World Journal of Urology (2020) 38:897–905
https://doi.org/10.1007/s00345-019-02898-1

TOPIC PAPER

Single-port robotic surgery: the next generation of minimally invasive urology

Ryan W. Dobbs[1] · Whitney R. Halgrimson[1] · Susan Talamini[1] · Hari T. Vigneswaran[1] · Jessica O. Wilson[1] · Simone Crivellaro[2]

Received: 4 June 2019 / Accepted: 28 July 2019 / Published online: 28 August 2019

Abstract

Introduction The da Vinci Single-Port (SP) platform (Intuitive Surgical Inc, Sunnyvale CA) is a recently approved robotic surgical platform which features several novel modifications from previously available single trocar models including a flexible camera, articulating instruments, and navigator guidance for real-time monitoring of instrument position. We sought to describe our clinical experience with this device as well as to review the current literature related to the use of the SP platform.

Methods We provide a narrative review of clinical data related to single-port robotic surgery within the field of urology. In addition, we report our initial clinical experience for surgical procedures performed with the SP platform between December 2018 and April 2019 following installation of the system at our institution.

Results Currently, the presently available literature for single-port robotic urological surgery consists of single-center case reports and series. Most major robotic urologic operations appear technically feasible using the da Vinci SP platform; however, additional multi-center studies and randomized trials are needed to determine what role the SP platform will play.

Conclusions Rather than an iterative step or a niche system, the SP platform provides for a new approach to single-site laparoscopic or robotic techniques and is demonstrated as a feasible approach for several major robotic urological operations. While comparative studies will be required to evaluate perioperative and long-term outcomes between SP and multi-port platforms, further technological advances will continue to push surgeons towards less morbid and more minimally invasive approaches for surgery.

Keywords Robotics · Minimally invasive surgery · Prostatectomy · Nephrectomy

Introduction and history

Viewing the current state of urology today, it may be easy to lose sight of the fact that a tremendous series of changes have occurred in both the technology and preferred surgical approach utilized over just the past few decades. While the first laparoscopic procedure was described by German surgeon Georg Kelling in 1901, it was not until 1976 before the first clinical use of laparoscopy in urology was performed to assist in the identification of a cryptorchid testis, ushering in the era of minimally invasive urology [1]. Improvements in laparoscopic technology led to broader adoption of this approach with descriptions of increasingly complex operations including the first laparoscopic nephrectomy in 1991 [2] and laparoscopic radical prostatectomy in 1998 [3]. Interest in minimizing the morbidity associated with multiple incisions led to descriptions of single-site laparoscopic procedures including sacrocolpopexy, nephrectomy, and orchiectomy [4, 5]. However, technical challenges associated with restricted instrument triangulation, poor ergonomics, and need for specialized curved laparoscopic equipment limited the widespread adoption of single-site laparoscopic technology.

In 2000, the Food and Drug Administration (FDA) approved the first da Vinci surgical robot (Intuitive Surgical, Sunnyvale CA), initiating the second generation of minimally invasive urology [6]. This system utilizes rigid instrument arms following linear trajectories through

✉ Simone Crivellaro
Crivesim@uic.edu

1 College of Medicine, University of Illinois at Chicago, Chicago, IL, USA

2 Department of Urology, College of Medicine, University of Illinois at Chicago, 820 S. Wood St, M/C 955, Chicago, IL 606012, USA

several small instrument trocars, allowing for access during abdominal and deep pelvic operations. This transition from open surgery to robotics required a brand-new approach for performing many operations and initial case reports bear out the difficulty of using this new technology. In the first clinical case series of robotic radical prostatectomies, Binder and Kramer reported a median operative time of 9 h (range 8.75–11 h) [7]. While robotic technology was initially adopted at only a handful of academic centers, the platform has been widely disseminated in the United States [8], becoming the preferred approach for many urological operations. As an example, prostatectomies performed with robotic approach increased from 1.8 to 85% between 2003 and 2013 [9]. The broad utilization of robotic technology in complex operations, such as radical prostatectomy and partial nephrectomy, may be attributable to several factors, including improvements in high definition laparoscopic cameras, motion scaling, and new instrument dexterity to enable complex intracorporeal tasks which were technically challenging using pure laparoscopic approaches.

