Future robotic platforms in urologic surgery: recent developments

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Purpose of review

To review recent developments at Vanderbilt University of new robotic technologies and platforms designed for minimally invasive urologic surgery and their design rationale and potential roles in advancing current urologic surgical practice.

Recent findings

Emerging robotic platforms are being developed to improve performance of a wider variety of urologic interventions beyond the standard minimally invasive robotic urologic surgeries conducted currently with the da Vinci platform. These newer platforms are designed to incorporate significant advantages of robotics to improve the safety and outcomes of transurethral bladder surgery and surveillance, further decrease the invasiveness of interventions by advancing LESS surgery, and to allow for previously impossible needle access and ablation delivery.

Summary

Three new robotic surgical technologies that have been developed at Vanderbilt University are reviewed, including a robotic transurethral system to enhance bladder surveillance and transurethral bladder tumor, a purpose-specific robotic system for LESS, and a needle-sized robot that can be used as either a steerable needle or small surgeon-controlled micro-laparoscopic manipulator.

Keywords

LESS, minimally invasive surgery, robotic surgery, steerable needles, TURBT

INTRODUCTION

To date, the growth of robotics use in urologic surgery has adapted the only commercially available platform, the Intuitive Surgical da Vinci robot, to a large variety of surgical procedures and anatomical locations. The advantages of the da Vinci robot allow even novices to potentially perform complex minimally invasive laparoscopic surgical tasks such as suturing and dexterous end effectors movement because of the wrist and manipulation control system. However, like all nonautonomous robotic systems, the da Vinci at present represents simply a ‘tool’, the ultimate control, performance, and decision-making process of the surgery lies with the surgeon.

The inherent kinematics and design of the da Vinci incorporate a computer-controlled mechanical interface with wire and pulley-driven end effectors. Such a mechanical structure limits the size of the instrument shafts to 5 mm or greater. The mounting and construct of the current patient side robotic da Vinci tower is not modular and, although highly adaptable, is constrained by the motion of the patient side manipulators and collision avoidance. Despite these limits, the da Vinci is a marvel of design and adaptability and has allowed many innovative clinicians to use the platform for a wide variety of surgical approaches in urologic, abdominal, thoracic, oral, and cardiac surgery. The next step for robotic surgical intervention may utilize development of alternative platforms, which allow for even more adaptable, less invasive, and purpose-specific surgical robotics [1]. Areas in development include commercially available systems for orthopedic procedures, new experimental platforms for neurosurgical and otolaryngology microsurgical

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KEY POINTS

- New purpose-specific surgical robots are in development for a variety of urologic and minimally invasive surgical procedures.
- The addition of the advantages of robotics, such as increased precision and depth of resection control combined with tissue interrogation techniques to transurethral resection of bladder tumor (TURBT) for bladder cancer, could improve cancer diagnosis, staging accuracy, and treatment interventions.
- Specific robotic platforms, such as the insertable robotic end-effectors platform (IREP), may enable optimization of single incision approaches and evaluation of the true benefits of single site (LESS) and NOTES surgical approaches.
- Steerable needle technology allows new nonlinear approaches to biopsy and ablation.
- Steerable cannula technology and robots allow for microlaparoscopic and microendoscopic robotic tools for new innovative surgical approaches.

procedures, less invasive single site surgery platforms, and robotics combined with image-guided surgery for biopsy and ablation procedures.

This review covers three robotic interventional platforms under development in collaboration between the authors at Vanderbilt University. All are applicable to urologic surgery as well as a variety of other surgical and interventional specialties.

TRANSURETHRAL BLADDER TUMOR: POTENTIAL FOR ROBOTICS

TURBT is a gold standard surgical intervention for initial pathological staging and treatment of non-muscle invasive bladder cancer (NMIBC). Initial TURBT has been shown in multiple clinical series to be inadequate for clinical staging and often results in incomplete tumor removal. Maruniak *et al.* [2] found that up to 51% of documented TURBT cases lacked muscularis propria in the pathologic specimen limiting staging. For NMIBC, the early recurrence rate at 3 months is high at up to 45% and varies between institutions [3]. This variation was unexplained by tumor factors and the authors concluded that the 'quality' of TURBT impacted recurrence rate [4]. Complete eradication of all visible tumors is recommended; however, Herr and Donat [4] studied 1312 patients with NMIBC and on repeat transurethral resection found residual disease in 51–78% of patients. Of patients with initial noninvasive disease at initial TURBT, 15% were upstaged to invasive disease at re-TURBT, and for patients with initial pT1 disease, 30% had muscle-invasive disease on re-TURBT.

