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Review

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***Abstract*:** Over the past 20 years, the field of robotic surgery has largely been dominated by the da Vinci robotic platform. Nevertheless, numerous novel multiport robotic surgical systems have been developed over the past decade, and some have recently been introduced into clinical practice. This nonsystematic review aims to describe novel surgical robotic systems, their individual designs, and their reported uses and clinical outcomes within the field of urologic surgery. Specifically, we performed a comprehensive review of the literature regarding the use of the Senhance robotic system, the CMR-Versius robotic system, and the Hugo RAS in urologic procedures. Systems with fewer published uses are also described, including the Avatera, Hintori, and Dexter. Notable features of each system are compared, with a particular emphasis on factors differentiating each system from the da Vinci robotic system.

Keywords: Avatera, Hinotori, Hugo, new robotic systems, Revo-i, Senhance, urology, Versius

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Introduction

Since the da Vinci™ robotic surgical system (Intuitive Surgical, Sunnyvale, CA, USA) was approved by the Food and Drug Administration (FDA) in the United States in 2000, it has revolutionized the field of minimally invasive surgery, particularly in urology. Robotic surgery has demonstrated improved outcomes, including decreased blood loss and transfusion rate, shorter length of hospital stay, and fewer complications when compared with the traditional open or laparoscopic approach.[1,2] After radical prostatectomy, which in the United States is now predominantly performed robotically,[3] continency and potency rates are also significantly improved.[2] Robotic-assisted surgery is more costly upfront than the laparoscopic or open alternative, although the decrease in complication rate and shorter length of hospital stay is thought to offset the higher cost at least partially.[4,5]

As of the third quarter of 2022, there were 7364 da Vinci surgical systems installed worldwide, an increase of 13% from 1-year prior.[6] Procedures grew by approximately 20% in the same year, resulting in a quarterly revenue of $1.56 billion.[6] Intuitive currently represents approximately 80% of the global market share of surgical robotics.[7] The high cost of purchase and maintenance of the da Vinci robotic system, however, remains a barrier for many hospitals, both in the United States and worldwide. With many of the initial patents filed by Intuitive reaching the 20-year expiration,[8] there remains opportunity for alternative options in robotic surgery. In addition to cost, frequent criticisms of the da Vinci system include difficult communication between surgeon and surgical team due to the closed console system, lack of haptic feedback, rigidity of arm placement, and large size.[9]

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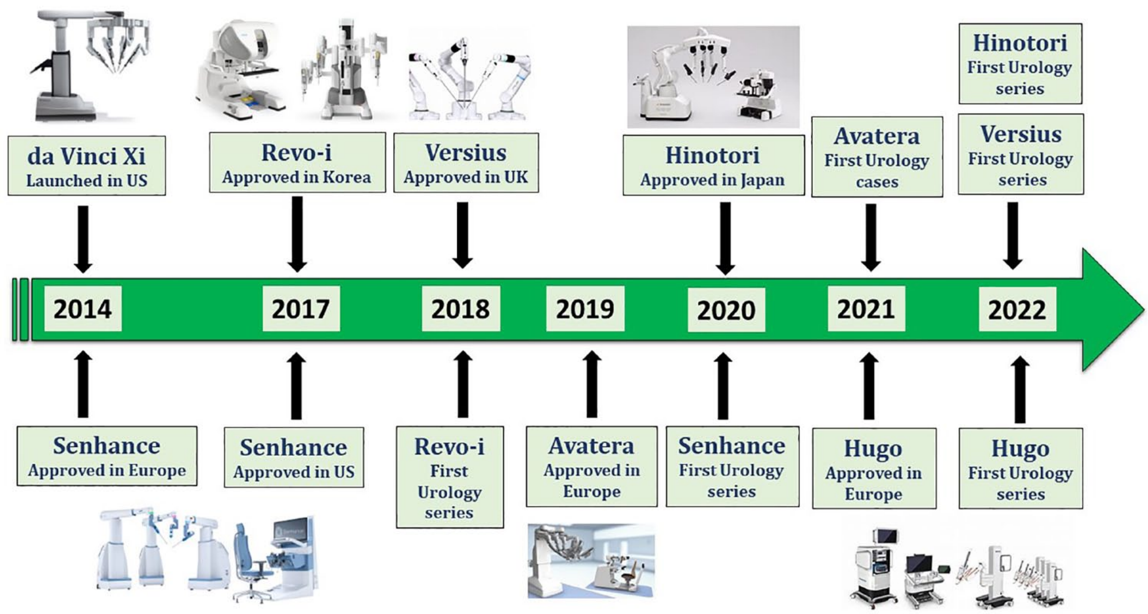

Figure 1. New multiport robotic surgical systems in urology: a temporal overview.

Nevertheless, numerous novel multiport robotic surgical systems have been developed over the past decade, and some have recently been introduced into clinical practice (Figure 1). These new technologies are likely to change the landscape of robotic surgery in urology in the near future.[10] This nonsystematic review aims to provide a comprehensive overview of all these recently introduced robotic systems, their initial clinical use and up to date outcomes in urologic surgery.

Methods

A literature review was performed in December 2022, and updated in March 2023, using the PubMed search engine. Given the limited publications regarding most novel robotic systems, the searches were kept broad. The search keywords used included 'Revo-I' ($n=17$), 'Senhance' ($n=71$), 'Senhance urology' ($n=15$), 'Versius' ($n=39$), 'Hugo ras' ($n=45$), 'avatera' ($n=9$), 'hinotori' ($n=7$), and 'Dexter robotic' ($n=5$). Where applicable, the search results were reviewed for publications that were specific to the clinical outcomes of the robotic systems for urologic surgical procedures. Original articles and review articles written in the English language were included. The Google search engine was used for each respective system to access the official device website.

