ROBOTIC SURGERY AND TELESURGERY IN UROLOGY

IOANNIS M. VARKARAKIS, SOROUSH RAIS-BAHRAMI, LOUIS RAPHAEL KAVOUSSI, AND DAN STOIANOVICI

Rapid technological developments and global communication in the past two decades have revolutionized the surgical sciences. Advances in optics and instrumentation encouraged a leap from traditional open operating techniques to the minimally invasive surgeries of today. Urology has been at the forefront of these innovations, introducing endourologic techniques into everyday practice to treat a myriad of genitourinary ailments. Patients have embraced these novel approaches as they have addressed concerns of postoperative pain, cosmesis, and convalescence.

However, inherent limitations with some advanced minimally invasive techniques have restricted universal mastery by urologists. For example, laparoscopic urologic surgery has been relatively slow to be incorporated into general practice. Two-dimensional visualization, restricted maneuverability, and dampened tactile feedback, present challenges to surgeons trained in traditional open approaches. Although general surgery has the cholecystectomy and gynecology has the tubal ligation, urology lacks a simple laparoscopic platform for acquiring the requisite skill. The learning curve for urologic laparoscopy is long, necessitating significant training and continued exposure.

The advent of computer-assisted robotic systems has provided a potential solution to address these limitations. They also open the door for developing novel, until now impossible, procedures. Moreover, the rapid expansion of Internet resources and modern audiovisual media has allowed for real-time guidance and remote surgical assistance. This review addresses the background, advances, and continuing challenges associated with robotic surgical systems and telesurgery.

From the James Buchanan Brady Urological Institute, Johns Hopkins Medical Institutions, Baltimore, Maryland

Reprint requests: Ioannis M. Varkarakis, M.D., Ph.D., James Buchanan Brady Urological Institute, Johns Hopkins Medical Institutions, 600 North Wolfe Street, Suite 161, Jefferson Street Building, Baltimore, MD 21287-8915. E-mail: medvark3@yahoo.com

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ROBOTS IN UROLOGIC SURGERY

Robotic Systems

The robots used in surgery should ideally be part of computer-integrated surgery systems. The robot is just one element of a larger system designed to assist a surgeon in performing a surgical procedure. Medical robots may be classified in many different ways: by manipulator design (eg, kinematics, actuation, degrees of freedom); by level of autonomy (eg, preprogrammed, image-guided, teleoperated, synergetic); by targeted anatomy/technique (eg, cardiac, intravascular, percutaneous, laparoscopic, microsurgical); by intended operating environment (eg, operating room, imaging scanner, hospital floor); by context of their role in computer-integrated surgery systems (surgical planner, surgical assistants).

Surgical Computer-Aided Design/Computer-Aided Manufacturing Systems. Surgical computer-aided design/computer-aided manufacturing (CAD/CAM) systems transform preoperative images and other clinical information into models of individual patients. These models can be used to preplan intervention and test a variety of potential clinical scenarios. Intraoperatively, these data can be registered to the actual patient and used as an image overlay display to assist in the accurate execution of a planned intervention.

The CAD/CAM systems can be incorporated with mechanical robotic devices to perform an actual intervention. Data from the model, as well as real-time patient data, are integrated and used to guide a needle, instrument, or probe into a desired target. Their purpose is to act as a trajectory-enforcement device, correctly aligning the end effectors based on ultrasonography, fluoroscopy, computed tomography, or magnetic resonance imaging. These systems can perform with great accuracy a task defined by the treating physician. By integrating preoperative planning and intraoperative decision-making, the potential exists for improved outcomes with minimal errors.

Orthopedics and neurosurgery were the first fields to use these surgical CAD/CAM systems because their procedures involved well-defined, fixed anatomic landmarks that were easily imaged.

