



Current and Upcoming Robotic Surgery Platforms and Adjunctive Technologies

Nikhil Sapre, Taimur T. Shah, and Prokar Dasgupta

1 Introduction

Over the last 30 years, laparoscopic surgery has transformed care of patients in urological surgery. However, laparoscopy is limited by its 2-dimensional (2D) vision, ergonomics, and limited range of motion. This has meant several aspects such as operating in a narrow field in the pelvis, and complex reconstruction remains challenging with a significant learning curve. The advent of robotic assistance has overcome several limitations of laparoscopy with its 3-dimensional (3D) vision, better dexterity and range of movement, HD visualization, motion scaling, and tremor filtration. Robotic assistance has increased the utilization of laparoscopy significantly changing the landscape of urological surgery. In urology, it has been used to perform pelvic surgery such as radical prostatectomy, cystectomy, and urinary diversion as well as upper tract surgery such as radical and partial nephrectomy, adrenalectomy, and pyeloplasty. More recently, we have seen robot-assisted laparoscopic surgery in female and functional urology as well as reconstructive urology. Robot assistance and autonomous systems are also being applied to BPH surgery, ureteroscopic stone surgery, and ultrasound-guided prostate biopsies.

Robot-assisted laparoscopy was first used in urology at Frankfurt, Germany, using the da Vinci surgical system (Intuitive Surgical Inc., Sunnyvale, CA, USA) [1] to perform radical prostatectomy. Since then, innovation in robot-assisted laparoscopy has seen several versions of this system enter the market from the original Si system to the current models such as Xi and SP (single-port) systems. Some patents for the da Vinci system expired in 2019 paving way for new platforms to enter the market.

In this chapter, we summarize the various robotic platforms available in the market currently as well as systems in development which are likely to enter the market in the near future. We also discuss various adjunct technologies that are in use on these robotic platforms for pre-operative planning as well as intra-operative guidance.

Finally, we discuss how precision robotics, connectivity, and surgical data science are being used to expand the horizons of robotic surgery.

2 Robotic Platforms

Table 1 summarizes the currently approved robotic assistance systems currently available in the market [2].

2.1 da Vinci Surgical System

Approved by the FDA in 2000, this is the main surgical system in the market and is used in adult cardiac, general, gynecology, head and neck, and urological surgery as well as in pediatric surgery [3]. This master–slave robotic system consists of a surgeons console system, which is used to control interactive robotic arms at the patient-side cart (Figs. 1 and 2). The robotic arms have EndoWrist technology and seven degrees of freedom and can act as retraction, cutting, or electrosurgical tools. Four generations of this system have since been released including the da Vinci, S, Si, and Xi. In 2018, the da Vinci SP (single-port) system was approved by the FDA.

The Xi system has an end-mounted camera that can be positioned in any port, thinner robotic arms, better endowrist joints, and longer instrument shafts allowing more efficient multi-quadrant procedures.

The SP system patient cart utilizes a single robotic arm with a 2.5 cm cannula, through which an oval 12 × 10-mm 3D-HD fully wristed endoscope and three 6-mm wristed and elbowed instruments can reach up to 24 cm depth. The can-

N. Sapre · T. T. Shah
Department of Urology, Guys Hospital, London, UK

P. Dasgupta (✉)
Department of Urology, Guys Hospital, London, UK

MRC Centre for Transplantation, Guy's Hospital, King's College
London, London, UK

Table 1 Currently approved robotic surgical systems

Robotic system	Surgeon console	Controller	Key features
da Vinci Xi	Closed	Finger loops	8 mm camera port and 8 mm instruments 10 uses per instrument Three instrument arms Port hopping camera Dual console
da Vinci SP	Closed	Finger loops	Single-port Single robotic arm through a 2.5 cm cannula with 360° of rotation 12 mm articulating camera Three 6 mm instrument arms
Senhance	Open/3D glasses	Laparoscopic handles	10 mm camera Four independent robotic arms (10 mm, 5 mm, 3 mm) Infrared eye tracking for camera control Haptic feedback Dock free design Reusable instruments
Revo-I	Closed	Finger loops	10 mm camera 7.4 mm instruments with 20 uses each Excessive force use warning
Versius	Open/3D glasses	Joystick handles	10 mm camera and 5 mm instruments Haptic feedback Portable independent arms, individually mounted in separate patient-side carts Surgeon can be in sitting or standing position Dock free design
Avatera	Open	Finger loops	10 mm camera with 5 mm instruments Only consists of 2 components Single use instruments
Hinotori	Semi-open	Finger loops	Dock free design Only approved for use in Japan

Fig. 1 The three components of the DaVinci Xi system and the surgeons console, visual tower, and patient cart on a single extendable and maneuverable boom

nula and the boom can rotate 360° allowing excellent vision. The surgeon console of the SP system, while similar to multi-port model, has additional features that allow the surgeon to move the entire robotic arm in addition to moving the instruments separately. The navigation interface also allows the surgeon to track the position of each instrument during surgery.

Many surgeons have since published their experience and outcomes of robot-assisted laparoscopic radical prostatectomy (RALP), robot-assisted radical cystectomy (RARC), robot-assisted radical nephrectomy (RARN) and robot-assisted partial nephrectomy (RAPN), robot-assisted pyeloplasty, and other reconstructive procedures using the SP system [4–8].



