Technological Advances in Robotic-Assisted Laparoscopic Surgery

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KEYWORDS

- Robot • Single-port • NOTES • Haptics • Simulator
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Despite its relative infancy, laparoscopic surgery has radically transformed the landscape of operative urology. The advent of surgical robotics at the turn of the new millennium heralded a quantum leap forward for minimally invasive urologists, who first used it successfully for performing robotic-assisted radical prostatectomy. Since then, there has been an unprecedented explosion in the use of robotics in other aspects of oncologic and reconstructive urologic procedures, with more than 55,000 radical prostatectomies performed with da Vinci® (Intuitive Surgical, Inc., Sunnyvale, California) robotic assistance in the United States in 2007[1] and more than 70,000 performed worldwide in 2008 (unpublished data, Intuitive Surgical, Inc., 2008). The increasing popularity of robotic-assisted laparoscopic surgery seems to be mirrored in Europe and other parts of the world, and in the arenas of cardiothoracic, gynecologic, and general surgery.[2–4]

Propelling this zeitgeist for surgical robotics have been exciting advances in robotic technologies and their potential applications in urologic surgery. This article therefore serves as a timely review of these promising innovations to date and discusses likely future directions for our craft as the practice of surgery becomes increasingly robotic-assisted and computer-aided.

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EVOLUTION OF UROLOGIC ROBOTIC SYSTEMS AND CURRENT STATE OF THE ART

Urologic robotic systems used in recent years have essentially comprised a computer with real-time imaging capability linked to various effector units for execution of specific tasks. Off-line (ie, fixed path) robots are automated systems that execute precise movements within specified confines based on preprogrammed imaging studies obtained before surgery, operating independently without requiring active input from the surgeon.[5] These include (1) robots for prostate access, such as the ProBot (prototype by a team from Imperial College, London–not commercially available and not manufactured), a robotic resection device with 7 *df*, and various robotic prostate biopsy systems,[6–8] and (2) renal access systems, such as the PAKY-RCM and Acubot robots (prototypes developed by Stoianovici et al at URobotics Laboratory, Johns Hopkins Medical Institute, Baltimore, Maryland), for precise percutaneous access to the kidney.[9,10]

Conversely, on-line robotic systems are designed to replicate the surgeon's movements in real time in the operative field with improved tremor-free precision and scale adjustment when applicable. These surgeon-directed robots may be broadly divided into endoscope manipulators and master-slave systems. Endoscopic manipulators, such as the Automated Endoscopic System for Optimal Positioning (AESOP; Intuitive Surgical Inc.) and Naviot (Hitachi Hybrid Network Co., Ltd., Yokohama, Japan) systems, have the benefits of being less expensive, smaller, and easier to set up with stable adjustable positioning, but their usefulness remains limited in complex operations.[5] Master-slave systems, such as the now obsolete Zeus (originally manufactured by Computer Motion, Inc., Goleta, California) and the da Vinci® system, comprise a computerized surgical console connected to an endoscopic manipulator with two or three robotic arms for instrument manipulation. Precise digital control of surgical instruments through the console eliminates movement tremors and allows motion scaling, wherein the surgeon's movements may be amplified or dampened.

The most commercially successful robotic system to date has been the da Vinci® system,[11] with more than 1000 systems currently installed in hospitals worldwide. From its inception, the benefits of the da Vinci® system over conventional laparoscopy were readily apparent: superior ergonomics; optical magnification of the operative field within direct control of the console surgeon; and enhanced dexterity, precision, and control of operative movements. Comprising a patient-side cart with three or four robotic manipulator arms connected to a master console, the da Vinci's binocular images obtained by means of the laparoscopic camera lens (0° or 30°) are integrated by the computer to provide a composite three-dimensional (3D) image when viewed by means of the immersive stereo viewer at the console. The patented robotic instruments also have additional articulating joints (EndoWrist; Intuitive Surgical, Inc.) that permit 7 *df* of movement, empowering the minimally invasive surgeon to perform intracorporeal suturing and dissection intuitively and effortlessly.

Its current state-of-the-art version, the da Vinci® S HD Surgical System (Intuitive Surgical, Inc.), integrates 3D high-definition vision capability with the existing robotic platform, providing twice the effective viewing resolution with improved clarity and detail of tissue planes (**Fig. 1**). Its digital zoom function reduces interference between the endoscope and instruments, and the integrated touch-screen monitor permits telestration for improved proctoring and team communication. In addition, the TilePro® (Intuitive Surgical, Inc.) multi-image stereo viewer enables simultaneous display of multiple video inputs in the surgeon console, integrating display of the patient's ultrasound, CT, and MRI images. Extended-reach instruments are also now available for multiquadrant access, with a 50% increase in pitch and yaw range of motion and four times the working volume.[12] Fewer cable connections between components has also helped to shorten setup time, and a high-speed fiberoptic connection in the surgical platform offers the potential for remote telementoring.

Despite these technical innovations, there still exist some limitations. First, the da Vinci® S HD Surgical System is unable to provide haptic feedback for the console surgeon, who must necessarily base his or her intraoperative decisions on visual cues encountered during surgical dissection. Second, the large size of the robot presents some challenges to the operating staff when docking and repositioning the robot during complex procedures. Third, there remains a lack of simulator technologies available to surgeons and residents desiring familiarity with the robotic console, with their options currently limited to attending training courses that are mostly didactic in nature. Finally, the high cost of this technology may limit or slow the adoption of robotic-assisted laparoscopic surgery on a larger scale internationally.

Against this background, we now review some exciting technological advances that promise to redress some of these technical issues and bring the practice of robotic surgery into the mainstream.