In 2018, the da Vinci Single-Port (SP) system was approved by the FDA for use in urology patients. Initial safety of the SP system was described in a human phase II clinical trial for urological surgery [10]. Since its approval, several case reports have been published describing successful approaches to complex urological procedures, including ureteral reimplantation, prostatectomy, donor nephrectomy, and cystectomy [11–16]. In this review, we report our center's experience with the SP system, describe both the advantages and drawbacks of this new technology, and examine its role as the third generation of minimally invasive urology.

The SP system

The SP platform shares multiple features with prior multi-port da Vinci platforms (S, Si, and Xi models) to create an experience familiar to experienced robotic surgeons. The platform leverages the same operative interface, including Endowrist® manipulators, high definition three-dimensional visualization with magnification and scaled movement, and tremor reduction. However, several technical advances in instrument and console design enable the use of multiple robotic instruments through a single incision.

The robotic platform utilizes a single surgical arm for placement of an 8 mm articulating flexible camera and three articulating 6 mm instruments through a single 27 mm entry guide (Fig. 1). Each instrument occupies a position along the "clock" (3, 6, 9, and 12 o'clock), is interchangeable and can move within the trocar independent of the others. Furthermore, the "clock" may be rotated to change the instrument deployment without requiring any exchange by the bedside assistant. While the single port groups the instruments and camera together at a common point of entry (Fig. 2a, b), several geometric modifications to the instruments provide the necessary angulation to visualize and perform complex surgical tasks.

A flexible camera represents a fundamental advancement from prior multi-port platforms. Surgeons will be familiar with standard camera adjustments (e.g., move in, out, left, and right), but a second point of articulation enables the camera to also flex in all directions. Thus, utilizing a 0° lens, the surgeon may position the flexible camera to provide new visualization angles, while the instruments maintain a fixed position.

Like the flexible camera, the three SP working instruments also utilize two points of articulation within the body to create sufficient angulation toward the surgical field. The most distal point of articulation (the "wrist") is located more proximally along the instrument than standard multi-port instruments. The change in geometry produces three notable differences from multi-port platforms. First, to accommodate two points of articulation, there is a smaller working distance between the instruments and the camera, thus making a smaller, overall field of view. Second, the more proximal wrist location limits the ability to throw suture at a full 90°, such as the 6 o'clock stitch of the vesicourethral anastomosis in a radical prostatectomy. Finally, multiple angulation points and the single point of entry reduce the lateral strength and range of motion of an instrument compared to the multi-port platform.

The SP requires increased coordination between the instruments and the camera to compensate for the smaller working area and field of view. The "Navigator" is a new visual overlay for the surgeon that monitors the relative position of each instrument and camera in real time. Being a virtual image, the navigator enables the surgeon to track instruments that may be off-camera and thus off-screen. The Navigator also provides additional visual warnings as instruments reach their motion limits for a given trocar position. Finally, the system also helps the surgeon to identify "optimal" positioning of the camera and instruments for a given surgical step by identifying "Cobra Mode", wherein the camera is midline and flexed approximatively 30° with an ideal overview of the instruments.

As surgeons must tolerate a smaller working space, the SP platform includes several special "modes" to assist the surgeon improve their angle of approach with coordinated instrument and camera movements within the working space. In the "adjust" mode, the working instruments maintain their position with respect to tissue, while the robotic trocar angle is changed. If reaching limits to lateral range of motion, it is possible to move the entire robotic arm using the "relocation" pedal. Adjustment of the full single port enables the SP use in surgeries that require extensive range of motion, such as the nephroureterectomy, or those with