Fig. 2 Surgeon sitting at the DaVinci Xi closed console

2.2 Senhance

Initially developed by the Sofar (Milan, Italy) and originally named the ALF-X, the Senhance surgical system (TransEnterix Surgical Inc., Morrisville, NC, USA) has been approved by FDA for general and gynecology procedures. It has CE Mark certification for all abdominal and non-cardiac thoracic procedures and recently its use for various urological procedures was described in Europe [9, 10]. It has a remote console unit called a cockpit, up to four independent robotic arms in separate patient carts. It provides 3D HD vision, haptic feedback, camera control using surgeon's eye movements via infrared eye tracking system and reusable laparoscopic tools.

2.3 Revo-I

The Revo-I is approved for use in Korea and is based on a similar platform to the da Vinci system. It consists of a four-arm patient cart with 7.4 mm wristed instruments, a closed surgeon console, and a HD vision cart with a 10 mm endoscope. It has been used to perform retzius-sparing RALP in the first human trial in 17 patients with acceptable peri-operative, early oncological, and continence outcomes [11]. Specifically, there were no conversions to open to laparoscopic surgery.

2.4 Versius

The Versius surgical system (Cambridge Medical Robotics Ltd, Cambridge, UK) received the European CE Mark in March 2019. The robotic arms, which have shoulders, elbows, and wrists, are individually mounted in separate patient-side carts allowing for optimization of port placements [12] (Fig. 3). Instruments are sleek at 5 mm diameter



Fig. 3 CMR robot dockless individual patient arms



Fig. 4 Surgeon standing at the CMR robot console

and are controlled through a joystick on the console. The open-console design with 3D HD vision allows for excellent communication between the console surgeon and the bedside team. The ability of the surgeon to be upright in the sitting and standing position allows for excellent ergonomics (Fig. 4). The system has been used in a preclinical setting, where multiple surgeons successfully performed prostate surgeries, renal surgeries, and pelvic lymph node dissection (PLND) on cadavers and porcine models [13].

2.5 Avatera

The Avatera system (Avateramedical GmbH, Jena, Germany) consists of only two components. The surgical robot has four robot arms, which controls up to 3, 5 mm avatera instru-

ments, which provide seven degrees of freedom and a 10 mm HD endoscope. The open-console control unit includes a microscope-like eyepiece, an integrated and flexible seat, and easy handling via haptic, manual input devices and foot-switches. All instruments are single use eliminating the need for sterilization.

2.6 Hinotori

The Hinotori system (Medicaroid Corporation, Kobe, Japan) is approved for human use in Japan only with plans for expansion internationally [14]. The surgeon cockpit is a semi-open console with microscope-like eyepiece, which provides a 3D HD view and loop-like handles, which control the wristed robotic arms. The operative unit has four robotic arms, which have multiple joints with movement in eight axes. There are no publications of its use in human studies yet.

2.7 Future Robotic Surgical Systems

The global market for robotic surgery is \$13.3 billion by 2026 [15]. It is not surprising that many companies have developed surgical robotic systems to enter this lucrative market. Multiport robotic systems recently launched include the Hugo RAS system (Medtronic, Dublin, Ireland), a modular, open-console surgical robot; and in development the BITRACK system (Rob Surgical, Barcelona, Spain), a three-arm, open-console system, the Tumai surgical robot (MicroPort, Shanghai, China), Verb surgical (Johnson & Johnson, USA), Virtuoso Surgical system (Nashville, TN, USA). The Single-Port Orifice Robotic Technology (SPORT) surgical system now rebranded as ENOS (Titan Medical, Toronto, Canada) is a robotic single access system with a flexible camera and two multi-articulated instruments [16] and is expected to compete with the da Vinci SP if it receives FDA clearance for commercial use.

2.8 Other Robotic Systems in Urology

The use of robotics is not only confined to laparoscopic surgery but has also been utilized within the fields of benign prostatic hypertrophy (BPH), urolithiasis, and diagnostic with a different method of application in each system.

Aquablation is a minimally invasive robotic system for the treatment of BPH using high-pressure saline. The aim being to destroy prostatic tissue through non-thermal hydrodissection, the system is made up of a conformal planning unit (CPU), a robotic hand-piece, and a console. Prior to commencing treatment, the prostate and ablation zone is

mapped out in advance with the required depth and angle of the water jet selected. The high-velocity jet is controlled by the surgeons foot pedal and will proceed along the pre-defined ablation map [17].

Since 2010, ELMED (Ankara, Turkey) has been working on a system specifically designed for Robotic flexible ureterorenoscopy (FURS) called the Avicenna Roboflex. The robot consists of the surgeon's console and the robotic arm which controls the flexible ureterorenoscope with different attachments available for the various endoscope manufacturers. The robotic arm is controlled from the console using a joystick and wheel which allow for very accurate and fine movements in all directions such as forward/backward, 220° rotation in both directions, and 262° of deflection bilaterally. The entire procedure can be performed from a sitting position, outside of radiation field. The laser fiber and the irrigation speed of the fluid can both be controlled from the console [18].

