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Review

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Robot-assisted flexible ureterorenoscopy: state of the art in 2022

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Abstract

Due to the technical improvements in endoscopes and armamentarium, flexible ureterorenoscopy (fURS) has increased in the management of nephrolithiasis over the last decade. fURS is a challenging procedure and therefore limited in some regions. To overcome these challenges, a master-slave robotic system might help dominate fURS. As with other robotic systems, the ergonomic deficits of fURS play an important role in the development of a new robot. All ureterorenoscopy (URS) robots thus far consist of a surgeon's console and the manipulator of a flexible ureterorenoscope. Handling and maneuverability of the different systems vary, but the master-salve system is common to all robots. Optimal ergonomics and comparable surgical results to conventional flexible URS demonstrate the successful use of some of these robots. In this narrative review, we provide an update on the robot-assisted flexible ureterorenoscopy, the different systems, and the final role and future perspective of robotic fURS.

Keywords: Robot-assisted flexible ureterorenoscopy, robotic stone removal, robotics, urolithiasis, robotic intrarenal surgery, ureterorenoscopy

INTRODUCTION

Due to the improvement of technologies, especially regarding video endoscopy, during the last decades, minimally invasive or even non-invasive surgery has almost replaced open surgery. Especially robot-assisted surgery has become commonplace in urology and is seen as the standard for some procedures, for example, robot-assisted radical prostatectomy. The dissemination of laparoscopy was thus greatly facilitated, especially among surgeons not trained in laparoscopy. The ergonomics of the surgeons could also be improved, and sometimes even the clinical outcome for the patient[1,2]. This trend led to the introduction of robot-assisted flexible ureterorenoscopy (rfURS). rfURS is a nascent field, which enables control of instruments via console and joystick and has emerged as a novel adaption. In this narrative review, we focus on the recent developments of rfURS and the impact of future stone treatment[3,4].

Originally, extracorporeal shock wave lithotripsy (SWL) replaced open surgery completely in treating especially renal stones. Endourologic techniques, such as ureterorenoscopy and percutaneous nephrolithotomy, decreased during the rise of SWL[5]. Due to continuous improvements and miniaturization of endourological instruments, as well as the patient collective, retrograde intrarenal surgery expanded significantly[6-9]. The prevalence of obese patients with urolithiasis, as well as patients with cardiovascular disease and therefore anticoagulatory treatments, leads to an increase in URS/retrograde intrarenal surgery for stones of different sizes, including large stones.

Nevertheless, limitations regarding flexible ureterorenoscopy (fURS) such as ergonomic deficiencies during stone manipulation, laser disintegration, or stone extraction and the increase of musculoskeletal disorders among urologists place technically high demands on the surgeon and the surgical team[10-12].

Usually, the surgeon stands and controls fluoroscopy and the laser device with two different foot pedals while maneuvering the endoscope with one hand and fixing the position with the other. The assistant is nearby and must insert the laser fiber or other armamentarium for stone removal. Furthermore, the urologist is exposed to X-ray radiation[13]. The intra-renal pressure caused by the irrigation during fURS could lead to infections[14,15]. Pressure of 40 cm of H_2O or higher can increase postoperative complication risks, including bleeding, perirenal collection, and sepsis.

Due to high costs, flexible ureterorenoscopy cannot be used daily in all regions. This has led to the development of smaller instruments for percutaneous nephrolithotomy (PCNL): super-mini, ultra-mini, super-ultra-mini, etc. Although these miniaturized PCNLs lead to fewer complications than full-size PCNL, it is a more invasive intervention with a higher risk of renal bleeding than a flexible ureteroscopy[16,17].

However, manipulating the flexible ureterorenoscope can be technically challenging and needs to be learned and mastered adequately. The robotic assistance in flexible ureterorenoscopy provides the same enabling assistance that robots did for laparoscopic surgery. Better ergonomics, superior vision, and tremor elimination are achieved by robotic assistance. The surgeon can even operate outside the radiation field as well. Flexible ureterorenoscopy places technically high demands on the surgical team, and not only endoscopic diagnostics but also interventions such as intracorporeal laser lithotripsy fall under it. One surgeon alone cannot perform all the manual operations (checking the device on the handpiece, inserting the instrument, inserting the laser fiber or a basket, and opening and closing the basket). In addition, X-ray fluoroscopy, laser lithotripsy, or irrigation must be activated via a foot pedal. The idea behind the robotic systems was to facilitate some of these steps and to physically separate the surgeon at the console from the assistant at the patient's bedside. In the meantime, several systems have been clinically tested partly on patients or on models.

