Journal of Robotic Surgery
https://doi.org/10.1007/s11701-020-01103-5

ORIGINAL ARTICLE

Analysis of performance factors in 240 consecutive cases of robot-assisted flexible ureteroscopic stone treatment

Jan Klein[1] · Nikos Charalampogiannis[2] · Marcel Fiedler[2] · Gamal Wakileh[1] · Ali Gözen[2] · Jens Rassweiler[2]

Received: 21 April 2020 / Accepted: 9 June 2020

Abstract

Flexible ureteroscopy is the keystone of modern kidney stone treatment. Although a simple surgical technique achieves good clinical results and a low complication rate, there are high demands on the surgeon's dexterity and ergonomic restrictions. Robotic-assisted flexible ureteroscopy (rfURS) could overcome these limitations. After 4 years of use of rfURS at a tertiary stone center, performance factors were analyzed to define the role of rfURS in kidney stone management. A rfURS system was installed in August 2014 at the SLK Kliniken (Heilbronn, Germany). Treatment data of $N=240$ consecutive patients undergoing rfURS were prospectively collected and analyzed. The patient cohort represents typical stone formers. $N=240$ renal units containing 443 stones with an average stone load of 1798 mm^3 were treated. Surgical parameters as well as the peri- and postoperative complications were recorded, analyzed and compared to the current data in the literature. OR time 91 min, stone treatment time 55 min, stone treatment efficacy 33 mm^3/min; perioperative complications 5.4%; robot times: preparation 5 min, docking 5 min, console time to stone contact 6 min, console time 75 min; postoperative complications 6.7%; postoperative length of stay 1.5 days; stone-free rate (residuals <2 mm) 90% and re-treatment rate 8.75%. This consecutive series represents real-life data about the utilization of rfURS. The detailed analysis of performance factors revealed the successful utilization of the first generation of robotic systems in endourologic stone surgery, and indicates that the robot performs comparably to conventional flexible URS. Optimal ergonomics maintain the surgeon's endurance in long-lasting surgeries.

Keywords Robotic endourology · Stone surgery · Robotic technology · Learning curve · Ureteroscopy · Robotic ureteroscopy

Abbreviations

SWL	Shock wave lithotripsy
RIRS	Retrograde intrarenal surgery
PCNL	Percutaneous nephrolitholapaxy
rfURS	Robotic flexible ureterorenoscopy
cfURS	Conventional flexible ureterorenoscopy
URS	Ureterorenoscopy
UAS	Ureteral access sheath
UPJ	Ureteropelvic junction
SD	Standard deviation
DJ	Double-J catheter

Introduction

Modern stone surgery underwent a dramatical change in the last decade. There has been a shift from shock wave lithotripsy (SWL) to endoscopic surgical procedures. Gaining the most popularity is flexible ureterorenoscopy (fURS). As this technique came into more common use in endourology, the benefits became obvious, but the limitations, mainly ergonomic restrictions, were also clearly demonstrated. Robotic master–slave systems were developed to overcome these limitations. First reports by Desai et al. [1, 2] about a robotic device used for retrograde ureterorenoscopy were published in 2008 and 2011. The working group used a steerable endovascular sheath—the Sensei System (Hansen Medical, Mountainview, Calif, US) developed for intracardiac electrophysiologic application. After promising early results, the system was abandoned. ELMED (Ankara, Turkey) launched the Avicenna Roboflex System in 2011. In 2013 and 2015, new prototypes followed. First feasibility

✉ Jan Klein
jan-thorsten.klein@uniklinik-ulm.de

[1] Department of Urology, Medical School Ulm, University of Ulm, 89075 Ulm, Germany

[2] Department of Urology, SLK-Kliniken Heilbronn, University of Heidelberg, 74078 Heilbronn, Germany

Published online: 16 June 2020

reports were published in 2014 [3]. After CE certification in 2013, the robot was introduced in clinical practice and tweaked for intraoperative use. To define the actual status of the robot, a comparison of our clinical data in a real-life scenario with the data of ureterorenoscopic endoscopic stone surgery techniques published in the literature is presented here. We defined performance factors of the procedure to standardize the reporting system of flexible URS data.

Materials and methods

Robotic system

The URS-Robot consists of a console and a manipulator. The manipulator is a mechanical scopeholder that can be maneuvered in multiple directions. The movements and steering mechanisms are described in Table 1. The console is the control unit of the manipulator. The robotic arm is operated using two joysticks at the console. The flexion of the scope is applied via a wheel that is installed at the right joystick. The level of irrigation and the tip of the laser fiber can be controlled via the console's touchscreen monitor. Two foot pedals connected to an universal foot pedal work as an interface between the console and further manipulators—e.g., the footswitch of the X-ray application or laser device.

Surgical technique

Under general anesthesia, the patient is placed in lithotomy position. The surgery includes a cystoscopy and a retrograde ureteropyelogram. A ureteral access sheath (UAS) is placed via a guide wire under fluoroscopic control. 94% of the patients were already presented. This improves the chance of accessing the ureter with a minimal risk of a ureteral injury. The manipulator arm is covered with sterile plastic bags. The sterilized UAS holders and stabilizers are fixed at the manipulator arm. The UAS holder and stabilizer are adjusted to the UAS. The scopeholders of the manipulator are armed with one of the varieties of different scopes (Table 1).