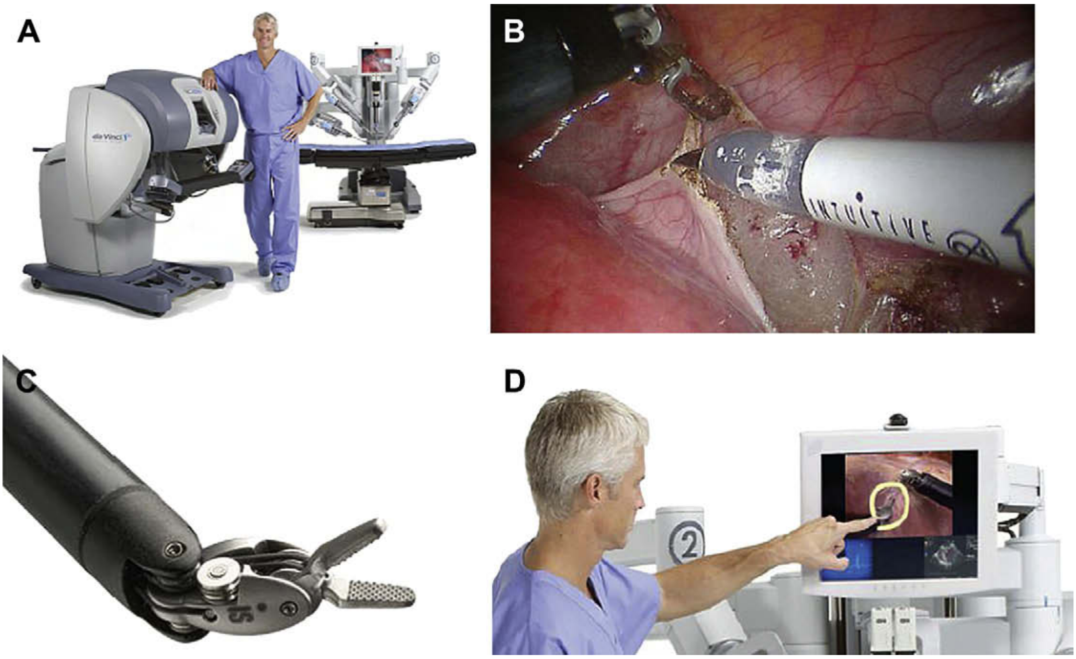

Fig. 1. (*A*) Surgeon console, patient cart, and robotic arms of the da Vinci® S HD Surgical System. (*B*) High-resolution 3D real-time images of the operative field as seen through the immersive viewer. (*C*) EndoWrist capable of 7 *df* of movement. (*D*) Interactive Tilepro® integrated touch-screen video display allows telestration and proctoring during live surgery, with multi-input display of a patient's preoperative clinical data and images. (*Courtesy of* Intuitive Surgical, Inc., Sunnyvale, CA; with permission.)

MINIATURIZATION OF ROBOTIC PLATFORM

The current design of the da Vinci's robotic cart is based on the traditional laparoscopic platform, wherein straight rigid instruments are used intracorporeally through small incisions by the surgeon maneuvering the instrument handles outside the patient's body. As a result, the current da Vinci® system occupies significant overhead over the sterile field, presenting spatial challenges for the patient-side assistants to overcome to operate dexterously alongside the robotic arms and cart.

In contrast, the Laprotek system (EndoVia, Inc., Norwood, Massachusetts, subsequently taken over by Hansen Medical, Inc., Mountain View, California) comprises slave instrument "motor packs" that are mechanically mounted on the existing bed rails of the operating table. The movements from these motors are then transmitted to the surgical instruments by means of stainless-steel cables. Whereas the da Vinci® system directs its straight instruments by moving their back handles through a 3D cone, the Laprotek system uses a curved guide tube to position its instruments intracorporeally. Its design occupies significantly less space in the sterile field, reducing collisions between the robotic instruments and camera (**Fig. 2**). Although not commercially available, it has been projected to cost significantly less than the da Vinci® system.

Working on the premise that the motion outside the patient should be confined to a line rather than

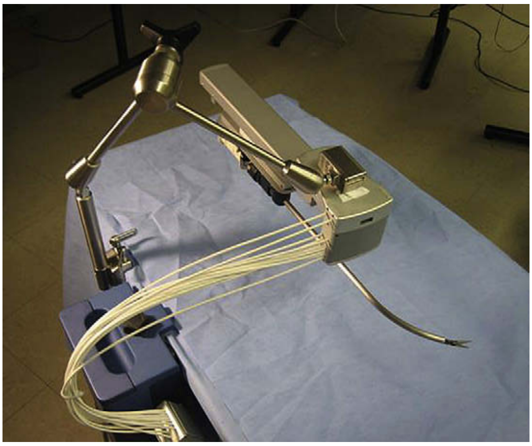

Fig. 2. Photograph of the Laprotek mainframe and guide tube. The stainless-steel guide tube controls upward and downward movement of the instrument, whereas the back end pivots about the incision. The arrow indicates the surgical port site position. (*From* Rentschler ME, Platt SR, Berg K, et al. Miniature in vivo robots for remote and harsh environments. IEEE Trans Inf Technol Biomed 2008;12:66–75; with permission.)

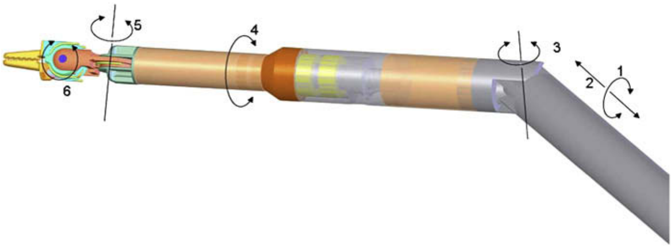

Fig. 3. Pictorial representation of new tool design permitting 6 *df* of movement intracorporeally. (*From* Dachs GW II, Peine WJ. A novel surgical robot design: minimizing the operating envelope within the sterile field. Conf Proc IEEE Eng Med Biol Soc 2006;1:1505–8; with permission. Copyright © 2006 IEEE.)

a cone (da Vinci® system) or a plane (Laprotek system), Dachs and Peine[13] proposed a new design wherein the robotic instruments would have two movable joints within the body that would permit 6 *df* of movement without requiring corresponding external pivoting motions (**Fig. 3**). Because the instruments would not be constrained to pivot about the port side, they could be easily mounted on a streamlined mechanical arm that supports its linear track to deliver comparable intracorporeal dexterity and precision. The advantages of their proposed design would include minimization of machinery in the exterior working envelope, giving surgical assistants more room to operate, and elimination of instrument collisions attributable to suboptimal port placement (**Fig. 4**).