Master-slave systems for flexible ureteroscopy

Most urological robots consist of a user station (master) and the instruments' station (slave) [Figure 1]. The first master-slave robot for surgery was developed and introduced in 1991 (SRI International, Menlo Park, USA)[18]. The most popular robot in surgery, the da Vinci Surgical system 2000 (Intuitive Surgical, Sunnyvale, United States), was first designed for coronary artery surgery, but in 2001 a clinical program for urological surgery was established[19,20].

Robots for fURS have also been proposed to improve conventional URS with a master-slave system. The first clinical application of a master-slave controlled robotic system (Sensai-Magellan) for fURS was introduced by Desai and colleagues in 2008[21]. Again, this system was modified from a cardiovascular intervention robot named Sensai[22]. In 2010, the development of a robot for fURS was started by Saglam and a Turkish company named ELMED (Ankara, Turkey). The Avicenna Roboflex has been improving since then and shows promising results. Talari and colleagues designed in 2017 a robot which allows 3D tip tracking and preoperative image overlay to minimize fluoroscopy and provide tip positioning guidance in the future[23]. Recently, two Chinese groups also developed two robots for flexible ureterorenoscopy. In 2020, Shu *et al.* published preliminary results of a robot with the potential to monitor intrarenal pressure and capture a variation of bending conditions in order to integrate a partial force feedback function[24]. Zhao and colleagues described in 2021 a new master-salve robot for fURS with an easy-to-use manner, which should reduce intraoperative time and mostly improve surgeons' ergonomics[25]. All the different robotic systems are explained in the following section and are summarized in Table 1. This table cannot guarantee completeness, as there are no yet clinical studies or publications on all currently available URS robots.

Different robotic systems for flexible URS

Sensai-Magellan system

In 2008, robotic fURS was first reported in 18 patients using the Sensei-Magellan system (Hansen Medical, Mountain View, USA), which was developed for cardiology and angiography by Fred Moll, the inventor of the da Vinci system. Desai *et al.* reported a 94% technical success rate for stone disruption and an 89% complete stone disruption rate in the 18 patients. There was no conversion to manual URS or intraoperative complications in this study[22].

The device consists of four components: surgeon console, flexible catheter system, remote catheter manipulation system, and electronic rack with computer hardware, power supplies, and video distribution units. The robotic flexible catheter system consists of an outer catheter sheath (14/12 F) and an inner catheter guide (12/10 F). A fiberoptic flexible ureteroscope (7.5 F) was inserted through the inner catheter guide. Remote control of the catheter system maneuvered the ureteroscope tip, which was taped to the inner guide. The tip of the outer sheath was positioned at the ureteropelvic junction to stabilize intrarenal navigation. The surgeon sits at the console and manipulates a steerable flexible tube normally used for transvascular intracardiac procedures. The computer program that transmits the surgeon's movements to the end effector was developed by the same company responsible for laparoscopic robots (Force Dimension, Nyon, Switzerland). Manipulation of the ureteroscope was only passive, which proved to be a problem. This may be useful for transvascular robotic ablation of atrial fibrillation but is inadequate for robotic fURS. This robotic catheter system was modified and equipped with a fiber endoscope and a customized ureteral catheter to perform ureteroscopy with the commercial master device Omega 3 (Force Dimension, Switzerland), although the existing drawbacks of inappropriate control mode and inadequate working range partially contributed to the termination and eventual failure of this project[22,26,27].

Table 1. Robot-assisted flexible URS studies

References	Year published	Robotic system/speciality	Study design	Patients
Desai *et al.*[27]	2008	Sensei	Porcine model	None
Desai *et al.*[22]	2011	Sensai	Prospective	18
Saglam *et al.*[28]	2014	Roboflex avicenna	Prospective	81
Geavlete *et al.*[29]	2016	Roboflex avicenna	Prospective	51
Talari *et al.*[23]	2017	Master-slave robot: 3D tip tracking and preoperative image overlay	Kidney phantom	None
Shu *et al.*[24]	2020	Master-slave robot: force feedback + intrarenal pressure	Kidney phantom	None
Klein *et al.*[31]	2020	Roboflex avicienna	Prospective	240; 443 stones
Zhao *et al.*[25]	2021	Master-slave configuration	Phantom and animal model (pig)	None; 2 animals with 8 trials
Kwon *et al.*[32,33]	2022	easyEndo robotic endoscopy system (EasyUretero)	Phantom	None

Table with different published studies on specific robotic systems including the year of publication, the study design, and whether patients or phantom models were used. Abstracts were excluded from the table. URS: Ureterorenoscopy.