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These landmarks could be used as reference points to determine specific targeted coordinates. Neurosurgical stereotactic procedures with the robot (NeuroMate, Integrated Surgical Systems, Davis, Calif) positioning the needle guides in predefined targets and hip replacement surgeries with the robot (Robodoc, Integrated Surgical Systems) milling a cavity to exactly fit the implant are examples of CAD/CAM surgical systems.[1–3]

In specialties dealing with soft-tissue organs such as urology, these systems have been more challenging to develop. The first urologic CAD/CAM system to be tested was the Probot at London's Imperial College. This device was built to aid in transurethral resection of the prostate. The relatively fixed position of the prostate and the repetitive motions involved in transurethral resection of the prostate made this an attractive candidate for robotic CAD/CAM assistance. The mechanical system used a standard resectoscope mounted on a stereotactic frame. The system used video and ultrasound information and the surgeon predefined the desired resection area according to the ultrasound images. The robot then resected as instructed and did so in an efficient manner. Drawbacks such as the inaccuracy of transrectal ultrasonography in determining prostate dimensions, as well as the need for manual chip removal and hemostasis, prevented further adoption into clinical practice.[4,5]

Another area of urologic interest in using surgical CAD/CAM robotic systems has been in percutaneous renal access. The surgeon can determine the calix target and provide this information to the robot, which then performs the task of placing the needle in the predefined point. A system with these features was developed at Johns Hopkins using an active robot and biplanar fluoroscopy. In a manner similar to extracorporeal lithotripsy, the surgeon selected the target calix on two images and the robot inserted the needle into the desired location.[6] The system proved the feasibility of fully automated needle placement in soft tissues. However, it also revealed several problems related to the mobility and deformability of the kidney, which were considered responsible for the 50% success rate on first attempt. Developing a reliable system of computer vision to predict and compensate for soft-tissue motion remains an important area of surgical robotic research.

Surgical Assistant Systems. Surgical assistant systems work interactively with surgeons to extend human capabilities in performing a variety of surgical tasks. They have many of the same components as the surgical CAD/CAM systems; however, the difference is an emphasis on intraoperative decision support and skill enhancement, rather than preplanning and accurate automated execution.

Two primary categories of surgical assistant robots are available: surgeon extenders and auxiliary surgical supports.

SURGEON EXTENDERS. Surgeon extenders are operated directly by the surgeon (surgeon-driven) and augment or supplement the surgeon's ability to manipulate surgical instruments. Most commonly, a master-slave relationship exists between this type of system and the surgeon, meaning that the surgeon's commands are computer processed and sent to "slave" components that carry out the task. These systems can computer process the surgeon's movements, allowing for modification, including motion scaling and tremor elimination. Complex end-effectors such as instrumentation with high-dexterity distal wrists can augment the surgeon's ability to perform complex surgical tasks. However, current systems have limitations in their ability to sense tool-to-tissue forces, providing inadequate tactile feedback to the surgeon.

To address the shortcomings of automated percutaneous needle placement into the kidney, our research group created a system called "percutaneous access of the kidney with a remote center of motion" or PAKY-RCM.[7] Unlike its predecessors, which relied on computer-based imaging and targeting, this new system mimics standard percutaneous renal access techniques. A radiolucent needle mounted on an RCM module situated at the terminal end of a passive robotic arm with seven degrees of freedom can be advanced by joystick control under real-time guidance of the urologist.[8–10] This system has been used in clinical trials. It has been proved safe and efficient with an initial attempt success rate (87%) comparable to that of manual percutaneous access.[11] PAKY-RCM has also been successfully used to gain percutaneous renal access during international telesurgical cases.[12]

The da Vinci (Intuitive Surgical, Mountain View, Calif) system is considered a surgical assistant and consists of a surgeon's console and a three-arm surgical manipulator. The surgeon sits at the control unit and is presented with a high-resolution three-dimensional (3D) view of the surgical field. The surgical manipulator consists of three robotic arms, two used for manipulating surgical instruments, and the third to control the laparoscope. As a surgeon-driven system, each motion of the surgeon is translated to a movement of the surgical instruments. However, this system is able to scale and filter motion, thus eliminating physiologic tremor and adding movement precision and stability. The instrumentation provides seven degrees of freedom, simulating the human wrist. A 3D view of the surgical field is incorporated into the system to help surgeons accomplish tasks such as intracorporeal suturing that are otherwise challenging to learn by conventional laparoscopy.