Robotic systems have also been developed for automated prostate cancer biopsies such as the transperineal biopsy iSR'obot Mona Lisa from Biobot Surgical Ltd., Singapore. It incorporates fusion of the pre-biopsy MRI with real-time transrectal ultrasound images to construct a 3D model of the prostate. As with other MRI-fusion systems the images are contoured prior to biopsies taking place; however, in the case of the iSR'obot™ Mona Lisa a software-controlled robotic arm mounted to the operation table that takes biopsies according to the pre-defined plan up to a sampling density of every 1 mm [19].

3 Adjunct Technologies for Robotic Surgical Systems

3.1 Instruments

3.1.1 Robotic Staplers and Sealers

The EndoWrist Stapler, a fully wristed endoscopic linear stapler, which can be introduced into the operative field through a 12 mm port, places more control in the hands of the console surgeon. It is equipped with *SmartClamp* technology, which detects whether the jaws can adequately close on the target tissue for the given staple height and informs the surgeon accordingly. It also notifies the surgeon and prevents firing when it detects that no reload or a spent reload is installed accidentally. The use of this system has been published in colorectal, thoracic, and upper gastrointestinal surgery but more evidence to document its equivalence to laparoscopic linear staplers are needed especially in urological surgery such as RARC and urinary diversion [20, 21].

The vessel sealer extend is another instrument compatible with the da Vinci Xi surgical system that has independent grasping, dissecting, cutting, and sealing functions. Its

wristed technology with 60° articulation can cut and seal vessel or bundles of tissue up to 7 mm with orthogonal transection at right angles and is manipulated directly by a surgeon utilizing a console. Used with the Erbe VIO dV generator system, a generator inserted in the vision cart of the da Vinci system, the energy and bipolar effect can be regulated, as with other instruments [22].

3.1.2 Magnetic Retraction System

Levita™ Magnetic Surgical System (LMSS) (Levita Magnetics, San Mateo, CA) is designed to magnetically grasp and retract the target tissue. It works by attaching a spring-loaded grasper, characterized by a small magnetic end, to the targeted tissue, subsequently controlling it using an external stronger magnet. This eliminates the need for a dedicated trocar and shafted instrumentation that may clutter the operative field. This may be especially useful in single-port surgery or reducing the number of ports in multiport surgery. Steinberg et al. [23] reported the feasibility of LMSS in 15 patients undergoing single-port RALP without any additional assistant ports or conversion to open surgery. They found that LMSS improved tissue exposure and ergonomics in single-port surgery, thus mimicking multiport surgery. Others have reported the safety and feasibility of LMSS during robotic upper tract surgery [24].

3.2 3-Dimensional Pre-operative Planning

Conventional surgical planning based on cross-sectional imaging requires complex cognitive processing to convert 2D images into a 3D reconstruction to guide intra-operative decision-making. The use of virtual 3D models and 3D printing has evolved to enable the surgeon to create a roadmap for more precise surgery. In urology, this has been applied principally to RALP and RAPN.

The current 3D model reconstructions utilize machine learning algorithms to convert cross-sectional images into a 3D image segmentation of the scan, which is then validated by engineers to create a final 3D rendered model. Startups such as Innersight Labs from academic institutions in the United Kingdom are paving the way for this technology to be used in patient selection, planning, and intra-operative guidance.

For RAPN, better surgical planning using 3D models can be useful in patients with complex anatomy such as ectopic or horseshoe kidneys [25] and may have a role in reducing warm ischemia times and better preservation of renal function by allowing selective and super-selective clamping [26].

Porpiglia et al. [27] in their study of 101 patients showed that nephrometric scores obtained using 3D models were lower for half of the cases than when scored using conven-

tional 2D CT images. Interestingly, their study also showed that the scores obtained using 3D information were better predictors of postoperative complications, which they attributed to better perception of tumor depth and its relationships with intra-renal structures.

Bianchi et al. [28] showed that during RAPN, the 3D-guided plan allows the surgeon to perform selective clamping in higher proportion of patients compared with the standard 2D-guided approach without increasing intra-operative and postoperative complications.

Such 3D reconstructions can actually be 3D printed to give surgeons a sense of touch and potentially reduce positive margins during RALP [29] or RAPN. Furthermore, these technologies can also be used for purposes of urology training, patient counseling, and patient consent.

3.3 Virtual and Augmented Reality and Artificial Intelligence

MIMIC technologies (Seattle, USA), the leading firm for virtual reality robotic simulators, has both standalone simulation systems such as the dV-trainer and FlexVR as well as the da Vinci skills simulator, a simulator co-developed by MIMIC and Intuitive which connects a simulation computer directly to the da Vinci console to allow for simulation directly on the console [30].

Although virtual reality simulators are used for training to improve a surgeon's skill set and shorten the learning curve, there is no high quality evidence of skills transfer from simulation to clinical surgery on real patients [31]. Some studies have used virtual reality models to show that it can aid the identification of the renal artery during RAPN, and plan and guide various surgical steps during RARP for peripherally placed and advanced tumors [12, 32].

3D reconstructed images from cross-sectional imaging may be superimposed onto in-vivo anatomy to allow better surgical navigation using data from fused virtual reality images as well as real-time in-vivo observations. Such augmented reality (AR) models have been developed and used for surgical navigation in RALP and RAPN [33–35].