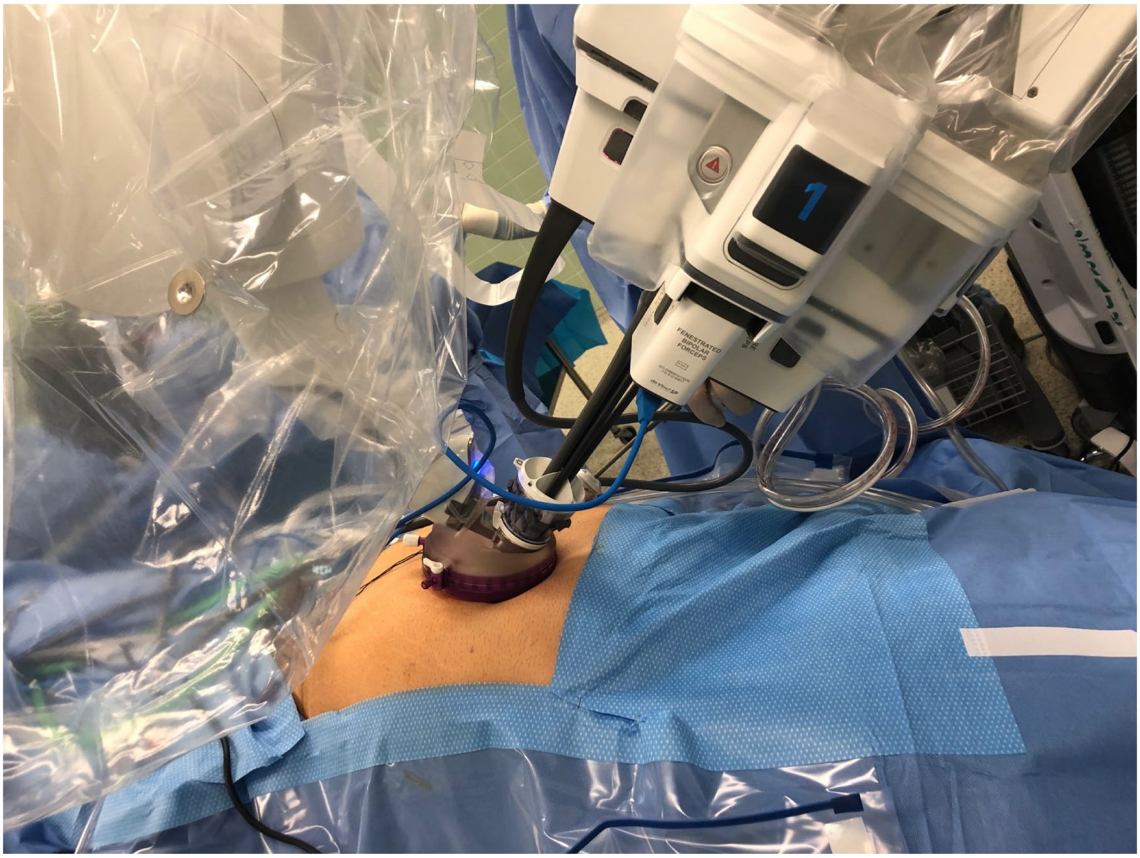

Fig. 1 da Vinci SP single robotic arm with multiple instruments entering through a single port

