Technology in the Operating Suite

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THE ADVANTAGES OF THE TECHNOLOGY REVOLUTION can be seen and felt in virtually every arena of modern life. Computer microchips now organize the vital events occurring within the basic mechanisms of automobiles, children match their fingers' reflexes, dance steps, and wits against virtual entities on video screens, and interactions with business colleagues, friends, and family occur electronically at any distance almost instantly. Until recently, the surgical teams in most operating rooms were using tools and techniques little different from those used decades ago. However, that is changing rapidly, and innovation is now invading the operating suite.[1]

The laparoscopic revolution that swept over general surgery in the 1990s was born of innovative technology and paved the way for further infiltration of technology into the operating room. The key transformation was the necessary disconnection between the surgeon and the tissue. In laparoscopic surgery, the surgeon could only see tissue by means of technology. This new dependence on images changed surgery in important ways. First, surgery now had a commonality with other procedural-based specialties such as gastroenterology (endoscopy), therapeutic radiology (fluoroscopy), and cardiology (angiography). Second, computer technology could now be used to digitize, enhance, transmit, and otherwise manipulate the image. The interjection of technology between the surgeon and the patient also meant that surgeons could no longer depend solely on their hands to intervene; they needed the assistance of industry to provide the needed technology.

The most visually dramatic change in the modern operating room is the arrival of remote computer-assisted telemanipulators, commonly referred to as "robots"[2] (FIGURE). These systems merge industrial robotic technology, 3-dimensional visualization systems, and computer technology. They are not really robots in that they do not function independently of human control and they do not perform automated sequences. The surgical manipulator is a large movable 3- or 4-armed device that, when in position, hovers over the operative site of the patient. The arms hold and move up to 2 or 3 instruments in addition to a stereotelescope that transmits 2 independent images. The instruments have 6 degrees of freedom of movement, meaning that they have joints that can move in a manner similar to the human wrist. The surgeon sits at a console separate from the operating table and the patient. With the surgeon's head in the console, the 3-dimensional image of the operative field is re-created via integration of the right and left camera outputs being viewed separately on individual television screens within the console. The system's advantages include vivid 3-dimensional visualization of laparoscopic surgery and the ability to manipulate tissue as the surgeon's hand would in open surgery. Disadvantages of the system include the cost (>$1 million per system), the absence of tactile feedback for the operating surgeon, and the cumbersome size and weight of the system.

Clinical Data

While few randomized controlled clinical trials of robotic surgery have been performed, a number of clinical robotic surgery series have been published.[3-6] Robotic systems have been used worldwide most effectively for prostatectomy in urology, heart valve replacement in cardiac surgery, tubal reanastomosis in gynecology, and esophagectomy and antireflux and bariatric procedures in general surgery.

In the last few years, the most significant clinical growth area for surgical robotics has been for resection of prostate cancer. Because conventional laparoscopic prostatectomy is prohibitively challenging from a technical standpoint, surgical robotics offers minimally invasive means for radical prostatectomy with potential for widespread adoption by urologists. In a prospective, nonrandomized trial comparing robotic with conventional radical retropubic prostatectomy among 60 patients, Menon and colleagues[7] found that the robotic approach significantly reduced intraoperative blood loss, postoperative hemoglobin decrease, and postoperative pain compared with the open approach. Furthermore, while the mean length of stay for patients in the conventional group was 4 days, two thirds of men undergoing robotic prostatectomy were home in less than 23 hours. These investigators have now performed more than 1000 robotic radical prostatectomies.[8]