Revo-i

The Revo-i robotic surgical system (Model MSR-5000; Meere Company Inc., Yongin, Republic of Korea) is a master–slave system consisting of a closed console and a four-armed operation cart.[11] Use in humans was approved by the Korean FDA in 2016.

After two initial preclinical reports,[12,13] the Yonsei Group used the Revo-i robotic system in a small initial series of 17 patients to perform Retzius-sparing radical prostatectomy.[14] Surgeons completed all cases without major complications and displayed overall satisfaction with the system's convenience and operative times.

In a more recent work, the same group reported a propensity score–matched comparison of Revo-i ($n=33$) to the da Vinci Si in Retzius-sparing radical prostatectomy ($n=33$).[15] Surgeries performed with the Revo-i robot showed a positive surgical margin rate of 16% and a 6-month biochemical recurrence rate of 4%. There were three minor (Clavien–Dindo Grade I–II) postoperative complications in each group and one Clavien–Dindo grade IIIA complication in the da Vinci group. Revo-i cases had longer operative times and a shorter length of stay compared with the da Vinci group. Estimated blood loss, positive margin rate, and complication rates were found to be similar in the two groups. In this same study, the authors claim Revo-I may be more cost-effective by lowering the costs of instruments and maintenance by 42% compared with the da Vinci system.[15]

Senhance

The Senhance® robotic system (Asensus Surgical, Durham, NC, USA), first introduced in 2012 (previously known as TELELAP Alf-X), was approved in Europe in 2014 and in the United States in 2017. The system consists of an open console and four separate, modular robotic arms.[16] It is designed to be compatible with traditional laparoscopic trocars and mimics laparoscopic style handles. Most instruments are 3–5 mm in diameter and are reusable. The system incorporates eye-tracking camera control and haptic feedback to improve the surgeon's ability to sense pressure and tension thresholds.[16] Robotic docking time has been reported to range from 3 to 10 min.[17,18] With the ability to incorporate laparoscopic instruments, the system is potentially significantly less expensive to maintain than the da Vinci. Most of the literature on this system has been in general surgery,[17] colorectal surgery,[18] and gynecology.[19] Several studies on the use of Senhance, however, can be found for a wide variety of urologic procedures (Table 1).[20–28]

The most frequently reported procedure for urology has been radical prostatectomy. Kastelan *et al.*[20] described an initial series of 40 cases done using the extraperitoneal approach. More recently, the same group reported updated data on 70 cases.[21] In addition, they reported a study comparing extraperitoneal Senhance-assisted radical prostatectomies with the standard laparoscopic technique and found no differences in operative time, blood loss, positive surgical margins, length of stay, or catheterization.[22]

Venckus *et al.*[23] published the largest series to date, a prospective analysis of 127 patients who underwent radical prostatectomies using the Senhance robotic system. A pelvic lymph node dissection was performed in 16.5% of these patients, and a nerve sparing on at least one side was performed in 29.1%. Both operative time and blood loss decreased with increasing surgeon experience. The positive margin rate in this series was 33.9% (28.7% in pT2 and 57.9% in pT3), which is slightly higher than the positive margin rate that has been reported for standard robotic and laparoscopic prostatectomy in high volume centers.[24] Fifteen patients (11.8%) experienced complications.

Published data regarding the use of Senhance in upper tract surgery is limited. One initial case series of two radical nephrectomies was reported by Kaneko *et al.*[25] The two procedures were successful without need for conversion or complications.

Kastelan *et al.*[21] described a series of 30 upper urinary tract procedures, including 9 adrenalectomies, 6 simple nephrectomies, 11 renal cyst fenestrations, and 4 pyeloplasties. In this series, there was one reported Clavien–Dindo grade II complication (fever) and one grade IIIb complication (bleeding). The same group described a case series of 12 patients undergoing adrenalectomy with the Senhance system for benign adrenal conditions.[26] Overall, outcomes were favorable, with one patient requiring reoperation for bleeding and one patient requiring conversion to laparoscopy due to adhesive perinephric fat.

In the uro-gynecology arena, Sassani *et al.*[27] showed the feasibility of the sacrocolpopexy procedure by reporting an initial series of 25 cases. Most patients had stage III and IV prolapse. Mean operative time decreased as the surgeons gained experience, and there were no major intraoperative complications. At a median follow-up of 16 weeks, no subjective recurrences or re-treatments were recorded. Two patients required postoperative readmission. The same group also reported a comparative cost analysis *versus* the da Vinci procedure.[28] Senhance cases had longer operative times by approximately 30 min; however, on multivariable linear regression, total cost was $908.33 lower for Senhance when adjusting for other variables.

Finally, the Senhance has been described in pediatric urology as well, in which the ability to use 3 mm and articulating 5 mm instruments could be of benefit.[29]

Table 1. Senhance® robotic system: reported clinical outcomes for urologic procedures.