MOBILE MINIATURIZED IN VIVO ROBOTS

Despite improvements in high-definition real-time clarity of tissue architecture and a wider field of view with the da Vinci® S HD Surgical System, the surgeon's visual and operative fields remain constrained by camera and instrument placement dictated by the entry incisions. To overcome these limitations, Rentschler and Oleynikov's group from the University of Nebraska[2,14] has explored the use of in vivo microrobots. They first reported the use of miniature in vivo adjustable-focus camera wheeled robots to augment visual feedback to surgeons during laparoscopic cholecystectomy in a canine model. Mounted on two helical wheels driven by direct current motors, these microrobots had sufficient traction to move over slick deformable abdominal viscera without causing injury (**Fig. 5**). The same investigators subsequently designed a fixed-base pan-and-tilt camera robot that permitted forward tilting at an angle of 45°. Comprising tripod legs that were spring-loadable and could be abducted during insertion through the laparoscopic port, this microrobot could then be guided into a desired intra-abdominal position with laparoscopic instruments, offering surgeons alternate views of the organs being operated on to that obtained by means of the laparoscopic camera.[15] Joseph and colleagues[16] recently

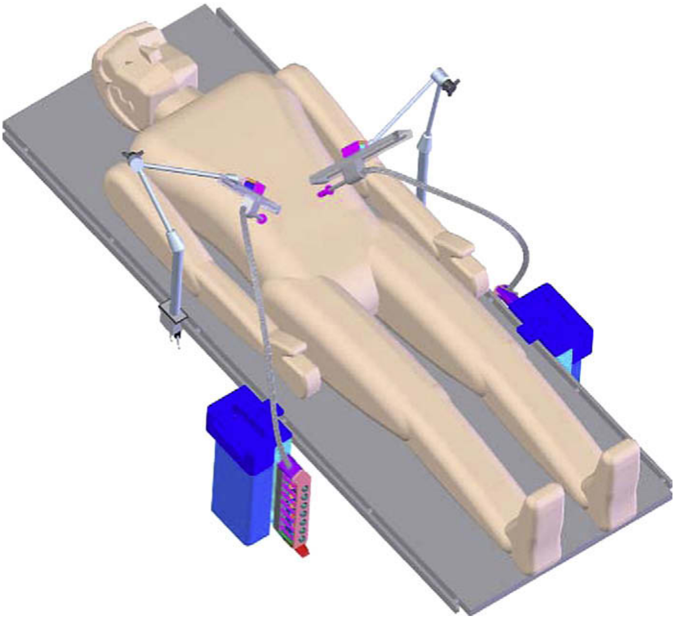

Fig. 4. Envisioned design of robotic setup as proposed by Dachs and Peine. (*From* Dachs GW II, Peine WJ. A novel surgical robot design: minimizing the operating envelope within the sterile field. Conf Proc IEEE Eng Med Biol Soc 2006; 1:1505–8; with permission. Copyright © 2006 IEEE.)