Representing an improved and renamed version of the MONA[13] that served as the first prototype surgical system developed at the Stanford Research Institute,[14] da Vinci was first used in Europe for cardiac surgery and received Food and Drug Administration approval in July 2000.

This system has been used in a variety of urologic applications but has gained most attention in robot-assisted laparoscopic radical prostatectomy (LRP). Schuessler *et al.*[15] reported the initial case of LRP in 1997. Guillonneau and Vallancien[16] and Abbou *et al.*[17] refined and popularized this minimally invasive approach. LRP, however, has proven to be a challenging operation requiring advanced laparoscopic skills. The lack of a 3D visual field and the limited dexterity of conventional laparoscopy limit the surgeon's working space and complicate tasks such as suturing and intracorporeal knot tying. To facilitate this procedure, several groups have developed robot-assisted LRP programs. Menon *et al.*[18,19] recently reported the results of their initial 200 cases and concluded that robotic LRP was comparable to conventional LRP and open radical prostatectomy in terms of oncologic control and complications. For surgeons with minimal laparoscopic skills, a very complex laparoscopic procedure was feasible with the help of this surgical assistant.

Other urology procedures, including donor nephrectomy, pyeloplasty, and adrenalectomy, have been performed with the assistance of this system.[20–23]

Although suturing for the inexperienced is easier with the robot, laparoscopic knowledge is still required, and the use of the robot requires a learning curve as well. Proper trocar placement is necessary to prevent mechanical interference between the robotic arms; however, because of the lack of tactile feedback, the surgeon must develop an intuition about the suture tension to avoid suture breakage and tissue strangulation. The aspects of surgery that require gross, rather than precise, movements, such as the reflection of the bowel or counter traction during dissection, are more difficult with the robotic arms. Therefore, laparoscopic surgeons experienced with intracorporeal suturing may find the robot not helpful. In addition, problems associated with cost, maintenance, functional storage, and use must be addressed before this technology is widely available. Finally, this system is expensive and bulky and requires large operating rooms.

The Zeus system (former Computer Motion, Santa Barbara, Calif) is very similar to the da Vinci system, because it consists of two robotic arms fixed to the operating table used for manipulating surgical instruments, and a master console at which the surgeon sits and manipulates laparoscopic instruments while viewing the operation on a video screen. The AESOP robotic arm (Intuitive Surgical, Sunnyvale, Calif) is used to hold the laparoscopic camera. The last generation of Zeus has instruments with comparable degrees of freedom and is capable of motion scaling, tremor elimination, and 3D visualization of the surgical field. This system's 3D imaging requires the surgeon to use specific glasses.

The advantages with fine tasks such as laparoscopic suturing were confirmed for this system.[24] However, its limited clinical experience in urologic laparoscopy demonstrated operating times longer than with conventional procedures.[25] The two companies, Intuitive Surgical and Computer Motion, merged, leading to limited support for the Zeus system. Currently, Intuitive offers a buy back program for the Zeus system if followed by purchase of a da Vinci system.

AUXILIARY SURGICAL SUPPORT SYSTEMS. Auxiliary surgical support systems work side by side with the surgeon and perform such functions as endoscope holding or retraction. These systems typically provide one or more direct control interfaces such as joysticks, head trackers, or voice control.

The Automated Endoscopic System for Optimal Positioning (AESOP, Computer Motion, Santa Barbara, Calif) is a robotic arm designed to hold and manipulate a laparoscope. The AESOP is affixed to the operating table, has six degrees of freedom, two of which are passive (meaning they are positioned by hand), and can be controlled with hand, foot, or voice control interface. Various laparoscopic operations have been successfully performed with the assistance of the AESOP, including nephrectomy, retroperitoneal lymph node sampling, varix ligation, pyeloplasty, Burch bladder suspension, pelvic lymph node dissection, orchiopexy, ureterolysis, and nephropexy.[26]

The AESOP can reliably replace a human camera holder, and it provides a stable camera platform that may diminish the risk of motion sickness in the operative team.[27] Skilled surgeons can use the AESOP to perform solo laparoscopic operations without a camera holder or surgical assistant. The cost/benefit ratio remains the major inhibitor of widespread adoption.