Reference	Institution	Procedure	Number of cases	Surgical outcomes[a]	Oncologic and functional outcomes	Postoperative complication rates, %
Kastelan *et al.*[20]	University Hospital Zagreb (Croatia)	RP	70	EBL: 200 ml; OT: 200 min LOS: 5 days	PSM rate: 25.7% Continence rate: 88.6%	Overall: 8.5 Major: 0
Kulis *et al.*[22]	University Hospital Zagreb (Croatia)		107	OT: 195 min; EBL: 300 ml LOS: 5 days; Conversion to lap: 8.4%	PSM rate:28% BR rate: 2% Continence rate: 79%	Overall: 9.3 Major:1
Venckus *et al.*[23]	Klaipeda University (Lithuania)		127	OT: 180 min; EBL: 250 ml	PSM rate: 33.9%	Overall: 11.8 Major: 2.3
Kaneko *et al.*[25]	Saitama Medical University (Japan)	RN	2	Console time: 122–143 min EBL: 3–50 ml	PSM rate: 0%	Overall: 0
Kastelan *et al.*[21]	University Hospital Zagreb (Croatia)	Upper urinary tract procedures[b]	30	OT: 160 min; EBL: 30 ml LOS: 4 days	–	Overall: 6 Major: 3
Knežević *et al.*[26]	University Hospital Zagreb (Croatia)	ADR	12	OT: 165 min; Docking time: 11.6 min; EBL: 47 ml LOS: 4.5 days; Conversion to lap.:8.3%	–	Major: 8.3
Sassani *et al.*[27]	University of Pittsburgh (USA)	SCP	25	OT (mean): 210.2 min; EBL: 35 ml	Anatomical recurrence without subjective bother: 8%	Overall: 8 Major: 4
Holzer *et al.*[29]	Klinikum Esslingen (Germany)	Pyeloplasty	1	OT: 4.5 h; LOS: 7 days	No recurrence	Overall: 100 Major: 0

ADR, adrenalectomy; BR, biochemical recurrence; EBL, estimated blood loss; LOS, length of stay; OT, operative time; PSM, positive surgical margins; RN, radical nephrectomy; RP, radical prostatectomy; SCP, sacrocolpopexy.
[a]Expressed in median values unless otherwise indicated.
[b]Including radical nephrectomy, adrenalectomy, and renal cyst decortication.

Versius

The Versius robotic system (CMR, Cambridge, UK) consists of an open console that can be used in a sitting or standing position and three or four individual bedside units.[30] The device controls are exclusively hand controlled, which is another major difference compared with the da Vinci console. Initial clinical series showing the feasibility of minor or intermediate gynecological and general surgery procedures using this novel system was reported by Kelkar *et al.*[31] In urology, Thomas *et al.*[32] reported the first preclinical assessment of the Versius system for renal and prostate procedures by testing it in human cadavers and pig models. A few clinical reports on the clinical use of Versius for urologic applications have recently become available (Table 2).

Table 2. Versius™ robotic system: reported clinical outcomes for urologic procedures.

Reference	Institution	Procedure	Number of cases	Key outcomes[a]	Postoperative complication rates, %
Reeves *et al.*[33]	Guy's and St Thomas' (UK)	RP	4	OT: 335 min; PSM rate: 0% 1-week continence rate: 50%	Overall: 10 Major: 0
		Pyeloplasty	3	OT: 157 min	
		Nephrectomy	2	OT: 156 min; Path: 1 benign, 1 RCC with negative margins	
		Adrenalectomy	1	OT: 152 min –	
Hussein *et al.*[34]	Sindh Institute (Pakistan) & Roswell Park (USA)	Multiple[b]	106	EBL: 123 ml; OT: 150 min; LOS: 3 days Transfusion rate: 24%; conversion to open: 5.6%; malfunction:1.8%	Major: 8
Rocco *et al.*[35]	ASST Santi Paolo and Carlo (Italy)	RP	1	Console time: 130 min; LOS: 3 days; negative margins	None
Gaia *et al.*[36]		Colposacropexy	1	OT: 75 min; LOS: 2 days	None

EBL, estimated blood loss; LOS, length of stay; OT, operative time; PSM, positive surgical margin; RCC, renal cell carcinoma; RP, radical prostatectomy.
[a]Expressed in median values unless otherwise indicated.
[b]Including adrenalectomy ($n = 4$), pyeloplasty (9), radical nephrectomy (10), renal cyst unroofing (3), simple nephrectomy (42), pyeloplasty and ureterolithotomy (11), radical cystectomy (1), simple prostatectomy (9), ureteral reimplants (2), varicocelectomy (3), and pyelo/uretero/cystolithotomy (17).

Rocco *et al.*[35] reported the successful use of Versius for radical prostatectomy. Docking time was 30 min, console time was 130 min, and intraoperative disruption was limited to an alarming due to collision between the trocar and the patient's skin. The patient's course was uneventful. The same group also reported a colposacropexy case.[36]

Reeves *et al.*[33] reported 10 cases performed in the United Kingdom, including 4 radical prostatectomies, 2 radical nephrectomies, 3 pyeloplasties, and 1 adrenalectomy. Preoperative training included 6 h of virtual reality training for surgeons and dry and cadaveric laboratories for the entire surgical team. There were no incidences of conversion or major complications. One prostatectomy patient experienced a urine leak requiring delayed catheter removal.

A larger series was reported by investigators from Sindh Institute of Urology and Transplantation in Pakistan and Roswell Park Comprehensive Cancer Center.[34] A total of 106 procedures were done in total for both benign and malignant disorders of the upper tract and pelvic/lower urinary tract. Six of these procedures required conversion to open, and malfunction of the robotic arms occurred in two. A major postoperative complication was recorded in eight patients (7.5%). A matched analysis of various procedures using the Versius *versus* standard da Vinci procedures showed no significant difference in perioperative outcomes. Overall, surgeons and bedside assistants endorsed that when compared with the da Vinci system, communication between the surgeon and the assistants felt easier due to the open console design. They did, however, report more frequent arm collisions than typically experienced with the da Vinci.