After introducing the scope into the UAS, the console surgeon takes over. The scope is navigated through the ureteropelvic junction into the renal pelvis. The caliceal system is approached and all calices are inspected. Fluoroscopy is used to support intrarenal mapping and navigation. After localizing the kidney stones, the laser fibre is deployed and armed.

Table 1 Technical details of the URS robot

Manipulator		Control console and chair	
Rotation	225° initial mounting	Chair	Ergonomic and adjustable
Deflection	275° Initial 0° Precise and normal control US/EU user option	Forward/backward Up/down	
Horizontal movement	210 mm Initial (0 mm) mid (100 mm)	Console	Touch screen 300 mm Height of arm rest: min/max: 630–930 mm
Vertical movement	300 mm Height from ground: 823–1123 mm	Memory	6 positions Height of chair Height of console Distance between chair and console Users name
Flexible scope adapters	Flex Xc (Karl Storz GmbH, Tuttlingen, Germany); Boa (Richard Wolf Company, Knittlingen, Germany); URF-V2 (Olympus, Shinjuku, Tokyo, Japan); LithoVue (Boston Scientific, Marlborough, Massachusetts, USA).	Wheel lock	Electro mechanical
Laser fibre protrusion	14 mm Initial 0 mm	Camera and X-ray image	Selectable and integratable imaging
Horizontal speed	Adjustable by 5 levels: 0.5–1–2–4.4–22 mm/s	Foot pedal	Individual for X-ray and LASER
Irrigation pump	25 Level and flush mode using a 4 mm hose 20–112 ml/min	Ureteral access sheath	Various companies In the study: flexor ureteral access sheath (14/12 Ch), length 35, 45, 55 cm depending on patient's anatomy COOK Medical (Bloomington, IN, USA)
Dimensions	980×500×970 mm	Dimensions	1100–650–1010 mm

The goal of stone treatment is an intrarenal lithotripsy of the stone to the tiniest fragments achievable or, alternatively, to break the stone and extract fragments > 2 mm using nitinol baskets. Depending on the stone composition, a combination of different laser techniques was applied, varying from dusting only to fragmentation and extracting. For fragment extraction, the positioning of the scope's tip is done by the console surgeon; while the basket is handled by the bedside assistant. The trapped stone is retracted together with the scope as far as possible into the UAS. After maximum retraction is achieved, the bedside assistant pulls the scope manually back to remove the stone. After stone extraction, the scope is reloaded. The surgery ends with the removal of the scope. If necessary a DJ is placed [4]. For all surgeries, a Flex Xc (Karl Storz GmbH, Tuttlingen, Germany) flexible ureteroscope was used. Docking was done using an UAS 12/14 Ch (35–55 cm) (Flexor®, Cook Medical, Bloomington, Indiana, USA).

Patient and patient selection

We prospectively recorded the data of all patients (Excel, Microsoft, California, US) undergoing robotic flexible ureterorenoscopy (rfURS) at the SLK-Kliniken, Heilbronn, Germany from 08/2014 to 04/2018 and analyzed the results using SPSS (Ver. 18; IBM, Armonk, New York, USA) to define the role of rfURS. All patients signed informed consent and the approval of data collection for statistical analysis. After approval of the institutional review board and after removing the cases that were not eligible for the study because they lacked full data sets ($N = 11$) a consecutive number of 240 patients were identified. The data were collected prospectively and analyzed retrospectively including a follow-up period of 3 months. The patient cohort represents typical stone formers. Patient characteristics are displayed in Table 2.

Stone parameters

Number, localization, and volume of the stones were analyzed using the bone mode of the preoperative CT scan. The stone parameters are displayed in Table 3 and in Fig. 1. The kidney stone volume was measured using the 3 diameters of the stone. Stone volume in mm^3 was calculated according to their geometric form.

Performance variables and factors

There are no data to classify a robot for URS or the procedure itself. Therefore, the following performance variables were measured and the resulting performance factors have been determined (Table 4): OR time (ORT) in min including the time needed for robot preparation and placement of the UAS, the docking process (DT), the console time (CT) and the console time until the mapping of the renal system including the locating and repositioning of the stones was finished (MT), was recorded; console treatment time (CT) in min; lasing time (LT) in mm^3/min; basketing time (BT) in mm^3/min; and stone treatment time (STT) in min.

Table 2 Patient demographics and kidney parameters

Parameter	Value	Min	Max
Number of patients (*N*)	240	–	–
Number of renal units	240	–	–
Male/female (%)	140/100 (58.3/41.6)	–	–
Age (SD)	55.7 ± 17.24	18	87
Weight in kg (SD)	81.17 ± 15.89	45	140
Height in m (SD)	1.70 ± 0.87	1.46	1.95
BMI (SD)	27.81 ± 4.90	17.6	49.5
ASA (SD)	1.93 ± 0.83	1	4
Comorbidities (%)	69.6	–	–
Hematocrit (SD)	40.22 ± 5.21	12.2	50.3
Serum creatinine (µmol/l)	93.7	35.2	1025.4
Serum creatinine (mg/dl) (SD)	1.10 ± 0.94	0.40	11.60
Antibiotic prophylaxis pre/intraop %	43	Trimethoprim Sulfamethoxazole 27%	Levofloxacin 11%
Single kidney %	2.5	–	–
Congenital abnormalities %	3.8	1.25 Double kidney	2.5 Horseshoe kidney
Complicating anatomical factors %	4.1	1.6 UPJ stenosis	1.25 Ureteral stricture