Another robotic camera holding system that has recently been introduced into clinical practice is the EndoAssist (Armstrong Healthcare, High Wycombe, Bucks, UK). This device is a freestanding laparoscopic camera manipulator controlled by infrared signals from a headset worn by the operator. The head movements to control EndoAssist can be rapidly learned by the surgeon, and the setup and dismantling times are less than 10 minutes. Overall, this system has proved to be practical and safe, reducing operating times compared with a skilled human camera-holding assistant.[28] In another study, the EndoAssist robot was significantly quicker compared with the AESOP device. This was attributed to the increased accuracy of movement in the EndoAssist compared with the voice recognition errors evident while operating the AESOP.[29]

TELESURGERY IN UROLOGY

Telesurgery is a relatively new field in urology and is full of technical terms that make comprehension difficult. A description of the most frequently used terms is presented in Table I.

Historic Perspective and Current Status

Although telemedicine had been assessed for decades, limitations in the ability to transmit data prevented widescale adoption. Studies were limited to point-to-point interactions; however, they did demonstrate the utility of such encounters. The explosion of broad bandwidth telecommunication in the 1990s provided a practical platform for medical applications. Physicians obtained the ability to affordably transmit patient records, radiographs, and micrographic images over the worldwide web, which engendered interest in teleconsultation among pathologists and radiologists.[30,31] The marked increased rate of electronic data transmission has also made real-time videoconferencing feasible. This type of interaction is crucial in telesurgical applications.

In 1994, Gagner *et al.*[32] were the first to demonstrate the reality of remote assistance in the operating room. Using an industrial robot as a camera holder, a surgeon in an adjacent room helped direct laparoscopic cholecystectomy. The initial urologic telementoring application was reported by Moore *et al.*[33] in 1996. From a remote site within the same hospital as the operating room (1000 ft away), an experienced laparoscopic surgeon guided a less experienced one through a varix ligation. All the remote components were directly wired to their sources in the operating room. Mentoring was accomplished with real-time video images and a two-way audio communication system. Remote control of the laparoscope was accomplished using the AESOP robotic system. In addition, the remote surgeon had activation control of the electrocautery unit. The short distance allowed for transmission of audiovisual data with minimal delays. This same group then used commercially available telecommunication systems and increased the distance between the operating surgeon and the remote surgical consultant.[34,35] Hardwired Trunk-1 lines made interaction possible between two hospitals in the same city separated by 3.5 miles. This link, operating at 1.544 Mbps, provided ample bandwidth for duplex video transmission with excellent resolution, frame rate, and imperceptible lag time.

The advent of integrated services digital network (ISDN) lines allowed for affordable intercontinental transfer of a large amount of data over long distances (more than 10,000 miles). The transmission speed was such that time delays were well below the threshold of 330 ms, the time at which a delay is perceptible to the surgeon.[36–38] Studies between the United States and Italy, Singapore, Brazil, and Thailand showed that an experienced remote surgeon could mentor a less experienced one through procedures such as laparoscopic nephrectomy and adrenalectomy.

The first true telesurgical procedure in urology was performed over a communications link between Baltimore and Rome, Italy (4500 miles). Percutaneous access of a hydronephrotic kidney was achieved using a purpose-built surgical robot (PAKY).[39,40] This robot placed a needle into the kidney in preparation for stone removal using two plain x-ray views. Data transfer was performed over commercially available transatlantic ISDN lines. The time lag between the motions of the surgeon's hands, the movements of the robotic instruments, and the returned video image was minimal.