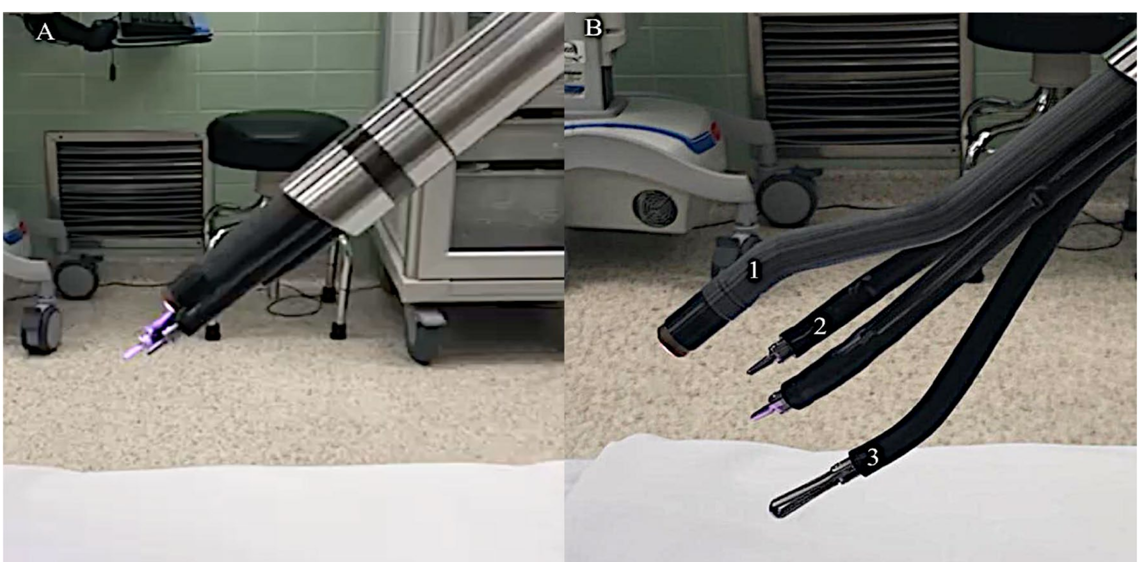

Fig. 2 **a** Instruments grouped together, passing through trocar. **b** Instruments independently deployed within single trocar: (1) optical system; (2) needle drivers; (3) cadiere

several steps, such as lymph-node dissection during radical prostatectomy or complex ureteral reconstruction.

In our experience, familiarity with movements of the instruments and the camera represent the most significant technical modification for operative technique with the transition from multi-port to SP technology.

Technical approach and modifications

Optimal utilization of the SP platform requires both an understanding of the system's advantages and disadvantages. During initial positioning, the SP system allows for defining a vertical limit for the range of motion of the robotic arm. Restricting the range of motion helps to prevent collisions with the patient and allows for omission of a Mayo stand. Another early modification includes placement of the single robotic trocar through a GelPOINT® (Applied Medical Resources, Rancho Santa Margarita, CA) advanced access platform to prevent robotic arm pressure on the patient skin, to improve the air seal, and to allow for expanded in-line relocation of the full trocar or "burping".

As discussed earlier, the new geometry of the robotic instruments and camera creates smaller working space and visual field of view and limits the lateral strength of the individual instruments. Such limitations may restrict traction or suturing when compared to multi-port technique, yet minor modifications (e.g., tightening suture in-line to the camera rather than perpendicular) and frequent camera adjustments overcome most difficulties. Furthermore, the flexible camera allows for continuous adjustment and readjustment of the visual perspective. While this requires more active management of the camera with more frequent adjustments than with the multi-port platform, it also obviates switching between multiple laparoscopic cameras such as the 0° and 30° that are used with the multi-port system.

While the SP system is advertised as a single-site surgical technology, most operations require a bedside surgical assistant to exchange instruments, suction, retract, and apply vascular clips. The numerous arms of the multi-port platforms significantly limit the available external working space, while the single robotic arm of the SP platform is less obstructive for the bedside assistant. At our center, we most frequently utilize a 5 mm Airseal® (ConMed Corporation, Utica NY) laparoscopic port placed 5–6 cm lateral to the main trocar to serve as the assistant port. One exception is for operations which require vascular control of major arterial vessels, such as the renal artery during radical nephrectomy, for which we use a 12 mm port to place Weck® Hem-o-lok® (Teleflex Inc, Morrisville NC) clips. The use of polymer clips was a technical modification following postoperative hemorrhage requiring re-exploration due to inadequate control of the renal artery with suture ligation after the first SP radical nephrectomy at our center. If a surgical drain is required postoperatively, we use this assistant port as the drain site. Similarly, in operations which require a stoma, the conduit may be brought through the assistant port with a locking Allys grasper to limit additional incisions [17].

There have been some reports of several novel solutions to avoid the use of an assistant port including use of a flexible nasogastric tube passed alongside the robotic trocar which can be manipulated by the console surgeon [14]. Similarly, a large gauge angiocatheter (14 Fr) may be used to introduce JJ stents under direct vision to omit use of an additional port [14].