Table 3 Stone parameters

Parameter	Total	Left	Right
Number of renal units, *N* (%)	240	136 (56.66)	104 (43.33)
Number of stones (%)	443	231 (52.14)	212 (47.85)
	Mean	Min	Max
Stones per kidney (SD)	1.9 ± 1.61	1	11
Stoneload/kidney in mm^3 (SD)	1798 1649.06 ± 2407.10	14	14,138
Hounsfield units (HU) (SD)	680 829.22 ± 385.37	340 205	1047 1800
Stone localization			
Renal pelvis (P) (SD) Stones/renal unit	1.13 ± 0.60 101 stones 89 renal units	1	6
Stone volume (P) in mm^3 (SD)	2592.8 ± 3023.9	15	14,138
Upper calyx (UC) (SD) Stones/renal unit	1.4 ± 0.80 63 stone 45 renal units	1	5
Stone volume (UC) in mm^3 (SD)	863 ± 2106.8	4.1	14,138
Middle calyx (MC) (SD) Stones/renal unit	1.35 ± 0.70 81 stones 60 renal units	1	5
Stone volume (MC) in mm^3 (SD)	484 ± 800.1	8	4189
Lower calyx (LC) (SD) Stones/renal unit	1.64 ± 1.53 198 stones 121 renal units	1	10
Stone volume (LC) in mm^3 (SD)	718 ± 1092.5	4.1 4.20	8181

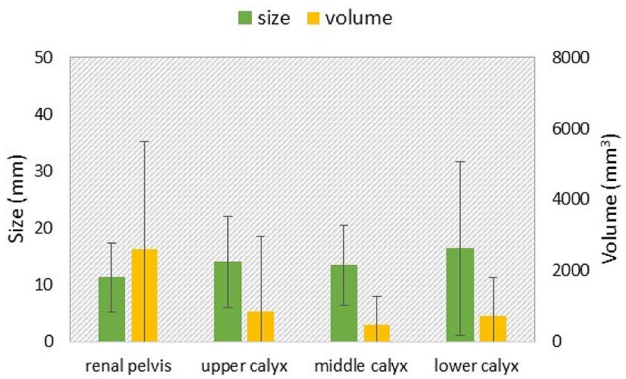

Fig. 1 Stone parameters

The performance factors have been calculated as described in Table 4: stone clearance rate in mm^3/min (SCR), stone treatment efficacy in mm^3/min (STE), and procedure efficacy (mm^3/min). The learning curve (LC) of the system has been determined analyzing the STE series of each prospectively recorded case of three main surgeons.

Results

Eight fURS-experienced surgeons performed the surgeries. Four surgeons (JR, JK, MF, NS) did 207 cases (86.25%). The surgical techniques were lasing of the stones (86%) and primary extraction of stones (14%). Extraction of stone fragments after laser disintegration was done in almost every case (96%). Only, 10 (4%) cases were treated by stone dusting alone without any fragment retrieval.

The OR time was 91 min (10–269 min). The time from starting cystoscopy until the exact positioning of the UAS was 7.8 min (1–80 min). The DT was 5 min (1–29 min). The MT was 5.54 min (1–27 min). The mean CT was 74 min (5–229 min). The lasing time was 32.3 min (0.25–139 min) and the basketing time 22 min (1–125 min). The DJ time including the retraction of the scope was 5 min (1–19 min). The different times measured are displayed in Fig. 2.

Perioperative complications were encountered in 5.6% of cases (13/240). Ureteral lesions caused by the placement of the UAS occured in 0.8% (2/240). Injuries of the mucosa combined with bleeding were seen in 2% (5/240). Technical errors of the system requiring conversion to cfURS were documented in 0.4% (1/240). Bad vision, mucosa perforation and stone dislocation occured in 1.25% (3/240). The complications are summarized and classified in Table 5.

Table 4 Intraoperative parameters

Parameter	Mean	Range	Comment
OR time (ORT) in min (SD)	91 **90.2 ± 49.95**	10–269	Including preparation and docking of robot and postoperative DJ placement
Access time in min (SD)	8 **7.91 ± 6.57**	1–80	Cystoscopy, retrograde pyelogram, placing the guidewire and placing of access sheath
Robot preparation time in min (SD)	5 **4.59 ± 2.80**	1–17	Cover the manipulator with sterile plastic bags and adjust the sterile UAS holder and the guide
Docking time (DT) in min (SD)	5 **4.95 ± 3.00**	1–29	Positioning of the sterile robot, fixing the UAS to the holder, backloading of the scope and fixing the scope at the robot
Console time (CT) in min (SD)	75 **74.32 ± 45.60**	5–229	Starts when the surgeon takes over the surgery at the console. Includes Console time till stone contact, lasing time and basketing time until surgeon leaves console
Console time till stone contact (MT) in min (SD)	6 **5.61 ± 4.95**	1–27	Mapping of the renal pelvis including the calices and repositioning of stones if necessary
Console treatment time (CTT) in min	69	–	Console time—console time till stone contact
Lasing time (LT) in min (SD) Lasing time (LT) in s (SD)	33 **32.41 ± 31.75** **1944.80 ± 1905.22**	1–139 **14–8340**	Time of application of laser energy
Basketing time (BT) in min SD	22 **23.65 ± 23.60**	1–125	Time used for fragment extraction
Stone treatment time (STT) in min	55	–	Mean lasing time + mean basketing time
Stone clearance rate (SCR) in mm^3/min	26	–	Stone volume/console treatment time
Stone treatment efficacy (STE) in mm^3/min	33	–	Stone volume/stone treatment time
Procedure efficacy (PE) in mm^3/min	20		Stone volume/OR time
DJ time in min	5	1–19	Time until DJ stent is inserted, including retraction of UAS under vision
Post surgery stent rate (PSR)	100		According to surgical protocol
Stone-free rate (SFR) in % Residual fragments in %	90 10	–	Checked at the time of DJ removal (US/KUB) and intraoperatively
Retreatment rate (RTR) in %	8.75	–	rfURS: 48% ($N=10$) cfURS: 43% ($N=9$) PNL: 9.5% ($N=2$)