TURBT presents a number of technical challenges. The geometric anatomic constraints of the urethrovesical junction make access to anterior regions of the bladder difficult without external manipulation to bring the bladder wall into the reachable workspace of the rigid resectoscope. The wall thickness and distension properties of the bladder combined with the need to resect into the muscle layer can contribute to bladder perforations and incomplete resections. Current TURBT is carried out piece-meal for all but less than 1 cm of tumors, possibly contributing to seeding and recurrence [5]. For most oncologic surgeries, suspicious tissue is resected in one piece (en-bloc) to prevent spread of malignant cells. Although en-bloc TURBT has been demonstrated clinically, the approach remains difficult with the limitations of current endoscopic technology [6–8].

From an instrumentation standpoint, limitations such as reduced resection accuracy, lack of intravesical tooltip dexterity, a limited instrumentation repertoire, and lack of in-vivo feedback and precise depth control impede TURBT improvement. Robotic assistance may allow improvement of TURBT patient surgical outcomes by enhancing safety, dexterity, and accuracy of resection, offering complete and potentially augmented visualization coverage for bladder surveillance, and facilitating en-bloc TURBT. Improving the initial technique of TURBT could potentially reduce the rate of re-resection, patient morbidity and discomfort, treatment costs and ultimately improve prognosis.

Four key improvements would seem essential: improve surveillance and staging; improve resection accuracy, dexterity, and instrument reach; provide means for delivering future in-vivo imaging modalities; provide a means for monitoring resection depth and enforcing methods to minimize perforation risks while optimizing obtaining definitive tissue for staging.

The tremor dampening stability and micro-movement control of a robotic platform can support intravesical augmented visualization and in-vivo sensory tool deployment, such as optical coherence tomography and ultrasound. Control algorithms can be developed to provide confirmation for full surveillance coverage and support-assistive telemanipulation control modes and increases in dexterity for laser or cautery ablation tools.

Improvement of the instrumentation for transurethral endoscopic urologic procedures has been an area of active interest in clinical and engineering research groups. de Badajoz *et al.* [9,10] reported a master-slave system for controlling a commercial rigid resectoscope. Hashimoto *et al.* [11] presented a robotic manipulator for transurethral prostate resection. Desai *et al.* proposed adaptation of a commercial Hanson robotic catheter system for direct visualization and treatment of stones and tested on an 18-patient clinical feasibility trial [12]. Yoon *et al.* [13] reported a shape memory alloy actuated mechanism for automated surveillance cystoscopy. Despite this active research, no system currently exists for simultaneously adding precision and improved dexterity in resection technique while providing a platform for deploying new imaging techniques and resection instruments.

We have collaboratively developed a prototype concept robot shown in Fig. 1 [14■■]. This robot fits though a standard endoscope sheath with an inner bore larger than 5 mm. The robot has eight actuators and a two-segment snake-like device that allows each segment to bend on two Degrees of Freedom (DOF). The snake robot has three working channels that allow the deployment of a standard biopsy tool, a fiberscope and integrated light source and a third working channel that is used for delivering an ablation laser fiber. The robot is axially actuated along the resectoscope sheath axis until deployed in the bladder where dexterous telemanipulation can begin (Fig. 2).

We recently published on our initial ex-vivo experiments [15■■]. The robotic prototype was deployed inside the bovine bladder through a standard resectoscope sheath (Fig. 3). The ex-vivo bovine bladder was insufflated with air and kept at constant distension for the procedure. Visualization feedback was obtained from both the on-board 1.2-mm fiberscope prototype and the external laparoscope. The external laparoscope was placed in the upper left lateral wall of the ex-vivo bovine bladder for observation because of the low resolution of this first fiberscope prototype.