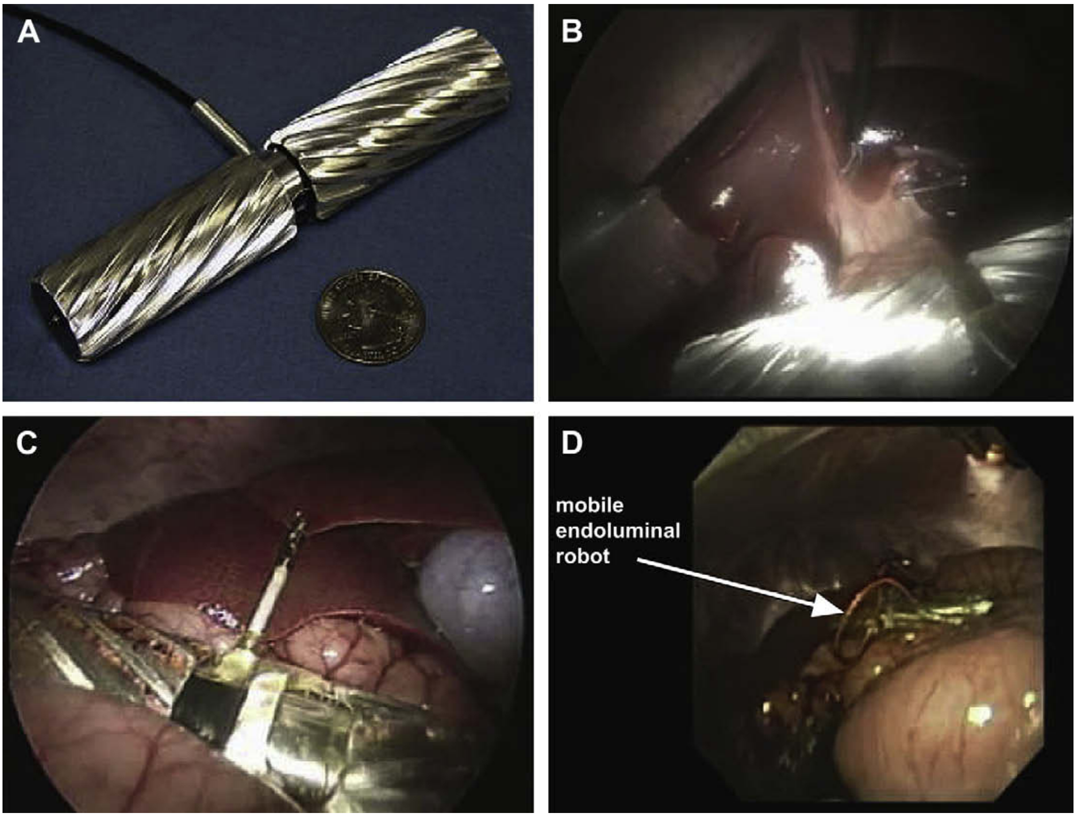

Fig. 5. (*A*) Mobile adjustable-focus robotic camera (MARC) prototype designed by researchers at the University of Nebraska. (*B*) Intracorporeal view of the MARC during porcine cholecystectomy, (*C*) Mobile in vivo robot executes liver biopsy. (*D*) Same robot performs peritoneoscopy. (*From* Oleynikov D. Robotic surgery. Surg Clin North Am 2008;88:1121–30; with permission.)

reported their collaborative experience with these prototypes in performing laparoscopic prostatectomy and laparoscopic nephrectomy in a canine model. Rentschler and colleagues[17] also demonstrated their use in guiding a surgically naive crew member to perform the steps of a laparoscopic appendectomy in a harsh environment by means of remote telementoring. Albeit successful, technical drawbacks encountered during these operations included the need for a separate controller to maneuver the robot into position; significant hindrance attributable to the tethered design for the robot's continuous power; and lack of a self-cleaning mechanism for the camera lens positioned between the helical wheels, which resulted in obscured images from direct contact with intra-abdominal organs and fluids.

The feasibility of using multiple miniature in vivo robots for bettering spatial orientation while facilitating tasks was recently reported by Lehman and colleagues.[18] They used three robots—a peritoneum-mounted camera robot, a lighting robot, and a retraction robot—together with a conventional upper gastrointestinal endoscope to augment the scope of natural orifice transluminal endoscopic surgery (NOTES) procedures in a porcine model.

Although still in their early stages, these and other feasibility studies[19–21] have demonstrated significant potential for eventual development of wireless robotic sensors to provide composite all-round real-time images and robotic manipulators that would obviate the need for multiple incision sites for instrument access.

ADVANCES IN ENDOSCOPIC NAVIGATION SYSTEMS

In performing laparoscopic urologic procedures with da Vinci® assistance, surgeons rely on visual cues instead of tactile feedback to achieve comparable outcomes to those reported for traditional open surgery. Suture tension, for example, has been dictated by the degree of deformation on the respective tissue. Imaging technologies based on virtual and augmented reality have evolved to provide real-time navigational guidance for the surgeon to perform image-guided surgery.

Augmented reality may be defined as the integration of computer-generated images (from reconstructed preoperative MRI, CT, or ultrasound images) to live video or other real-time images, such as ultrasound, allowing visualization of visceral anatomy and surrounding structures.[22]

The initial experience of such image-guided surgery in neurosurgery, maxillofacial surgery, and orthopedics was based on integrating images over fixed bony landmarks.[23–25] Attempts to extrapolate its use in abdominal surgery have highlighted the challenges of imaging viscera that constantly shifts and undergoes deformation: (1) to find constant intra-abdominal reference points and (2) to merge preoperative images over constantly shifting soft tissue anatomy attributable to breathing, heartbeat, patient movement, and surgical instrumentation.[22,26]

Ukimura and Gill[27] recently described their experience of using a color-coded zonal navigation system to perform laparoscopic partial nephrectomy. Such a system affords the surgeon a 3D visual surgical roadmap based on preoperative CT images to identify safe resection margins during surgery by giving different colors to the tumor and its adjacent tissues. Ukimura and his colleagues[28–30] further reported the use of intraoperative transrectal 3D ultrasonography to guide the course of laparoscopic nerve-sparing radical prostatectomy.

Attempts at incorporating conventional fluoroscopy during robotic procedures have been hindered by spatial difficulties of reconciling the sizable overhead footprint of the fluoroscopic and da Vinci® systems over the sterile field. In addition, fluoroscopy only provides cursory images of calcified or radiopaque structures, with limited soft tissue information; the need for operating staff to wear heavy protective gowns to protect them from collateral radiation exposure is an unattractive prospect during complex laparoscopic procedures; and the anterior-posterior images afforded by fluoroscopy leave many “blind spots” during surgical dissection.[31]

The TilePro® system uses a “picture in picture” viewer in the da Vinci® surgeon’s console to toggle among images from various sources. Bhayani and Snow[32] recently described their experience with this system to assimilate images from preoperative CT or MRI scans, real-time ultrasonographic images, and 3D images viewed through the da Vinci® surgeon console during robotic-assisted laparoscopic partial and radical nephrectomy. In 2 of 17 partial nephrectomies, superselective arterial control was possible using Doppler information fed into the surgical console during tumor resection. Although providing invaluable information during surgery, the images were static and not superimposable to the mobile operative field. Although the TilePro® system has increased the availability of anatomic images available to the console surgeon during surgery, the ultimate direction would certainly be to integrate these images in real time onto the operative field as seen through the immersive viewer.

ROBOTIC NATURAL ORIFICE TRANSLUMINAL ENDOSCOPIC SURGERY AND SINGLE-PORT SURGERY

NOTES has made significant advancements since its inception in the late 1990s. Using a natural orifice to conceal surgery has not been a new concept to urology, because transurethral procedures, including cystoscopy, prostatectomy, and ureteroscopy, have been routinely performed through a natural orifice for several decades now. Previous limitations in equipment and technique had daunted minimally invasive surgeons from attempting intraperitoneal procedures through a natural orifice, however. Gettman and colleagues[33] successfully performed the first transvaginal NOTES nephrectomy in a porcine model, using conventional laparoscopic equipment through a single abdominal 5-mm trocar. Single-port NOTES access through transvaginal,[34] transgastric,[35] transvesical,[36,37] and even transcolonic[38,39] routes has now been reported. Nonetheless, NOTES procedures remain limited by the degree of mobility and stability afforded by current endoscopic technologies.