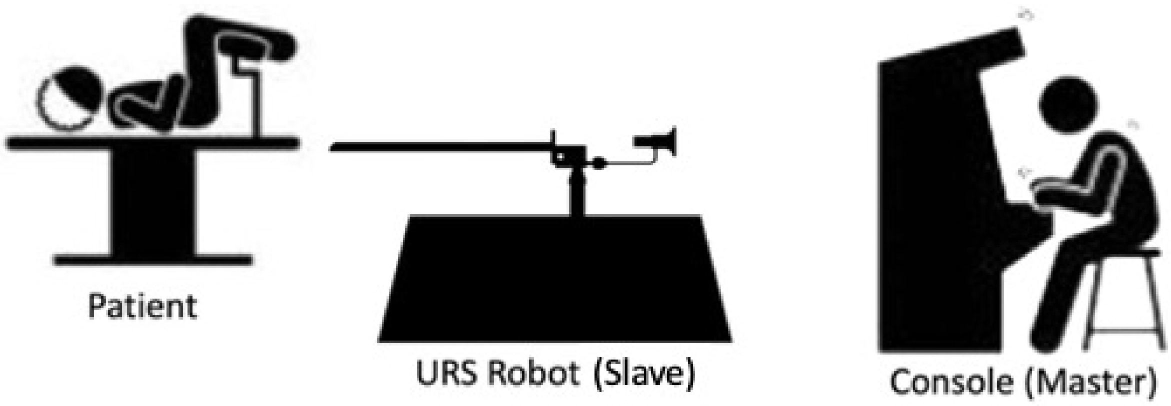

Figure 1. Pictogram of robot-assisted ureterorenoscopy with master-salve system. URS: Ureterorenoscopy.

Avicenna Roboflex system

The next generation of robot-assisted fURS was the Roboflex Avicenna, a master-slave robot developed specifically for flexible URS by ELMED (Ankara, Turkey). The device has had the CE mark since 2013, and FDA approval is pending. The surgeon sits at a console and the flexible URS is attached to a robotic arm on the patient. This arm can rotate up to 220°, advance up to 150 mm, retract, and deflect up to 262°. Irrigation and movement of the laser fiber can be controlled by the surgeon at the console. There are two joysticks and foot pedals for moving, controlling, and turning on the laser or fluoroscopy. The system is compatible with a wide range of digital flexible ureteroscopes, access sheaths, laser fibers, and baskets. Saglam *et al.* demonstrated in 81 patients that robotic fURS with the Roboflex Avicenna system (Prototype 2) was within acceptable limits in terms of console time and operating time. Only one patient had to be switched to a normal flexible URS due to a technical error. The stone-free rate in this study was 96%[28]. Geavlete *et al.* published a prospective comparative study between the Roboflex Avicenna system (Prototype 2) and conventional fURS. The study found a similar safety profile and similar three-month stone-free rates for the two methods (89.4% for conventional fURS *vs.* 92.4% for robotic fURS). Treatment time (51 *vs.* 50 min) and fragmentation time (37 *vs.* 39 min) were similar[29]. Rassweiler *et al.*, and Klein *et al.*, in a prospective multicenter study, reported 97% technical success in stone disruption and device failure in only two patients

(0.7%) for kidney stones with an average size of 14 mm[30,31]. The preliminary results suggest that the stone-free rate with robot-assisted fURS is not inferior to conventional fURS. Optimal ergonomics maintain the surgeon's endurance in long-lasting surgeries.

Talari (2017): master-slave robot with 3D tip tracking and preoperative image overlay

This robot-assisted system propagates a rapid change from normal URS to robot-assisted URS, even intraoperatively. It is titled a "snap-in" system. The goal of this system is to minimize fluoroscopy by controlling or displaying the position of the tip through electromagnetic tracking. This could be done with a technique similar to "roadmapping" in interventional radiology. Fluoroscopy units typically have two monitors, one for a live image and one for a reference image. The urologist often fills the renal pelvis and calices with contrast and takes a single fluoroscopy reference image. Then, as the urologist moves the endoscope into different renal calices, he or she takes more fluoroscopic images and compares the new live image to the reference image. If electromagnetic tracking could be used instead to track the ureteroscope tip, the tip could be tracked as it moves, and the image would be updated in real time without the need for additional fluoroscopy. The robotic system described is small and compact and would be placed between the patient's legs. To manipulate the ureterorenoscope, the urologist uses a joystick control. Preliminary experiments show the potential of the device. In future work, the system might be used in clinical practice to provide tip positioning guidance while minimizing the use of fluoroscopy[23].