Preprocedure, Indigo blue dye was manually injected submucosally in the bovine bladder to define the target resection areas. Eleven targets were chosen throughout the bladder in all of the quadrants including the anterior bladder wall. The robot was then telemanipulated to the target area as shown in Fig. 4. A 0.55-mm holmium laser fiber was deployed through one of the access channels and energy was delivered to all the targets. Additional experiments were carried out to demonstrate the feasibility of cancer resection and biopsy. A disposable biopsy forcep was delivered through

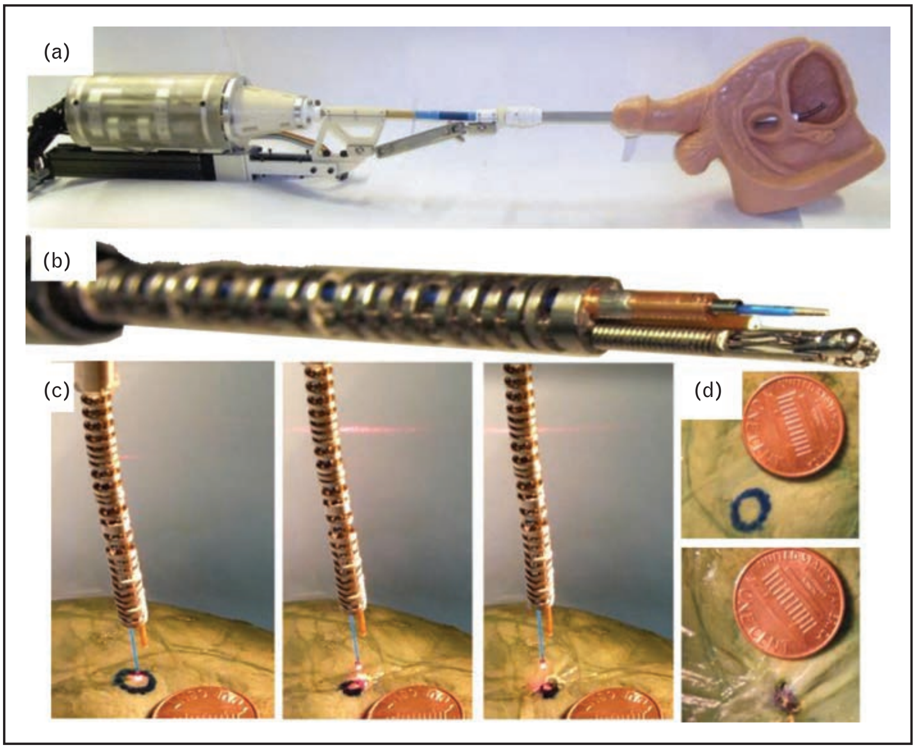

FIGURE 1. (a) Prototype dexterous manipulator robot deployed through sheath into male urethra bladder model [Reproduced with permission from [14■■]]; (b) dexterous segment and end effectors including laser, grasper, and fiberscope camera deployed [Reproduced with permission from [14■■]]; (c) Laser ablation of drawn circle on tissue model [original]; (d) before and after laser ablation of marked circle [original].

