A Review of the Role of Robotics in Surgery: To DaVinci and Beyond!

by Patrick Probst, MD

With new systems and applications routinely coming to market, it continues to be an exciting avenue for new research and development as well as improving the patient care experience.

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Abstract

Since its inception in 1985, robotic surgery has evolved into a mainstream surgical approach that has become virtually synonymous with minimally invasive surgery (MIS) and adopted across several specialties offering decreased patient morbidity and improved post-operative outcomes. This article discusses the current role of robotics in MIS and its varied applications, prevalence in the community and the future of the field.

Background

Advancements in surgery tend to occur within one of several broad categories – cost reduction, improved patient satisfaction, and improvement in clinical outcomes. Historically, progress was achieved by individuals altering surgical technique or implementing lessons accrued from their own post-operative experiences into intra-operative decision making. While this granular improvement is vital and continues in modern surgery, paradigm shifts in the foundation of surgical principles and instrumentation have accelerated the evolution of modern surgical medicine.

Numerous significant shifts in surgery have occurred in the past few decades including the introduction of endoscopic equipment for not only diagnostic but therapeutic management of disease. Since the dissemination of laparoscopy, surgeons have continued to explore less invasive approaches now in the form of robotic assisted surgery.

It is the natural progression for the evolution of surgery to push the degree of invasiveness towards the extreme of the spectrum over time in order to improve patient satisfaction and clinical outcomes. The typical hindrance of such innovation is related to cost.

However, with modern advancements in optics, mechanics, energy, computing power, and more, this progression and adaptation into everyday practice is occurring at an ever-increasing speed. Robotic surgery continues to be at the forefront of MIS innovation given its ability to minimize human error and increase surgical precision and operative standardization. But, it is important to define what constitutes robotic surgery. Currently, "robotic surgery" is often used synonymously with the most widely recognizable robot, the DaVinci surgical system. This platform by Intuitive consists of three components that allow the surgeon to indirectly control robotic arms that grasp, transect, coagulate, staple, clip and suture. While this master-slave or passive apparatus