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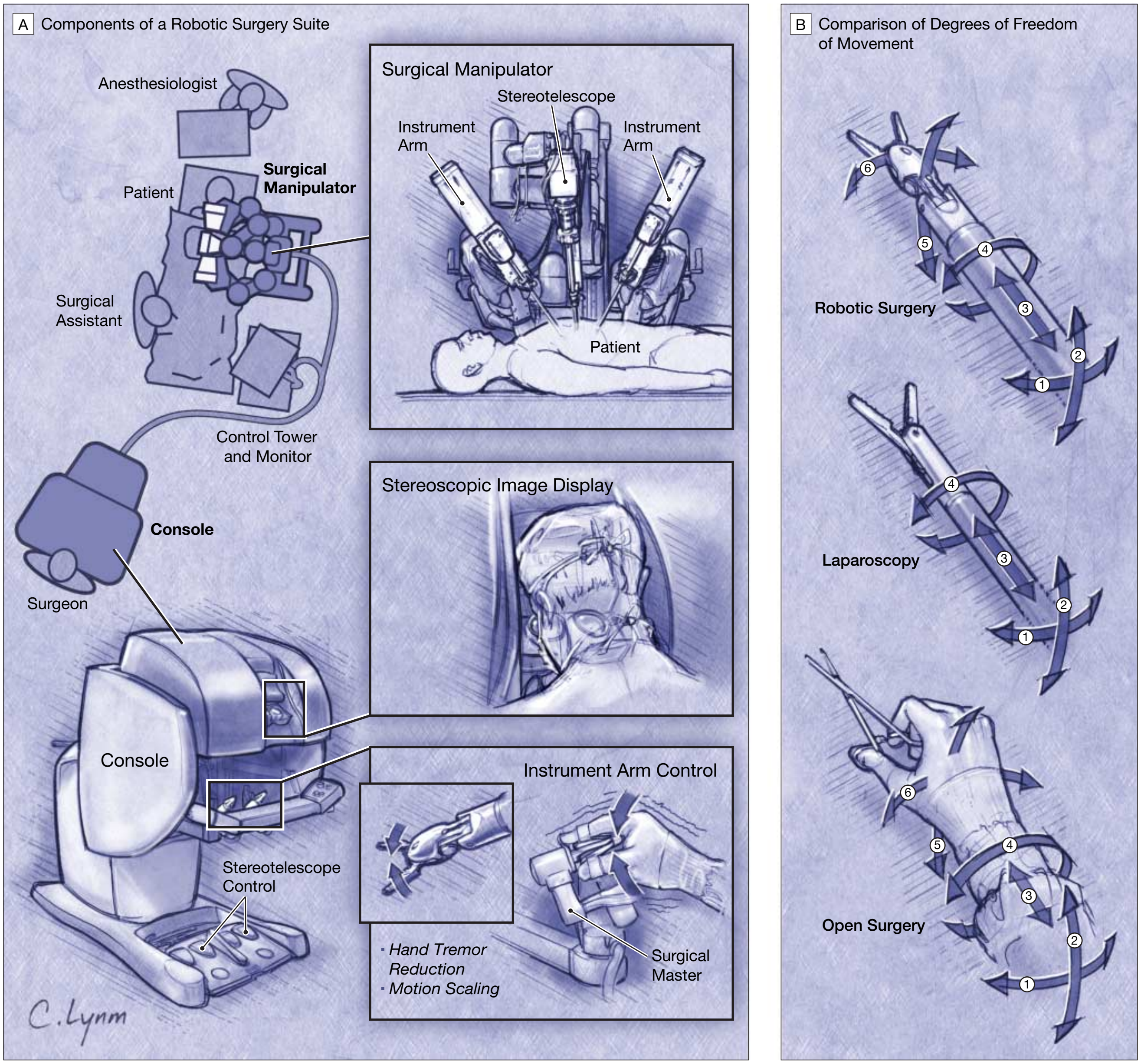
Figure. A Surgical Robotic System and Comparison of Degrees of Freedom of Conventional Laparoscopic and Robotic Instruments



A, Layout of the major components of a robotic surgery system. The surgical manipulator (inset) has 3 or 4 arms, 2 or 3 that move surgical instruments and an additional arm with a stereotelescope that transmits 2 independent images of the operative site. At the console (inset), the surgeon looks through a binocular eyepiece to view a magnified, high-resolution, 3-dimensional image of the operative site transmitted via the stereotelescope. The surgeon controls the surgical instruments with the surgical masters (inset). B, Robotic instruments have 6 degrees of freedom of movement, similar to that of the human wrist and arm. In comparison, laparoscopic instruments have only 4 degrees of freedom of movement (based on an original concept by Cory Sandone).

In cardiac surgery, excellent results have been achieved with robotic mitral valve repair through a 4- to 5-cm minithoracotomy.[9] In a recently published prospective series of 38 consecutive patients, Nifong et al[9] reported no operative deaths, strokes, or conversions to open sternotomy. The average total operative time was less than 5 hours and the mean length of stay was 4 days.

Because the "wristed" instruments of surgical robotic systems greatly enhance the surgeon's ability to sew laparoscopically, the greatest interest in robotics has been for surgical procedures that require anatomic reconstruction. This has held true for gynecologic surgery in which microsurgical tubal reanastomosis has been investigated. While tubal patency rates are outstanding for the robotic approach to this operation[10] compared with "conventional" laparoscopic reanastomosis, significant improvements in operative outcomes and clinical pregnancy rates have not been demonstrated.[11]

Robotic Nissen fundoplication has been compared with the conventional laparoscopic approach in 2 published controlled clinical trials: Cadiere and colleagues[12] randomized 21 patients and Melvin and colleagues[13] enrolled 40 patients (consecutive, but nonrandomized). Both studies found robotic antireflux surgery to be feasible and comparably safe. However, operative time and cost were increased when the robot was used. While the long-term durability of robotic antireflux procedures has yet to be determined, it has been proposed that patients with large hiatal hernias receiving a technically superior robotic repair may have better long-term outcomes.[14,15] As minimally invasive approaches to transhiatal esophagectomy are investigated,[16] the advantages of surgical robotics make it a likely area for growth.[17] The final area of robotic interest for gastrointestinal surgeons is in the realm of bariatric surgery. In the largest published study to date, a multi-institutional series of 107 robotically assisted Roux-en-Y gastric bypasses, no postoperative leaks and no deaths occurred. The authors describe a number of advantages to the robotic approach that they believe contributed to their excellent outcomes, including better control of the gastrojejunostomy stoma size, avoidance of stapler costs, and elimination of the potential for oropharyngeal and esophageal trauma.[18]