In operations which do not require extensive bedside assistance, it may also be feasible to place an assistant port adjacent to the robotic trocar through the GelPOINT port through the same incision [18]. There are some downside to this approach, including the necessity of make the fascial incision at least 1 cm longer and the conflicts between any laparoscopic instruments and the robotic trocar. Future devices are in development and promise to solve this problem to allow to safely move toward pure single port.

One consideration to be aware of is that while the SP robotic arm is less intrusive for the bedside assistant, for deep pelvic operations, the arm often approaches the patient's head and airway access for anesthesia personnel may be limited.

Cadaveric research

Prior to use in human patients, the SP system has been evaluated for several operations in cadaveric models to determine the feasibility and technical approach that would be most advantageous for this system [19–21]. Given the ability of the SP system to operate within a small operative radius, some investigators have demonstrated the feasibility of perineal approaches for robotic radical prostatectomy [20], robotic cystectomy [21], and even intracorporeal ileal conduit urinary diversion with pelvic lymph-node dissection [17]. While this approach may be less familiar to many urologists than a trans-abdominal technique, there may some benefits for longer cases to minimize the morbidity of prolonged Trendelenburg positioning, to reduce need for additional abdominal incisions beyond the creation of the stoma, and to improve the final cosmetic result.

Clinical research

From these initial feasibility studies in cadavers and following FDA approval, several centers of excellence have created an initial body of clinical evidence for the SP system.

While these centers presently represent high-volume clinical settings with experienced minimally invasive surgeons, this initial development mirrors that of the multi-port platforms.

From these reports, there have been descriptions of ureteroneocystostomy, [14] ureteral reimplantation [18], radical cystectomy [22], and radical prostatectomy [15, 23] with generally similar perioperative outcomes, intraoperative complication rates, and operative times to comparable multi-port operations. The summary of initial perioperative outcomes and complications for these studies is shown in Table 1. While these represent a heterogenous range of operations from experienced robotic surgeons with small patient sample sizes, it appears that most complex robotic operations may be safely performed with the SP platform.

Long-term oncological results will require additional follow-up beyond these initial reported case series. Of note, positive surgical margins for prostatectomy were noted to range between 20 and 33% in initial case series, which may reflect the initial learning curve for this technology [11, 15, 23]. As such, it may be reasonable to initially utilize the platform for lower risk patients to develop a familiarity and experience with the technical approach prior to adoption of the SP platform in high-risk patients.

While a subjective improvement in cosmesis with single-site operations has not been a major concern in the urological literature, operations with younger patients such as living-donor nephrectomy have previously demonstrated improved patient satisfaction and equivalent outcomes using a single-site laparoscopic approach [28]. As such, demonstrations of the safety of the SP system for donor nephrectomy may represent an opportunity to improve patient satisfaction and increase the potential pool of organ donors [12]. Similarly, while the SP system has not yet been approved for pediatrics cases, this patient population may benefit more from improved cosmesis and cosmetic outcomes should be prospectively evaluated for this group.

One potential concern of the SP platform is a perceived increase in surgical complexity, as some authors have noted an increased number of steps and operative time in donor nephrectomy despite improved visualization over their standard single-site laparoscopic nephrectomy technique [12].

Table 1 da Vinci SP platform-assisted operations performed in the literature

	Operation	*N*	Operative time (range)	EBL (ml)	Length of stay (median days)	Conversions from planned operation	Complications (Clavien)
Kaouk 2019 [22]	SP radical cystectomy and intracorporeal diversion	4	75 (67–90) (diversion only)	N/A	5	Conversion to extracorporeal diversion due to adhesions ($n=1$)	Grade I—Nausea ($n=1$)
Agarwal 2019 [15]	SP radical prostatectomy	49	161 (IQR: 134–194)	200 (IQR: 75–300)	1	None	Grade II—Blood transfusion ($n=2$), wound dehiscence ($n=1$) Grade I—Ileus ($n=1$)
Kaouk 2019 [24]	SP radical cystectomy	4	454 (420–496)	312	5	None	Grade I—Nausea ($n-1$)
Kaouk 2019 [25]	SP partial nephrectomy	3	180	180	N/A	None	Grade IIIa—Post-operative hemorrhage requiring angioembolization ($n=1$)
Kaouk 2019 [18]	SP ureteroneocystostomy	3	165 (150–180)	50	1.33	None	None
Kaouk 2019 [11]	SP radical prostatectomy	3	226 (200–300)	83	1	None	None
Herbert 2019 [14]	SP ureteroneocystostomy	1	127	20	N/a	None	None
Bertolo 2019 [26]	SP perineal radical prostatectomy	1	160	N/a	1	None	None
Kaouk 2019 [27]	SP radical prostatectomy	2	140	N/a	1	None	None
Dobbs 2019 [23]	SP radical prostatectomy	10	234 (191–258)	65 (20–150)	1	None	None