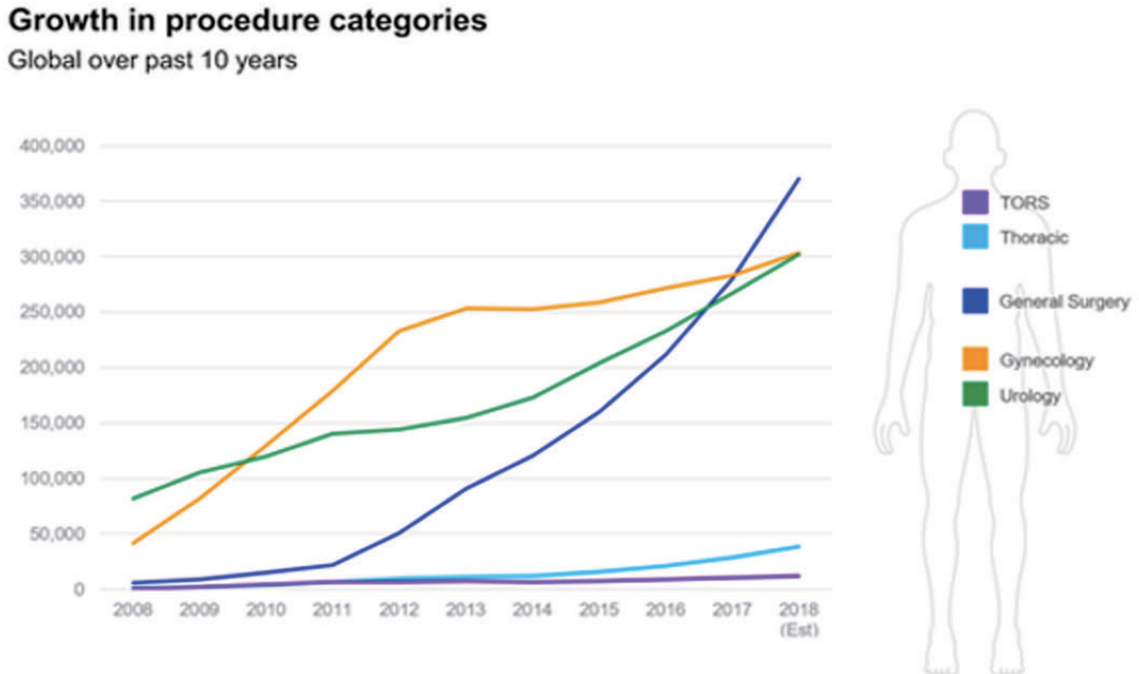

Image 1. Trends in Number of Robotic Cases by Sub-Specialty

that allows for telesurgery remains the most popular globally, other surgical robots can be classified into two other categories: supervisory-controlled, and shared control.[1]

Supervisory-controlled systems allow pre-operative planning with robotic execution under close supervision, such as with aquablation of the prostate in urology. Shared-control systems allow the surgeon and robot to function simultaneously, such as with spine and arthroplasty robots in neurosurgery and orthopedics.[1] This article will highlight the current role of robotic systems in minimally invasive surgery.

Robotic-Assisted Laparoscopic Surgery

DaVinci Laparoscopy

The DaVinci robotic surgical platform (Intuitive surgical Inc., Sunnyvale, CA, USA) was first made commercially available in 2001. It has subsequently undergone three iterations and its most modern format is the DaVinci Xi. Since its inception, this platform has been widely adopted and now used in over 10 million cases over two decades, in five specialties and grown to dominate the robotic assisted laparoscopic (RAL) market (Image 1).[2] At least 85% of prostatectomies are performed robotically and the number of hysterectomies performed robotically has increased by 300% over the last decade.[3,4] In comparison to open surgery, use of the DaVinci robot has shown significant improvement in clinical outcomes often demonstrating less blood loss, a shorter length of stay and less opioid consumption as supported by numerous multi-specialty reports in the literature.[5,6,7,8]

These well-described clinical benefits and rapid adoption by a growing number of surgeons ensures that, for the foreseeable future, the DaVinci robot will continue to be a mainstay in the minimally invasive surgical management of oncologic and reconstructive pathologies in cardiothoracic surgery, general surgery, urology and gynecology. In fact, multiple medical specialties now incorporate training modules and robotic skills courses into their curriculum and require residents to have robotic platform specific training in order to graduate.

However, the original DaVinci patents have now expired and significant robotic system development and competition is expected, particularly in

Robot	Uses	Port	Arms	Haptic Feedback	Eye Tracking	US FDA Approval
DaVinci Xi	MIS	MP	4	No	No	Yes
DaVinci SP	MIS NOTES LESS	SP	1	No	No	Yes
Senhance	MIS	MP	4	Yes	Yes	Yes
Revo-i	MIS	MP	4	Yes	No	Pending (Korea)
SPORT	MIS NOTES LESS	SP	1	No	No	Pre-Clinical
Versius	MIS	MP	4	No	No	Pending (Europe)
MiroSurge	MIS	MP	3	Yes	No	Pre-Clinical
SurgiBot	LESS	SP	1	N/a	N/a	Pending (China)
NeoGuide	NOTES	N/a	1	No	N/a	Yes
Invendoscopy	NOTES	N/a	1	No	N/a	Yes
Flex Robotic	NOTES	N/a	1	No	N/a	Yes
Monarch	NOTES	N/a	1	No	N/a	Yes
Ion	NOTES	N/a	1	No	N/a	Yes
PROCEPT	NOTES	N/a	1	N/a	N/a	Yes
Roboflex	NOTES	N/a	1	No	N/a	Yes

Table 1. Current and Popular Robotic Surgical Systems Worldwide (MP – multiport, N/a – not applicable)[60]

regards to novel technology, reduced cost and size reduction.[9] Current DaVinci platforms do not utilize haptic feedback, the experience of touch by applying resistance to the user, or biometric integration such as eye tracking cameras or head tracking robotic arms that can better replicate a traditional open surgical environment.[10] Additionally, the sizable physical footprint of the DaVinci robot tower, arms and console has proven restrictive in its implementation as well as the significant cost of the system, as the Xi still costs approximately $1.5 million per system.[11] With the expected increase in number of robotic laparoscopic cases over the next decade, numerous companies have entered and expanded the market (Table 1).