The bold numbers represent the standard deviation

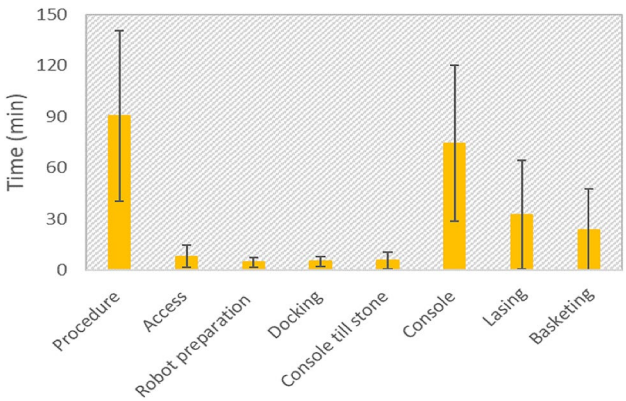

Fig. 2 Duration of the surgical steps of the procedure

The stone-free rate (SFR) after one session of rfURS was 90%. Of the 24 patients that were not stone-free, 3 (1.25%) refused any further stone treatment. In 21 cases (8.75%) a second look procedure was performed. A re-Roboflex procedure in 10 cases (47.6%) led to stone-free status; in 9 cases (42.9%), a cfURS was performed; and in 2 cases (9.5%), a PCNL was used for complete stone clearance. The surgical parameters are listed with comments in Table 4.

Postoperative complications were classified using the Clavien–Dindo classification [5, 6]. The overall complication rate was 6.7%. The range of complications encountered was Clavien I–V. Two patients showed relevant bleeding with a significant drop in hematocrit so that one patient (0.4%) needed the transfusion of two units of erythrocyte concentrates. Nine patients (3.8%) developed a postoperative urinary tract infection. Within this group, seven (2.9%) patients developed postoperative fever and two (0.8%) patients developed severe urosepsis that needed treatment in our ICU. In one case (0.4%), a patient experienced a lethal myocardial infarction. In this case, a severe coronary heart disease was previously known, and the patient had multiple coronary stents. Other unspecific complications were recorded in four

Table 5 Perioperative complications using the modified Satava classification system

Kind of complication	All size stones		Management according the kind of complication
	Value in %	*N* (*x*/240)	
Overall	5.41	13	According the kind of complication
Grade 1: Incidents without consequences for the patient			
Bad vision	0.41	1	Prolong OR time, optimize irrigation, change ureteroscope
Technical failure of the robot	0.41	1	Conversion to cfURS, malfunction of cable connection was causing the failure
Mucosal bleeding	2.5	6	Optimization of irrigation, Inject contrast medium, wait and extract coagula
Grade 2a: Managed intraoperatively with endoscopic surgery			
Lesion of the ureter	0.83	2	DJ-stent placement
Perforation of calyx and stone dislocation	0.83	2	Try to extract fragments as well as possible. Limit OR time
Grade 2b: Managed with retreatment (additional surgery) endoscopically			
Subcapsular renal hematoma	0.41	1	PCS Injury due to guide wire while access during ureteroscopy. Retreatment with rfURS after 3 weeks

Table 6 Postoperative complications using the Clavien–Dindo classification

Kind of complication	All size stones		Clavien–Dindo classification[a]
	Value in %	*N* (*x*/240)	
Overall	11.25	27	I–V
Bleeding overall	0.83	2	I
Bladder spasms	2.5	6	I
DJ-stent discomfort	0.41	1	I
Pain/discomfort after DJ removal	0.83	2	I
Hydronephrosis	1.25	3	I
Obstipation	0.41	1	I
Urinary tract infection	0.83	2	II
UTI + fever	2.91	7	II
Bleeding and transfusion	0.41	1	II
UTI and sepsis	0.41	1	IVa
Myocardial infarction	0.41	1	V
UTI and sepsis	0.41	1	V

cases (1.7%). The complications are summarized and classified in Table 6.

The postoperative length of stay was 1.5 days (1–15 days). The readmission rate within 3 months was 13.75% overall, including DJ removal. In 1.7% of cases, the readmission was caused by a complication of the procedure.

Comparison with cfURS as reported in literature

There are numerous cfURS publications, generally with a low patient numbers and with no standardized way of reporting the results. This makes it difficult to compare the different studies. Seven studies display the performance status of current cfURS. The performance parameters and factors we defined were calculable from the data in the studies and are listed in Table 7.