Porpiglia et al. [35] demonstrated that using hyper accuracy 3D (HA3D) AR models during RAPN of complex renal masses can lead to lower rates of global ischemia with less violation of the collecting system and lower drop of the estimated renal plasma flow at 3 months. Their tumor enucleation rate was also higher using HA3D models than intra-operative ultrasound (US) guidance.

Using HA3D models in 30 patients undergoing RARP, Pulliati et al. showed 100% and 79% accuracy in predicting the location of the index lesion and ECE, respectively, using histopathological specimens as gold standard [33]. Their team also developed elastic HA3D AR models of the prostate

that allowed identification of ECE with 100% accuracy compared to 47% with the 2D MRI cognitive models [34].

In the field of robotics, artificial intelligence (AI) has so far been used mainly to assess surgical performance. Baghdadi et al. [36] used machine learning and logistic regression algorithms to train a model for computerized assessment of PLND during RARC. Compared to an expert panel of surgeons, the model was 83.3% accurate in assessing the quality of the lymph node clearance. Another study showed that automated performance metrics using an AI model could distinguish surgeon expertise in various areas such as time, movement efficiency, camera manipulation, and tissue trauma during vesicourethral anastomosis of RALP [37].

3.4 Image-Guided Surgery

3.4.1 USS Guidance

The introduction of the drop-in ultrasound controlled by the ProGrasp forceps allows the surgeon to optimize the intra-operative assessment of the extent of the tumor, allowing for precise tumor excision and enucleation [38]. This is a useful tool especially when resecting endophytic tumors. Contrast-enhanced ultrasonography (CEUS), which uses microbubble-based contrast agents with existing ultrasound techniques, allows for enhanced evaluation of macrovascular and microvascular structures, potentially allowing for selective clamping and reducing warm ischemia times [39]. Rao et al. [40] have described a novel technique of occlusion angiography using intra-operative contrast-enhanced ultrasound scan (CEUS) for zero-ischemia RAPN in five patients. However, more studies are needed to assess whether this technology will consistently translate to better functional and oncological outcomes.

3.4.2 Fluorescent Dyes

Fluorescence imaging in robotic surgery relies on detection of variable uptake of a molecular marker in different tissues, which can be detected by a high-resolution endoscope using near infrared (NIR) light spectrum. Indocyanine green (ICG) is the most commonly used fluorescent dye in robotic urological surgery, as it can be detected using NIRF [41]. ICG has been used for guidance in selective clamping for nephron sparing during RAPN [42]; assess tissue vascularity during robot-assisted ureteral reconstruction [43, 44], precise dissection of prostatic neurovascular bundle [45], identification of lymph nodes during lymphadenectomy for renal cancer [46], and during RARP and robotic PLND [47].

Renal tumors are hypofluorescent after ICG administration as they are deficient in the transporter bilitranslocase which is present in normal renal parenchyma [46]. However, Manny et al. [48] showed that this property cannot reliably

identify malignant renal lesions. In their study of 100 RAPN cases, they were able to identify malignant tumors with a positive predictive value of 87% and negative predictive value of 52%.

The risks of blood loss and suboptimal views leading to potential positive surgical margins on the off-clamp approach and risk of reperfusion injury and nephron loss in the on-clamp approach have driven the interest in selective arterial clamping [49]. ICG-based fluorescence imaging has been used to help identify the arterial supply to the tumor and adequacy of selective clamping to improve the functional outcomes [41]. In this large series of 318 patients undergoing ICG-guided RAPN, the authors showed that ICG-guided surgery is a promising tool for guiding the surgeon strategy of global versus selective during robot-assisted partial nephrectomy especially in cases with challenging vascular supply or impaired renal function. They reported a trifecta rate of 80%; however, their study lacked a control group. Other studies have also shown that ICG-guided selective clamping during RAPN shows promise with lower glomerular filtration rate (GFR) reduction compared to global clamping [49–51]. Other potential uses of ICG-guided RAPN lie in localization of completely endophytic tumors and assessment of potential positive margin due to differing fluorescence of malignant and benign renal tissue [41, 52].

The use of ICG-guidance during ureteral reconstruction has helped in identification of the ureter in cases of inflammation and fibrosis as well as allow precise marking of diseased or strictured segments of the ureter allowing complete resection and guiding subsequent reconstruction. This may help prevent recurrences while allowing maximal preservation of the healthy ureter in cases such as complex pyeloplasty, ureteric reimplantation, ureteroureterostomy, and uretero-ileal stricture repairs post urinary diversion [43, 44].

Patel et al. demonstrated that ICG-guidance revised 30% of neurovascular bundle dissections [45] during RALP. Further studies are needed to assess if this can translate to better functional outcomes of continence and erectile function. Similarly, ICG-guided PLND has been explored for lymphatic mapping with an aim to reduce the morbidity associated with extensive PLND but with suboptimal results to conventional PLND [53]. Others have reported improved results with ICG bound to fluorescent radiotracers with the hybrid ICG-^{99m}Tc-nanocolloid tracer capable of identifying 80.4% of the lymph nodes detected by the combined pre-operative lymphoscintigraphy and SPECT/CT [54].