Laparo-endoscopic Single-site Surgery (LESS)

The SinglePort (SP) system, created in 2018, is Intuitive's venture into the LESS space. Through a 2.5cm incision, a solitary port releases 1 camera and 3 robotic arms which are controlled from the console by the surgeon similar to the Xi. This approach allows for better cosmetic outcomes – a single incision, quicker patient recovery, and similar optics and dexterity of the instruments. Clinical adoption has continued to increase. Between 2020 and 2021, there has been a 56% increase in the number of SP robotic systems nationwide.

Few companies thus far have made a meaningful impact in the LESS space. However, the STRAS system, version 2 (iCUBE, Strasbourg, France) is a flexible endoscopic system capable of single port intraluminal surgery. Although still in preclinical development, its main advantage over current LESS platforms is its significantly smaller size and the option for table mounting arms. The Single Port Orifice Robotic Technology (SPORT) Surgical System (Titan Medical Inc., Toronto, Canada) also uses a 2.5cm incision to deliver two articulating instruments and a camera for LESS. It is pending FDA approval but has demonstrated success in a single port partial nephrectomy in animal models.[11]

Non-Laparoscopic Robotic Surgical Platforms

Natural Orifice Translumenal Endoscopic Surgery (NOTES)

Robotic NOTES is an exciting area of research and advancement in MIS. The NeoGuide Endoscopy System (Intuitive Surgical Inc., Sunnyvale, CA) and the Invendoscopy E210 System (Ambu, ballerup, Denmark) are flexible self-propelling colonoscopes that have had FDA approval since 2006 and 2016, respectively.[12,13] The lightweight systems are easier to manipulate and apply less force to the colon wall to reduce the colonic looping phenomena that is responsible for the majority of post-operative pain. Similarly, the Flex Robotic system (Medrobotics Corp., Raynham, MA, USA) is a robotic platform intended to increase accessibility to deep organs. Its current indications include transoral procedures and recent feasibility studies demonstrate a role for rectal cancer resection.[14] This platform has had FDA approval since 2015.

Although these systems are segregated into their own unique approaches, their enhanced visualization has spurred ongoing research to assess the potential to combine NOTES, LESS and other laparoscopic robotic approaches for more diverse and complex surgical applications.

Bronchoscopy Platforms

Bronchoscopy and transthoracic needle aspiration are the two main approaches for diagnostic biopsy of peripheral lung lesions. However, the diagnostic yield of bronchoscopy ranges from 67-84% compared to 92% in needle aspiration due to “getting lost” in the peripheral airways.[15,16] The addition of robotic guidance systems, Monarch platform by Aurius health in 2018 and Ion Endoluminal System by Intuitive Surgical in 2019, has the potential to increase yields close to 95% and increase the ability to localize and precisely puncture peripheral nodules.[17,18] These systems increase structural support with a locking outer sheath but have an inner flexible controllable bronchoscope with electromagnetic navigation guidance and continuous visualization. This allows for 4-way adjustable angulation to reach farther than conventional bronchoscopy, prevent accidental displacement during sampling, and visualize and tamponade bleeding.[19] As this technology expands, there is the potential for adding ablative therapies for the treatment of oligometastatic or inoperable peripheral lung tumors.[20]