Discussion

Current evidence of the Roboflex

The evidence comparing the Roboflex System to cfURS is still limited. Geavlete et al. [7] described their first Romanian experience in a matched-pair analysis ($N = 132$) showing no significant difference in terms of clinical parameters and outcome between the two therapy options, but they describe a lower re-treatment rate of the robot group and, therefore, a better stone-free rate at 3 months. Statistically, both results represent trends supporting the robot group but not a significant difference. The study group mentions secondary advantages, mainly ergonomic improvements, for the surgeon as especially noted in long-lasting surgeries due to difficult stone parameters or a big stone load to treat [7].

Study population and data collection

The study population of our study does not differ significantly in terms of BMI, male/female ratio, or comorbidities from the population of the global URS Study from the CROES Group 2014 [8]. It represents a typical group of stone formers in the western countries. It is a consecutive data collection of real-life data and no randomized control group exists. As a result of the German health care system, most patients with symptomatic renal or proximal ureter

Table 7 Comparison of the rfURS data with cfURS data as reported in the literature

Study/parameter	Our series	Somani et al. [31]	York et al. [32]	Cecen et al. [33]	Hyams et al. [34]	Cohen et al. [35]	Al-Qahtani et al. [36]	Kandemir et al. [37]
No. of patients (*N*)	240	59	214	66	120	145	123	30
SL mm^3	1798	508	125	1232	7238	12770	9203	796
ORT min	91	45	54	–	103	–	89	51
STT min	55	10	–	–	74	–	–	27
STE mm^3/min	33	44	–	–	98	–	–	29
PE mm^3/min	20	11	2.5	–	70	–	103	16
iCR %	5.4	0.9	–	4.5	1.0	2.1	3.25	–
pCR %	11.25	–	–	18	6.7	3.5	8.1	20
SFR %	90	86	73	93	47	45	58.5	86.7
LOS days	1.5	–	–	–	1	–	1.5	0.8
RTR %	8.75	–	–	7.5	2.5	55	41.5	0

Stone load in mm^3 (SL). OR time (ORT) in min including the time needed for robot preparation and placement of the UAS and DJ placement. Stone treatment time (STT) in min. Stone treatment efficacy in mm^3/min (STE). Procedure efficacy in mm^3/min (PE). Intraoperative complication rate (iCR). Postoperative complication rate (pCR). Length of hospital stay in days (LOS). Stone free rate (SFR) checked after 3 months. Retreatment rate (RTR)

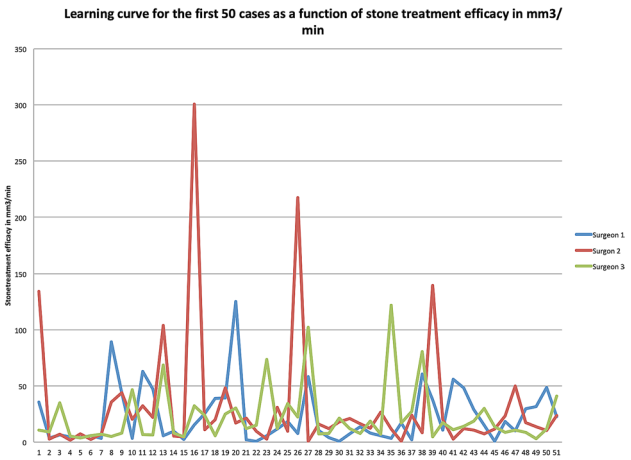

Fig. 3 Learning curve of rfURS

stones have a DJ inserted prior to the definite stone removal. So, 94% of our patients were already presented before stone surgery.

Learning curve

rfURS is a new procedure, so a learning curve (LC) has to be hypothesized. Four surgeons were the first surgeons for the vast majority of patients. A plateau phase was not reached within 50 cases. The peaks represent cases with a high stone load. The heterogeneity of the curves represents the real-life data collected and indicates that there is a very steep learning curve that makes the cfURS experienced surgeon able to shift to rfURS with a minimal loss in quality of the surgery (Fig. 3).

The OR Team also has a learning curve, but the additional time needed for robot preparation and docking is neglectable because this can be done parallel to the surgery. The DP itself is not time consuming and shows a plateau of 5 min (1–29 min) after 120 cases.

Surgical technique

The manipulator of the robot is attached to an UAS, and the safety of UAS placement has to be considered [9–11]. UAS of different sizes can be used. The limiting factor is the intrarenal pressure, which should not exceed 30 cmH_2O [12, 13]. The intrarenal pressure is affected by a variety of different factors [14]. One of the main factors is the combination of the size of the ureteroscope used and the diameter of the UAS. Different combinations, including the use of the pump of the robotic device, have been investigated and their influence on the intrarenal pressure was measured [3, 15]. The diameter of the UAS relative to scope size has to be chosen properly [16]. We used the 14/12 Ch Flexor® UAS (Cook, Bloomington, Indiana, US) in different lengths (35, 45, 55 cm) in combination with a Flex Xc ureteroscope adapted to each patient's requirements.

Stone surgery technique

The choice of surgical laser technique to use for optimal stone treatment is still under debate [17]. Though in the literature, dusting seems to shorten the OR time, a combination of dusting, fragmenting, and basketing was used in the majority of cases in our series to achieve the best stone-free status [18]. Extractable fragments larger than 1 mm were

extracted using a standard frontloading basket (N-Gage, COOK, Bloomington, IN, USA).