More complex procedures were also performed using more advanced robotic and telecommunication devices. The Zeus robotic system allowed for the first telerobotic cholecystectomy to be successfully performed from New York to Strasburg, France in 2001.[41] Subsequently, multiple procedures have been performed on a daily basis between Hamilton Ontario and North Bay.[42]

Recently, a novel application of telemedicine has been explored: "telerounding." Using a robot that can be driven remotely from room to room, Ellison *et al.*[43] studied the feasibility and patient satisfaction in having their physician visit them remotely. The system was capable of exchanging real-time audiovisual data over a broadband wireless Internet connection. The unit could be remotely guided from a workstation anywhere with broad bandwidth Internet access using a standard video game joystick. This system allowed the remotely located caregiver and patient to see each other and communicate simultaneously. A patient satisfaction survey revealed similar satisfaction when comparing robotic to in-person visits during "rounds."

Technical Support Required for Telesurgery

Telesurgery is performed between a primary operating theater and a remotely located control room. Both sites should be connected with high bandwidth communication lines over which audiovisual (teleconferencing) and motion data (robot control) will be transmitted.

The remote control room should be equipped

TABLE I. *Definitions of terms frequently encountered in telemedicine and robotics*

Term	Definition
Telemedicine	Describes integration of multimedia, telecommunications, and robotic technologies to provide medical or surgical care over a distance. It has the potential to extend reach of medical/surgical specialists beyond their medical center and onto global scale.
Teleconsultation	Involves transmission of still or video images for review by remote specialists who then communicate their recommendations to local surgeon/physician.
Teleproctoring	Refers to real-time observation and evaluation of surgeon's performance by specialist not physically present in operating room. It usually involves simple one-directional audiovisual stream from local operating room to remote specialist's workstation.
Telementoring	Involves active real-time teaching and requires videoconferencing between local and remote surgeons. This interaction depends on transmission of audiovisual signals simultaneously in both directions.
Robotic surgery	Performance of procedures through surgical robot directly hardwired to workstation in physical proximity to operating room.
Telesurgery	Involves active control of surgical instruments through surgical robot by remote surgeon located at a distance from operating theater, transmitting data over telecommunication lines.
Telerounding	Remote visiting of patients by treating physician. This involves transmission of audiovisual signals between physician's location and patient's room.
Transmission	Sending of information over data communications media such as optical fiber or copper wire from one station to another.
Transmission speed/bandwidth	Amount of data that can be transmitted over a line or channel in a fixed amount of time. For a digital channel, this amount is defined per bits per second (bps), kilobits per second (kbps; 1024 bps) or megabits per second (Mbps; 1024 kbps). A higher bandwidth results in greater information-carrying capacity.
Duplex transmission	Transmission in both directions, either one direction at a time (half-duplex) or both directions simultaneously (full-duplex).
Broadband	High-speed, high-capacity transmission channel. Generally carried on coaxial or fiber optic cables that have higher bandwidth than conventional telephone lines.
Frame rate	Measure of how information is used to store and display motion video. Each frame is a still image; and the frame is described as frames per second (fps). In general, the minimal frame rate needed to avoid jerky motion is 30 fps.
Lag time	Time delay for an instruction to be encoded on a local machine, propagated over a transmission line to a remote machine, decoded, and executed.
ATM (asynchronous transfer mode)	Communication standard enabling transmission of high volumes of voice data and video at speeds ranging from 1.5 Mbps up to gigabits of bandwidth.
T-1	Hardwired lines operating at up to 1.544 Mbps for duplex video transmission of high-quality resolution and frame rate.
T-3	High bandwidth circuit equivalent to 28 T-1 lines.
ISDN (integrated services digital network)	International standard for transmitting data over digital telephone lines. Basic rate ISDN offers two simultaneous 64 kbs data channels, as well as a 16-kbs carrier channel, for signaling and control information. Combined data rate, 128 kbs, allows for videoconferencing capabilities. This original version of ISDN uses base-band transmission. Another version, called B-ISDN, uses broadband transmission and is able to support transmission rates of up to 1.5 Mbps. B-ISDN requires fiber optic cables and is not yet widely available. Multiple B-ISDN connections further increase data rate and transmission quality.
DSL (digital subscriber lines)	Sophisticated modulation schemes that pack large amounts of data onto copper telephone wires. These systems provide high bandwidth (up to 32 Mbps) connections to Internet.
Modem	Device used to convert serial digital data from transmitting terminal to signal suitable for transmission over telephone lines.
Cable modems	Digital modems that support Internet access using coaxial cable provided by cable television providers. Bandwidth is approximately 2 Mbps.