3.4.3 Gamma Probes and Sentinel Lymph Nodes

Laparoscopic gamma probes have enabled identification and resection of sentinel lymph nodes in robotic surgery. While the original probes have limitations of their length, movement, and being only been able to be controlled by the assis-

tant, more recent trials have reported drop-in gamma probe that can be controlled by the ProGrasp robotic forceps for sentinel lymph node dissection during RALP [55]. When used for intra-operative identification and excision of metastatic lymph nodes in robotic salvage PLND, ^{99m}Tc Technetium-prostate-specific membrane antigen (PSMA) and ^{111}In dium-PSMA revealed a sensitivity of 83.6% and 92.3%, specificity of 100% and 93.5%, respectively [56, 57].

3.5 Intra-operative Pathological Processing

3.5.1 NeuroSAFE

To optimize oncological outcomes while maintaining functional outcomes, NeuroSAFE, a frozen section-navigated nerve sparing during RALP, was first described by the Martini-Klinik in Hamburg, Germany [58]. While some have reported positive reports on the benefits of NeuroSAFE [16, 59, 60], others retrospective series do not show a clear benefit and highlight the logistical problems of NeuroSAFE [61, 62]. Randomized controlled trials are currently underway to prospectively evaluate this technique [63].

3.5.2 Confocal Microscopy

Intra-operative pathological processing can be resource and time intensive limiting its use in routine practice. Newer technologies have emerged such as confocal LASER microendoscopy (CLE) [64] which uses intravenous fluorescein in vivo assessment of prostatic and periprostatic tissue using LASER probes and ex vivo fluorescence confocal microscopy (FCM), which uses lasers to provide rapid histopathological confirmation with high accuracy compared to traditional hematoxylin and eosin staining. Lopez et al. published an initial report showing the feasibility of using CLE (Mauna Kea Technologies, Paris, France) to identify prostate pedicles and neurovascular bundles [64]. Two other studies show a 91–100% accuracy of FCM (MAVIG GmbH, Munich, Germany; Caliber I.D.; Rochester, NY, USA) in differentiating benign and malignant prostate on intra-operative biopsies [65, 66]. While these technologies show initial promise, more studies are needed to assess their feasibility and impact on avoidance of positive margins while maintaining functional outcomes.

4 Future Directions

4.1 Connectivity

A unique aspect of robotic surgery that has been lacking is a robust support for telepresence surgery over large distances. There is an unmet need for this in terms of training, mentoring, performing surgery in remote locations and to allow

complex sub-specialist procedures to be performed remotely by highly skilled surgeons. A limitation has been our global communication infrastructure with robotic surgery needing very low latency high bandwidth networks to remove and perceptible delay. Over the past decade, there has been significant development of high bandwidth wired and now wireless networks such as 5G. AI may also be able to augment this process using predictive movement models to give the surgeon-console signal enough time to cover very long distances [67].

4.2 Surgical Data Science

The surgical data science initiative workshop in 2016 defined surgical data science as an emerging scientific field with the objective of improving the quality of interventional health-care and its value through capturing, organization, analysis, and modeling of data [68]. This may be applied not only in the robotic operative theater for decision support but also for performance assessment and surgical training.

While a robotic surgical system may help with many assistance functions, the surgeon will always remain the one making the decisions. A future where the robot gathers and processes data from sensors, videos, images, and haptic feedback and provides assistance and feedback to the surgeon in real time to aid decision-making is very likely.

Similarly, data science registries could provide performance feedback to the surgeon and culture of continuous measurement, assessment, and improvement using evidence from data is likely to become a key component of surgical practice and quality assurance for institutions.

In surgical practice, poor technical skills as well as poor non-technical skills such as judgement and decision-making are both associated with adverse surgical outcomes [69, 70]. Data collected from simulation training and real-time operating theater performance can be used in the future to provide targeted feedback and facilitate assessment, learning, and improvement of technical skills as well context-specific decision-making [71–73].

4.3 Precision and Soft Robotics

Current versions of the da Vinci do not provide haptic feedback, resulting in the surgeon having to rely on visual cues to assess tension on tissues. Some emerging robotic surgical systems on the market have incorporated haptic feedback technology into their systems. Surgeons and engineers continue to enhance haptic feedback in the form of force or tactile feedback and these developments may have a role in further reducing intra-operative injury [74]. Improvements in motion scaling and tremor filters are likely to make sur-

gery more dextrous. While fully autonomous surgery is still some while away, increasing automation in established surgical systems is likely to lead to further incremental improvements in delivering precision robotic surgery. While this will be challenging, especially in tasks that require contextual understanding, simpler tasks such as suturing are more likely to have incremental automation applied to them. At each step, we will need to ensure through research that these systems are ready for clinical use.

Current robotic systems are made from rigid structures limiting their access to certain sites. Soft robotics uses flexible systems where their stiffness can be controlled to overcome these barriers. A team at Kings College, London, through the STIFFness controllable Flexible and Learnable manipulator for surgical OPERations (STIFF FLOP) project, have developed a soft-robotic arm that can be squeezed through a 12 mm Trocar-port, reconfigure and stiffen itself to perform tasks. This also allows greater flexibility and incorporation of haptic feedback in robotic surgery.