Hugo

The Hugo RAS™ system (Medtronic, Minneapolis, MN, USA) includes an open console with two arm-controllers used with a pistol-like grip, and a footswitch that is used to control the camera, energy source, and reserve arm.[34] There are four independent arm carts, each of which has six joints to increase range of motion. It incorporates head tracking technology *via* specific three-dimensional (3D) glasses.[37] The first clinical case took place in 2021 in Chile,[38] and the system was approved for use in the European Economic Area (EEA) for gynecological and urological procedures in 2022, although it has not yet received FDA approval in the United States.[37]

Most clinical series with the Hugo system were reported over the past year (Table 3). The initial series was done in India and reported by Ragavan and Mottrie.[39] A total of seven cases were performed, including radical prostatectomy ($n=3$), simple prostatectomy ($n=1$), radical nephrectomy ($n=1$), and simple nephrectomy ($n=2$). There were no intraoperative or postoperative complications. Bravi *et al.*[40] later reported an initial radical prostatectomy series of five cases in Belgium. All procedures were completed without need for conversion or placement of additional ports, and no failure of the system was recorded. One patient experienced acute urinary retention requiring re-catheterization (Clavien–Dindo grade II). Another initial small series of 7 cases was reported by Totaro *et al.*,[41] and no major system faults were observed. A nonrandomized study comparing radical prostatectomy outcomes between the Hugo RAS and the da Vinci system found no differences in total operative time or console time.[42] The authors note that while the docking process was longer with the Hugo RAS, the independent arms allow for better flexibility and more working space for the bedside assistant.

Mottaran *et al.*[43] reported a simple prostatectomy using the Hugo RAS in a 72-year-old male with a prostate volume of 155 g. Docking, operative, and console times were 9, 150, and 120 min, respectively. There was no need for conversion or placement of additional ports, and no postoperative complications occurred. The postoperative uroflowmetry revealed a maximum flow of 26.2 ml/s, without postvoid residual volume. The same group also reported a series of five cases of sacrocolpopexy.[44]

Gallioli *et al.*[45] published a series of 10 patients who underwent robotic-assisted partial nephrectomy using the Hugo system. One case required conversion to laparoscopy, and the patient later required selective arterial embolization after developing a bleeding pseudoaneurysm (Clavien–Dindo IIIa). There were no other reported complications. Median lesion size was 3 cm, median length of stay was 4 days, and no positive surgical margins were reported. Elorrieta *et al.*[46] described the use of the Hugo system in five non-oncological urologic diseases, including ureteral reimplant ($n=2$), simple nephrectomy, pyeloplasty, and ureterolithotomy There were no postoperative complications, intraoperative instrument clashes, or system failures.

Finally, the Hugo system has been described in a series of five adrenalectomies, with a median lesion size of 3.9 cm (range = 3.0–9.0 cm).[47] Preoperative diagnoses included Cushing's syndrome ($n=3$), adrenal cystic lesion, and pheochromocytoma. No intraoperative complications or conversions to alternative modalities were reported.

The Expand URO US clinical trial is currently being conducted pursuant to an investigational device exemption (IDE) from the US FDA. The first patient was enrolled in December 2022 and up to 122 patients will be enrolled in 6 US centers.[48]

Avatera

The Avatera (Avateramedical, Jena, Germany) consists of a console unit with an eyepiece that allows the surgeon's mouth and ears to be uncovered and a robotic cart with four robotic arms.[49] It uses 5 mm working instruments with 7 df (degrees of freedom) range of motion that are fully disposable. It was introduced in clinical practice in Germany in 2022.[50]

While no clinical series have been published to date, feasibility studies of robot-assisted radical nephrectomy and radical cystectomy with ileal neobladder using this novel system in a porcine model were recently published.[51,52] In an SWOT (strengths, weaknesses, opportunities, threats) analysis looking at the projected market costs of this system, Liatsikos *et al.*[53] calculated that the elimination of sterilization costs of instruments could potentially translate into a cost reduction of €800–900 for a standard radical prostatectomy in Greece.

Hinotori

The Hinotori robotic system (Medicaroid, Kobe, Hyogo, Japan) consists of a patient cart with four

Table 3. Hugo RAS™: reported clinical outcomes for urologic procedures.

Reference	Institution	Procedure (number of cases)	Key outcomes[a]	Complication rate
Ragavan *et al.*[39]	Apollo Hospitals (India) Orsi Academy OLV Hospital (Belgium)	RP (3)		Overall: 0%
		Simple nephrectomy (2)	OT: 184 min, 110 min EBL: 100 ml, 150 ml LOS: 2 days, 1 day	
		Simple prostatectomy (1)	OT: 176 min EBL: 150 ml LOS: 1 day	
		Radical nephrectomy (1)	OT: 90 min EBL: 400 ml LOS: 3 days	
Bravi *et al.*[40]	Orsi Academy OLV Hospital (Belgium)	RP (5)	OT: 170 min LOS: 3 days EBL: 400 ml	Overall: 20% Major: 0%
Ragavan *et al.*[42]	Apollo Hospitals (India)	RP (17)	OT: 210 min LOS: 1 day PSM rate: 23.5% 3-month continence: 100%	
Mottaran *et al.*[43]	Orsi Academy OLV Hospital (Belgium)	Simple prostatectomy (1)	OT: 150 min Uroflow: 26.2 ml/s PVR: 0	None
Mottaran *et al.*[44]	Orsi Academy OLV Hospital (Belgium)	Sacrocolpopexy (5)	Docking time: 8 min OT:130 min Console time: 80 min	
Gallioli *et al.*[45]	Puigvert (Spain)	Partial nephrectomy (10)	Docking time: 8 min Console time: 138 min EBL: 90 ml LOS: 4 days	10%
Elorrieta *et al.*[46]	Finis Terrae University (Chile)	Ureteral reimplant (2) Simple nephrectomy (1) Pyeloplasty (1) Ureterolithotomy (1)	Docking time: 8.5 min OT: 150–257 min Console time: 89–164 min LOS: 2–5 days	None
Raffaelli *et al.*[47]	Policlinico Gemelli Rome (Italy)	Adrenalectomy (5)	Docking time: 5 min OT: 119 min Console time: 55 min LOS: 2 days	Overall: 20% Major: 0%