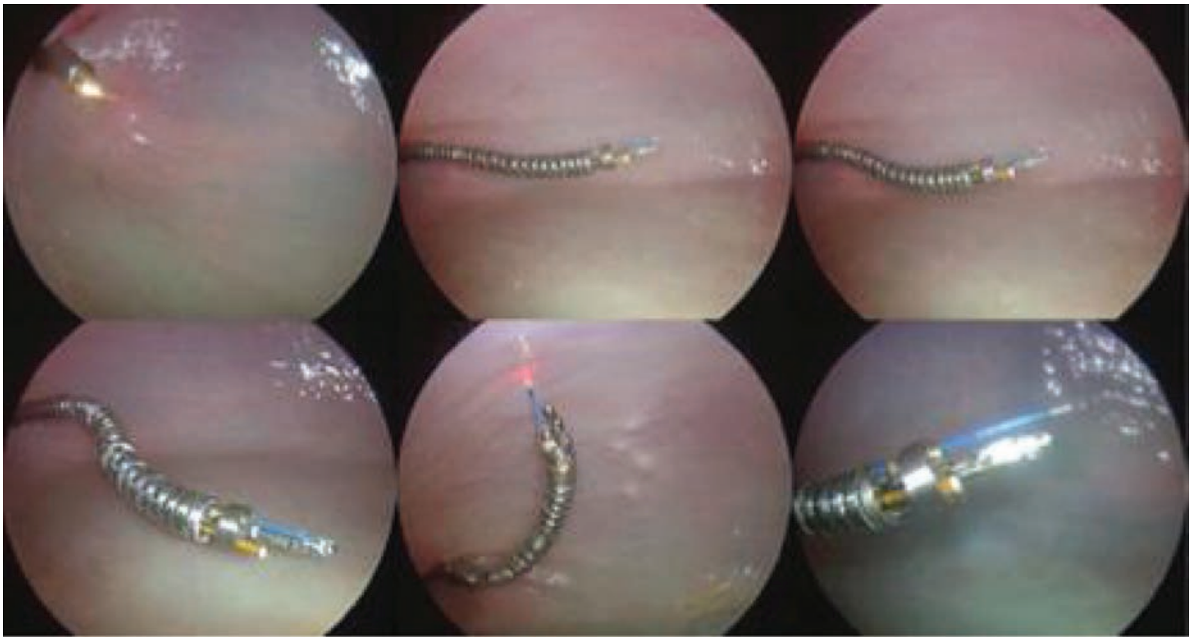

FIGURE 2. The prototype is passed axially through the resectoscope sheath and maneuvered via telemanipulation of the dexterous robot into surveillance and treatment positions with end effectors such as laser and grasper in place. Images are recorded via transvesical laparoscope. Reproduced with permission from [14▪▪].

the third access channel and target tissue was gripped and elevated as the laser was delivered to resect the sample as shown in Fig. 4c. The dexterity of the robot allows for pivoting about the contact point and performing potential en-bloc resection. Current limitations of the initial prototype included the ability to add degrees of freedom to the end effector manipulations such as grasping and wider and angled laser fiber deployment. Augmentation of control mechanisms such as depth of resection setting and augmented visualization modalities are planned for subsequent prototype generations.

FIGURE 3. Overview of ex-vivo bovine bladder experimental set-up. Screen shows endoscopic robot view. Transvesical laparoscope used for procedure monitoring and capture of images. The figure shows the slave robot's actuation unit and the master manipulator (Sensible Phantom Omni) along with endoscopic view on screen in background. Reproduced with permission from [15▪▪].

Our current robot system under development will improve on the prototype's optics and ability to maneuver and control resection and will be designed to fit through the same diameter of a standard resectoscope's outer sheath working channel. The Dexterous Arm robot will provide three working channels for resection, and auxiliary visualization. The addition of a rod lens straight endoscope in the central stem will provide a fixed general view of the field and the bending fiberscope will provide a close view for surveillance and monitoring of fine resection (Fig. 5). Ex-vivo model trials are in progress.

LESS SURGERY: THE INSERTABLE ROBOTIC END

Laparoscopic endoscopic single site surgery (LESS), also known as single-port access surgery, is a relatively recent addition to the minimally invasive surgical approaches armamentarium, which is viewed as a potential step toward true 'natural orifice' surgery (NOTES) [16,17▪▪]. Although several academic groups have performed urologic procedures such as nephrectomy, donor nephrectomy,