Master-slave robot with intra-renal pressure and partial force feedback

Shu and colleagues presented a new robotic system for fURS with the ability to show torque feedback and monitor the intra-renal pressure, which might be crucial in fURS. In addition, they proposed a method based on neural networks to optimize the master manipulator. The movement condition of the bending section and the impact of the surgical instrument will be fed back to the urologist through the torque variation. The urologist gets feedback if he or she is stuck in a bending position and still wants to turn the knob. To feel the torque variation effectively, it may take the urologist some time to practice. In general, the results indicate that the torque feedback function is indeed meaningful and feasible because both the movement condition of the bending section and the impact of the surgical instrument will be fed back to the urologist through the torque of the bending knob. To measure the intra-renal pressure, they used a very thin wire, which is difficult to be placed adequately and may increase operating time. To successfully place the thin sensor wire, a ureteral access sheath is always required[24]. This master-slave system has only been used in phantom models.

Master-slave robotic system that is easy to use

The advantage of this novel robot-assisted system for fURS by Zhao *et al.* is excellent adaptability to cope with different ureterorenoscopes to fit various clinical cases[25]. Phantom and animal experiments showed the easy-to-use manner, short learning curve, and enhanced surgical ergonomics. Thus far, no clinical studies have been carried out, but the phantom experiment showed better results in operation time in the robot groups, which shows the intuitive robotic operation mode and might lead to a short learning curve in the future. The mechanical design is simple and can only provide the basic functions for operations, and the presented control strategy is not sufficient for complex operations[25]. Future work also involves applying shape-sensing techniques to enable force feedback and closed-loop control for accurate operations.

EasyEndo robotic endoscopy system (EasyUretero)

The EasyEndo robotic endoscopy system consists of a robotized endoscope and instrument and a controller. The robotized endoscope and instrument are composed of a motorized endoscope and instrument and a positioning arm. The conventional endoscope and instrument are motorized by electromechanical components directly attached to the endoscope body. All DOFs (degrees of freedom) of the endoscope are robotized except for the insertion of the endoscope. Nine novices and eighteen physicians tried this new robot on a renal model. The novices completed the tasks more quickly and with a lower workload when using robotic manipulation, whereas the experts showed the opposite trend. The learning rate in all groups was greater for robotic manipulation (21.02% on average) than for conventional manipulation (13.75%)[32,33].

DISCUSSION

More precisely, surgical robots are made for surgeons because they primarily improve the surgeon's ergonomics[11,34]. One-third of urologists report hand-wrist and other ergonomic problems during classical fURS[11]. The learning curve for the procedure is shorter, and the quality may improve as well. The Avicenna Roboflex shows a really short learning curve of a maximum of five cases[28]. Of course, a fURS is less complicated compared to a robot-assisted prostatectomy, and, when treating a small stone (< 8 mm), the surgeon might extract the stone with a basket directly, but especially suboptimal ergonomics may increase operating time or complication during fURS. Furthermore, second sessions or frequent repair of the endoscope will be necessary. The main reason for repair in the study by Carey *et al.* was errant laser firing (36%) and excessive torque (28%)[35]. Using a robotic fURS could reduce the need for repairs. In practice, however, there are several factors that affect the service life of an endoscope, such as improper handling during sterilization and cleaning of the instrument or technical failure of the chip. Not all of these factors can be avoided by using a robot.

Some of the criticism of using a robot for fURS are the concerns regarding cost and robotic hype[36]. The main strength of the robot is to facilitate stone fragmentation and extraction by improving ergonomics compared to the classic fURS. This is mainly achieved by separating the surgeon at the console from the assistant at the patient's bedside. A study with a dimple model for endoscopic navigation showed that there is no difference between the techniques[37]. There is always a discussion about the lack of tactile feedback. The surgeon can observe at any time on the screen or console in which direction and by how many degrees the endoscope is deflected. This must be consistent with the endoscopic image to minimize the risk of damage to the mucosa and/or the instrument. One of the newer robotic systems shown by Shu *et al.* proclaims partially tactile feedback to the surgeon. In other words, the movement state of the bending part and the effects of the surgical instrument are communicated to the urologist by the torque change[24]. For example, if the bending part of the flexible ureteroscope is stuck in the renal structure, the unusual force will be communicated to the urologist when he or she continues to turn the knob. However, it may take some time for the urologist to develop a sense of the change in torque. Thus, if there were a method that can help the urologist to be more sensitive to such variations or abnormalities, it would help to shorten the learning curve of the urologist. Therefore, an intelligent detection algorithm for the fURS robot may be a research direction for the future. The torque feedback function can partially compensate for the loss of force perception caused by the use of remotely controlled robots, thus improving safety[24].