EBL, estimated blood loss; LOS, length of stay; OT, operative time; PSM, positive surgical margin; PVR, post-void residual; RP, radical prostatectomy.
[a]Expressed in median values unless otherwise indicated.

8-axis operation arms and an ergonomically friendly semiclosed surgeon console.[54] It boasts a 'docking-free' system, designed to reduce interference between arms and with the bedside assistant. It is regulatory approved for use in Japan.

In the first report in the urology literature on the Hinotori robot, the authors performed multiple urologic procedures in both cadaver and porcine models.[55] In addition, radical prostatectomy was performed on 30 live patients. Median console time was 165 min, and there were four episodes of equipment malfunction. There were four patients with positive surgical margins and a 10% adverse event rate. A more recent study described a series of 30 patients undergoing robotic-assisted partial nephrectomy using the Hintori robot.[56] Both intraperitoneal and retroperitoneal approaches were used. No conversion to alternative approach, major perioperative complications, or positive surgical margins were reported.

Dexter

Dexter® (Distalmotion, Lausanne, Switzerland) features a mobile, adaptable open console that allows surgeons to operate in a seated or standing position.[57] The surgeon remains sterile while operating from the console, allowing them to switch easily between laparoscopy and robotic surgery. It uses 8 mm, single-use, fully articulated instruments but is designed to be compatible with all laparoscopic instruments and can be used with any commercial laparoscopic tower. The first urological surgeries, a radical and a simple prostatectomy, were completed in Bern in June 2022.[58]

Discussion

Several robotic systems have come to the stage over the past decade, some of which are approved for clinical use, although none of them are yet available on a worldwide scale. Each of these systems presents key features that were conceived to address the technical or cost limitations of the da Vinci platform (Table 4). While awaiting widespread implementation of these systems, several centers are paving the way to demonstrate their safety and clinical applicability for a variety of surgical procedures. Differently to the da Vinci, which was a predominately urology-based system when it was initially introduced for clinical use, other surgical specialties are heavily involved in initial use of these novel robotic systems.

When examining the current evidence in terms of clinical cases among these new systems, the largest number of urology procedures (>200) has been reported with the Senhance, which is being proposed as a form of 'digital' rather than 'robot-assisted', laparoscopy. The Versius system has been described in a variety of clinical cases for different indications, with largely good clinical outcomes. Evidence is building on Hugo, with less than 50 reported urology cases, and Hinotori, with at least 30 reported cases. Evidence on other systems, such as Avatera and Dexter, remains anecdotal at best.

When comparing the novel robotic systems to the current state of the da Vinci system, several factors must be considered. Since its initial approval in 2000, there have been four generations of the multiarm da Vinci system: the 2000, S, Si, and Xi.[59] The robotic platforms discussed in this review are at their first generation, and it is foreseeable that they will be improved and optimized. There has also been the recent introduction of the da Vinci single port (SP) robotic system, which was FDA approved for use in late 2018. It differs from the traditional robotic systems in that all instruments and the camera enter through a single point of entry, which may translate into reduced invasiveness and improved postoperative recovery.[60] The SP system is currently available in the United States, Korea, and Japan; intuitive reported 99 installed SP robot systems as of 31 December 2021.[61] It remains to be determined what impact this system will have in the robotic market as it becomes globally available. An in-depth analysis of the SP is outside the scope of the present review.

A large-limiting factor to implementation of the da Vinci, particularly in resource poor settings, is cost. The reported cost of the da Vinci system is variable, including acquisition of the system, annual maintenance, and per-procedure instrument and accessory cost.[62] While it is often cited that the lower complication rate and shorter hospital stay offset the high cost of robotic procedures, the data supporting this assertion is variable.[4,63] Certain novel robotic systems aim to offer lower cost options; the Revo-i system claims a 42% cost reduction when compared with the da Vinci,[15] while the Avatera's use of single-use instruments eliminates sterilization costs.[56] The Senhance system allows for incorporation of traditional laparoscopic instruments, which are less costly than robotic instruments, and the system is less expensive to maintain than the da Vinci.[53] While it is unlikely that many hospitals who have already invested significantly in the da Vinci system will purchase additional robotic systems, they may be an option for health systems looking for a cheaper alternative.

In addition to cost, other barriers exist to widespread implementation of new robotic systems. Surgeon comfort and skill with novel robotic systems will need to be developed, and the learning curve for each system will be variable. With the current interest in incorporating artificial intelligence (AI) into medicine, the question of how robotic technology can evolve remains to be seen. Autonomous robotic surgery has been reported to

Table 4. Notable features of novel multiport robotic surgical systems.

