Minimally Invasive and Robotic Surgery

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Advances in surgery have focused on minimizing the invasiveness of surgical procedures, such that a significant paradigm shift has occurred for some procedures in which surgeons no longer directly touch or see the structures on which they operate. Advancements in video imaging, endoscope technology, and instrumentation have made it possible to convert many procedures in many surgical specialties from open surgeries to endoscopic ones. The use of computers and robotics promises to facilitate complex endoscopic procedures by virtue of voice control over the networked operating room, enhancement of dexterity to facilitate microscale operations, and development of virtual simulator trainers to enhance the ability to learn new complex operations. Future research will focus on delivery of diagnostic and therapeutic modalities through natural orifices in which investigation is under remote control and navigation, so that truly "noninvasive" surgery will be a reality.

JAMA. 2001;285:568-572 www.jama.com

SUBSTANTIAL IMPROVEMENTS IN the art and science of surgery were made over the 150 years since the introduction of antiseptic techniques by Lister, including improved anesthetic agents, antibiotics, surgical nutrition, and organ transplantation, in which the basic tools and techniques remained basically unchanged. The core task of "surgery," that is, "cutting and sewing," with hand instruments and direct visualization of and contact with the organ or tissue has remained the same. However, during the last quarter of the 20th century, and especially during the last decade, there has been a paradigm shift in the methods for performance of surgery. For many procedures, the "invasiveness" involved has been dramatically reduced resulting in superior outcomes manifested as improved survival, fewer complications, and quicker return to functional health and productive life. This focus on less or "minimal" invasiveness has gained momentum and has been the subject of intense investigation in recent years.

Developments in Minimally Invasive Surgery

The methodological innovations in surgery are only beginning. For the first time, it is possible for surgeons neither to look directly at nor touch the tissues or organs on which they operate. Building on the precedent of pelviscopy in gynecology and arthroscopy in orthopedic surgery, the use of minimally invasive approaches into other surgical specialties, including general surgery, urology, thoracic surgery, plastic surgery, and cardiac surgery, has changed not only the performance of specific operations but more important the strategic approach to all surgeries.

The pain, discomfort, and disability, or other morbidity as a result of surgery is more frequently due to trauma involved in gaining access to the area to perform the intended procedure rather than from the procedure itself. For example, following a cholecystectomy, the need for hospitalization was not related to the removal of the gallbladder but rather was necessary because of the pain from the trauma to the abdominal wall caused by the incision to gain access the gallbladder.

Following the introduction of the laparoscopic cholecystectomy by Mouret in France and shortly thereafter by Reddick in the United States, a cascade of events was set in motion that impact on the performance of surgery in the 21st century.[1] The concepts of "surgery through a scope" dated to the end of the 19th century but the technology of the late 20th century made laparoscopic surgery and minimally invasive surgery not an isolated event but a reality.[2,3] These technologies facilitated this shift: (1) development of the charge coupling device (CCD) chip that allowed high resolution video images to be transmitted through an optical scope to the surgeon, (2) high intensity xenon and halogen light sources that improved visualization of the surgical field, and (3) improved hand instrumentation designed for endoscopic approaches. For the first time, the surgeon did not look directly at the target structure but viewed digitally enhanced images that provided a better visualization because of the magnification and illumination.

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Within a few years gallbladder surgery changed from an open technique to an endoscopic procedure (TABLE). Laparoscopic techniques were then applied to other procedures in the abdominal cavity, including hernia repair,[4] esophageal reflex surgery,[5] and colon surgery.[6] Applications include pelviscopy in gynecology, blebectomy and lung biopsy in thoracic surgery,[7] and cardiac surgery.[8,9] However, the enthusiasm and momentum initiated by laparoscopic cholecystectomy (lapcholy), led to unrealistic expectations of early conversion of other surgical procedures to less invasive approaches. The immediate and overwhelming success of this one procedure was not repeated with other procedures.

Surgical procedures can be categorized based on complexity and can be divided into either excisional, in which a structure is removed (eg, appendectomy, cholecystectomy); ablative, in which tissue is destroyed (eg, cryosurgery of hepatic tumors); or reconstructive, in which structures are joined or connected (eg, bowel or Fallopian tube anastomosis, coronary artery bypass grafting). Excisional or ablative procedures are easier to perform than reconstructive procedures and are more easily adaptable to endoscopic techniques.