Cost considerations are a valid concern for the dissemination of this technology. The level of investment required to run a robotic program is formidable, including upfront purchasing costs of the robotic consoles, per-case instrument costs, and maintenance costs throughout the life cycle of the system [6]. The SP platform requires an entirely new investment effort as there is no shared component for now. Future developments may allow for compatibility for the console and with the Xi platform. Furthermore, many hospitals have already invested heavily in the multi-port platform. As such, determining the variety and scale of cases that would benefit meaningfully from this technology and regionalization of care may be necessary to ensure a cost-effective approach towards the SP system.

The UIC experience

Between December 2018 and April 2019, a total of 45 SP operations were performed at the University of Illinois at Chicago Medical Center. A summary of SP cases for patients with postoperative follow-up is shown in Table 2. The majority of cases performed were SP prostatectomies for prostate cancer ($n=24$); however, 21 additional cases were performed, including partial nephrectomy ($n=6$), vaginoplasty ($n=3$), nephrectomy ($n=2$), vesicovaginal fistula repair ($n=2$), and ureteral reimplantation ($n=2$). Of all 45 cases, one required an unplanned addition of a hand port and no procedures required a conversion from a robotic approach to an open technique. Intraoperatively, possible serosal injuries of the small bowel were noted during a prostatectomy and an infected renal cyst decortication and a thoracic duct injury occurred during an adrenalectomy. All intraoperative complications ($n=3$, 6.7%) were treated with simple oversewing at the time of the injury without additional sequelae.

Postoperatively, six patients ($n=6$, 13.3%) had Clavien–Dindo [29] grade IIIa or higher postoperative complications. These complications included two cases (4.4%) which required reoperation: a vaginal bleed for an SP revision vaginoplasty for Mayer–Rokitansky–Küster–Hauser (MRKH) syndrome and a postoperative hemorrhage for inadequate vascular control of the renal artery following SP nephrectomy. Since this initial nephrectomy, we have amended our operative technique with the addition of a 12 mm assistant port for placement of polymer clips as previously discussed. One patient (2.2%) experienced postoperative respiratory failure requiring overnight intubation and temporary pressor requirement following radical prostatectomy due to pre-existing comorbidities. Additional Clavien IIIa complications included a urine leak requiring cystogram and Foley catheter exchange following SP radical prostatectomy ($n=1$), angioembolization for a bleeding interpolar artery following SP partial nephrectomy ($n=1$), and insertion of a Peripherally Inserted Central Catheter (PICC) line for prolonged ileus after SP radical cystectomy ($n=1$).

These complication rates likely reflect both the heterogeneous sample of cases as well as the initial learning curve for the surgical technique with the SP platform. While the overall sample size for individual operations is small and with short-term follow-up, our initial results are encouraging that the SP system may be used for a broad range of complex oncological and reconstructive operations.

Future directions

While authors have suggested that robotic surgery should be considered the new gold standard for some operations, such as radical prostatectomy, one point of contention has been a lack of comparative data between the established gold standard (open surgery) and robotic approaches. Given the pervasiveness of the multi-port platform, we would expect similar difficulty enrolling patients in a randomized trial comparing open surgery to SP surgery as previously observed with the multi-port platform [30]. One potential acquiescence to such comparisons is that prospective randomized trials to compare outcomes between multi-port and SP platforms should be feasible given the current utilization and acceptance of robotic surgery. Ultimately, as the current available literature for SP robotic urological surgery consists of single-center case reports and series from experienced robotic surgeons, the results of these initial descriptions of SP robotic surgery feasibility require validation with prospective studies across multiple sites and clinical practices. Additional areas of investigation could also include human factors research to evaluate surgical comfort and experience with the transition to a novel surgical platform [31].