with the following: (a) a high-resolution video monitor allowing for simultaneous presentation of both external and internal operating video images from the primary operating site; (b) a multidirectional microphone and speaker to allow communication between the remote and primary surgeons; (c) a robotic control console, haptic interface, or even a control pad to allow the remote surgeon to control the remotely located robotic device (eg, AESOP, electrocautery); and (d) a telestrator video sketchpad, which may be very instrumental for the remote surgeon to illustrate the operative plan to the local team.

Similarly, the persons in the primary operating suite should be able to see and listen to the remote instructor with the help of similar audiovisual media (video, microphone, speaker). An additional external camera coupled by a motor to pan and tilt when controlled from the remote site will transmit images of what is happening in the distant operating room. Finally, the purposely built robotic device should be located near the patient in the operating suite and remotely controlled from the distant control room.

Delays in the transmission of information must be less than 300 ms, otherwise remote task performance will be significantly hindered. For transport of the high number of audio, video, and medical images required during telesurgery, dedicated asynchronous transfer mode (ATM) lines are considered the most reliable and safe. Communication delays are dependent on the distance between the sites, but previous experience[36–38] (delays of only up to 155 ms) and speed calculations have shown that these delays are acceptable when performing earth-to-earth connections.

Benefits of Telesurgery

The use of telemedicine/telesurgery offers a potential solution to a variety of problems. It has the ability to provide specialty care in remote and underserved areas. This includes situations involving military operations and space travel. Telesurgery may also serve as an avenue to propagate novel surgical techniques. Expert surgeons can guide less experienced ones stepwise through infrequently performed or technically demanding operations, improving the final outcomes. Telementoring may have a future role in teaching laparoscopic surgery to urology residents. Studies have already indicated that telementoring is a safe and effective teaching technique and assessment tool to determine when trainees are adequately trained to perform independent and unsupervised operations.[44] Teleproctoring may also allow a method to assess competence in novel procedures.

Finally, telemedicine interactions can increase patient access to physicians. Surgeons with particular areas of expertise may operate at any hospital around the world, obviating time-consuming and logistical travel concerns for both patient and physician. Eliminating travel and intervening earlier can decrease cost. Many healthcare facilities and long-term care communities lack the resources to maintain a staff composed of all the medical specialists needed. Visiting patients by “telerounding” can markedly increase the physician panel and enable remote medical experts to “virtually” consult with caregivers, residents, patients, and family members.

Limitations of Telesurgery

Remote interventions present many practical challenges. Although physicians are not needed at the point of care, the staff need to be trained not only in tele-interactions, but also, in the case of surgery, must be just as familiar with the case as with their local surgery cases. Flexibility is a necessity with telesurgical procedures. The availability of the surgical teams in different locations and time zones must be coordinated. Also, the involvement of two different hospitals presents the predicament of billing for services at both medical centers for the personnel involved.

Telepresence surgery involves the transfer of real-time data over long distances. This transmission must be fast and reliable. New high-speed, broadband technologies, such as cable modems and digital subscriber lines (DSL) are widely available. Data transmission bandwidth with wireless technology has reached levels that can be used in telemedical applications. However, the availability of these technologies is not universal. Also, redundancy needs to be built into the system as backup against primary signal disruption.

Several legal issues have been raised with this new field of medicine. Patient privacy and data confidentiality during transfer of this information over telecommunication wires is crucial. The connections used for the transfer of patient data should be secure, preventing interruption, redirection, or tampering with sensitive information. Advanced encryption protocols are beginning to be applied with success. Finally, intercontinental, as well as interstate, licensure and liabilities issues have not been well addressed.

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