Ureteroscopy Platforms

Ergonomic deficiencies during stone manipulation, laser disintegration, surgeon fatigue, exposure to radiation during fluoroscopy and the need for assistance while performing ureteroscopy has led to the development of robotic ureteroscopes. The first clinical application of robotic ureteroscopy (URS) was introduced in 2008 by Desai and colleagues with the Sensei-Magellan system.[21] Since that time the Avicenna Roboflex system, introduced in 2013, has been the only system that remains in clinical use.[22] The surgeon sits at the console controlling a flexible arm that can rotate, advance, retract and deflect as well as manipulate irrigation, lasers and stone baskets. Treatment times, safety profiles, and three-month stone free rates were similar to conventional URS.[23] As these systems develop, the ability to have tactile feedback from the tip of the ureteroscope, 3D positioning and memory to find stones based off of pre-operative imaging, and adaptive intelligent control of the laser settings as the stone is being fragmented could allow for further utility and offset the higher cost of using a robotic system.[22]

Image 2. The Procept aquabeam handpiece

Aquablation

Aquablation (AA) is the newest robotic platform being used in the field of urology. It is a surgeon-planned, ultrasound-guided, robotically executed technique to resect prostate tissue athermally using a high velocity water jet.[24] It is approved for use in men with benign prostatic hyperplasia with 30-150g prostates with or without a median lobe.

The AA system, developed by Procept, uses a transrectal ultrasound to visualize the prostate. The proprietary software is then used to map the prostate dimensions and the anatomic areas of the median lobe, transitional zone and peri-verumontanum tissue (Image 2, 3). A robotically controlled transurethral waterjet is then programmed by the surgeon to resect a specific amount of prostate tissue in a precise location, up to 0.25mm at a time. The robotic system is then activated by the surgeon and the pre-determined tissue is removed within minutes.

This has quickly gained popularity in the urologic community given its short learning curve,

