional aircraft. However, the controls with which the pilot interacts with the new technology are very similar to those found in traditional aircraft.

Ease of Use

For robotics to be accepted in the operating room environment, the instrumentation must be easy to use. New technological advances that require a steep learning curve will be adopted only gradually as younger surgeons who have been
trained in their use during residency mature in their practices. On the other hand, robotic instrumentation that is transparent will be adopted much more quickly, even by seasoned surgeons who are expert in using the “old” technology. Consequently, the burden of adaptation must be on the technology and its designers, not on the surgeon. As with the F22 aircraft, in which the technology is designed so that the pilot does not need to learn a new way to fly, robotic systems in the operating room must be designed so that the surgeon performs procedures in a familiar manner.

Other Factors

Robotics will become an integral part of surgical care when the technology allows human skills to be augmented or sup-

perceded. An example might be technology that permits surgery from within the lumen of a vessel or gut. This technology, currently in development for endoluminal procedures, uses a flexible, catheter-like robot to provide precision surgery at a remote site (Fig. 10.7). This class of instrument would enable multivessel cardiovascular surgery on the anterior and posterior surfaces of the beating heart, negating the requirement for extracorporeal blood circulation. Placing dexterous “hands” on a conventional endoscope would enable noninvasive correction of reflux disease, portless cholecystectomy, as well as bowel and mucosal resection (Fig. 10.8).

Robotic automation will be most useful in those situations where the computer can assume some autonomy in its actions so that the surgeon does not have to consider each individual action of the robot. This may be illustrated by again considering the horse and carriage versus the car. When a driver in a car falls asleep behind the wheel, he or she is fortunate to survive the experience. When a driver of a horse and carriage falls asleep, the horse most likely takes the driver home. The horse behaves in an autonomous manner, doing what the rider wants without having to be given specific instructions for each action. The car, a complex piece of machinery without a brain, requires constant direction and attention from the driver to get to its destination.

GOING BEYOND HUMAN SKILLS

The possibilities afforded by the use of robots and computerized instrumentation in the operating room are greatest where human skills can be enhanced. The procedure for which this is most evident is laparoscopy. Robotic systems can provide certain advantages over human-controlled laparoscopic procedures, allowing for more degrees of freedom and removing the fulcrum effect in laparoscopic surgery. More importantly, the robotic system can reduce any tremors that the surgeon may have and can allow for a scaling of movement. This will
lead to the ability to perform even more delicate procedures
at scales beyond the capability of the human hand.

The incorporation of sensors into the robotic "fingers" used
in surgical procedures can enable nonanthropomorphic mapping
in identification of anatomical structures, allowing for
greater accuracy in dissection and other surgical actions, and
can lead to much lower incidence of serious adverse effects
of surgical procedures.

Nonanthropomorphic Mapping

Part of the art of surgery is to know where to cut and where the
danger zones are located. The surgeon relies on visual clues to
determine where important anatomical structures are located.
The surgeon also relies on palpation. Landmarks such as bony
prominence, ligament insertions, and position of muscles and
solid organs guide the surgeon during tissue dissection. One
of the major complications of surgery is inadvertent transec-
tion of nerves, vascular structures, and hollow viscus, such
as the bowel and ureters.

Nonanthropomorphic mapping is a technique for generat-
ing a display of body structures that are not observable or
otherwise easily located by normal human senses. For exam-
ple, if a nonvisible field, such as an electric, radio-emitting,
or thermal field, surrounding a critical structure may be gen-
erated and then detected by a sensor, it can be displayed on a
monitor along with the visible structures to alert the surgeon
of possible danger. The human finger is incapable of deter-
mining voltage potentials, temperature gradients less than 2°
or 3°, or radioactive fields. However, one could imagine using
off-the-shelf technologies such as voltmeters, Geiger coun-
ters, and thermistors capable of sensing 0.001°F temperature
gradients. These technologies are easily incorporated into
the robotic fingers at the tip of the instrument to act as sensors. As
an extension of this, the robotic system may have a method
of mapping the sensor's information to the surgeon's fingers.
This might be a feedback signal, such as a tactile signal of
force or vibration, when the robotic system detects the pre-
essence of a nerve bundle, blood vessel, or ureter.

Consider the current prostatectomy procedure, which re-
sults in impotence from pudendal nerve damage in a very
high proportion of patients, or head and neck procedures that
place the facial nerve at risk. A robotic system that warns the
surgeon of the presence of nerves in the area of the dissection,
or one that physically prevents the surgical implement from
severing the nerve, would be a very useful adjunct for these
procedures. Because voltage potential varies inversely with
distance around a nerve, a voltmeter can be used to calculate
distance of the instrument from a nerve. Brock and Rogers
(38) have filed patents in which a voltmeter is coupled to the
robotic dissecting instruments. Thus, the dissecting tips are
capable of sensing the electrical field around a nerve bun-
dle. The voltage potential identified at the slave end (tip of
dissecting instrument) can be mapped as vibration to the sur-
geon's finger at the interface. As the voltage potential rises
(increasing proximity to the nerve), the amplitude of vibra-
tion increases. Alternatively, if coupled to scissors, increasing
force would be required to close the jaws, up to a predefined
point at which the jaws will not close, as the voltage potential
reaches a peak. Thus, transection of a critical nerve can be
avoided.