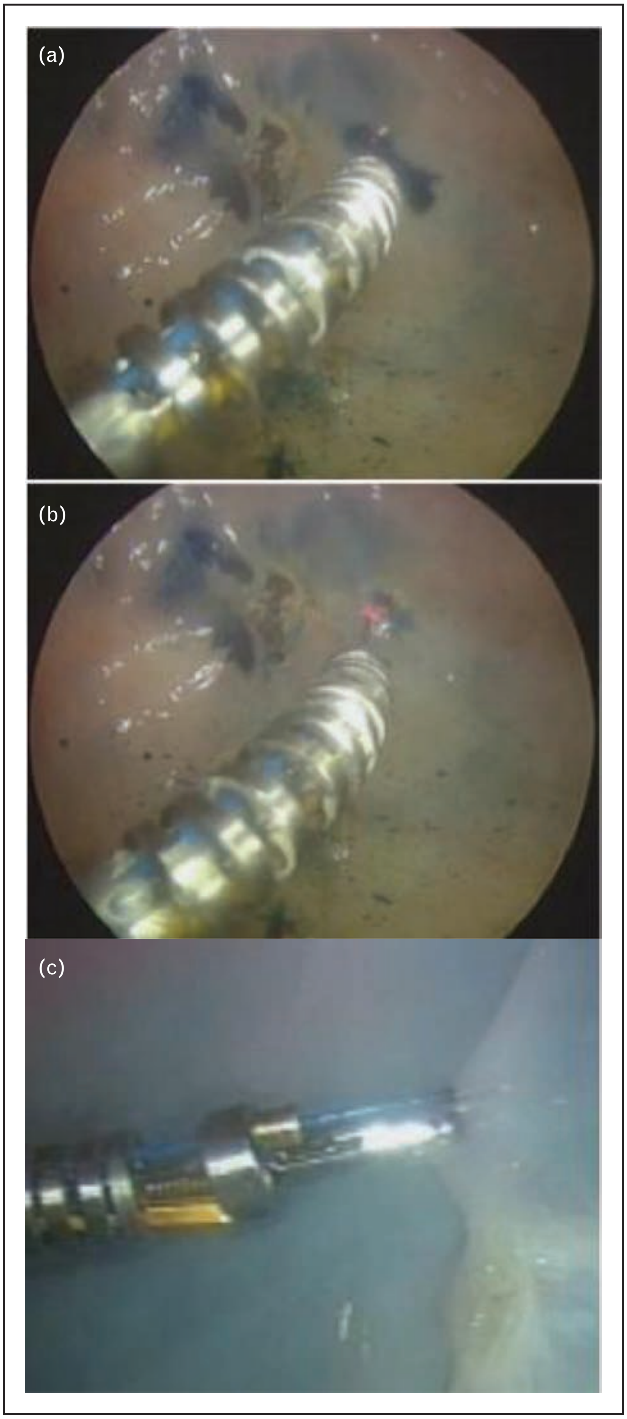

FIGURE 4. (a) The dexterous robot is maneuvered into position to laser ablate a lateral submucosal dye 'lesion'; (b) holmium laser treatment is initiated; (c) grasping end effector is used to elevate and retract tissue, as laser energy is used circumferentially for 'en-bloc' model resection. Reproduced with permissiom from [15▪▪].

prostatectomy, among others with pure hand-controlled instrumentation, crossed instrumentation and clashing pose daunting challenge to widespread acceptance [18,19]. In fact, in many cases, extra 'sites' were used with needlescopic or other instruments. After some initial success using both standard and specially developed articulating laparoscopic hand instrumentation, the majority of urologic authors pursuing LESS have incorporated the da Vinci robot to overcome the significant challenges [20▪▪,21]. At present, the potential benefits of LESS include improved cosmesis, and reductions in wound infection rates, recovery, and postoperative hernia. However, these benefits cannot be fully evaluated until the size of single-site trocar incisions and tools are optimally miniaturized. At this point of time, the only potential universally accepted advantage of the current LESS approach may be in cosmesis for the patient, towing to the lack of purpose-designed robotics.

The da Vinci platform is not specifically designed for LESS and clashing, larger 'single' incisions for insertion, and a difficult learning curve have limited translation. Recently, Intuitive Surgical has marketed an adaptive instrument set including curved cannulas and flexible instruments for LESS cholecystectomy, which is potentially adaptable to some urologic procedures. However, the curvature of the instrumentation required elimination of the multiple degree of freedom 'wrist', one of the da Vinci's main advantages [22].

