The first robotic-assisted surgery was performed by Kwoh in 1985. He modified a standard industrial robot to hold a fixture next to a patient’s head so drills and biopsy needles could be inserted at a desired location for neurosurgery.

Abstract
Within the last decade, robotic-assisted surgery has emerged with the promise of extending the benefits of minimally invasive surgery to virtually every surgical specialty while decreasing patient morbidity and improving postoperative outcomes. This article reviews the history, development, current and future applications of robotics in surgery, and its increasing prevalence in the field of urology.

Introduction
Since Erich Mühe, MD performed the first laparoscopic cholecystectomy in 1985, surgeons have continued to search for ways to implement minimally invasive techniques within all specialties. Due to the need for superior visualization or complex reconstruction, many of these procedures were simply not feasible using standard laparoscopic techniques or instrumentation. The emergence of computer-assisted and robotic technology has allowed surgeons, once again, to achieve that end by augmenting their abilities, often beyond what is humanly possible. This article highlights these technologies by reviewing the history, development, current and future applications of robotics in surgery, and its increasing prevalence within the field of urology.

Definition and Evolution of Robotic Systems
The term ‘robot,’ derived from the Czechoslovakian word robota meaning ‘forced labor’, was made popular by the playwright Karel Capek in his 1921 play Rossum’s Universal Robots about autonomous human-like devices that were created to perform common tasks. For the next half-century, robots, defined by the Robotic Institute of America as ‘reprogrammable multifunctional manipulator[s] designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks’ did just that, as they handled hazardous waste, performed repetitive tasks (auto industry) or assembled parts (computer chips) with great precision. These devices have been categorized into either active, semi-active, or passive (master-slave) systems. Active systems perform a task autonomously requiring only the supervision of a surgeon while passive systems possess no autonomy and require a surgeon’s input entirely.

The first robotic-assisted surgery was performed by Kwoh et al. in 1985 who modified a standard industrial robot to hold a fixture next to a patient’s head so drills and biopsy needles could be inserted at a desired location for neurosurgery. In 1991, Davies et al. used a similar industrial robotic arm coupled with a stereotactic frame to...
perform a transurethral resection of the prostate.3 Named the ‘Probot,’ this marked the first time that an active robot was used to automatically remove soft tissue from a patient.3 Near the same time, Taylor et al. developed the ROBODOC® (Integrated Surgical Systems, Sacramento, CA) as an industrial arm that would accurately core out the femur for hip replacements.6 This marked the first commercially available surgical robotic system. Despite a large clinical trial demonstrating that the system produced radiographically superior fits for implants while eliminating femoral fractures, the device was associated with greater blood loss and operative times and has not yet achieved Food and Drug Administration (FDA) approval in the United States.7

Additional work in robotics was taking place simultaneously with a collaboration between Scott Fisher, PhD at the National Aeronautics and Space Administration (NASA) Ames Research Center (Palo Alto, CA) and Joseph Rosen MD, a plastic surgeon at Stanford University.8 Both envisioned ‘telepresence surgery’ by integrating interactive virtual reality with surgical robotics. This was presented to roboticist Phil Green, PhD and his team at Stanford Research Institute (SRI) to develop a telemanipulator for enhancing nerve and vascular anastomoses in hand surgery.8 Recognizing the impact such a system could have on macroscopic endoscopic surgery, Richard Satava, MD, a general surgeon, collaborated with researchers with funding from the U.S. Army to aid in developing the Green Telepresence System. This system was envisioned to decrease mortality in war by “bringing the surgeon to the wounded soldier through telepresence.”8 A wounded soldier would be placed in a vehicle with robotic equipment and operated on by a surgeon located remotely at a Mobile Advanced Surgical Hospital (MASH). This was successfully implemented with an animal model but never for battlefield casualty care.

Also with initial funding from the U.S. Army, Yulun Wang, PhD developed a table mounted robotic arm controlled by the operating surgeon to manipulate an endoscopic camera, the AESOP (Automated Endoscopic System for Optimal Positioning), and formed his own company (Computer Motion, Inc.). This device eliminated the need for a camera holding assistant and, in 1993, became the first surgical robotic device to gain FDA approval, thus ushering in the era of robotics in surgery.

While the AESOP was enjoying an early success, the SRI Green Telepresence System was licensed by Intuitive Surgical, Inc.® (Sunnyvale, CA), extensively redesigned, and reintroduced as the da Vinci® Surgical System.8 In March 1997, Cardiere et al. performed the first robotic-assisted laparoscopic cholecystectomy in Belgium using this platform.9 Shortly thereafter, Computer Motion, Inc. produced a competing telemanipulating platform, Zeus. This consisted of the AESOP system with 2 additional table mounted robotic arms controlled by a surgical workstation. In the Zeus system, the surgeon was seated upright in a chair with a 2-dimensional video monitor and instrument handles positioned ergonomically to maximize dexterity. Later in its development, 3 dimensional viewing became available. In March of 2003, the two competing companies merged and production of the Zeus system was discontinued.