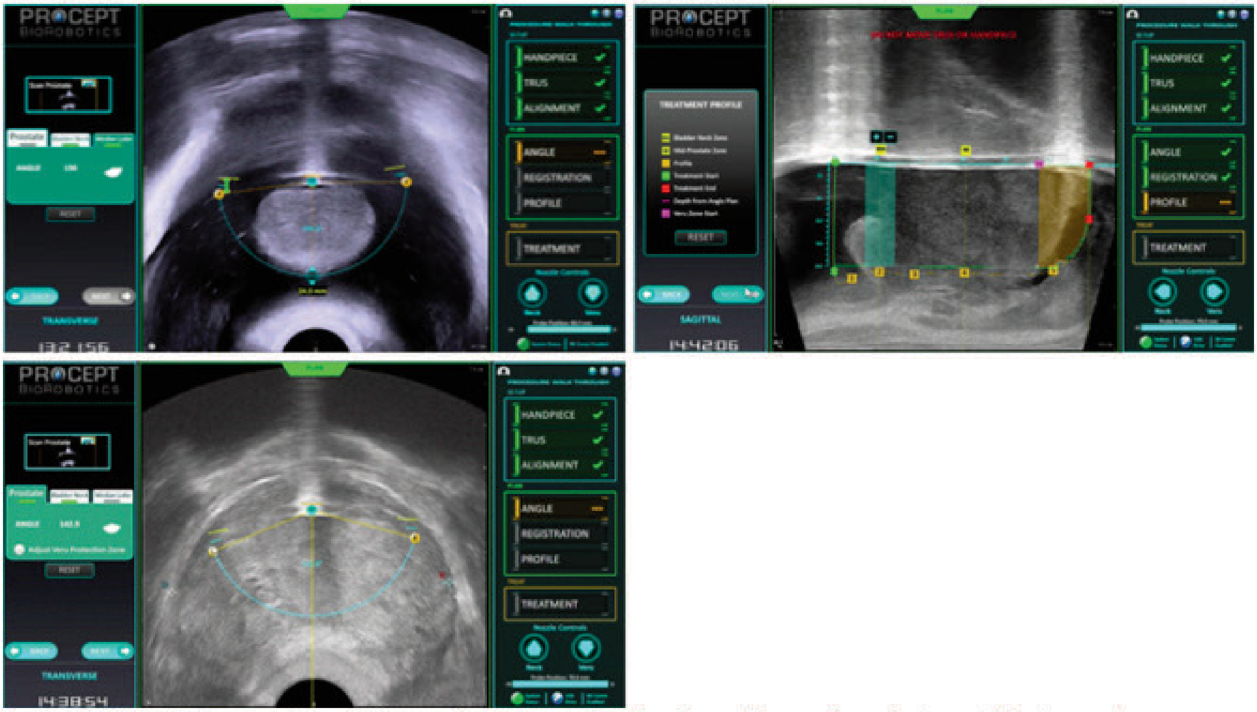

Image 3. Prostatic mapping of the median lobe, mid-gland, and dynamic points – sphincter and bladder neck

use of common urologic skills (transrectal ultrasound and rigid cystoscopy), short operative times, wider range of patient inclusion and encouraging clinical outcomes. There is a 6% incidence of restarting medications or requiring surgical retreatments compared to 12.3% with the gold standard TURP, preservation of sexual function and a 50% reduction in retrograde ejaculation compared to alternative surgical approaches for BPH.[25,26] Due to these advantages, the number of AA systems has increased by 52% over the last 9 months.

Robotic Arm-assisted Arthroplasty

The success of knee and hip arthroplasty relies on surgeons' technical ability to achieve optimal position and alignment of the prosthesis.[27] Computer-assistance with navigation allows for pre-planning and real-time intra-operative feedback while the robotic arm stabilizes and optimizes positioning of the prosthesis and surgical instruments. ROBODOC (Integrated surgical systems, Davis, CA, USA), introduced in 1992, was an active system independently performing the osteotomy and only allowed for the surgeon to start and stop the procedure.

A semi-active system, such as RIO by MAKO Surgical Corp., is now the most widely used system in modern orthopedics. Using a pre-operative extremity CT scan, a 3D model with pre-programmed boundaries is created that limits the range of movement of the surgical instruments controlled by the robotic arm.[28,29] All actions, such as reaming and osteotomy, are performed according to pre-operative planning, but the final manipulation depends on surgeon execution.

Compared to traditional total hip arthroplasty, the MAKO system can reduce varus and valgus deformities of the femoral prosthesis, restore the offset, and more accurately position the acetabular cup prosthesis in the safety zone.[30,31,32,33] Although several studies report the benefit for less intra-operative blood loss, low complication rate and shorter hospital stay with robotic systems, the literature doesn't report a significant difference in short-term clinical efficacy through the Harris hip score or other scoring systems.[33,34]

The FDA has approved MAKO and NAVIO surgical robots for uni-compartmental/total knee arthroplasty (UKA/TKA) as well. These systems employ visual, tactile and auditory feedback to improve surgical efficiency and achieve a more precise osteotomy alignment.[35]

Over the last decade, use of robotic systems for UKA has more than doubled in certain regions of the US due to the definite and repeatable evidence of improved femoral and tibial prosthetic positioning accuracy by 3 and 3.4 times, respectively.[36,37] Additionally, soft tissue balance improves and the joint dynamics of the knee have better function and greater longevity.[35]

Patients report superior pain scores at 2 months and functional scores at 3 months when compared with traditional approaches.[38] Continued long-term, prospective and randomized-controlled trials are needed to further study the use of MAKO in TKA patients.

Spine Robot Platforms

The Mazor robotic platform (Medtronic Navigation, Louisville, CO, USA; Medtronic Spine, Memphis, TN, USA) was first FDA approved in 2004 and is currently one of the most popular systems in the world for spinal pedicle screw placement. The initial system, SpineAssist, had a patient-mounted track that used pre-operative or intra-operative CT imaging to plan hardware trajectory. The current model, Mazor X Stealth Edition, released in 2019, no longer requires a patient-mounted track, has faster computing speed, the vertebral bodies can be registered individually, and an optic camera allows for self-detection of the robot to avoid intra-operative collisions.