Building on their experience with single-port laparoscopic urologic surgery, Kaouk and his colleagues from the Cleveland Clinic[40–42] recently pioneered the use of the da Vinci® system for natural orifice procedures, first in the porcine model[43] and subsequently in humans.[44] The first technical constraint their group encountered was to overcome the critical distance between robotic arms required for uninterrupted maneuverability during surgery. Second, traditional transabdominal placement of robotic trocars creates a fulcrum at the fascial level, allowing the robotic system to recognize a pivot around which the robotic arm can rotate. Altering the ideal location of this fulcrum and constricting port placement potentially predispose to inadvertent tissue injury and restricted movement.

Despite these limitations, configuring the robotic arms in unorthodox positions provided an opportunity to explore the potential of robotics in NOTES. Box and colleagues[39] successfully completed a robotic NOTES porcine nephrectomy by placing the robotic scope through a single abdominal trocar site while the right and left arms of the robot were placed transvaginally and transcolonically, respectively. Given the configuration, the robotic camera required manual control, whereas the robotic arms were manipulated by the surgeon at the console. The porcine nephrectomy was completed uneventfully despite the expected clashing of robotic arms externally. In contrast, Kaouk and colleagues placed the robotic camera lens and one arm through the umbilicus, with the other robotic arm inserted through the vagina, permitting successful completion of more than 30 robotic NOTES procedures to date. The arm configuration provided for greater articulation and closely mimicked internal triangulation as appreciated during standard laparoscopy. In all, robotic NOTES dismembered pyeloplasty, partial nephrectomy, and completion nephrectomy were successfully performed.[43]

Immense interest recently in laparoscopic single-port surgery has also witnessed the emergence of urologic procedures being accomplished through a single multichannel port.[45–48] As in NOTES, critical analysis of surgical technique identified limitations of the da Vinci® system in instrumentation and dissecting capabilities in such a confined space, chiefly that the proximity of robotic arms through a single multichannel port would invariably lead to external clashing. Attempting novel modifications to port and robotic instrument configuration, Kaouk and colleagues[44] reported the first successful series of single-port robotic procedures in humans, including radical prostatectomy, dismembered pyeloplasty, and radical nephrectomy. A salient highlight of these procedures was the improved facility for intracorporeal dissecting and suturing. During urethral-vesical anastomosis and ureteropelvic anastomosis, a continuous running suture creating a watertight closure was possible because of greater instrument articulation and rigidity.

ADVANCES IN FLEXIBLE ROBOTICS

Abbott and colleagues[49] from Purdue University have been working to develop an endoluminal robotic system (ERS) comprising a camera lens with two adjacent robotic instruments, each having at least 6 *df* plus an end-effector gripping action. The first-generation design, the ViaCath system (EndoVia Medical, Norwood, Massachusetts), was fashioned on the Laprotek master console with haptic interfaces and flexible robotic instruments that run alongside a standard gastroscope or colonoscope. The key components of these robotic instruments are a mechanical coupler to the position arm, a flexible shaft, and an articulating tip with an end effector delivering a total of 7 *df* within the scope's visual field (**Fig. 6**). The early results in an in vivo porcine model revealed various technical difficulties, chiefly difficulty in intubating the patient and positioning the instruments at the desired site, the instruments catching on tissue during deployment, and the limited lateral force produced by the instruments being insufficient for effectively executing the intended procedures on gastrointestinal tissue. To redress these limitations, the investigators have proposed a second-generation flexible ERS and instruments to improve kinematic instrument control and reduce inherent friction to boost the force available for instrument actuation and manipulation.

Apart from laparoscopic and intraperitoneal procedures, flexible robotic systems have also been applied during ureterorenoscopy. A novel device created by Hansen Medical, Inc. incorporates a robotic console to manipulate and control the deflection of a flexible ureteroscope (**Fig. 7**). Using this novel remote system, retrograde ureterorenoscopy was successfully performed in a swine model.[50,51] The increasing range of motion and stability of the platform parallel that of laparoscopic robotic systems. Further refinements in the product may ease the learning curve required during flexible upper tract ureterorenoscopy.

ADVANCES IN HAPTICS

Despite affording the surgeon improved operative dexterity and optical magnification, the current da Vinci® system is unable to deliver the element of haptics. Haptics has been categorized by Okamura[52] as being kinesthetic (involving forces and positions of the muscles and joints) or cutaneous (tactile, related to skin), encompassing the spectrum of force, distributed pressure, temperature, vibrations, and texture. The sense of touch has long been considered essential in limiting inadvertent tissue injury during surgical procedures. Haptics in robotics has demonstrable benefits in reducing tissue injury and reducing suture breakage while maintaining respectable operative time in the hands of an experienced surgeon.[53–57]

Attempts at developing sensory information from the robotic end effectors are cursory at this time and are largely focused on force-feedback systems. Although successfully used in various engineering situations, the translation of current commercial force-feedback sensors to live surgery has been hampered by constraints in size, design, cost, compatibility, and ability to withstand conventional sterilization procedures.