Surgical procedures also can be categorized as either high volume or low volume. High-volume procedures are more successful in a shorter period of time than low-volume procedures because of the opportunity to learn the procedure more quickly and because of the "market opportunity" presented for technology development. The success of the lapcholy was in large part due to the simple excisional procedure, the opportunity (400 000 procedures per year) for surgeons to perfect the approach, and for the medical device industry to invest in development. Other excisional procedures have not been as quick to convert because of lower case volumes. Neither have other high-volume procedures, such as coronary artery bypass grafting, been as rapidly converted to an endoscopic approach because of the complexity and reconstructive nature of the surgical procedure.

Table. Surgical Procedures Performed by a Minimally Invasive Approach, 1999*

	No. of Procedures	Minimally Invasive, %†
General surgery		
Gallbladder	1 084 882	85
Nissen fundoplication	47 087	95
Adhesiolysis	215 760	72
Appendectomy	334 388	22
Colon resection	380 000	7
Hernia repair	820 191	14
Total	**2 882 308**	47
Gynecology		
Hysterectomy	582 000	15
Myomectomy	64 977	70
Pelvic floor reconstruction	160 000	40
Removal of adnexal structures	350 059	65
Total	**1 157 036**	37
Urology		
Nephrectomy	44 863	75
Cystocele/rectocele	158 144	45
Pediatric urology (orchiopexy, vesicoreflux)	25 000	80
Adrenalectomy	20 000	60
Total	**248 007**	55
Plastic surgery		
Breast reconstruction	182 000	15
Face and forehead lifts	80 000	25
Total	**262 000**	18
Thoracic surgery		
Lung biopsy	90 000	75
Lung resection	47 124	60
Total	**160 000**	60
Cardiothoracic surgery		
Coronary artery bypass surgery	330 000	17
Heart valve replacement	81 000	15
Congenital defect surgery	25 000	20
Total	**436 000**	17
Vascular interventional surgery		
Saphenous vein harvest	220 000	35
Peripheral vascular bypass	80 000	2
Aortoiliofemoral bypass	75 000	1
Abdominal aortic aneurysm	51 000	10
Total	**426 000**	20

*Data from Medtech Insight, Mission Viejo, Calif.
†Percentages are rounded.

Minimally Invasive Cardiac Surgery

Although cardiac surgery has been performed successfully more than 10 million times in the past 30 years with generally good results, splitting the sternum and spreading the rib cage to gain access to the heart contributed to significant morbidity. Cardiac surgery is different than other surgical procedures because the heart-lung machine adds further morbidity. Although coronary artery bypass graft surgery was performed in the late 1960s on a beating heart,[10] the heart-lung machine fostered growth of cardiovascular surgery and allowed routine wide-spread application. It is now clear that the morbidity associated with cardiopulmonary bypass is higher than that of the sternotomy.[11]

Two approaches in the 1990s attempted to make cardiac surgery less invasive. The MIDCAB (minimally in-

Technology Development and Forecast: Robotics and Computer Assistance in Surgery

Task	Function	Forecast
Surgical Assistant	Voice-Activated Endoscopic Holder/Positioner	Becoming Routine
Dexterity Enhancement Motion Scaling Tremor Filtration Force Feedback	Facilitate Precision Endoscopic Procedures	Of 1000 Procedures Now Performed, 50% Are Cardiac and 50% Are Laparoscopic
Operating Room Systems Networking	Surgeon Control of or Via Voice Activation, Touch Screen	Rapid Integration of Operating Room Systems in Near Future
Telepresence Surgery Remote Surgery	Surgeon at Remote Site From Patient Using Broadband Transmission or Internet	No Clear Path to Clinical Application
Telementoring	Proctoring From a Remote Site	Demonstrated to Have Potential for New Educational Paradigm
Information Enhancement 3-Dimensional Modeling and Reconstruction Image Referencing Guidance	Real-Time Data Acquisition and Nonvisual Imaging	3-Dimensional Reconstruction of Computed Tomography, Magnetic Resonance Imaging, and Ultrasonography With Surgical Overlays to Facilitate Percutaneous Therapy
Virtual Stillness (Motion Stabilization)	"Gate" Time Visualization and Surgical Instruments to Heart Motion to Create Illusion of Stillness	Facilitate Endoscopic "Beating Heart" Surgery
Virtual Simulators	Flight Simulators for Surgery	About to Become Realistic and Affordable
Information Enhancement Sensory Feedback	Action in Response to Nonvisual Feedback	Potential for Integrated "Smart" Local Delivery of Drug/Energy Based on Tissue-Level Feedback
Microelectronic Mechanical Systems	Miniature Autonomous Robots	Remote Diagnosis and Delivery Via Body Lumina

vasive direct coronary artery bypass) procedure involved a single vessel bypass on the anterior surface of the heart on a beating heart through a small anterior thoracotomy.[12] The Port Access approach attempted totally endoscopic coronary artery bypass surgery on an arrested heart still using cardiopulmonary bypass.[13] Because of the complexities involved with cardiac surgery, the totally endoscopic approach was prohibitive and both mitral valve and simple coronary bypass procedures were performed through a small thoracotomy incision.