Similar nonanthropomorphic mapping may be used dur-
ing sentinel node biopsy in breast cancer or melanoma. Cur-
rent procedure requires the use of a sterile-wrapped Geiger
counter in the surgical wound after injection of a radioactive
substance that is concentrated in the "hot" lymph nodes. Fur-
ther dissection and Geiger counter testing are performed until
the radioactive sites are fully identified and resected. This is
a time-consuming and laborious process in which the opera-
tive field landmarks and lymph nodes shift in space with each
insertion and removal of the instruments. A system that in-
corporates the gamma-sensor into the robotic fingers would
greatly increase the efficiency of this procedure.

The Future: Semi-autonomous Operation

The ideal interaction of robot and human in the operating
room is one in which the cognitive tasks are performed by
the surgeon and the routine, repetitive tasks are performed by
the robot, under supervision by a human. Another case
in which robots will be useful is the situation in which the
instrumentation augments human skills or capabilities, such
as with microsurgery. It is unlikely that the robot will be au-
tonomous; it is in the balance of robotic and human skills
that the benefit will be maximized. Again, the analogy au-
tomation in the aviation industry is useful. Automation in the
cockpit has increased the safety of air travel and extended
its use into circumstances in which the aircraft would be
grounded without it. However, pilots of airliners are often
resentful of the extent to which automation has taken over
their work. Although the pilot is still ultimately responsible
for all decisions and activities related to flying, he or she no
longer performs many of the routine tasks involved in flying.
These tasks are performed by an ever-increasingly sophisti-
cated autopilot. This can lead to inattention and degradation
in pilot performance. It is important that the analogous sit-
uation be avoided in the surgical environment. The surgeon
must never be in a situation in which he or she abdicates
control. Rather, technological advances should enable the
surgeon to extend his or her skills beyond human capabil-
ities, and relieve him or her of routine tasks. For example,
during wound closing the surgeon may place one stitch and
then tell the robot to "copy," 20 times, activating a "macro"
routine.

Long-distance telesurgery (more than 10,000 km) will not be
feasible without semi-autonomous robotic control. This is
because of the progressively increaseing lag between operator
action and slave response with increasing distance. Lag is
introduced by the finite speed of electron movement in the
wire, or light or radio waves in air; consequently, telesurgery
over long distances, such as between continents or between
earth and a space station, is limited by this law of physics.
To become imperceptible to the surgeon, a time delay must
be less than 6 ms. Beyond this, the surgeon will perceive the
delay and will be unable to accomplish tasks that require relatively quick movement. For example, if the surgeon attempts to grab a pulsating blood vessel that has been severed, he or she will always lag behind the actual movement of the vessel and be unable to secure it. This is a function of physical laws that cannot be overcome: the speed of electrons in a wire is related to the speed of light, which is a universal constant. However, it may be possible to circumvent this type of problem by providing some autonomy to the robot. In the situation mentioned, the robot would recognize that the surgeon is trying to grab the blood vessel and clamp it, and would perform that action. The system would then wait for the surgeon to “catch up” before performing any other action. The semiautonomous responses of the robot would not be perceptible to the surgeon, who would simply see the vessel being clamped, which was the intended action of the surgeon at the console. This semiautonomy granted to the robot in this scenario is analogous to that of the F22 aircraft, which “understands” the pilot’s command and performs all the necessary operations to carry it out.

**SUMMARY**

Robots in the operating room are currently in the first generation of technology. They represent a technical marvel, but have not yet reached the level of sophistication that will allow seamless integration into the operating room environment. Further generations of robotics will address these problems and will be more readily accepted by operating room personnel. Future efforts in developing endoscopic and telesurgery technology must take into consideration the limitations of human information-processing capabilities and minimize the additional information-processing demands imposed on the surgeon. A compatible display and control system for visualization of, and manipulation in, the remote environment can mean the difference between life and death in telesurgery procedures. Much effort is currently devoted to this area of research and development. Lessons learned from the aviation industry are also being applied to further the science of advancing technology in medicine.

To date, no robotic system has demonstrated convincing benefit over current standard instrumentation controlled by human hands. For robotic instrumentation to be useful and accepted, it must provide a clear and convincing clinical benefit. It is not enough simply to provide increased precision; the clinical outcome, such as patient survival or quality of life, must be improved.

A balance must be struck between human and robot; effective coupling of surgeon with robot is critical for the successful implementation of robotic technology into the operating room. The human mind is better suited to functions requiring creativity. Routine activities that may be done by rote are better done by robots. As Dr. Richard Satava said, “The future of surgery is not about blood and guts; the future of surgery is about bits and bytes.”

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