Another feature of the robotic system of Shu *et al.* is a thin sensor wire (diameter = 0.22 mm) used to measure the intra-renal pressure. The pyelovenous backflow occurs above 40 mmHg[24]. During upper tract endourology, complications such as pyelorenal backflow, sepsis, and renal damage are directly related to increased intra-renal pressure. Duration of increased intra-renal pressure and concomitant obstruction are independent predictors of complication development[38]. Therefore, it might be reasonable to include an intra-renal pressure measurement, although the thin wire as used by the Chinese group seems to be complicated to place in the renal caliceal system.

The newer robotic systems by Talari, Shu, and Zhao *et al.* need to demonstrate their usefulness in clinical cases to be compared with the Avicenna Roboflex system[23-25]. The first Sensai robot has not been further developed, so the only system in clinical use is still Roboflex. Some promising features such as 3D tip tracking with image overlay or force feedback and intra-renal pressure measurement are nevertheless important improvements. The robotic systems seem to be smaller and might be even more intuitive to use than the Avicenna Roboflex, which incorporates two separate joysticks to control the three-DOF motion of the flexible ureteroscope. However, these are only speculations since the other robots are prototypes and there has been no clinical application thus far.

Advantages of robotic systems

Theoretically, some advantages of a robotic system could improve fURS. Firstly, to manipulate a flexible ureterorenoscope takes time, sometimes a whole residency, depending on the usage during this stage of clinical education. Movements on the handle include rotation, tilt, yaw, forward, and backward, and the surgeon needs to deflect the tip with the thumb lever. To arrive at a certain location, the surgeon needs to simultaneously control different variables. Using a robot and a controller at the console seems to be much easier. In the future, the surgeon might decide which calyx he or she wants to go to, and the robot would simply follow a pre-calculated route there. Electromagnetic sensors might also help to correlate the images preoperatively with the real-time fluoroscopy. 3D vision even improves in finding the stone or other structures in the renal calyceal system. EM sensing positioning technology has been used in the robotic bronchoscopy system. If real-time ultrasound were added, this could also help guide surgeons to any remaining stones or fragments that have been displaced during the procedure[39,40]. A robot platform could control the ureterorenoscope, laser settings, stone sizes for basketing, and fluid irrigation by adapting to the specific features automatically. For example, if the stone has been found, the laser settings could be altered by monitoring the fragmentation, type of dust, sizes, etc., to decrease the mass either by basketing or dusting, depending on the stone and the surgeon's preference. When extracting a fragment through the access sheath, the ureterorenoscope could find the way back to the fragments automatically. Here, it is important to have a force sensor to not cause lesions and prevent ureteral avulsion. This would all take place while the surgeon stands by at the console. The fragments could then be easily removed by the physical assistant standing at the patient's side.

Understandably, there is always a debate about the high acquisition and possibly maintenance costs of surgical robots. Longer durability of the flexible endoscopes, a possible shorter operation time, or fewer follow-up interventions could make the acquisition of the robot profitable. Currently, there is no marketing regarding robot-assisted ureterorenoscopy that would increase patient demand, similar to the Da Vinci system. Nevertheless, better ergonomics and the reduction of radiation exposure for the surgeon should be taken into consideration, although, as with other robotic systems, this has no financial impact[41].

CONCLUSION

Despite increasing use, fURS remains a technically difficult procedure, especially in complex cases. Advances in robotic ureterorenoscopy will help target stones more effectively and reduce radiation exposure, especially for the surgeon. Furthermore, these new robotic technologies can train inexperienced endourologists and improve their skills. The future is promising, and we are at the dawn of the next era of robotic ureteroscopy. Nevertheless, future studies are needed to evaluate the ultimate role of robotic fURS and determine which URS robot will prevail. Ultimately, the adoption of these systems will depend on their clinical applicability and cost. It remains to be seen how these technological developments will facilitate surgery and whether their use will lead to better outcomes for our patients.

DECLARATIONS

Authors' contributions

Writing, idea and data acquisition: Rassweiler-Seyfried MC, Grüne B

Made substantial contributions to conception and design of the study and performed data analysis and interpretation: Rassweiler J, Michel MS, Herrmann J

Performed data acquisition, as well as provided administrative, technical, and material support: Herrmann J, Klein J

Availability of data and materials

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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