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Technical Aspects and Clinical Outcomes of Robotic Ureteroscopy: Is It Ready for Primetime?

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Abstract

Purpose of Review Robotic surgery in urology has already been widely employed in robotic-assisted laparoscopic surgery for minimally invasive procedures (MIS). We wanted to analyse rapidly developing robotic ureteroscopy (RoboURS) for the treatment of renal stone disease.

Recent Findings A comprehensive literature review was performed for technical aspects and clinical outcomes of RoboURS. RoboURS has made significant breakthroughs with each model proving that this technology improves ergonomics and supports surgeon and instrument longevity while minimising musculoskeletal issues in retrograde intra-renal surgery (RIRS). Further randomised controlled trials are required to compare the efficacy of RoboURS vs manual flexible ureteroscopy (FURS). The cost-effectiveness will also need to be assessed prior to widespread acceptance into urological infrastructure and mainstream practice.

Summary RoboURS continues to evolve despite the limitations of infrastructure and cost-effectiveness. It holds the promise of a better future for surgeon longevity, reduced peri-operative morbidity and better workplace environment.

Keywords Robotic ureteroscopy · Robot · Ureteroscopy · Kidney calculi · RIRS

Introduction

Urolithiasis comprises a significant proportion of urological conditions. It affects patient quality of life and often requires surgical intervention. The incidence for the same has been increasing in the recent decades and is expected to continue to rise along with volumes of surgeries performed [1–3]. The latter has been mirrored by the continuous development and improvement in technology and interventional modalities for treatment of kidney stone disease (KSD). A glimpse into the past reflects how far we have progressed in urolithiasis management, from the days of primitive perineal lithotomy for bladder stone which was associated with risks of sepsis, fistula and death [4, 5] through extracorporeal shock wave

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lithotripsy (ESWL) to modern-day advanced endoscopic management of KSD. With evolution in RIRS surgery to tackle more complex stones, both patient and surgeon factors are being considered to improve quality of surgical outcomes and ergonomical efficiency for surgeons performing RIRS [6•]. This has helped expedite patient management as day cases and greatly improve patient outcomes. As we continue this journey of evolution, we find ourselves embarking upon the journey of robot-assisted surgeries, to not only help improve patient-related factors, but also involve surgeon well-being as part of the wider goals of health care.

Robotic surgery in urology has already been widely employed in robotic-assisted laparoscopic surgery for minimally invasive procedures (MIS) such as prostatectomy, cystectomy and nephrectomy [7, 8]. Our aim was to assess the feasibility of applying similar principles of robotic surgery in the setting of flexible URS (FURS) for treatment of KSD.

Methods

Our review database included PubMed and Google Scholar. The search categories included “urological robot”, “robotic flexible ureteroscopy”, “robotic ureteroscopy”, “robotic RIRS” and “robotic urology”. Only papers published in English were included in this study, and abstracts without papers were excluded from this study. Papers discussing trials and outcomes of robotic ureteroscopy for KSD were included, and any papers describing any other robotic urological intervention were excluded from this study. An initial search revealed 54 papers of which only 14 discussed development of robotic URS (RoboURS) and surgeon–patient related outcomes and were included in this analysis of RoboURS (Table 1). The robots found with the master–slave configuration during the analysis of this study are enlisted in Table 2 with their respective details.

Results

The first robotic trial published by Desai et al. [9••] in 2008 was performed using Sensei robot (Sensei, Hansen Medical, Mountainview, CA, USA). This robot was originally designed for cardiac procedures and was then modified for first ever ureterorenoscopic intervention. This study was carried out in 10 porcine renal models in 5 pigs using a 14Fr robotic catheter system and a remote catheter manipulator. Holmium/yttrium-almunium-garnet (Holmium) laser fibre was used for the treatment of renal stones. They reported 98% success in ureteric manipulation with only 2 cases requiring balloon manipulation. The time required for visual inspection was reduced from first kidney procedure to the 10th. They measured surgeon-related technical outcomes on the visual analogue scale

Table 1 Studies included, where IDEAL means Idea, Development, Exploration, Assessment and Long-Term Follow-up)