Future of Surgical Robotics

The current robotic systems are intriguing and represent an important step forward in minimally invasive surgery. The systems' strengths and limitations have directed important development research regarding future systems and improvements to current systems.[19]

Cardiac surgery groups are investigating the use of computer technology to allow more precise suturing on the beating heart.[20] Imagine the robotic arms linked electronically to the rhythmic movement of the heart muscle in a manner so precise that the arm, instrument, and needle all move exactly as the heart muscle does. This would make the heart appear to be standing still to the operating surgeon, allowing precise suturing on the beating heart. Other groups are finding ways to replace the missing tactile sense in current systems by providing surgeons with visual and even auditory force feedback data.[21] One group is developing miniature robots that function within the peritoneal cavity without direct connections through the abdominal wall.[22] These remote-controlled devices can move within the abdomen, sending video signals and receiving command signals via radio waves.

Laparoscopic surgery has significantly reduced the size of incisions. Kalloo and colleagues[23] have taken this a step further and have devised a means to perform intra-abdominal surgery with no external incisions. They have taken advantage of a preexisting orifice, working via the mouth using endoscopes; their strategy is to endoscopically incise the stomach from the inside to access the peritoneal cavity. Then, insufflating the peritoneum via the scope, procedures can be performed intra-abdominally. Pathologic tissue can be pulled back into the stomach and removed via the mouth. Then, the defect in the stomach wall is closed from within the stomach. While this may sound far-fetched, this group has already performed cholecystectomies and tubal ligations in animate models using this strategy (Anthony Kalloo, MD, oral communication, January 2004).

Augmented reality surgery, in which preoperative and real-time image data (eg, computed tomography, ultrasonography) are overlaid on the surgeon's view of the operative field, is an area of active development. With such technology, one can easily imagine how surgeons will soon be able to operate where their view is obscured by tissue, just as the modern pilot can take off, land, and fly through bad weather using radar and infrared picture substitution.[24]

Because robotic surgery requires all information exchanged between surgeon and patient to be digitized, surgical robotics has also ushered in the era of telesurgery. A transatlantic telerobotic laparoscopic cholecystectomy between New York and Strasbourg, France, using a surgical robot has been performed.[25] Furthermore, robotic telesurgery has been used to perform advanced laparoscopic procedures in patients living in medically underserved and remote areas of Canada.[26] While a number of legal, economic, and social factors currently prevent pervasive adoption of routine telesurgery, it is clear that telemedicine and the invasion of technology into the operating room will have a significant impact on the practice of surgery—even with respect to aspects of medicine as fundamental as the patient-physician relationship.

The introduction of robotic and other technology into the operating room has necessitated the development of training programs to teach surgeons how to use the technology.[27-29] Furthermore, through the design of virtual reality simulators for surgical technology, difficult and dangerous scenarios can be practiced in low-stakes environments. A drivers education–type console is currently being developed for one robotic system and should help facilitate graduate medical education and continuing medical education for surgical robotics. These are but a few examples of the exciting work that is bringing innovative technology to the world of surgery.

As surgery has rushed into the world of innovation, a few cautionary flags are in order. Innovative technology is very expensive. Who is going to pay for these advances? Which innovations are truly better for patients and which are simply enticing? Who will pay for the studies to distinguish between these? Are those technology-based procedures that appear to be better truly cost-effective? Are there sufficient safeguards in place? Should the free market be allowed to decide which technologies will become entrenched, or should the government take a bigger role? These are all important questions. The search for these answers, and the pursuit of further innovation, will be exciting challenges for the next generation of surgeons.

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EDITORIALS

Medical Applications of Biotechnology

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INNOVATIONS AND DISCOVERIES IN BIOTECHNOLOGY ARE revolutionizing medical research. Recent advances in molecular biology, proteomic technologies, genomic applications, cellular and tissue engineering, computational methods, and bioengineering and bioimaging techniques have markedly accelerated the pace of medical research and have created unprecedented opportunities for progress in medical science.

This theme issue of *JAMA* illustrates the promise and potential of biotechnology in medicine, with reports that demonstrate cutting-edge advances and novel discoveries in several rapidly evolving areas of medical research. In 2 studies on cancer detection, Casey and colleagues[1] demonstrate that conversion analysis increases the diagnostic yield of germline mutations in colorectal cancer compared with conventional genomic sequencing, while Grossman and colleagues[2] report that a proteomic assay may be a useful adjunct to cystoscopy for detecting bladder cancer. The elegant study by Nettles and colleagues[3] using an ultrasensitive genotyping assay to detect drug resistance mutations suggests that intermittent episodes of detectable viremia (ie, "blips") in patients receiving highly active antiretroviral therapy for human immunodeficiency virus infection most likely repre-

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