LESS and NOTES would seem to require continued miniaturization, dexterity, and collision avoidance between surgical tools operating in confined spaces. Simaan *et al.* at Columbia University designed and constructed a new IREP for LESS [23,24▪▪,25,26] (Fig. 6). The IREP can be inserted through a 15-mm trocar into the abdomen. It has two dexterous arms and a stereoscopic vision module, which deploy inside the patient. This stereoscopic vision module implements automated tool tracking capabilities as an extension of earlier designs by Hu *et al.* [27]. Each dexterous arm has a hybrid mechanical architecture comprised a two-segment continuum robot, a parallelogram mechanism for improved dual-arm triangulation, and a distal wrist for improved dexterity during suturing. The IREP is unique because of the combination of continuum arms with active and passive segments with rigid parallel kinematics mechanisms. The total weight of the IREP is approximately 8.20 kg (18 lb). It is mounted to the frame of the surgical bed such that reorientation of the patient and bed during surgery is possible to optimize gravitational retraction of organs.

Other researchers have developed robotic assistance tools for LESS/NOTES. Abbott developed a wire-actuated dual-arm robotic system for NOTES, which has 16 DOF and a diameter larger than 20 mm [28]. Phee *et al.* presented a 9-DOF 22-mm dual-arm

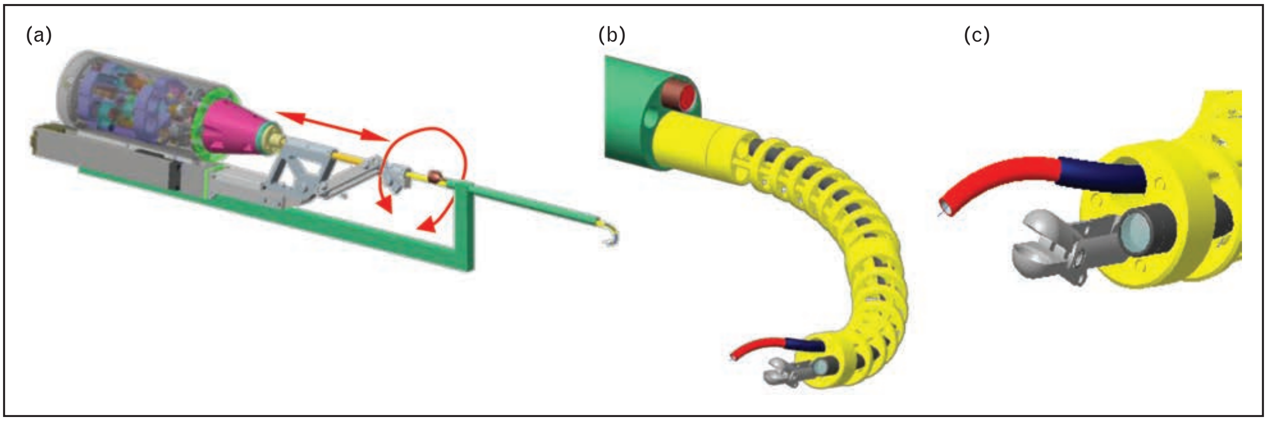

FIGURE 5. Next-generation prototype. (a) Proposed deployment through resectoscope type sheath. (b) Rigid scope (green) will carry rod lens optical fixed endoscope for wide visual guidance and irrigation and outflow. (c) Dexterous Arm robot (yellow) will carry additional optical fiberscope and end effectors. Grasper and steerable laser fiber shown in diagram. Original figure from Simaan and Herrell.

robot [29]. More recently, Harada *et al.* [30] introduced a novel concept of reconfigurable self-assembling robot for NOTES. This concept has yet to be experimentally proven. Picciagallo *et al.* [31] presented a dual-arm robot for LESS. This design used embedded motors inside the links; it has a diameter of 23 mm. Finally, Intuitive Surgical is developing a dual-arm LESS system that uses wire-actuated snake-like articulated linkages [32].

In 2010, Simaan *et al.* [24▪▪] joined the Vanderbilt University School of Engineering and we have collaboratively continued development work on the IREP platform and have demonstrated in the laboratory the ability to perform complex tasks such as suturing in inanimate models (Fig. 7). Continued development on the advanced versions of the IREP platform is progressing and currently moving toward animal evaluation.