Serial number	Author name	Paper name	Year of publication	Type of study
1	Desai et al. [9••]	Flexible robotic retrograde renoscopy: description of novel robotic device and preliminary laboratory experience	2008	Initial animal study
2	Desai et al. [9••]	Robotic Flexible Ureteroscopy for Renal Calculi: Initial Clinical Experience	2011	First human study
3	Saglam et al. [12]	A New Robot for Flexible Ureteroscopy: Development and Early Clinical Results (IDEAL Stage 1-2b)	2014	IDEAL stage 1 and 2 trial (simulator and human)
4	Geavlete et al. [13]	Robotic Flexible Ureteroscopy Versus Classic Flexible Ureteroscopy in Renal Stones: the Initial Romanian Experience	2016	Human study
5	Proietti et al. [14•]	Ureteroscopic skills with and without Roboflex Avicenna in the K-box® simulator	2017	Simulator study
6	Talari et al. [15]	Robotically assisted ureteroscopy for kidney exploration	2017	Simulator study
7	Rassweiler et al. [16]	Robot-assisted flexible ureteroscopy: an update	2018	Human study
8	Zhao et al. [17]	Design and Performance Investigation of a Robot-Assisted Flexible Ureteroscopy System	2021	Animal and simulator study
9	Klein et al. [18]	Analysis of performance factors in 240 consecutive cases of robot-assisted flexible ureteroscopic stone treatment	2021	Human study
10	Al-Ansari et al. [19]	Robotic Assisted Flexible Ureteroscopy in Covid-19 Positive Patient Using Thulium Fiber Laser: Case Report and Literature Review	2021	Human study
11	Shu et al. [20••]	Safety enhanced surgical robot for flexible ureteroscopy based on force feedback	2022	Simulator study
12	Park et al. [21]	The usefulness and ergonomics of a new robotic system for flexible ureteroscopy and laser lithotripsy for treating renal stones	2022	Animal and simulator study
14	Gauhar et al. [22]	Robotic Retrograde Intrarenal Surgery: A Journey from “Back to the Future”	2022	Robot comparative study
13	Lee et al. [23]	Robotic flexible ureteroscopy: A new challenge in endourology	2022	Robot comparative study

Table 2 Types of robots available for flexible ureteroscopy mapping progression of technology, where RoboURS is robotic ureteroscopy

Type of robot (cost)	Master console features	Slave robot features	Additional features	Improvements from previous models	Limitations
Sensei robot, Hansen Medical, Mountainview, Calif	1. LCD display and master input device 2. Remote catheter manipulation 3. Electronic rack 4. Master input device (3D joystick) 5. Display monitors with CT imaging syncing 6. User interface module	1. Steerable catheter system containing outer catheter sheath- 14/12 Fr and inner catheter sheath 12/10 Fr 2. Catheter guide channel for inflow and outflow of irrigation fluid and contrast	Works in fluoroscopic and endoscopic mode—interchangeable	Initial model modified from cardiac robot	1. Limited manoeuvrability 2. Passive control of URS only 3. Wide diameter of scope initially, later modified
Roboflex Avicenna, ELMED, Ankara, Turkey	1. Armrest adjustment 2. 2 joysticks to control endoscope—right for deflection upward and downward; left for sideways movement and advancement and retraction 3. 2 foot pedals for laser device and fluoroscopy	1. Motor system and robot arm holds endoscope 2. Catheter system to attach to URS with 10/12 Fr access sheath	Robotic arm can be rotated by 210° each side with 1 N/mm^2 force to minimise renal injury	Memory function Size reduction Active control to surgeon Adjustment of irrigation flow rate	1. Limited FURS scopes can be inserted into scope 2. No correlation with respiratory movement
Proietti et al. RoboURS [14•]	4. Quadrant view—axial, coronal, sagittal and volume rendered on surgeon console	Slave robot controlled by master console	Reconstruction from images gives information about tip position without using fluoroscopy	1.Independent control of 3 degrees of freedom 2. Robot snaping of URS—can be mounted with ease as and when required 3.Electromagnetic tracking for image memory and planning	1. Potential to add tracked sensor for respiratory movement to implement compensation methods 2. Only simulator trial available
Rassweiler et al. RoboURS [16]	Standard console- main work on slave arm	1. Offers 2° of freedom for movement for height and inclination adjustment 2. Local translational joints with joint to joint mapping strategy for control and intuitive motion	During manual evacuation power transmission can be cut off temporarily by clutch mechanism	Height and inclination can be adjusted	Only simulator and animal trial available
EasyUretero, ROEN surgical Inc, Daejon, Korea	1. 32-in touch screen control 2. Gimble handle—jog wheel and button for movement and trigger 3. Clutch for motion	Laser and stone basketing with inbuilt assistant	Monitoring information regarding length, flexion of instrument tip and degree of rotation available on master console	More sophisticate gimble handle for fine finger movement	No human studies available yet
ILY RoboFURS, Sterlab, Sophia, Antipolis, France	Wireless mini surgeon console	Multiple degrees of freedom near patient	Degrees of freedom controlled by surgeon remotely by wireless technology	1. Wireless technology 2. Accessory movement with assistant	No human studies available yet

with reproducibility of auto-retraction being ranked as 8, reproducibility of access as 10 and instrument tip stability being ranked as 10/10 (1 being worst outcome and 10 being excellent).