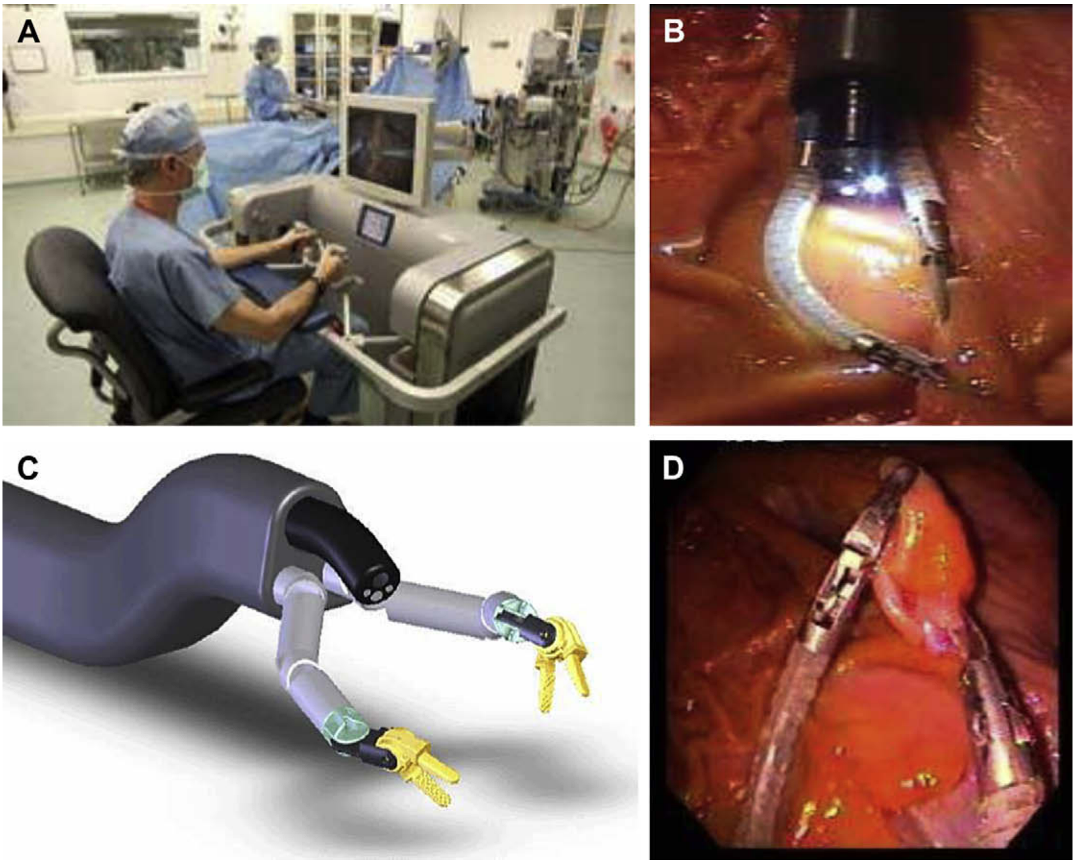

Fig. 6. The ViaCath system. (*A*) Laprotek surgeon console drives the ViaCath system. (*B*) ViaCath instruments use a double-flex section design at the distal tip for articulation. (*C*) Articulated overtube facilitates introduction of the flexible endoscope with its two highly articulated instruments. (*D*) In vivo visualization of abdominal viscera in a porcine model. (*From* Abbott DJ, Becke C, Rothstein RI, et al. Design of an endolumenal NOTES robotic system. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems. San Diego, CA: October 29-November 2, 2007. p. 412; with permission.)

Preliminary evidence that haptic feedback with robotics is possible has emerged, wherein specialized grippers are attached to the jaws of existing robotic instruments to deliver haptic feedback.[57,58] Redesigning robotic instruments to integrate force-sensing capability has also been reported but has not been met with much enthusiasm, given the recurrent prohibitive costs of disposing of these surgical expendables after each case in current practice.

Robotic haptic technology has also found new use in the arena of disaster and emergency medicine.[59] Robotics used for hazardous waste identification and removal has removed individuals from danger by means of direct exposure. These “hazbot” platforms with haptics have demonstrated greater reproducibility and ease of use with novice manipulators. Comparative evaluation between standard robotic systems and more refined humanistic platforms may propel robotics to a new level to improve surgeon ability further.

ADVANCES IN SIMULATOR TRAINING PLATFORMS FOR ROBOTICS

Another significant hurdle in assimilating robotics into the vanguard of mainstream urologic surgery involves the training of robotic-naive surgeons with no prior experience at the robotic console. The high costs of purchasing and housing a dedicated dry laboratory “training” da Vinci® system and the cost of surgical expendables used during training cases in wet laboratories often mean that console experience obtained at various hands-on courses is limited and fleetingly transient. In addition, heightened expectations from patients undergoing robotic surgery, medicolegal implications of accountability of attending surgeons, and demands from hospital administrators to turn