Imagining the next revolution in surgical technology, iterative improvements may be on the near horizon for better instruments with improved suction or retraction to obviate the assistant and enable true single-port technique. At present, Intuitive Surgical and the da Vinci surgical platform represent the dominant company in the field of surgical robotics with a near monopoly in market penetration. However, several potential competitors including Verb Surgical (Mountain View, CA), Medtronic (Minneapolis, MN), TransEnterix (Morrisville, NC), and Titan Medical (Toronto, Canada) have announced plans to enter the market with new surgical robotic platforms which will ideally promote innovation and drive downwards competitive price pressure for these technologies [32]. On the distant horizon, one can imagine miniaturization, Wi-Fi, and machine learning algorithms that create semi-autonomous robotic behaviors and disrupt the traditional master–slave relationship of current robotic configurations [33]. With the rapid acceleration of technological advancement, these technologies do not

Table 2 Summary of SP operations performed at the University of Illinois at Chicago (December 2018–April 2019)

Operation	Patient #	Median operative time (range) (min)	Median EBL (ml)	Length of stay (median days)	Conversions from planned operation	Intraoperative complications	Postoperative complications (Clavien)
Prostatectomy (15 PLND)	24	237 (191– 343)	75	1	No	Serosal injury ($n=1$)	Grade I—Nausea ($n=1$), Ileus ($n=2$), urine leak requiring prolonged Foley catheterization ($n=2$), electrolyte derangement ($n=1$) Grade II—Urinary tract infection ($n=2$) pelvic hematoma requiring transfusion ($n=1$) Grade IIIa—Urine leak requiring cystogram and Foley exchange ($n=1$) Grade IVb—Postoperative respiratory failure, transient pressor requirement ($n=1$)
Partial nephrectomy	6	216 (186–249)	50	1.5	None	None	Grade I—Nausea ($n=1$), urinary retention ($n=1$) Grade II—Urinary tract infection ($n=1$)
Vaginoplasty	3	418 (309– 471)	117	5.5	None	None	Grade IIIb—Vaginal bleed, deep venous thrombosis ($n=1$)
Nephrectomy	2	219 (133–306)	255	4	Y—handport required (1)	None	Grade IVa—Hemorrhage and re-exploration ($n=1$)
Vesicovaginal fistula repair	2	272 (271–273)	22.5	2.5	None	None	None
Ureteral re-implant	2	229 (163–295)	35	1.5	None	None	Grade I—Nausea ($n=1$)
Prostatectomy and partial nephrectomy	1	405	300	9	None	None	Grade IIIa—Angioembolization of bleeding interpolar artery requiring transfusion ($n=1$)
Pyeloplasty	1	278	5	6	None	None	Grade I—Nausea ($n=1$)
Adrenalectomy	1	142	20	2	None	Thoracic duct injury ($n=1$)	None
Pyelolithotomy	1	148	10	1	None	None	Grade I—Nausea ($n=1$)
Renal cyst Decortication	1	440	300	2	None	Serosal injury ($n=1$)	None
Cystectomy	1	480	300	13	Y—planned extracorporeal diversion	None	Grade IIIa—PICC line placement for ileus ($n=1$)

seem so distant and merit discussion regarding the medico-legal and ethical considerations of such next generations of robotic technology.

Conclusions

Rather than an iterative step or a niche system, the SP platform provides for a new approach to single-site laparoscopic or robotic techniques and is demonstrated as a feasible approach for several major robotic urological operations. While comparative studies will be required to evaluate perioperative and long-term outcomes between SP and multiport platforms, further technological advances will continue to push surgeons towards less morbid and more minimally invasive approaches for surgery.

Funding None.

Compliance with ethical standards

Conflict of interest Dr. Crivellaro is a consultant for Intuitive Surgical.

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