FIGURE 6. The phase I in-vivo single port access system shown in a deployed state with two 7 Degrees of Freedom dexterous arms and a controllable stereovision camera head. Original figure from Simaan and Herrell.

CONCENTRIC TUBE ROBOTS: STEERABLE NEEDLES AND BEYOND

’Steerable’ needles come in a variety of designs and configurations, see the introduction of Rucker *et al.* 2013 [33]. Webster *et al.* [34] have described a steerable needle configuration based on nested, precurved concentric Nitinol tubes. As the number of tubes and complexities of the curves and path route increase, the kinematics and control necessitate the use of motorized drive and computer control (robotics) [35]. These needles are made from several (typically at least three) precurved tubes that are nested within each other (Fig. 8). These tubes are made from Nitinol (the same material used in cardiac stents), providing both strength and flexibility. The computer-controlled robotic system co-ordinates the linear and rotational motion of all of the tubes, and thereby is able to move the curved needle as specified by the surgeon. These needles can be made in a large range of diameters, limited only by the availability of Nitinol tubes of various diameters. Such tubes are currently available in stock from various manufacturers at diameters as small as 0.2 mm up to sizes larger than 4 mm. Potential roles for steerable needles in Urologic Surgery include biopsy and ablation delivery to previously unreachable or inaccessible areas combined with precise control and nonlinear path control [36,37,38▪▪].

Webster *et al.* [39] recently described the use of multiple of these concentric tubes as the arms of

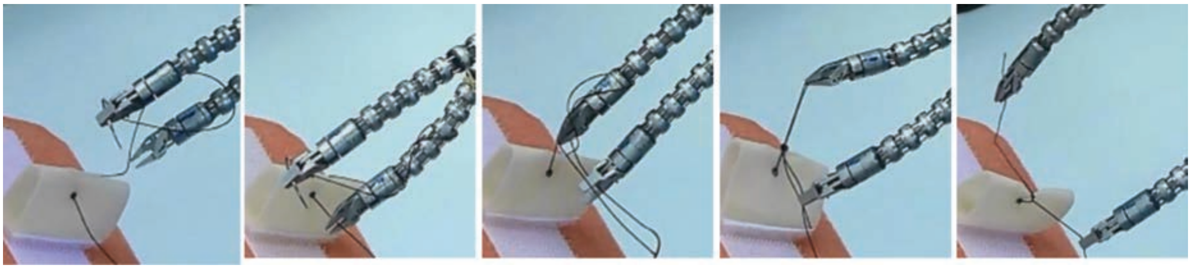

FIGURE 7. Insertable robotic end-effectors platform (IREP) arms and graspers performing knot tying task in inanimate trainer. Reproduced with permission from [24■■].

a miniature tentacle-like surgical robotic device (Fig. 9). With graspers and other end effectors attached at the end, these small manipulators can be controlled by the surgeon to potentially function similar to a microlaparoscopic instrument with some additional DOF. Visualization of the surgical field is possible by using either a conventional endoscope or by attaching a chip-tip camera to the robot.

The significant customizability of this device is one of its strengths. These robots can carry a wide variety of surgical instruments through their central working channel. Thermal ablators can be delivered through them and forceps or other small tools can be mounted to their tips. Tubes can be chosen based on the required payload. Furthermore, the robot's stiffness – and thus the amount of force that can be applied using it – can also easily be adjusted to suit the requirements of various surgical procedures by tube diameter selection. The curvatures of each tube can also be set to suit application requirements using a heat treatment process [40].

In Urology and a variety of other surgical fields, these robots offer many potential advantages. Current da Vinci instruments are limited in their size by the underlying wire and pulley architecture (Fig. 10). Concentric tube robots have now reached an exciting stage in their life cycle, in which the mathematical models and mechanical design concepts underlying them have reached a level of maturity that now enables purpose-specific systems to be developed for many specific surgical procedures. We are currently using them in laboratory studies in the contexts of biopsy, thermal ablation, as a microlaparoscopic robotics platform, and to create new types of transendoscopic robotic instrumentation.