Increasing automation, in future, may have the advantages of further reducing the learning curve in robotic surgery, reducing dependence on surgical volume to achieve outcomes and thus making these technologies available to areas where they current may not be [75].

5 Discussion

The past decade of robotics technological advances has been dominated by Intuitive and the Da Vinci system. It has led to the widespread adoption of robotic-assisted laparoscopic surgery across all urological subspecialties. The next decade will bring much change in this field with new devices and companies entering the market. Each system will have its own pros and cons. In addition to these advances in 3D modeling, intra-operative imaging, real-time fusion of cross-sectional imaging, ICG, haptics, Neurosafe, and remote telepresence have the potential to improve many surgical steps and also lead to better outcomes for the patients. Ultimately it will be the clinical results, cost, and how easily these new technologies are integrated into the surgical plan that will lead to their success.

References

- Binder J, Kramer W. Robotically-assisted laparoscopic radical prostatectomy. *BJU Int.* 2001;87(4):408–10.
- Koukourikis P, Rha KH. Robotic surgical systems in urology: What is currently available? *Investig Clin Urol.* 2021;62(1):14–22.
- DaVinci Surgical System's world. Available online: www.intuitive-surgical.com.
- Heo JE, et al. Pure single-site robot-assisted pyeloplasty with the da Vinci SP surgical system: initial experience. *Investig Clin Urol.* 2019;60(4):326–30.
- Kang SK, et al. Robot-assisted laparoscopic single-port pyeloplasty using the da Vinci SP(R) system: initial experience with a pediatric patient. *J Pediatr Urol.* 2019;15(5):576–7.
- Kaouk J, et al. Step-by-step technique for single-port robot-assisted radical cystectomy and pelvic lymph nodes dissection using the da Vinci((R)) SP surgical system. *BJU Int.* 2019.
- Agarwal DK, et al. Initial experience with da Vinci single-port robot-assisted radical prostatectomies. *Eur Urol.* 2020;77(3):373–9.
- Billah MS, et al. Single port robotic assisted reconstructive urologic surgery-with the da Vinci SP surgical system. *Transl Androl Urol.* 2020;9(2):870–8.
- Samalavicius NE, et al. Robotic surgery using Senhance((R)) robotic platform: single center experience with first 100 cases. *J Robot Surg.* 2020;14(2):371–6.
- Kastelan Z, et al. Extraperitoneal radical prostatectomy with the Senhance Surgical System robotic platform. *Croat Med J.* 2019;60(6):556–9.
- Chang KD, et al. Retzius-sparing robot-assisted radical prostatectomy using the Revo-i robotic surgical system: surgical technique and results of the first human trial. *BJU Int.* 2018;122(3):441–8.
- Kobayashi S, et al. Assessment of surgical skills by using surgical navigation in robot-assisted partial nephrectomy. *Int J Comput Assist Radiol Surg.* 2019;14(8):1449–59.
- Thomas BC, et al. Preclinical evaluation of the versius surgical system, a new robot-assisted surgical device for use in minimal access renal and prostate surgery. *Eur Urol Focus.* 2021;7(2):444–52.
- Medicaroid. Hinotori robotic assisted surgery system [Internet]. Kobe: Medicaroid; 2020. Accessed 2021 April 9. <http://www.medicaroid.com/en/product/hinotori/>
- Insights on the Surgical Robotic Systems Global Market to 2026 - Industry Analysis and Forecasts. Research and Markets. Accessed 2021 April 9. <https://www.researchandmarkets.com/r/hsc5zl>
- Schlomm T, et al. Neurovascular structure-adjacent frozen-section examination (NeuroSAFE) increases nerve-sparing frequency and reduces positive surgical margins in open and robot-assisted laparoscopic radical prostatectomy: experience after 11,069 consecutive patients. *Eur Urol.* 2012;62(2):333–40.
- Taktak S, et al. Aquablation: a novel and minimally invasive surgery for benign prostate enlargement. *Ther Adv Urol.* 2018;10(6):183–8.
- Rassweiler J, et al. Robot-assisted flexible ureteroscopy: an update. *Urolithiasis.* 2018;46(1):69–77.
- Miah S, et al. A prospective analysis of robotic targeted MRI-US fusion prostate biopsy using the centroid targeting approach. *J Robot Surg.* 2020;14(1):69–74.
- Gutierrez M, Ditto R, Roy S. Systematic review of operative outcomes of robotic surgical procedures performed with endoscopic linear staplers or robotic staplers. *J Robot Surg.* 2019;13(1):9–21.
- Johnson CS, et al. Performance of da Vinci Stapler during robotic-assisted right colectomy with intracorporeal anastomosis. *J Robot Surg.* 2019;13(1):115–9.
- Galetta D, et al. New stapling devices in robotic surgery. *J Vis Surg.* 2017;3:45.
- Steinberg RL, et al. Magnet-assisted robotic prostatectomy using the da Vinci SP robot: an initial case series. *J Endourol.* 2019;33(10):829–34.
- Fulla J, et al. Magnetic-assisted robotic and laparoscopic renal surgery: initial clinical experience with the levita magnetic surgical system. *J Endourol.* 2020;34(12):1242–6.
- Raman A, et al. Robotic-assisted laparoscopic partial nephrectomy in a horseshoe kidney. a case report and review of the literature. *Urology.* 2018;114:e3–5.
- Porpiglia F, et al. Hyperaccuracy three-dimensional reconstruction is able to maximize the efficacy of selective clamping during robot-assisted partial nephrectomy for complex renal masses. *Eur Urol.* 2018;74(5):651–60.