System	Notable features
Revo-i	Closed master console 10 mm 3D HD camera Four arm system Reduced cost per procedure Reusable instruments (20 times)
Senhance	Open console Eye-tracking camera control 3D HD visualization Haptic feedback Standard reusable instruments Ergonomic seating Open platform architecture Minimal learning curve
Versius	Open console Individual bedside units with mounted arms Small, lightweight and modular design Ergonomic console that allows sitting or standing
Hugo	Up to four independent arm carts Open surgical console 3D glasses with head tracking system Tower compatible with pure laparoscopy
Avatera	Open console unit with slender eyepiece Disposable 5 mm instruments
Hintori	Semiclosed, ergonomic console Docking-free system Four 8-axis operation arms
Dexter	Mobile, open console Surgeon remains sterile Compatible with traditional laparoscopic instruments

HD, high definition.

be successful and by some criteria superior to human skill,[64] although this has yet to be tested on human patients in any large-scale platform. Telerobotic surgery, the ability to use robotic instruments to perform a surgical procedure remotely, is also of interest and may be key in bringing robotic technology to remote areas in which no qualified surgeons exist. Successful implementation of telerobotic surgery has been described, including a renal cyst ablation between Baltimore and Munich in 2002.[65] Recently, telerobotic robotic gastrectomy cases were successfully completed in porcine models in Japan using the Hintori robot.[66] These cases were completed by two centers approximately 30 km apart and exhibited a latency time of 125 ms. Despite these advances, telerobotic surgery faces numerous barriers, including legal concerns, the need for a reliable, high-speed network, latency, and cyber security threats.[67]

Conclusion

The da Vinci system has dominated the field of robotic surgery since its approval in 2000, but the competition and diversity within the field appears to be growing. Despite its widespread success, the da Vinci does leave room for alternatives, namely, with features such as an open console, modularity, compatibility with traditional instruments, reduced size, and reduced costs. As clinical experience matures and technology evolves, the role of these novel systems in the different surgical fields and different types of healthcare systems will be better defined. There is a significant burden on medical device companies to prove safety and efficacy before widespread adaptation can be achieved and given the dominance of the da Vinci system in the United States in particular, competitors face an uphill battle. Regardless, it is imperative that urologists stay informed about emerging technology, and their clinical use as the robotic surgical system landscape becomes more diverse.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Author contributions

Morgan Salkowski: Conceptualization; Writing – original draft.

Enrico Checcucci: Formal analysis; Writing – original draft.

Alexander K. Chow: Conceptualization; Writing – review & editing.

Craig C. Rogers: Supervision; Validation; Visualization.

Firas Adbollah: Writing – review & editing.

Evangelos Liatsikos: Validation; Visualization; Writing – review & editing.

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References

1. Li KP, Wan S, Wang CY, *et al.* Perioperative, functional, and oncologic outcomes of robot-assisted versus open partial nephrectomy for complex renal tumors (RENAL score ⩾ 7): an evidence-based analysis. *J Robot Surg*. Epub ahead of print 13 March 2023. DOI: 10.1007/s11701-023-01565-3.
2. Huang X, Wang L, Zheng X, *et al.* Comparison of perioperative, functional, and oncologic outcomes between standard laparoscopic and robotic-assisted radical prostatectomy: a systemic review and meta-analysis. *Surg Endosc* 2017; 31: 1045–1060.
3. Moretti TBC, Magna LA and Reis LO. Radical prostatectomy technique dispute: analyzing over 1.35 million surgeries in 20 years of history. *Clin Genitourin Cancer*. Epub ahead of print 16 February 2023. DOI: 10.1016/j.clgc.2023.02.005.
4. Ng AP, Sanaiha Y, Bakhtiyar SS, *et al.* National analysis of cost disparities in robotic-assisted versus laparoscopic abdominal operations. *Surgery*. Epub ahead of print 21 March 2023. DOI: 10.1016/j.surg.2023.02.016.
5. Baghli A, Achit H, Audigé V, *et al.* Cost-effectiveness of robotic-assisted surgery vs open surgery in the context of partial nephrectomy for small kidney tumors. *J Robot Surg*. Epub ahead of print 15 March 2023. DOI: 10.1007/s11701-023-01552-8.
6. Intuitive. Intuitive announced third quarter earnings, 2022, https://isrg.intuitive.com/news-releases/news-release-details/intuitive-announces-third-quarter-earnings-2
7. BIS Research. Global surgical robotics market – analysis and forecast 2018– 2024, 2018, https://bisresearch.com/industry-report/surgical-robotics-market.html
8. Intuitive. Patent notice, https://www.intuitive.com/en-us/about-us/company/legal/patent-notice
9. Namdarian B and Dasgupta P. What robot for tomorrow and what improvement can we expect? *Curr Opin Urol* 2018; 28: 143–152.
10. Cisu T, Crocerossa F, Carbonara U, *et al.* New robotic surgical systems in urology: an update. *Curr Opin Urol* 2021; 31: 37–42.
11. Revo surgical solution, http://revosurgical.com/render/view/revo_i/discover_revo_i.html
12. Abdel Raheem A, Troya IS, Kim DK, *et al.* Robot-assisted fallopian tube transection and anastomosis using the new REVO-I robotic surgical system: feasibility in a chronic porcine model. *BJU Int* 2016; 118: 604–609.
13. Kim DK, Park DW and Rha KH. Robot-assisted partial nephrectomy with the REVO-I robot platform in porcine models. *Eur Urol* 2016; 69: 541–542.
14. Chang KD, Abdel Raheem A, Choi YD, *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: 441–448.