All calculi in this study were fragmented with no post-operative ureteric necrosis; however, there was 1 renal perforation which was attributed to surgeon error due to retraction in flexed position. Their autopsy findings revealed extravasation of fluid in all 5 cases, and this was corrected by reduction in size of instrument to 7.5 Fr and tested and proven in ex vivo models and 1 more porcine model. The advantages of using a RoboURS were enumerated as an increased range of motion, instrument stability and improved ergonomics. This heralded the path for further robotic ureteroscopic studies.

The first recorded human trial for RoboURS was reported in 2011 by Desai et al. [10••] in 18 patients with no intra-operative complications and 56% and 89% stone-free rate (SFR) in 2 and 3 months respectively on post-operative imaging. The post-operative complications were minimal and Clavien Dindo (CD) 1 and 2 only (Table 3). All their patients were pre-stented, and they used 7.5 Fr FURS with a 3.4 Fr working channel for treating all 5–15-mm stones. They reported their technical outcomes using the visual analogue score and gave 8.5 points for robot control, 9.0 points for stability and 9.2 points for ease of fragmentation. Their limitations were size of the scope, limited manoeuvrability and no available comparison to manual URS.

Following this pathbreaking development, in the year 2013, McCulloch et al. [11•] described the IDEAL concept (Idea, Development, Exploration, Assessment and Long-Term Follow-up) which has been applied to the upcoming field of robotic surgery in urology. Saglam et al. [12] described IDEAL stages 1 and 2 of idea and development using Roboflex Avicenna designed by ELMED (Ankara, Turkey) specifically for FURS (Fig. 1). A total of 81 patients with renal calculi were operated upon by 7 trained surgeons after appropriate simulator training. They reported using access sheath in 88.8% of cases with 2 patients requiring secondary procedures and 97% cases attaining complete stone disintegration. Details of robot are in Table 2. They reported RoboURS being ergonomically better for the operating surgeon, with safety and reproducibility of procedure having been met.

Geavlete et al. [13] reported a prospective randomised trial in 132 patients in Romania comparing RoboURS to manual FURS. They also used Avicenna Roboflex for their study and treated renal stones. They found 1 case of intra-operative bleeding in manual FURS-treated conservatively, with no reported intra-operative complications in RoboURS. They also found a significantly lower retreatment rate in RoboURS at 9.1% vs 15% in FURS. Complete intra-operative stone integration was found in 98.5% cases in RoboURS and 95.4% cases in manual FURS. SFR on follow-up imaging at 3 months was found to be 89.4% in manual FURS and 92.4% in RoboURS. They also stated RoboURS being ergonomically better, though this was not objectively compared in this study.

In 2017, Proietti et al. [14•] compared the learning curve of manual URS vs RoboURS using K-box (Porges coloplast) simulator in 10 final year medical students with 10 lessons in 10 days. This was analysed with single blinding randomisation using Objective Structured Assessment of Technical Skills (OSATS) and measured on LIKERT scale. They also used Roboflex Avicenna for RoboURS and Olympus URF-V2 for FURS. Their assessed outcomes included global ability to perform the task, total exercise duration, qualitative analysis of knowledge, instrument handling and trainees' competence. This was analysed via 2 different exercises. They found a significantly improved stability in students trained using RoboURS with no difference in exercise time, flow or orientation between the 2 groups. They also found better respect for surrounding tissue and better maintenance of centred vision in RoboURS, though this was not statistically significant.

Talari et al. [15] in 2017 created a prototype model for RoboURS-assisted renal calyceal exploration (Table 2). They used electromagnetic tracking for image memory and planning. It gives 4 quadrant images with axial, coronal, sagittal and volume rendered view, and they recommended adding road mapping utilising interventional radiology (IR) techniques to further enhance the surgical technique. They have not mentioned specific outcomes in simulator settings but stated that urology fellow involved in it found intuitive information useful in reducing fluoroscopic guidance for intra-renal positioning, thereby reducing radiation exposure.