Although these initial developments catalyzed the minimally invasive movement in cardiac surgery, they now constitute a minority of cardiac surgery procedures. However, they did evolve to the current OPCAB (off pump coronary artery bypass grafting) procedure in which multivessel bypass is performed on a beating heart through a median sternotomy incision. Although wide exposure is still presented and the surgeon performs the procedure under direct vision with conventional instruments, elimination of the heart-lung machine and performance of the procedure on a beating heart improves outcomes. This approach is less invasive than conventional cardiac bypass surgery.[14,15] The success of these procedures is facilitated by mechanical stabilizers, that provide local immobilization and stabilization of the coronary artery to be bypassed while the rest of the heart beats and supports the circulation. The technique is still evolving but now is used in approximately 18% to 20% of all coronary artery bypass procedures in the United States (Hospital Corporation of America hospital system case-mix database, 1999).

Complex Minimally Invasive Surgical Procedures

The application of the minimally invasive procedure to more complex surgeries will require the new technology and techniques. In general surgery, techniques such as hand-assisted laparoscopy attempt to bridge the gap between open and completely endoscopic procedures. Other possibilities include developing new ways to perform conventional surgical tasks as a way to adapt these procedures to an endoscopic or less invasive approach. Examples include using implantable devices to treat gastroesophageal reflex disease and replacement of sutures and staples by biological glues and sealants.

Much effort is being expended to improve endoscopic coronary bypass surgery.[16] To facilitate a totally endoscopic approach on a beating heart, there is an intense interest in the use of facilitated vascular anastomosis with connectors, coupling devices, glues, and sealants, to perform a task now possible only with suturing. An alternative is the use of precision enhancement, potentially with robotics.

Advances in Robotics

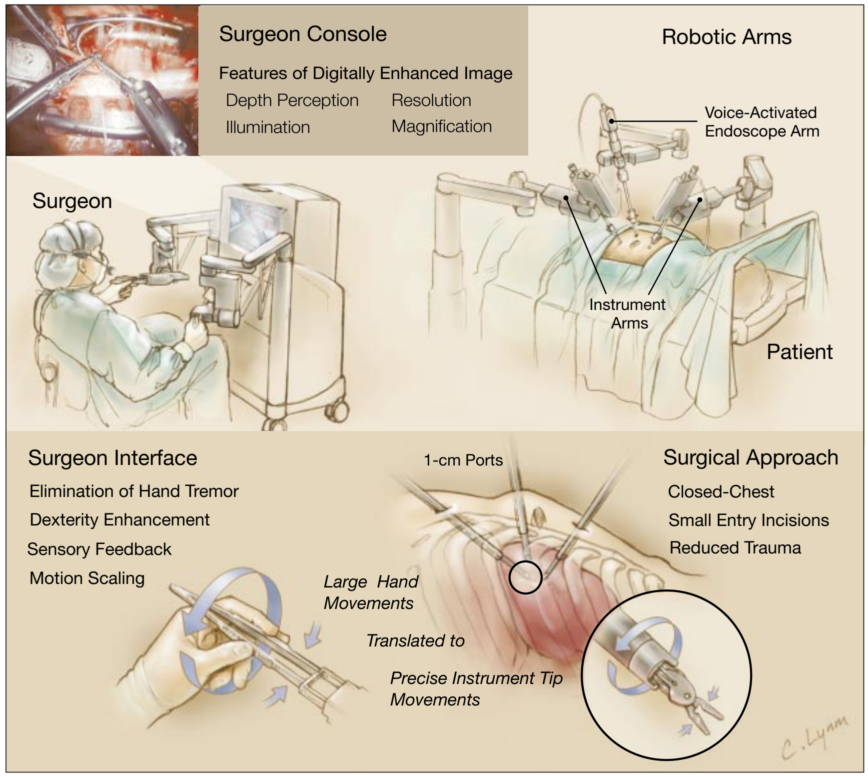
The initial concept of robotics in surgery involved operating at a site remote from the surgeon. The ability to transpose surgical and technical expertise from one site to a distant site (eg, a battlefield, space station, or developing country) was thought to expand surgical application. Although simple surgical procedures have been performed remotely, there is no clear path to practical application at present because of expense, transmission delay, and medical and legal issues.[17] Application of telepresence surgery in the foreseeable future will probably be limited to telementoring rather than to remote manipulation. Telementoring will allow the surgeon to teach or proctor performance of an advanced or new technique at a remote site using real-time teleobservation and monitoring.