15. Alip S, Koukourikis P, Han WK, *et al*. Comparing Revo-i and da Vinci in Retzius-sparing robot-assisted radical prostatectomy: a preliminary propensity score analysis of outcomes. *J Endourol* 2022; 36: 104–110.
16. Senhance, https://www.senhance.com/us/digital-laparoscopy
17. Melling N, Barr J, Schmitz R, *et al*. Robotic cholecystectomy: first experience with the new Senhance robotic system. *J Robot Surg* 2019; 13: 495–500.
18. McKechnie T, Khamar J, Daniel R, *et al*. The Senhance surgical system in colorectal surgery: a systematic review. *J Robot Surg* 2023; 17: 325–334.
19. Gueli Alletti S, Rossitto C, Cianci S, *et al*. The Senhance™ surgical robotic system ('Senhance') for total hysterectomy in obese patients: a pilot study. *J Robot Surg* 2018; 12: 229–234.
20. Kastelan Z, Hudolin T, Kulis T, *et al*. Extraperitoneal radical prostatectomy with the Senhance robotic platform: first 40 cases. *Eur Urol* 2020; 78: 932–934.
21. Kastelan Z, Hudolin T, Kulis T, *et al*. Upper urinary tract surgery and radical prostatectomy with Senhance robotic system: single center experience-first 100 cases. *Int J Med Robot* 2021; 17: e2269.
22. Kulis T, Hudolin T, Penezic L, *et al*. Comparison of extraperitoneal laparoscopic and extraperitoneal Senhance radical prostatectomy. *Int J Med Robot* 2022; 18: e2344.
23. Venckus R, Jasenas M, Telksnys T, *et al*. Robotic-assisted radical prostatectomy with the Senhance robotic platform: single center experience. *World J Urol* 2021; 39: 4305–4310.
24. Carbonara U, Srinath M, Crocerossa F, *et al*. Robot-assisted radical prostatectomy versus standard laparoscopic radical prostatectomy: an evidence-based analysis of comparative outcomes. *World J Urol* 2021; 39: 3721–3732.
25. Kaneko G, Shirotake S, Oyama M, *et al*. Initial experience of laparoscopic radical nephrectomy using the Senhance robotic system for renal cell carcinoma. *Int Cancer Conf J* 2021; 2910: 228–232.
26. Knežević N, Penezić L, Kuliš T, *et al*. Senhance robot-assisted adrenalectomy: a case series. *Croat Med J* 2022; 3063: 197–201.
27. Sassani JC, Glass Clark S, McGough CE, *et al*. Sacrocolpopexy experience with a novel robotic surgical platform. *Int Urogynecol J* 2022; 33: 3255–3260.
28. Glass Clark S, Shepherd JP, Sassani JC, *et al*. Surgical cost of robotic-assisted sacrocolpopexy: a comparison of two robotic platforms. *Int Urogynecol J* 2023; 34: 87–91.
29. Holzer J, Beyer P, Schilcher F, *et al*. First pediatric pyeloplasty using the Senhance® robotic system – a case report. *Children* 2022; 229: 302.
30. CMR Surgical, https://cmrsurgical.com/versius
31. Kelkar D, Borse MA, Godbole GP, *et al*. Interim safety analysis of the first-in-human clinical trial of the Versius surgical system, a new robot-assisted device for use in minimal access surgery. *Surg Endosc* 2021; 35: 5193–5202.
32. Thomas BC, Slack M, Hussain M, *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: 444–452.
33. Reeves F, Challacombe B, Ribbits A, *et al*. Idea, development, exploration, assessment, long-term follow-up study (ideal) stage 1/2a evaluation of urological procedures with the Versius robot. *BJU Int* 2022; 130: 441–443.
34. Hussein AA, Mohsin R, Qureshi H, *et al*. Transition from da Vinci to Versius robotic surgical system: initial experience and outcomes of over 100 consecutive procedures. *J Robot Surg* 2023; 17: 419–426. DOI: 10.1007/s11701-022-01422-9.
35. Rocco B, Turri F, Sangalli M, *et al*. Robot-assisted radical prostatectomy with the Versius robotic surgical system: first description of a clinical case. *Eur Urol Open Sci* 2023; 48: 82–83.
36. Gaia G, Sighinolfi MC, Afonina M, *et al*. Uro-gynecological surgery with the Versius robotic system: first description of a clinical case. *Minerva Urol Nephrol*. Epub ahead of print 23 March 2023. DOI: 10.23736/S2724-6051.23.05301-6.
37. Medtronic. Hugo ™ RAS system, https://www.medtronic.com/covidien/en-us/robotic-assisted-surgery/hugo-ras-system.html?sfdcid=7014O000001JF3G&cid=PPC:GOOG:%2Bhugo%20%2Brobot:ras-hugo
38. Medtronic. First procedure in the world with Medtronic Hugo ™ robotic-assisted surgery system performed at Clinica Santa Maria in Chile, 2021, https://news.medtronic.

com/2021-06-22-First-Procedure-in-the-World-with-Medtronic-Hugo-TM-Robotic-Assisted-Surgery-System-Performed-at-Clinica-Santa-Maria-in-Chile

39. Ragavan N, Bharathkumar S, Chirravur P, *et al*. Evaluation of Hugo RAS system in major urologic surgery: our initial experience. *J Endourol* 2022; 36: 1029–1035.