Current Robotic Platform Overview

As the only commercially available telerobotic system in the world, use of the da Vinci® Surgical System (Intuitive Surgical, Inc.®) has exploded since first obtaining FDA approval for general surgical procedures in July 2000. Over 460 systems are currently installed worldwide; over 350 are in the United States. As a purely passive, or ‘master-slave’ system, most roboticists would agree that the platform is not really a robot at all, but merely computer-assisted surgery at best. The platform consists of 3 main components: an ergonomic surgeon console, a vision cart holding a dual light source and dual 3-chip cameras, and a movable surgical cart which contains 2 or 3 mounted arms and a camera arm (See Figure 1). The master console consists of an image processing center generating a magnified 3-dimensional image in the

Figure 1
The da Vinci® Surgical System with its 3 components (from left to right): surgeon console, surgical side cart (with 3 or 4 arms), and vision tower. 
(Courtesy of Intuitive Surgical, Inc.®)
Advantages

Surgical robotic platforms like the da Vinci® offer many advantages as they overcome several of the obstacles inherent in laparoscopic surgery by providing improved visualization, increased dexterity, restored proper hand-eye coordination, and an ergonomic position. With the binocular vision provided by the optical system (See Figure 4), surgeons can regain the depth perception they forfeited with conventional laparoscopy. Additionally, the system offers 6 to 12 times magnification (depending on the distance from the tissue), thus providing views that allow meticulous dissection to be performed. Since the camera is controlled by the surgeon, he or she can maintain an always stable, optimal view of the surgical field without concern for camera-driver fatigue. In addition to the added dexterity with the instruments increased range of motion, the system incorporates software that filters out physiologic tremor and allows for adjustable motion scaling. This might allow for increased precision as large hand movements can be translated to smaller instrument motion. Additionally, the system’s mechanical power may greatly assist in surgery of the morbidly obese by overcoming the often troublesome abdominal wall stiffness that makes precise dissection with conventional laparoscopy in these patients difficult.10 The ergonomic surgeon’s console markedly decreases fatigue and thus allows for the completion of more complex and time consuming procedures without potentially adversely affecting the surgery. Finally, the surgical platform allows even the novice laparoscopist with a firm foundation in open surgery to transfer his skills to perform complex laparoscopic procedures.

Disadvantages

Despite these well recognized benefits, the current robotic platforms are not without profound disadvantages. Most notably, the cost of acquiring and

Figure 2
View of the operative field (above) and the instrument controls (below) in the console of the da Vinci® Surgical System. Surgery is greatly facilitated as the surgeon’s hand-eye axis is positioned to give the illusion of directly operating on the patient through an open incision. (Courtesy of Intuitive Surgical, Inc.)

view port, foot pedals to control the electrocautery, camera and instruments, and master control grips that drive the robotic arms at the patient’s side. The surgery is greatly facilitated as the surgeon’s hand-eye axis is positioned to give the illusion of directly operating on the patient through an open incision while he or she is seated comfortably at

the console (See Figure 2). The articulating laparoscopic instruments (EndoWrist®) have complex cable driven joints at the distal end allowing the same seven degrees of freedom (in/out, axis rotation, up/down [pitch], left/right [yaw], grip, and pitch and yaw at the wrist) present in the human hand during open surgery (See Figure 3).
maintaining this new technology can be prohibitive. With the older 3 arm da Vinci® Surgical Systems costing just under 1 million dollars, additional costs include a yearly service contract of roughly $130,000 as well as the cost of the proprietary instruments, which currently have a limited number of uses (10) before requiring replacement. Newer and more popular versions of the da Vinci® system include the 4 arm model, and the da Vinci S™ system introduced in January 2006. These systems currently cost approximately $1.33 million and $1.53 million, respectively. Additionally, they require a strong commitment not only by the operating surgeon, but by the entire hospital staff as the devices require additional training and experienced personnel. Another disadvantage of the system is its large size. The floor based surgical cart is heavy and the robotic arms can be cumbersome and often limit table side access to the patient. The combined footprint of just the surgeon console and surgical cart (22 square feet) not only may cause headaches in setting up an operating room but often limits which operating rooms can even house robotic procedures. An important limitation in the current robotic systems is the lack of haptics (sensory feedback). At present, the operating surgeon can only sense interaction with rigid structures (tool-on-tool collisions) and thus is forced to learn to ‘feel with their eyes’ by developing ‘near proprioception.’ This inability to know how hard one is grasping tissue or a needle not only may lead to frustration with inadvertent needle or suture breaks, but more importantly, to unrecognized tissue injury. Certainly, this is one facet of surgery where the open technique clearly maintains an advantage. Although research is ongoing, it appears that sensory feedback will be a feature to be desired for some time. Additionally, with only one vendor supplying the da Vinci® system, surgeons must operate with a limited number of available instruments. This increases the reliance on the tables side assistant to perform more of the operation. Lastly, despite tremendous enthusiasm among all the surgical subspecialties, no peer reviewed investigations with long term follow-up have demonstrated a clear advantage of robotic-assisted surgery over conventional laparoscopy. It is expected that with the maturation of data, however, that this will eventually be the case.