Rassweiler et al. [16] reported their clinical experience with Roboflex Avicenna for RoboURS in 2017. They reported reduced use of fluoroscopy due to the memory function, adjustable irrigation speed and URS insertion and retraction speed as favourable aspects of RoboURS. The shortcomings in this study were the longer docking time as compared to previously reported studies with 2 cases of technical failure requiring conversion to manual URS.

Zhao et al. [17] in their paper titled "Design and Performance Investigation of a Robot-Assisted Flexible Ureteroscopy System" describe requirements of an ideal robot as follows:

- Adjustable user-friendly master–slave console
- Gravity balance being realised by symmetrical configuration
- Sufficient control accuracy by increasing distance between spin axis and handle
- Stability improvement by 2 handed make
- Thumb fatigue reduction by second rotational joint
- Height and inclination adjustability

Table 3 Details of intra-operative and post-operative complications across studies involving human cases only

Author	Name of study	No. of patients involved	Intra-operative complications	CD 1 and 2 post-operative complications	CD 3 and 4 post-operative complications	CD 5 post-operative complications
Desai et al. [9••]	Robotic Flexible Ureteroscopy for Renal Calculi: Initial Clinical Experience	18	Nil reported	2 cases of transient post-operative fever; 1 case of temporary limb paresis in known case of severe kyphoscoliosis	Nil reported	Nil reported
McCulloch et al. [11•]	A New Robot for Flexible Ureteroscopy: Development and Early Clinical Results (IDEAL Stage 1-2b)	81	Nil reported	Nil reported	Nil reported	Nil reported
Saglam et al. [12]	Robotic Flexible Ureteroscopy Versus Classic Flexible Ureteroscopy in Renal Stones: the Initial Romanian Experience	132	Nil reported	Nil reported	Nil reported	Nil reported
Talari et al. [15]	Robot-assisted flexible ureteroscopy: an update	Not mentioned	2 cases of technical failure requiring conversion to open	Nil reported	Nil reported	Nil reported
Zhao et al. [17]	Analysis of performance factors in 240 consecutive cases of robot-assisted flexible ureteroscopic stone treatment	240	2 cases of ureteric lesion; 5 cases of intra-operative bleeding; 1 case of conversion to manual due to technical failure; mucosal perforation, poor vision and stone dislocation in 3 cases	2 cases of significant drop in haematocrit, 1 transfused; 9 cases of urinary tract infection; 7 cases of post-operative fever; 4 cases of unspecified complications	1 case of myocardial infarction	2 cases of severe post-operative sepsis requiring intensive care unit admission
Klein et al. [18]	Robotic Assisted Flexible Ureteroscopy in Covid-19 Positive Patient Using Thulium Fiber Laser: Case Report and Literature Review	1	Nil reported	Nil reported	Nil reported	Nil reported

Fig. 1 Roboflex Avicenna, ELMED, Ankara, Turkey. Image source: original image

- Robot evacuation for emergencies and stable mode for stone evacuation
- Insertion and evacuation of endoscope without buckling
- Active mechanism for 3D degree of freedom for endoscope and auxiliary instruments

They also implemented an "incremental-proportional strategy" which enhances images at master console as translated from the slave slide.

They used 20 engineering students initially for simulator efficacy analysis and then switched to experienced surgeons for animal experiment. Two pigs were used for animal study, and both cases were completed with success for renal calyceal exploration. In the robotic arm, the operative time was seen to reduce more from first exploration to last than in manual URS arm.

Klein et al. [18] performed the largest human study using RoboURS after Roboflex Avicenna gained CE certification for clinical practice in 2013. They performed a prospective study on 240 patients undergoing FURS for renal stones and included 2.5% cases with solitary kidney, 3.8% cases of congenital abnormality and 4.1% cases of complicated anatomy. Their study included 8 surgeons for this study and reported a SFR of 90% with 8.75% of patients requiring a secondary procedure. However, they did have CD 5 post-operative complications in 2 patients requiring intensive care unit (ICU) admission for severe sepsis and 1 patient having an episode of myocardial infarction who had a known cardiac comorbidity history (Table 3).

Al-Ansari et al. [19] reported a case study during COVID-19 pandemic times when they used robotic URS in a COVID-positive patient to treat renal stone in renal pelvis, causing mild to moderate hydronephrosis, and found RoboURS an efficient and safe for treatment while also reducing surgical team's exposure to radiation. They reported no post-operative complication, and the patient was discharged as a day case.