40. Bravi CA, Paciotti M, Sarchi L, *et al*. Robot-assisted radical prostatectomy with the novel Hugo robotic system: initial experience and optimal surgical set-up at a tertiary referral robotic center. *Eur Urol* 2022; 82: 233–237.

41. Totaro A, Campetella M, Bientinesi R, *et al*. The new surgical robotic platform HUGO™ RAS: system description and docking settings for robot-assisted radical prostatectomy. *Urologia* 2022; 89: 603–609.

42. Ragavan N, Bharathkumar S, Chirravur P, *et al*. Robot-assisted laparoscopic radical prostatectomy utilizing Hugo RAS platform: initial experience. *J Endourol* 2023; 37: 147–150.

43. Mottaran A, Paciotti M, Bravi CA, *et al*. Robot-assisted simple prostatectomy with the novel HUGO™ RAS system: feasibility, setting, and perioperative outcomes. *Minerva Urol Nephrol* 2023; 75: 235–239.

44. Mottaran A, Bravi CA, Sarchi L, *et al*. Robot-assisted sacropexy with the novel HUGO robot-assisted surgery system: initial experience and surgical setup at a tertiary referral robotic center. *J Endourol* 2023; 37: 35–41.

45. Gallioli A, Uleri A, Gaya JM, *et al*. Initial experience of robot-assisted partial nephrectomy with Hugo™ RAS system: implications for surgical setting. *World J Urol* 2023; 41: 1085–1091.

46. Elorrieta V, Villena J, Kompatzki A, *et al*. ROBOT assisted laparoscopic surgeries for nononcological urologic disease: initial experience with Hugo Ras system. *Urology* 2023; 174: 118–125.

47. Raffaelli M, Gallucci P, Voloudakis N, *et al*. The new robotic platform Hugo™ RAS for lateral transabdominal adrenalectomy: a first world report of a series of five cases. *Updates Surg* 2023; 75: 217–225.

48. Medtronic announces first patient enrolled in U.S. clinical trial for Hugo™ robotic-assisted surgery system, https://news.medtronic.com/2022-12-15-Medtronic-announces-first-patient-enrolled-in-U-S-clinical-trial-for-Hugo-TM-robotic-assisted-surgery-system

49. Avateramedical, https://www.avatera.eu/en/avatera-system

50. Avateramedical. Avateramedical robot-assisted surgery system progresses to clinical use, 2022, https://www.avatera.eu/en/company/news/detail?tx_news_pi1%5Bnews%5D=42&cHash=84ba505a890ba27dcf6bec17706087cf

51. Gkeka K, Tsaturyan A, Faitatziadis S, *et al*. Robot-assisted radical nephrectomy using the novel avatera robotic surgical system: a feasibility study in a porcine model. *J Endourol* 2023; 37: 273–278.

52. Peteinaris A, Kallidonis P, Tsaturyan A, *et al*. The feasibility of robot-assisted radical cystectomy: an experimental study. *World J Urol* 2023; 41: 477–482.

53. Liatsikos E, Tsaturyan A, Kyriazis I, *et al*. Market potentials of robotic systems in medical science: analysis of the Avatera robotic system. *World J Urol* 2022; 40: 283–289.

54. Medcaroid, https://www.medicaroid.com/en/product/hinotori/

55. Hinata N, Yamaguchi R, Kusuhara Y, *et al*. Hinotori surgical robot system, a novel robot-assisted surgical platform: preclinical and clinical evaluation. *Int J Urol* 2022; 29: 1213–1220.

56. Miyake H, Motoyama D, Matsushita Y, *et al*. Initial experience of robot-assisted partial nephrectomy using hinotori surgical robot system: single institutional prospective assessment of perioperative outcomes in 30 cases. *J Endourol*. Epub ahead of print 28 March 2023. DOI: 10.1089/end.2022.0775.

57. Distalmotion, https://www.distalmotion.com/product/

58. Distalmotion. First Dexter surgeries in urology carried out in Bern, 2022, https://www.distalmotion.com/news

59. Koukourikis P and Rha KH. Robotic surgical systems in urology: what is currently available? *Investig Clin Urol*. 2021; 62(1): 14–22.

60. Kaouk JH, Haber GP, Autorino R, *et al*. A novel robotic system for single-port urologic surgery: first clinical investigation. *Eur Urol* 2014; 66: 1033–1043.

61. Intuitive annual report, 2021, https://isrg.intuitive.com/static-files/704322bf-cb0d-4ed1-954c-8eb46a070f70

62. Childers CP and Maggard-Gibbons M. Estimation of the acquisition and operating costs for robotic surgery. *JAMA* 2018; 320: 835–836.

63. Okhawere K, Milkhy G and Shih I. Comparison of 1-year health care expenditures and utilization following minimally invasive vs open nephrectomy. *JAMA Netw Open* 2022; 5: e2231885.

64. Shademan A, Decker R, Ofperman J, *et al*. Supervised autonomous robotic soft tissue surgery. *Sci Transl Med* 2016; 8: 337.

65. Anvari M, McKinley C and Stein H. Establishment of the world's first telerobotic remote surgical service: for provision of advanced laparoscopic surgery in a rural community. *Ann Surg* 2005; 241: 460–464.

66. Nakauchi M, Suda K, Nakamura K, *et al*. Establishment of a new practical telesurgical platform using the hinotori™ surgical robot system: a preclinical study. *Langenbecks Arch Surg*. 2022; 407: 3783–3791.

67. Mohan A, Wara UU, Shaikh MTA, *et al*. Telesurgery and robotics: an improved and efficient era. *Cureus* 2021; 13: e14124.