Nevertheless, robotics can be expected to impact the field of minimally invasive surgery. Potential tasks facilitated by computers and robotics include information gathering and networking, navigation and guidance,[18] dexterity enhancement,[19] and simulation of virtual environments. The goal is to create a completely integrated system that converts information to action. The ideal would be to transcend human limitations by information gathering and sensing (computed tomography, magnetic resonance imaging, and ultrasonography) or by improved delivery either on a microscale basis or areas of the body difficult to access.

Current applications of robotics include surgical assistance, dexterity enhancement, systems networking and image-guided therapy. Dexterity is enhanced by placing a microprocessor between the surgeon's hand and the tip of the surgical instrument. Doing so allows performance of microscale (superhuman) tasks not possible without computer enhancement. "Motion scaling" in which gross hand movements can be reduced and in which precision and eventually force feedback can be enhanced allow surgeons to perform tasks not possible today. One such example is retinal vein cannulation with a needle for administration of a local therapy for retinal vein thrombosis; this technique (involving cannulation of a 100-micron structure) would not be possible without the dexterity enhancement of robotic assistance.[20]

Another focus on dexterity enhancement is in laparoscopic surgery and endoscopic coronary artery bypass surgery using surgical robotic systems (FIGURE).[21,22] Endoscopic coronary bypass procedures performed on a beating heart have been performed although enhancements and further technique development are necessary before routine application. Virtual immobilization or motion stillness should eventually allow beating heart surgery under the illusion of stillness by "gating" or timing the instrumentation and scope with the heart beat.

Figure. Endoscopic Surgery With a Robotic System



The use of robotics or "computer assistance" enhances the performance of complex endoscopic procedures, such as coronary artery bypass graft surgery.

Endoscopic approaches involve special challenges. First, loss of degrees of freedom are lost by the limitation of performance of a task in a confined space and the range of motion of instruments is restricted automatically. Robotics and the other techniques should address this issue. Second, 3-dimensional imaging is lost on a 2-dimensional television screen, and potential solutions to current 2-dimensional imaging systems include digital enhancement, shadowing to create the illusion of 3 dimensions, and high resolution image display. Three-dimensional imaging has been limited by the loss of resolution associated with filtering systems and by the size of the visualization system necessary to produce depth perception. These challenges are being addressed by some current and soon to be available systems.

Potential use of nonvisual imaging techniques, including 3-dimensional modeling and reconstruction of imaging data from computerized tomography, magnetic resonance imaging, and ultrasound, provide real-time data acquisition of pathological characteristics and to assess delivery of percutaneous therapy remotely. Other possible roles for computer and robotic assistance in surgery include voice control over surgical manipulators and information manipulators. At present, technology exists to give the surgeon voice control over virtually all operating room equipment including electrocautery, operating table position, endoscopic manipulation, lighting, and telephone. Future developments promise the overlay of additional data to the operative field, including 3-dimensional magnetic resonance imaging reconstructions and physiologic data acquisition.

Conclusion

Advancements in the last 10 years made it possible to perform a surgical procedure without directly visualizing or touching the organ being operated on. Efforts are now focused on those techniques that facilitate the more complex tasks by minimally invasive approaches. Technologies that will impact surgery include those that allow procedures to be performed through natural orifices, such as treatments for esophageal reflex disease performed through a transoral rather than a laparoscopic approach and with flexible miniaturized instruments capable of delivering sutures, clips, or energy sources for excising or shrinking tissue. Developments in the remote delivery of focused energy (eg, ultrasound and radiation) under image guidance (eg, magnetic resonance imaging and ultrasound) will permit the ablation of tumors of the prostate, breast, liver, and lung without the need for an incision. Noninvasive approaches may potentially be used for ablating plaques in arteries, revascularizing the myocardium, treating tennis elbow, and nonunion fractures.

Advancements in microchip and wireless technology may allow the development of swallowable cameras, implantable sensors and medical records, microrobots for completing surgical procedures, and magnetically controlled implants that can be navigated remotely. The technology is here, the potential is enormous, and the path is minimal.

Funding/Support: The Albert and Mary Lasker Foundation provided an honorarium to Dr Mack for preparation of this article.

Acknowledgment: I thank Jodi Akin, RN, MS, Ronald Aronoff, MD, and Sharon L. O'Reilly for their contribution of valuable information in preparation of the manuscript and Sheri Mullins for manuscript preparation.

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