Shu et al. [20••] identified deficits in force feedback in the current RoboURS model and worked on a robot that includes 3 movements including translation, rotation and bending with an inbuilt irrigation system, and with a neural network to help give operating surgeon force feedback and avoid inadvertent patient injury. They performed 10 simulator trials and found that in all 10 cases, operator can become aware of FURS being stuck and can therefore stop the action and avoid further harm to the patient. This robot has not been reported in humans or animals in the literature yet.

In 2022, Park et al. [21] used EasyUretero designed by REON Surgical Inc, Daejon, Korea, and used it for in vitro and in vivo study. Their study model involved 2 expert professors in urology (> 500 cases experience), 2 urology fellows (> 50 cases experience) and 2 urology residents (no URS experience). In the in vitro study, they found that task completion duration was longer in all 3 cohorts, but ergonomics was better, whilst in the in vivo phase,

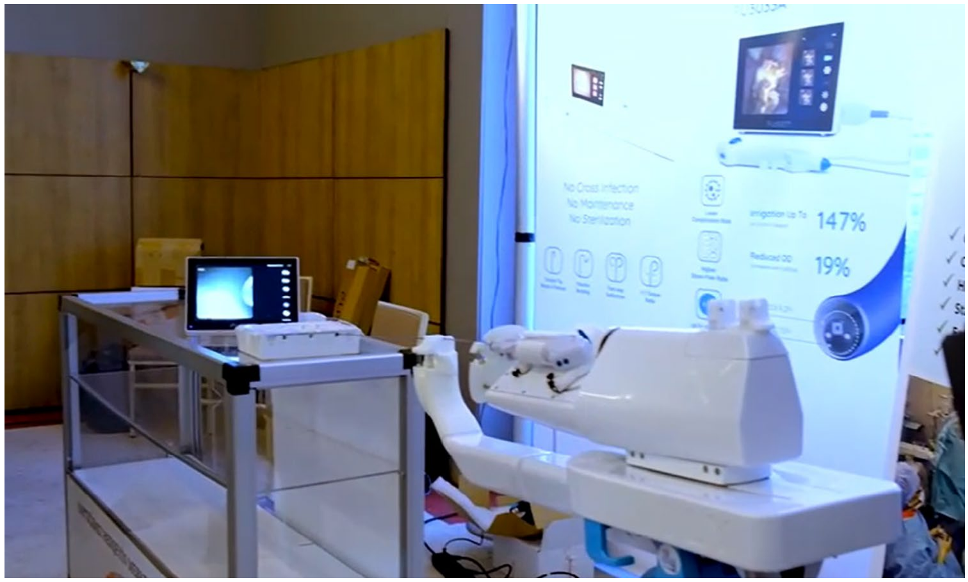

Fig. 2 ILY RoboFURS, Sterlab, Sophia, Antipolis, France. Image source: original image

the task completion was satisfactory without any conversion to manual URS. They found manual URS to be better than RoboURS for learning curve for URS. Gauhar et al. in their paper [22] mention the first human clinical trial using EasyUretero system which has been completed in April 2022 in Seoul National University, South Korea, on 47 patients successfully.

Another RoboURS named ILY Robo FURS developed by Sterlak, Sophia, Antipolis, France (Fig. 2) has been reported by Lee et al. [23] which offers remote manipulation of URS and multiple degrees of freedom near patient, and remotely while controlled by surgeon using wireless technology. Monarch Endoscopic Robotic platform [24] has been approved in USA recently which offers excellent visualisation with X-box type of controller. It is diffusion in clinical practice however is yet to be assessed.

Discussion

Ureteroscopy has fast become a favoured treatment modality for KSD among urologists offering a safe and efficacious operative profile and outcomes for all patients. It has been reported to cause musculoskeletal and postural damage to urologists due to the positioning of the scope, surgeon and limited operative fields with small calibre and fragile instruments [25–27]. Robotic surgery enhances endoluminal endourological interventions by improving ergonomics and potentially reducing operative duration by aide of memory function in the robot. This also helps in conveniently reducing the time taken for the surgeon to re-orient themselves inside the kidney with regards to upper, middle and lower pole.