**Current Applications of Robotic Surgery**

While early robotic applications involving orthopedic and neurosurgical procedures showed promise and are commercially available outside of the United States (ROBODOC® and NEUROMATE® of Integrated Surgical Systems, Sacramento, CA), the robotic surgical systems with the greatest potential are those involving telem manipulation.

**Cardiac Surgery**

The initial commercial telepresence systems were designed for applications within cardiac surgery, specifically coronary artery bypass grafting in a closed-chest system. While this was successfully accomplished by Carpentier et al. in 1999, the challenges of the procedure have limited its general acceptance and the procedure continues to await FDA approval. Robotic mitral valve repair, however, has been approved by the FDA.
Robo-Docs Make Physicians Robo-Rooters

by John C. Hagan, III, MD

Remote Presence Seven (RP-7) (Figure 1) medical robots address the need of most physicians to be in two places at once. From home, clinic, or any ControlStation™ location (computer, special software, video camera, microphone, joystick, broadband internet access), a physician can control a blue and black, five foot five inch, 200 pound RP-7 robot “working” in a hospital ICU, ER or patient care floor as a digital physician extender (Figure 2). Robo-Doc, under the direct control of the physician, can move freely (at 2 miles/hour) to interact with patients, family members and hospital staff. The physician is also able to simultaneously access electronic medical records, view diagnostic monitors or equipment and obtain patient data through devices connected to this medical R2-D2 such as a digital stethoscope.

Hundreds of RP-7 clones are presently working in at least 65 medical centers across the country including 5 in Kansas City. Robo-Docs are often in the most demanding medical venues such as ICU, acute stroke and post-operative neurosurgical care. Unlike his human masters, RP-7 never sleeps, eats, complains and works 24/7/365 without threatening to strike or unionize.

Manufactured by Intouch Health of Santa Barbara, California, RP-7 rents for $4750/month with a 4 year contract. The ControlStations are available for a one-time fee of $2500 and require two thirty minute instruction sessions. Rollo-Doc (the nicknames are endless) has 30 infrared sensors which allow for assisted driving and 360 degree awareness of objects. RP-7 has been well received by physicians, nursing and hospital personnel and most importantly patients. One patient was quoted as saying, “It’s not as good as the doctor being there but it sure beats talking to his voice mail.”

Alleged benefits include better patient care, more efficient use of precious medical personnel and resources, shorter patient stays and eventually it’s hoped lower costs of medical care.

Investigations of these applications note that, at present, robotic-assisted surgery results mostly in an increase in operative times and expense with little demonstrable benefit.

General Surgery

Within the realm of general surgery, surgical robotic systems have been applied to nearly every laparoscopic procedure including cholecystectomy, splenectomy, antireflux procedures (Nissen fundoplication), small and large bowel resection, bariatric surgery, and even partial pancreatectomy.9, 10, 15, 16

Urology

Like general surgery, robotic technology has been applied to many established laparoscopic urologic procedures. Utilizing robotic assistance for extirpative procedures such as nephrectomy and adrenalectomy is feasible, but appears to offer little advantage. In contrast, the robotic platform is optimally suited for laparoscopic procedures requiring complex reconstruction or suturing such as in pyeloplasty (plastic surgery on the kidney) and in radical prostatectomy. Since first reported by Schuessler and colleagues in 1993, laparoscopic pyeloplasty has been accepted as a minimally invasive approach.
with outcomes comparable to the open technique. However, because the procedure requires expert laparoscopic suturing skills, it has not been readily accepted outside of a few academic centers. Thus far, the robotic-assisted technique appears to provide equivalent results to standard laparoscopic and open approaches.