ExcelsiusGPS (Globus Medical, Inc., Audubon, PA, USA) was the first spine robot with a fully integrated navigation platform, real-time instrument tracking and pedicle screw placement without guidewires. Similar to the Mazor X Stealth Edition, intra-operative fluoroscopic imaging can be merged with pre-operative CT scans (Image 3).

These robotic systems aid in maintaining a fixed working angle to reduce inaccuracies and tremors by the surgeon and thus allow for more consistent, safe and improved patient outcomes. While, studies demonstrate a high accuracy rate of robotic assisted pedicle screw placement (91-98%) comparisons with traditional approaches have not shown an overwhelming improvement in accuracy.[39,40,41,42] A recent meta-analysis has demonstrated decreased screw revision risk when using robotic-assisted and navigated screw placement over free-hand techniques.[43] Additionally, robotic assistance can reduce the risk of proximal facet joint violation, compared to freehand techniques, which can minimize the risk of adjacent segment disease.[44,45,46]

Limitations to robotic spinal surgery include cost, lack of diverse indications for its use, increased operative times and lack of direct evidence of benefit. In fact, several database studies report increased risk of re-operation, 30 day readmission rate and complication rate with robotic assistance in lumbar spinal fusion.[47,48] While the technology continues to improve, more research is needed to increase the implementation of robotics in spine surgery.

The Future

Two on-going areas of intense research include robotic telesurgery and micro-robotics. The new 5G network deployed by telecom companies worldwide offers rapid communication and the potential for telesurgery in order to reduce health care costs and improve patient access to quality care. Studies have determined that a lag time <400ms is imperceptible to the surgeon and this can be achieved using 5G networks. Telesurgery has been performed in China, Germany, Italy and Spain with promising results. Remote nephrectomy was safely performed without complication and conversion with a median distance of 187km between surgeon and patient. The median round trip delay was 26ms and total delay was 200ms.[49,50] Over time, the extent and feasibility of telesurgery will continue to be tested. This is promising for use on aircraft carriers, for future space travel and in underserved areas worldwide. As of this year, however, a radical cystectomy was performed remotely from a distance of nearly 3000km with an average total delay lag time of 254ms.[51]

Investigative micro-robotic prototypes are freely mobile capsule endoscopes that offer a variety of diagnostic, targeted drug delivery and surgical applications.[52] One such robot is a millimeter in size and has been, in porcine models, directed with extracorporeal magnets to apply a single functional nitinol clip and stop colonic bleeding following biopsy.[53]

Research is ongoing around four categories specific to micro-robotics: contained propulsion, miniaturized functionality, accurate telemanipulation and consistent visualization.[2]

Propulsion can be achieved externally via electromagnetic fields or ultrasonographic energy while internally driven systems are more restricted as they require chemical reactions for motion and a separate navigational source.[9,54] Several studies have demonstrated proof-of-concept for cutting, grasping and ablation on the micro-scale.[55] There is also early promise with phototaxis of polysterene beads and magnetically directed chrome spheres using MRI for telemanipulation. Finally, studies have demonstrated the ability for live-tracking of ferromagnetically labeled microalgae to model microbots in rats, X-ray angiography tracking of a radio-dense robot in the aorta of a rabbit, and US tracking of a magnetically-labeled robot through muscle tissue in a chicken model.[56,57,58,59]

The age of microbots is clearly in its infancy. However, as further research is performed to address safety to the patient and operator, cost and accessibility, creation of 3D tracking and the potential role of fluorescence, significant advancements could create another major paradigm shift in minimally invasive surgery.

Conclusion

Robotic technology has created a unique paradigm shift in the surgical care of the patient beginning several decades ago. With new systems and applications routinely coming to market, it continues to be an exciting avenue for new research and development as well as improving the patient care experience. As advancements in computer processing, optics, mechanics and haptic feedback continue to rapidly progress, robotic surgery has cemented its role in modern surgical medicine and its near universal adoption across surgical and medical specialties offers promise to continue to improve medical care around the world.

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Disclosure

None reported.

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