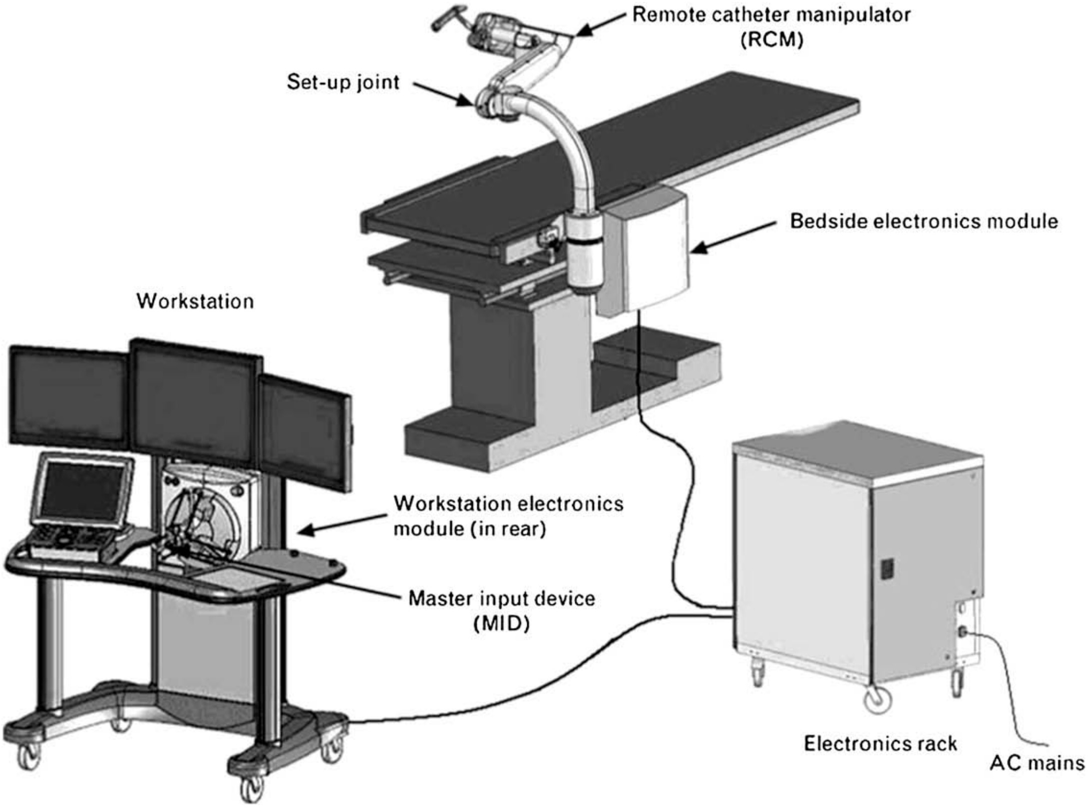

Fig. 7. Pictorial illustration of the flexible robotic catheter-control system. AC, alternating current. (*Courtesy of* Hansen Medical, Mountain View, CA; © 2009 Hansen Inc. Used with permission.)

around robotic procedures have resulted in limited opportunities for urology residents to gain operative maturity at the console.

The dV-Trainer (MIMIC Technologies, Inc., Seattle, Washington) has been developed in collaboration with Intuitive Surgical, Inc. as a solution to some of these current obstacles in surgical training.[60,61] It consists of a master console with finger-cuff telemanipulators connected to a binocular 3D visual output that aims to reproduce the look and feel of the da Vinci® console. The program encompasses exercises in EndoWrist manipulation, camera control, clutching, object transfer and placement, needle handling, needle driving, knot tying, and suturing. The cable-driven system also provides haptic feedback for the trainee as he or she executes surgical movements spatially (**Fig. 8**). Among 15 subjects with varying experience with robotic surgery, Lendvay and colleagues[62] reported significant reduction of total task time, economy of motion, and time the telemanipulators spent outside of the center of the platform's workspace in the experienced group compared with the novice group.

Researchers at the University of Nebraska are also working to produce a da Vinci®-compatible virtual reality simulator, using kinematic data from the da Vinci® console through LabVIEW (National Instruments, Austin, Texas) to drive simulation software (Cyberbotics, Ltd., Lausanne, Switzerland).[63,64] Medical Education Technologies, Inc. (Sarasota, Florida) has also made an attempt to produce a robotic surgery simulator for its SurgicalSIM package,[65] although the reception to this has yet to be reported.

ADVANCES IN REMOTE ROBOTIC SURGERY

In 2001, Marescaux and colleagues[66] reported the first experience of performing transatlantic robotic-assisted laparoscopic cholecystectomies in six pigs and one human, with the surgeon based in New York and the Zeus system installed in Strasbourg, France. Anvari and colleagues[67] subsequently reported their experience of 21 telerobotic laparoscopic operations between St. Joseph's Hospital in Hamilton, Ontario, Canada and North Bay General Hospital 400 km north of Hamilton. Through an IP-VPN (15 Mbps of bandwidth)

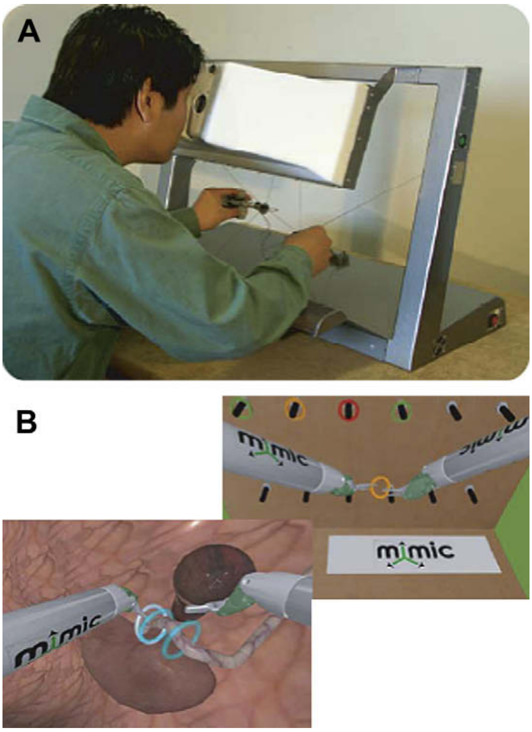

Fig. 8. The dV-Trainer. (*A*) Binocular console with 3D image viewer. (*B*) Virtual reality images seen through the viewer. (*Courtesy of* MIMIC Technologies, Seattle, WA; with permission.)

network that linked the Zeus robotic console in the teaching institute with the three arms of the Zeus TS System (Computer Motion Inc., Santa Barbara, California) in the rural hospital, the surgeons were able to operate together with the same surgical footprint, with overall latency at 135 to 140 milliseconds.[67] Their experience, albeit with two-dimensional vision, demonstrated the huge potential of robotic platforms to deliver care in remote areas and combat situations, in addition to telestrating complex robotic-assisted laparoscopic procedures to surgeons on the learning curve.

Sterbis and colleagues[68] recently reported the first experience with transcontinental robotic surgery using the da Vinci® system. Video and robotic signals were transmitted over the Internet using nondedicated lines and commercial video coding and decoding systems (Plycom, Pleasanton, California and Haivision, Montreal, Quebec, Canada). This enabled surgeons at two separate consoles (1300 and 2400 miles away from the robot, respectively) to control different parts of the same robot to complete four nephrectomies in a porcine model successfully. The round-trip delay of 900 milliseconds using a bandwidth of 3 Mbps resulted in intermittently poor vision, whereas the second console surgeon using a bandwidth of 8 Mbps had good visualization throughout with a latency of 450 milliseconds (with the difference in bandwidth being attributable to the 3D instead of two-dimensional images being transmitted).