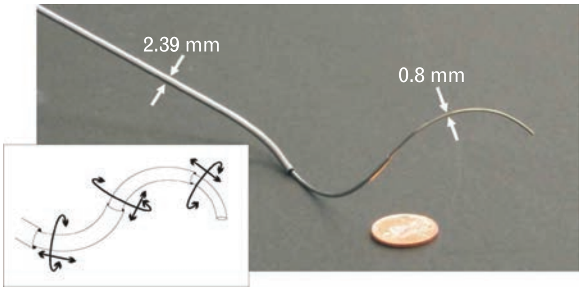

FIGURE 8. Steerable needle robot. Reproduced with permissiom from [39].

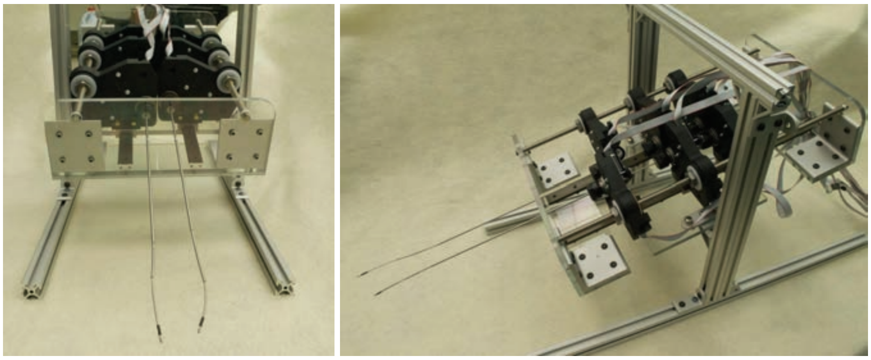

FIGURE 9. Cannula robot with microlaparoscopic-sized end effector manipulators. Original figure from Webster and Herrell.

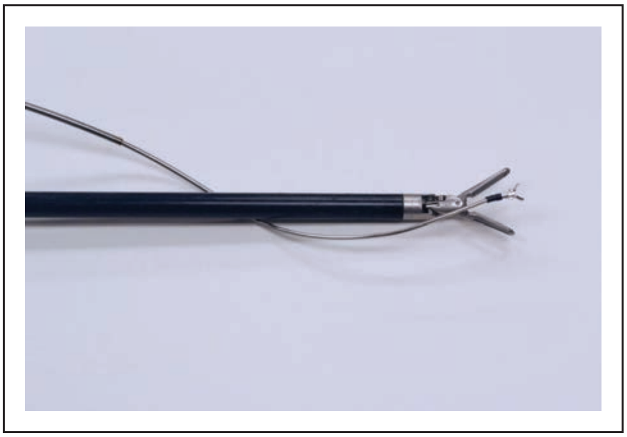

FIGURE 10. Cannula robot with microlaparoscopic sized end effector manipulator compared to standard da Vinci instrument. Original figure from Webster and Herrell.

CONCLUSION

Robotic surgical platforms, as evidenced by the adoption of the da Vinci, have had a rapid and far reaching impact on the performance of minimally invasive surgical procedures in urologic surgery as well as other disciplines. Further developments in robotics will continue to enhance the performance, and promises to improve outcomes in a variety of surgical fields. Future platforms, such as those reviewed in this article, may allow surgeons to leverage the benefits of robotics in surgery in increasingly effective ways. Such systems promise to provide enhanced dexterity, even smaller minimally invasive incisions (leading to reduced recovery time), incorporation of new imaging modalities, and ‘enhanced’ approaches to a variety of disease processes. We believe that the same technology and control algorithms developed for robotic TURBT, LESS specific robotics, such as the IREP, and the cannula-based robotics systems will also provide a valuable platform for other types of transluminal intracavitary surgery in areas such as bronchoscopy, transoral, endoluminal, and transanal surgery and may facilitate further developments in natural orifice surgery (NOTES). The field of urologic surgery has been a leader in robotic surgery development and this technologic revolution in the operating room continues to redefine urology as well as all of surgery.

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Conflicts of interest

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