27. Porpiglia F, et al. Three-dimensional virtual imaging of renal tumours: a new tool to improve the accuracy of nephrometry scores. *BJU Int.* 2019;124(6):945–54.
28. Bianchi L, et al. The impact of 3D digital reconstruction on the surgical planning of partial nephrectomy: a case-control study. Still time for a novel surgical trend? *Clin Genitourin Cancer.* 2020;18(6):e669–78.
29. Chandak P, et al. Three-dimensional printing in robot-assisted radical prostatectomy - an Idea, Development, Exploration, Assessment, Long-term follow-up (IDEAL) Phase 2a study. *BJU Int.* 2018;122(3):360–1.
30. MIMIC Technologies. Available at mimicsimulation.com. Accessed April 9 2021.
31. Moglia A, et al. A systematic review of virtual reality simulators for robot-assisted surgery. *Eur Urol.* 2016;69(6):1065–80.
32. Mehralivand S, et al. A multiparametric magnetic resonance imaging-based virtual reality surgical navigation tool for robotic-assisted radical prostatectomy. *Turk J Urol.* 2019;45(5):357–65.
33. Porpiglia F, et al. Augmented-reality robot-assisted radical prostatectomy using hyper-accuracy three-dimensional reconstruction (HA3D) technology: a radiological and pathological study. *BJU Int.* 2019;123(5):834–45.
34. Porpiglia F, et al. Three-dimensional elastic augmented-reality robot-assisted radical prostatectomy using hyperaccuracy three-dimensional reconstruction technology: a step further in the identification of capsular involvement. *Eur Urol.* 2019;76(4):505–14.
35. Porpiglia F, et al. Three-dimensional augmented reality robot-assisted partial nephrectomy in case of complex tumours (PADUA ≥ 10): a new intraoperative tool overcoming the ultrasound guidance. *Eur Urol.* 2020;78(2):229–38.
36. Baghdadi A, et al. A computer vision technique for automated assessment of surgical performance using surgeons' console-feed videos. *Int J Comput Assist Radiol Surg.* 2019;14(4):697–707.
37. Chen J, et al. Use of automated performance metrics to measure surgeon performance during robotic vesicourethral anastomosis and methodical development of a training tutorial. *J Urol.* 2018;200(4):895–902.
38. Di Cosmo G, et al. Intraoperative ultrasound in robot-assisted partial nephrectomy: state of the art. *Arch Ital Urol Androl.* 2018;90(3):195–8.
39. Alenezi AN, Karim O. Role of intra-operative contrast-enhanced ultrasound (CEUS) in robotic-assisted nephron-sparing surgery. *J Robot Surg.* 2015;9(1):1–10.
40. Rao AR, et al. Occlusion angiography using intraoperative contrast-enhanced ultrasound scan (CEUS): a novel technique demonstrating segmental renal blood supply to assist zero-ischaemia robot-assisted partial nephrectomy. *Eur Urol.* 2013;63(5):913–9.
41. Diana P, et al. the role of intraoperative indocyanine green in robot-assisted partial nephrectomy: results from a large, multi-institutional series. *Eur Urol.* 2020;78(5):743–9.
42. Bjurlin MA, et al. Near-infrared fluorescence imaging: emerging applications in robotic upper urinary tract surgery. *Eur Urol.* 2014;65(4):793–801.
43. Lee Z, et al. Use of indocyanine green during robot-assisted ureteral reconstructions. *Eur Urol.* 2015;67(2):291–8.
44. Tuderti G, et al. Transnephrostomic indocyanine green-guided robotic ureteral reimplantation for benign ureteroileal strictures after robotic cystectomy and intracorporeal neobladder: step-by-step surgical technique, perioperative and functional outcomes. *J Endourol.* 2019;33(10):823–8.
45. Kumar A, Samavedi S, Bates A. Use of intra-operative indocyanine green and Firefly technology to visualize the “landmark artery” for nerve sparing robot assisted radical prostatectomy. *Eur Urol Suppl.* 2015;2(14):eV36.
46. Tobis S, et al. Near infrared fluorescence imaging with robotic assisted laparoscopic partial nephrectomy: initial clinical experience for renal cortical tumors. *J Urol.* 2011;186(1):47–52.
47. van den Berg NS, et al. Multispectral fluorescence imaging during robot-assisted laparoscopic sentinel node biopsy: a first step towards a fluorescence-based anatomic roadmap. *Eur Urol.* 2017;72(1):110–7.
48. Manny TB, Krane LS, Hemal AK. Indocyanine green cannot predict malignancy in partial nephrectomy: histopathologic correlation with fluorescence pattern in 100 patients. *J Endourol.* 2013;27(7):918–21.
49. Mattevi D, et al. Fluorescence-guided selective arterial clamping during RAPN provides better early functional outcomes based on renal scan compared to standard clamping. *J Robot Surg.* 2019;13(3):391–6.
50. Borofsky MS, et al. Near-infrared fluorescence imaging to facilitate super-selective arterial clamping during zero-ischaemia robotic partial nephrectomy. *BJU Int.* 2013;111(4):604–10.
51. Krane LS, Hemal AK. Surgery: Is indocyanine green dye useful in robotic surgery? *Nat Rev Urol.* 2014;11(1):12–4.
52. Simone G, et al. “Ride the green light”: indocyanine green-marked off-clamp robotic partial nephrectomy for totally endophytic renal masses. *Eur Urol.* 2019;75(6):1008–14.
53. Chennamsetty A, et al. Lymph node fluorescence during robot-assisted radical prostatectomy with indocyanine green: prospective dosing analysis. *Clin Genitourin Cancer.* 2017;15(4):e529–34.
54. KleinJan GH, et al. Multimodal hybrid imaging agents for sentinel node mapping as a means to (re)connect nuclear medicine to advances made in robot-assisted surgery. *Eur J Nucl Med Mol Imaging.* 2016;43(7):1278–87.
55. Meershoek P, et al. Robot-assisted laparoscopic surgery using DROP-IN radioguidance: first-in-human translation. *Eur J Nucl Med Mol Imaging.* 2019;46(1):49–53.
56. Maurer T, et al. (99m)Technetium-based prostate-specific membrane antigen-radioguided surgery in recurrent prostate cancer. *Eur Urol.* 2019;75(4):659–66.
57. Rauscher I, Eiber M, Maurer T. PSMA-radioguided surgery for salvage lymphadenectomy in recurrent prostate cancer. *Aktuelle Urol.* 2017;48(2):148–52.
58. Beyer B, et al. A feasible and time-efficient adaptation of NeuroSAFE for da Vinci robot-assisted radical prostatectomy. *Eur Urol.* 2014;66(1):138–44.
59. Mirmilstein G, et al. The neurovascular structure-adjacent frozen-section examination (NeuroSAFE) approach to nerve sparing in robot-assisted laparoscopic radical prostatectomy in a British setting - a prospective observational comparative study. *BJU Int.* 2018;121(6):854–62.
60. Fromont G, et al. Intraoperative frozen section analysis during nerve sparing laparoscopic radical prostatectomy: feasibility study. *J Urol.* 2003;170(5):1843–6.
61. Heinrich E, et al. Clinical impact of intraoperative frozen sections during nerve-sparing radical prostatectomy. *World J Urol.* 2010;28(6):709–13.
62. Gillitzer R, et al. Intraoperative peripheral frozen sections do not significantly affect prognosis after nerve-sparing radical prostatectomy for prostate cancer. *BJU Int.* 2011;107(5):755–9.
63. Dinneen E, et al. NeuroSAFE robot-assisted laparoscopic prostatectomy versus standard robot-assisted laparoscopic prostatectomy for men with localised prostate cancer (NeuroSAFE PROOF): protocol for a randomised controlled feasibility study. *BMJ Open.* 2019;9(6):e028132.
64. Lopez A, et al. Intraoperative optical biopsy during robotic assisted radical prostatectomy using confocal endomicroscopy. *J Urol.* 2016;195(4 Pt 1):1110–7.
65. Puliatti S, et al. Ex vivo fluorescence confocal microscopy: the first application for real-time pathological examination of prostatic tissue. *BJU Int.* 2019;124(3):469–76.
66. Rocco B, et al. Real-time assessment of surgical margins during radical prostatectomy: a novel approach that uses fluorescence