The University of Nebraska team also recently reported the feasibility of telementoring the crew of the National Aeronautics and Space Administration (NASA) Extreme Environment Mission Operations (NEEMO) 9 mission in executing the steps of a laparoscopic appendectomy using these in vivo microrobots.[17] In this study, the crew member was telementored by means of video conferencing software after viewing a 30-second video describing the steps of the appendectomy and successfully dissected, stapled, and removed the appendix (**Fig. 9**). Lum and colleagues[69] from the

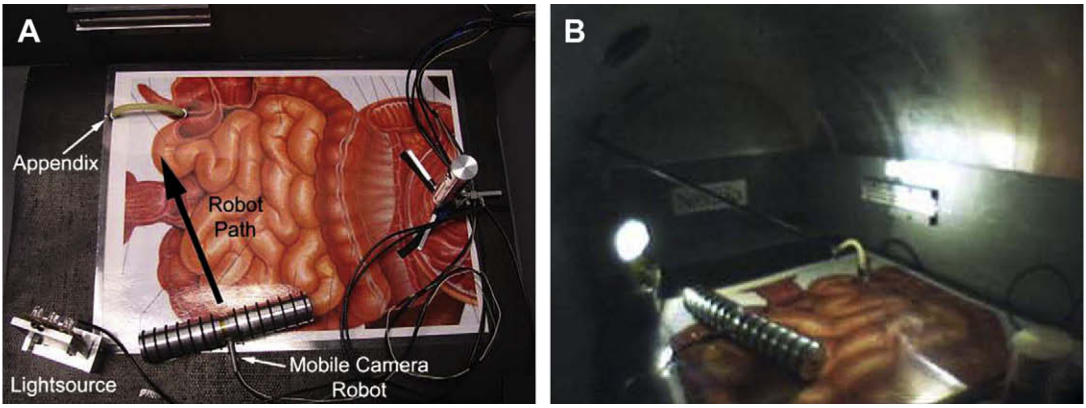

Fig. 9. (*A*) Setup for telementoring of the surgically naive crew of the NEEMO 9 mission to perform a simple appendectomy. (*B*) Real-time visual feedback of the appendectomy by means of the mobile robot's adjustable camera. (*From* Rentschler ME, Platt SR, Berg K, et al. Miniature in vivo robots for remote and harsh environments. IEEE Trans Inf Technol Biomed 2008;12:66–75; with permission.)

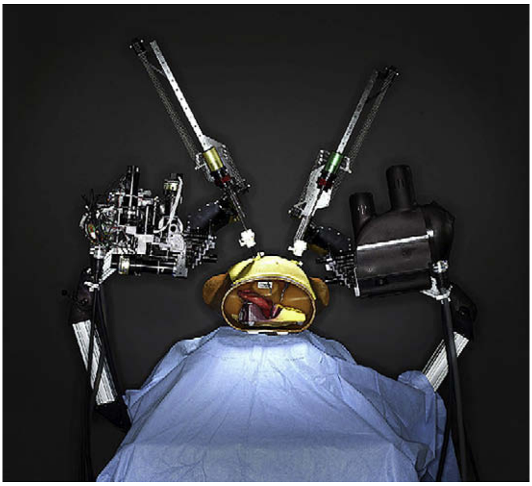

Fig. 10. The RAVEN robot designed at the University of Washington. (*From* Oleynikov D. Robotic surgery. Surg Clin North Am 2008;88:1121–30; with permission.)

University of Washington also reported their experience with the RAVEN robot (prototype designed by Dr. Blake Hannaford and his team from the Biorobotics Laboratory, Department of Electrical Engineering, University of Washington, Seattle, Washington–not yet commercially available), a prototype smaller in size than the da Vinci® system with the capability of being mounted on the patient and operated in harsh and remote environments (**Fig. 10**). Bell and colleagues[70] from the same institute also reported on their experience with a brain-computer interface that allows a person to control a humanoid robot directly using noninvasive brain signals from the scalp through electroencephalography. In that study, a partially autonomous robot was able to perform complex tasks like walking to specific locations and picking up specific objects under direction from nine different users.

As rapid advances in Internet technologies for swifter and more secure transmission of data couple the developments in surgical robotics, it is foreseeable that robotic telestration and remote surgery are likely to become commonplace practices in the not too distant future, possibly even with hands-off control of advanced robotic instruments.

SUMMARY

The advent of novel robotic and compatible technologies has occurred at a breathtaking pace in the past decade, mirroring the rapid adoption of robotic surgery among urologists and their patients worldwide. The current da Vinci® S HD System represents the state of the art, incorporating several new features that have made surgery more ergonomic and interactive for console surgeons and their patient-side assistants. Early trials of microelectrical mechanical systems devices have been encouraging, and the next step would be to refine these technologies further for empowering the surgeon with augmented real-time visualization of tissue and intracorporeal dexterity, possibly even through a single port. Virtual reality simulator training packages compatible with the da Vinci® system are going to be commercially available soon, giving robotically naive surgeons a much needed bridge for gaining familiarity and confidence at the console before live surgery. Image-guided surgery should also become increasingly more popular as technologies develop to overcome the current limitations of working with deformable mobile viscera. Developments in data and image transmission over Internet protocols and satellite platforms may soon allow remote telestration of complex robotic operations, obviating the need for surgeons to be physically present to perform or mentor such operations and delivering improved patient care to those living in remote or hazardous environments. These promising innovations look set to usher in a new era in operative urology in the near future, and the authors look forward with immense interest to how this article may be deemed archaic in a few years.

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