Stone-free status

There still is not a consistent definition of stone-free status. In concert with the methods of the EDGE Research Consortium and Ghani et al., we classified stones or clinically insignificant stone fragments < 2 mm in KUB and/or ultrasound control as a stone-free status since readmissions and complications resulting from those very small fragments are rare [19]. One has to recognize that the use of KUB and/or ultrasound underestimates the real stone-free status. Our stone-free rate of 90% is comparable to the basketing group in a study comparing dusting vs. basketing techniques of the EDGE Research Consortium [18].

Stone load

The total stone load of the patients in this study shows a broad spectrum in volume and size. The volume was calculated according to the recommendations of the EAU guidelines [20–22]. The stone volumes were calculated according their 3 dimensions in mm and the most suitable formula according to their geometrical ellipsoidal shape was used [23].

Since the usage of robot technology is here to explore the limits of cfURS, a trend to max out the limits is reflected in this consecutive series. All patients with either a very small stone volume for stone extraction as well as patients with a high stone volume up to 14,138 mm^3 were included. This could lead to a bias in the data and the learning curve since stones bigger than 2 cm in diameter are usually treated with mini- or standard PCNL. In comparison to other cfURS series and rfURS series our OR time seems to be longer [3, 8, 24, 25].

OR time

To compare the results of different studies, it is necessary to define what time measure should be used. In our view, stone treatment efficacy (STE) is a good parameter to compare the time spent on stone disintegration and extraction in different procedures. The STE in our series was 33 mm^3/min. This is comparable with other studies if one focuses on URS typical medium-size stone loads (500–4000 mm^3). The procedure efficacy (PE) includes the parameters stone load and OR time. The PE is very much associated with the stone load. In high stone loads, the PE is optimal but there are also growing retreatment rates up to 41.5% indicating that a single session of cfURS is not enough for the treatment of high stone loads.

A subgroup analysis of medium-size stones (524–4189 mm^3) ideally designed as a matched-pair analysis to compare cfURS and rfURS in a big study cohort (> 100 each group) would be necessary to define the ideal case using rfURS.

Precision

The precision of the system has been investigated by Proietti et al. in a K-box Simulator. There was no significant difference between the performance of the rfURS users and the cfURS group, with a slight advantage in speed for the cfURS group and a slight significant advantage for the rfURS group in terms of stability, centering of the picture, tissue respect and maneuverability at least in one of the two exercises [26].

Limitations of rfURS

Almost all technical aspects of cfURS have been adopted by the rfURS, so there is no technical limitation. In rare cases where a massive torque of the instrument is needed, e.g., in the treatment of a diverticulum or a very complex renal anatomy, the robotic system shows limitations. But these cases are also difficult to treat in cfURS.

Technical failures

Technical failures occur rarely. If persisting, they are solved by conversion to cfURS without impact on the patient's safety. Saglam et al. [3] report an technical failure rate of approximately 1%. In our series, the technical failure rate is even lower.

Lack of tactile feedback

The robot has no tactile feedback, which is the typical drawback of using master–slave systems. Different companies trying to overcome the limitation of tactile feedback and technical developments show promising early results but a definite solution is not yet on the market [27].

Navigation

The mapping of the caliceal system is crucial. Depending on the anatomy, orientation can be difficult. This was addressed by the manufacturer by displaying the status of the instrument on the monitor.

Costs

The main restrictions of the rfURS are the high initial costs of purchasing the machine. The costs for the maintenance and the single use materials are neglectable.

Complications

The complication rate does not differ from large cfURS series. The main complications are infection and bleeding. Since the technique requires the insertion of an UAS, UAS-related ureteral injuries may also occur [8].

Advantages of the URS robot

The performance of flexible URS in terms of stone treatment and patient safety of rfURS and cfURS shows non-inferiority, though the data were biased by the learning curve of the surgeons. There are various secondary advantages offered by the system.

Ergonomics

In a recent meta-analysis, ample evidence shows serious health risks of prolonged standing, including lower back pain, physical fatigue, muscle pain, tiredness, and body part discomfort. Prolonged standing affects the cardiovascular system as well [3, 28]. The wearing of a protective lead gown can obviously amplify posture-related health problems. Sitting in a personalized position with an armrest at the console reduces physical stress and improves the endurance of the surgeon [3].

Radiation exposure

There are growing concerns about the radiation exposure of patients due to medical procedures. Kidney stone patients are at high risk of being exposed to significant radiation doses. Stone surgeons perform several surgeries per day. They and their assistants stay in striking distance of the radiation source. The robotic approach makes it possible to increase the distance between the team and the radiation source. According to the inverse square law, the exposure of scattered radiation decreases rapidly with distance [29]. There are no long-term data on the effects of radiation exposure in urologic surgeons but ample studies see robotic approaches to be a suitable solution [30].

Adaptiveness

The system is adjustable to almost all flexible ureteroscopes available on the market. Changes in the configuration of the scopes are rapidly addressed by exchangeable 3D-printed scopeholders.

Limitations of the study

Though the data was recorded prospectively, this is a retrospective monoinstitutional study. The comparison of our data with the current literature was difficult because there has been no standardized way of reporting surgery related data like stone size and times so our newly defined performance parameters had to be recalculated for existing studies. There were eight surgeons performing the rfURS procedures so eight learning curves influence the results.