- confocal microscopy for the evaluation of peri-prostatic soft tissue. *BJU Int.* 2020;125(4):487–9.
67. Kim SSY, Dohler M, Dasgupta P. The Internet of Skills: use of fifth-generation telecommunications, haptics and artificial intelligence in robotic surgery. *BJU Int.* 2018;122(3):356–8.
 68. Maier-Hein L, et al. Surgical data science for next-generation interventions. *Nat Biomed Eng.* 2017;1(9):691–6.
 69. Birkmeyer JD, et al. Surgical skill and complication rates after bariatric surgery. *N Engl J Med.* 2013;369(15):1434–42.
 70. Nathwani JN, et al. Relationship between technical errors and decision-making skills in the junior resident. *J Surg Educ.* 2016;73(6):e84–90.
 71. Vedula SS, Ishii M, Hager GD. Objective assessment of surgical technical skill and competency in the operating room. *Annu Rev Biomed Eng.* 2017;19:301–25.
 72. Greenberg CC, et al. Surgical coaching for individual performance improvement. *Ann Surg.* 2015;261(1):32–4.
 73. Singh P, et al. A randomized controlled study to evaluate the role of video-based coaching in training laparoscopic skills. *Ann Surg.* 2015;261(5):862–9.
 74. Okamura AM. Haptic feedback in robot-assisted minimally invasive surgery. *Curr Opin Urol.* 2009;19(1):102–7.
 75. Svoboda E. Your robot surgeon will see you now. *Nature.* 2019;573(7775):S110–1.