Similarly, since first reported by Schuessler et al. in 1997 and refined by Guillonneau, Vallancien, and Abbou, laparoscopic radical prostatectomy remains a technically demanding procedure that requires expert dissection and suturing skills. Although recognized for equivalent functional and oncologic outcomes with less blood loss and a more rapid convalescence, the procedure is limited to centers with laparoscopic expertise due to its demanding nature. The utilization of the robotic platform, beginning in 2001, has markedly shortened the learning curve for this procedure. It was this demanding nature of the conventional laparoscopic technique that led Dr. Mani Menon and his team at Henry Ford Hospital to adopt and develop the robotic-assisted approach for radical prostatectomy that is utilized by most urologists today. Results from several series including two groups that compared their own personal results with open surgery and robotic-assisted laparoscopic radical prostatectomy (RaLP), demonstrated similar operative times but a statistically significant reduction in blood loss, transfusion rates, complication rates, hospitalization time, and urinary catheter duration in the RaLP cohort. Both groups and others have reported comparable oncologic outcomes (overall positive margin rates 15-18%) and continence rates (75-80% no pads at 3 months). Potency data has been immature, but many studies report equivalent or slightly improved results over open surgery (55%-84% for those < 60 years of age and 40%-64% for those > 60 years of age at 1 year). This has been attributed to the ability to perform a more precise penile nerve sparing procedure due to the improved visualization in the robotic-assisted approach. A multi-institutional prospective study of RaLP outcomes using validated instruments is currently underway and the results should be available within the next few years.

Other pelvic procedures described with the robotic-assisted approach include robotic radical cystoprostatectomy and sacrocolpopexy. Many surgeons use the robotic platform to perform the cystoprostatectomy and bilateral pelvic lymph node dissection and then remove the specimen and perform the bowel reconstruction extracorporeally through the same incision. Others have completed the entire procedure laparoscopically. Both techniques have demonstrated decreased blood loss and a more rapid convalescence with increased operative times. Because of the increased operative times and technical nature of the procedure, robotic-assisted cystoprostatectomy has not proven as popular as RaLP. Robotic-assisted sacrocolpopexy offers the advantage of facilitating intracorporeal suturing and improved vision, but often can be completed via the conventional laparoscopic approach as only a few stitches are necessary and an extracorporeal knot pusher can be utilized.

Because of the complex intracorporeal suturing often needed for laparoscopic partial nephrectomy, the robotic platform may offer some advantages for this procedure. However, its general acceptance has been slow since the renal dissection requires large sweeping movements of the camera that can be cumbersome and because many have concerns about the potential delay in accessing the kidney if undocking were necessary emergently to secure renal hemostasis.

In addition to urologic laparoscopic procedures, investigators have even demonstrated advantages in microsurgery with the robotic platform. Separately, Schiff et al. and Kuang et al. first reported using the da Vinci® system to perform vasovasostomy and vasoepididymostomy. These authors noted the magnification, elimination of physiologic tremor, and ability to utilize motion scaling could provide an attractive alternative to traditional microscopic techniques, especially to the surgeon less experienced in microsurgery.

**Gynecology**

The reversal of tubal ligation using a robotic platform has been well described. With the recent FDA approval (April 2005) of the da Vinci® system for gynecologic procedures, robotic-assisted tubal reanastomosis, hysterectomy, myomectomy, ovarian resection, and sacrocolpopexy will likely become commonplace.

**The Future-A Brave New World**

Although in its infancy, robotic-assisted surgery appears to offer distinct advantages by providing an interface by which complex laparoscopic procedures can be performed. The salient question dictating its future success is its true economic viability. If industry continues to follow Moore’s law (the doubling of computer power and halving of price every 2 years), it seems highly probable that robotic-assisted surgery will be commonplace in the near future. With the addition of haptics, real-time imaging, a smaller footprint in the operating room, and the ability to mentor a case remotely, these surgical systems offer great promise. However, this promise is tempered by reality. In the last seven years, Intuitive Surgical, Inc.®, currently the only commercial manufacturer of a telerobotic system in the world, has made only modest
improvements (slightly smaller size, arms with increased range of motion for cross-specialty use, and the potential for integrated imaging) in its latest system (da Vinci S introduced in January 2006) with no decrease in cost. Despite the expense, the number of robotic procedures being performed in urology alone continues to grow exponentially, as an estimated 35% of all prostatectomies in the United States will be performed robotically in 2006 (oral communication, September 2006, Intuitive Surgical, Inc.). This clearly demonstrates the incredible interest and patient demand for this technology.

Conclusions

Although in its infancy, robotic-assisted surgery is rapidly evolving. This technology appears to offer the greatest advantages in procedures requiring complex reconstruction or dissection as it allows surgeons skilled in open surgery to provide their patients with the known benefits of laparoscopy (decreased pain and more rapid convalescence). At present, these advantages continue to be countered by cost and the lack of long term results from prospective randomized trials evaluating its efficacy and safety. If and when these obstacles are overcome, the use of robotic technology in surgery may indeed become standard in every operating room.

References


Disclosures

None reported.

Contact the Author

Contact the author(s) Justin Albani, MD, through his business Internet website at www.urologyspecialistskc.com.