Conclusion

After experience with $N = 240$ cases of rfURS, the analysis of the performance factors shows comparable results to cfURS with slightly longer OR times. Stones at the limit of retrograde intrarenal surgery can be treated successfully robotically. The use of robotic technology maintains the endurance of the surgeon during long-lasting surgeries due to optimal ergonomic working conditions and it can help to reduce the radiation exposure of the whole OR team. It is the first generation of robots utilized for RIRS; therefore, limitations exist. Updates of the system as well as integration of newest laser and navigation technology will probably boost the use of robotic technology in endourology.

Funding The robotic device was provided by ELMED, Turkey.

Compliance with ethical standards

Ethical approval All procedures being performed were part of the routine care. Ethical approval was obtained by the local Ethical commitee.

Informed consent All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000. Informed consent was obtained from all patients for being included in the study.

Identifying information No identifying information about patients is included in the article.

Conflict of interest Jan Klein MD declares that he has no conflict of interest. Nikos Charalampogiannis MD declares that he has no conflict of interest. Marcel Fiedler MD declares that he has no conflict of interest. Gamal Wakileh MD declares that he has no conflict of interest. Ali Goezen MD declares that he has no conflict of interest. Jens Rassweiler MD declares that the Avicenna Roboflex system used in this study was provided by ELMED Medical Company (Ankara, Turkey).

References

1. Desai MM, Aron M, Gill IS et al (2008) Flexible robotic retrograde renoscopy: description of novel robotic device and preliminary laboratory experience. Urology 72(1):42–46 **(Epub 2008/03/29)**
2. Desai MM, Grover R, Aron M et al (2011) Robotic flexible ureteroscopy for renal calculi: initial clinical experience. J Urol 186(2):563–568 **(Epub 2011/06/21)**