The memory function aides not only in reduced surgical time, but also in reducing radiation exposure. Radiation exposure [28] in URS is unavoidable due to the nature of endoscopic surgery, and surgeon awareness has led to reduced patient and team radiation exposure. However, endourologists and involved surgical team members are constantly exposed to X-rays due to fluoroscopy-guided URS. Radiation exposure for operator ranges from 1.7 to 56 μSv/operation, and RoboURS offers to reduce the same for the operator [29, 30]. In Table 4, we have summarised the utility features of various robots currently available and what would entail an ideal robot according to our findings. With RoboURS and its memory function aide, we expect a reduction in patient, surgeon and surgical team radiation exposure. The future of RoboURS looks promising in terms of patient and surgeon outcomes with improved operating conditions for surgeon and team, and day-case patient outcomes for treatment of urolithiasis which is also known to severely affect quality of life.

As supported by Rassweiler et al. [8], Gettman et al. [31] and Hasan et al. [32], RoboURS when cost-effective represents the future of URS and KSD treatment and carves pathway for better surgical working conditions.

Limitations of Robot

1. Mostly renal stones have been treated so far.
2. Majority cases require access sheath.
3. Studies mostly had pre-stented patients.
4. Limited data for complicated stones or solitary kidneys.
5. Cost-effectiveness is not well documented.

Table 4 Utility features in various robots being utilised for ureteroscopy, where NS is not specified

	Roboflex Avicenna	ILY Robot	Monarch Robot	The EasyUretero	Rassweiler et al. [16] Robot	Proietti et al. [14•] Robot	Ideal Robot for URS
Available in market				X	X	X	X
Supportive ergonomics							
Master console		X	X				
Compatible with FURS			Not required				
Radiation protection for surgeon							
X-ray pedal		X	X	X	X	NS	
Lasering pedal		X	X		X	NS	
Laser setting		X	X	X	X	NS	
Laser movement		X	X		X	NS	
Basketing	X	X	X		X	NS	
Irrigation control		X	X	X	X	NS	
Intra-renal pressure information	X	X	X	X		NS	
Intra-renal temperature information	X	X	X	X	X	NS	
Respiratory adjustment available	X	X		X	X	NS	
Memory for repetitive tasks	X	X	X		X		
Safety detection for size	X	X	X		X	NS	
Detects collision	X	X	X		X	NS	
Haptic feedback	X	X	X	X		NS	
Artificial intelligence	X	X		X	X	NS	
Supports PCNL	X	X		X	X	NS	
Supports 5G	X	X	X	X	X	NS	

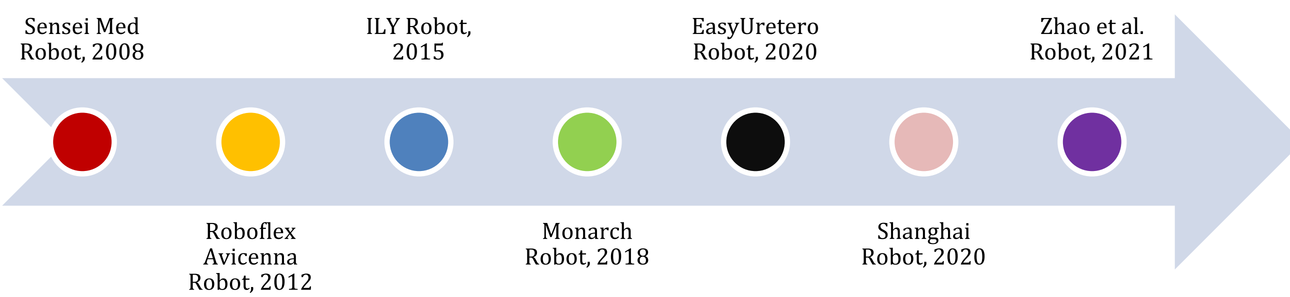

Fig. 3 Timeline of robots as introduced and published in literature. Zhao et al. [16] have not yet introduced their robot in market. Image source: original image

Conclusion

RoboURS continues to evolve (Fig. 3) despite the limitations of infrastructure and cost-effectiveness. The potential advantages it offers of remote-assisted surgery, ergonomical efficiency, comparable stone-free rate, intra- and post-operative patient-related outcomes whilst minimising radiation exposure are the key reasons it still remains an attractive option for endourologists. Perhaps with worldwide acceptance, a true balance of cost-effectiveness for precision-based intervention can be assessed.

Certainly, more instrumental and technological improvement is warranted along with randomised control trials to prove this efficacy.

RoboURS holds the promise of a better future for surgeon longevity, reduced peri-operative morbidity and better workplace environment.

All of our figures and tables are original.

Compliance with Ethical Standards

Conflict of Interest There are no conflicts of interest to declare for this paper.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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