3. Saglam R, Muslumanoglu AY, Tokatli Z et al (2014) A new robot for flexible ureteroscopy: development and early clinical results (IDEAL stage 1-2b). Eur Urol 66(6):1092–1100 **(Epub 2014/07/26)**
4. Astroza G, Catalan M, Consigliere L, Selman T, Salvado J, Rubilar F (2017) Is a ureteral stent required after use of ureteral access sheath in presented patients who undergo flexible ureteroscopy? Cent Eur J Urol 70(1):88–92 **(Epub 2017/05/04)**
5. Dindo D, Clavien PA (2008) What is a surgical complication? World J Surg 32(6):939–941 **(Epub 2008/04/17)**
6. Dindo D, Demartines N, Clavien PA (2004) Classification of surgical complications: a new proposal with evaluation in a cohort of 6336 patients and results of a survey. Ann Surg 240(2):205–213 **(Epub 2004/07/27)**
7. Geavlete P, Saglam R, Georgescu D et al (2016) Robotic flexible ureteroscopy versus classic flexible ureteroscopy in renal stones: the initial romanian experience. Chirurgia (Bucur) 111(4):326–329 **(Epub 2016/09/09)**
8. de la Rosette J, Denstedt J, Geavlete P et al (2014) The clinical research office of the endourological society ureteroscopy global study: indications, complications, and outcomes in 11,885 patients. J Endourol 28(2):131–139 **(Epub 2013/10/24)**
9. De Coninck V, Keller EX, Rodriguez-Monsalve M, Audouin M, Doizi S, Traxer O (2018) Systematic review of ureteral access sheaths: facts and myths. BJU Int 122(6):959–969. https://doi.org/10.1111/bju.14389 **(Epub 2018/05/13)**
10. Schoenthaler M, Buchholz N, Farin E et al (2014) The Post-Ureteroscopic Lesion Scale (PULS): a multicenter video-based evaluation of inter-rater reliability. World J Urol. 32(4):1033–1040 **(Epub 2013/10/19)**
11. Traxer O, Thomas A (2013) Prospective evaluation and classification of ureteral wall injuries resulting from insertion of a ureteral access sheath during retrograde intrarenal surgery. J Urol 189(2):580–584 **(Epub 2012/09/18)**
12. Breda A, Territo A, Lopez-Martinez JM (2016) Benefits and risks of ureteral access sheaths for retrograde renal access. Curr Opin Urol 26(1):70–75 **(Epub 2015/11/12)**
13. Tokas T, Herrmann TRW, Skolarikos A et al (2019) Pressure matters: intrarenal pressures during normal and pathological conditions, and impact of increased values to renal physiology. World J Urol 37(1):125–131. https://doi.org/10.1007/s00345-018-2378-4 **(Epub 2018/06/20)**
14. Jung H, Osther PJ (2015) Intraluminal pressure profiles during flexible ureterorenoscopy. Springerplus 4:373 **(Epub 2015/07/29)**
15. Buttice S, Proietti S, Dragos L, Traxer O (2017) Are you familiar with the flow of the Roboflex avicenna pump? Allow me to explain. J Endourol 31(4):418–419 **(Epub 2017/01/06)**
16. Sener TE, Cloutier J, Villa L et al (2016) Can we provide low intrarenal pressures with good irrigation flow by decreasing the size of ureteral access sheaths? J Endourol 30(1):49–55 **(Epub 2015/09/19)**
17. Matlaga BR, Chew B, Eisner B et al (2018) Ureteroscopic laser lithotripsy: a review of dusting vs fragmentation with extraction. J Endourol 32(1):1–6 **(Epub 2017/10/25)**
18. Humphreys MR, Shah OD, Monga M et al (2018) Dusting versus basketing during ureteroscopy-which technique is more efficacious? A prospective multicenter trial from the EDGE research consortium. J Urol 199(5):1272–1276 **(Epub 2017/12/19)**
19. Tracey J, Gagin G, Morhardt D, Hollingsworth J, Ghani KR (2018) Ureteroscopic high-frequency dusting utilizing a 120-W holmium laser. J Endourol 32(4):290–295 **(Epub 2017/12/15)**
20. Bultitude M, Smith D, Thomas K (2016) Contemporary management of stone disease: the new EAU urolithiasis guidelines for 2015. Eur Urol 69(3):483–484 **(Epub 2015/08/26)**
21. Turk C, Petrik A, Sarica K et al (2016) EAU Guidelines on interventional treatment for urolithiasis. Eur Urol 69(3):475–482 **(Epub 2015/09/08)**
22. Turk C, Petrik A, Sarica K et al (2016) EAU guidelines on diagnosis and conservative management of urolithiasis. Eur Urol 69(3):468–474 **(Epub 2015/09/01)**
23. Finch W, Johnston R, Shaida N, Winterbottom A, Wiseman O (2014) Measuring stone volume—three-dimensional software reconstruction or an ellipsoid algebra formula? BJU Int 113(4):610–614 **(Epub 2013/09/24)**
24. Rassweiler J, Fiedler M, Charalampogiannis N, Kabakci AS, Saglam R, Klein JT (2018) Robot-assisted flexible ureteroscopy: an update. Urolithiasis 46(1):69–77 **(Epub 2017/11/25)**
25. Turna B, Stein RJ, Smaldone MC et al (2008) Safety and efficacy of flexible ureterorenoscopy and holmium:YAG lithotripsy for intrarenal stones in anticoagulated cases. J Urol 179(4):1415–1419 **(Epub 2008/02/22)**
26. Proietti S, Dragos L, Emiliani E et al (2017) Ureteroscopic skills with and without Roboflex Avicenna in the K-box((R)) simulator. Cent Eur J Urol 70(1):76–80 **(Epub 2017/05/04)**
27. Amirabdollahian F, Livatino S, Vahedi B et al (2018) Prevalence of haptic feedback in robot-mediated surgery: a systematic review of literature. J Robot Surg. 12(1):11–25 **(Epub 2017/12/03)**
28. Waters TR, Dick RB (2015) Evidence of health risks associated with prolonged standing at work and intervention effectiveness. Rehabil Nurs 40(3):148–165 **(Epub 2014/07/22)**
29. Douk HS, Aghamiri MR, Ghorbani M, Farhood B, Bakhshandeh M, Hemmati HR (2018) Accuracy evaluation of distance inverse square law in determining virtual electron source location in Siemens Primus linac. Rep Pract Oncol Radiother 23(2):105–113 **(Epub 2018/04/24)**
30. Talari HF, Monfaredi R, Wilson E et al (2017) Robotically assisted ureteroscopy for kidney exploration. Proc SPIE Int Soc Opt Eng 10135:1013512. https://doi.org/10.1117/12.2253862 **(Epub 2017/02/01)**
31. Somani BK, Al-Qahtani SM, de Medina SD, Traxer O (2013) Outcomes of flexible ureterorenoscopy and laser fragmentation for renal stones: comparison between digital and conventional ureteroscope. Urology 82(5):1017–1019 **(Epub 2013/09/05)**
32. York NE, Zheng M, Elmansy HM, Rivera ME, Krambeck AE, Lingeman JE (2019) Stone-free outcomes of flexible ureteroscopy for renal calculi utilizing computed tomography imaging. Urology 124:52–56 **(Epub 2018/11/06)**
33. Cecen K, Karadag MA, Demir A, Bagcioglu M, Kocaaslan R, Sofikerim M (2014) Flexible ureterorenoscopy versus extracorporeal shock wave lithotripsy for the treatment of upper/middle calyx kidney stones of 10–20 mm: a retrospective analysis of 174 patients. Springerplus 3:557 **(Epub 2014/10/22)**
34. Hyams ES, Munver R, Bird VG, Uberoi J, Shah O (2010) Flexible ureterorenoscopy and holmium laser lithotripsy for the management of renal stone burdens that measure 2 to 3 cm: a multi-institutional experience. J Endourol 24(10):1583–1588 **(Epub 2010/07/16)**
35. Cohen J, Cohen S, Grasso M (2013) Ureteropyeloscopic treatment of large, complex intrarenal and proximal ureteral calculi. BJU Int 111(3 Pt B):E127–E131 **(Epub 2012/07/05)**
36. Al-Qahtani SM, Gil-Deiz-de-Medina S, Traxer O (2012) Predictors of clinical outcomes of flexible ureterorenoscopy with holmium laser for renal stone greater than 2 cm. Adv Urol 2012:543537 **(Epub 2011/07/09)**
37. Kandemir A, Guven S, Balasar M, Sonmez MG, Taskapu H, Gurbuz R (2017) A prospective randomized comparison of micropercutaneous nephrolithotomy (Microperc) and retrograde intrarenal surgery (RIRS) for the management of lower pole kidney stones. World J Urol 35(11):1771–1776 **(Epub 2017/06/08)**