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UPPER TRACT SURGERY
REVIEW

Robotic stone surgery – Current state and future prospects: A systematic review

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KEYWORDS

Robotic stone surgery;
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Stone disease;
Endourology

ABBREVIATIONS

EAU, European Association of Urology;
ESUT, European section of Uro-Technology;
EULIS, EAU Section of Urolithiasis;
PCNL, percutaneous nephrolithotomy;

Abstract ***Objective:*** To provide a comprehensive review of robot-assisted surgery in urolithiasis and to consider the future prospects of robotic approaches in stone surgery.

Materials and methods: We performed a systematic PubMed© literature search using predefined Medical Subject Headings search terms to identify PubMed-listed clinical research studies on robotic stone surgery. All authors screened the results for eligibility and two independent reviewers performed the data extraction.

Results: The most common approach in robotic stone surgery is a robot-assisted pyelolithotomy using the da Vinci™ system (Intuitive Surgical Inc., Sunnyvale, CA, USA). Several studies show this technique to be comparable to classic laparoscopic and open surgical interventions. One study that focused on ureteric stones showed a similar result. In recent years, promising data on robotic intrarenal surgery have been reported (Roboflex Avicenna™; Elmed Medical Systems, Ankara, Turkey). Initial studies have shown its feasibility and high stone-free rates and prove that this novel endoscopic approach is safe for the patient and comfortable for the surgeon.

Conclusions: The benefits of robotic devices in stone surgery in existing endourological, laparoscopic, and open treatment strategies still need elucidation. Although recent data are promising, more prospective randomised controlled studies are nec-

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RIRS, retrograde intrarenal surgery; SFR, stone-free rate; SWL, shockwave lithotripsy; (f)URS, (flexible) ureterorenoscopy

essary to clarify the impact of this technique on patient safety and stone-free rates.

Introduction

Urolithiasis is a common disease affecting men and women of all ages. Over the last decade, the prevalence and incidence of urinary tract stones has increased [1]. However, the incidence of urolithiasis depends on geographical, racial, and socioeconomic factors. The probability of stone formation is reported to be highest in Saudi Arabia (20.1%) and the USA (13%) but seems lower in Europe (5–9%) and Asia (1–5%) [2]. Stone disease is more frequent in Caucasians than in Blacks; however, a significant increase in the prevalence of urolithiasis in the Black race can be seen once they adopt Caucasian eating habits [3,4]. Generally, dietary habits seem to play an important role in the formation of calculi in the urinary tract. In particular, the intake of animal protein might increase the risk of stone formation and affect the chemical composition of stones [5]. With increasing patient numbers worldwide, urolithiasis is a present social and economic problem [6].

Currently, there are a variety of therapeutic options for urolithiasis. With minimally invasive techniques gradually replacing open surgery, treatment has changed considerably since the 1970s. The development of technologies, such as ureterorenoscopy (URS), percutaneous nephrolithotomy (PCNL), shockwave lithotripsy (SWL), laparoscopy, and robot-assisted interventions, has shifted treatment away from open surgery. Over the last two decades, interventional therapy for urinary calculi has increased significantly [7]. Whilst SWL rates have increased by 26%, URS approaches increased by 86% in the UK [8]. The significant increase in URS is clearly connected with the introduction of flexible endoscopes and, thus, retrograde intrarenal surgery (RIRS), improvements in laser technology, and better availability of devices [9]. PCNL rates increased with respect to the total number of treatments but were relatively stable compared to other treatment options. The total number of open surgery procedures decreased, whilst the total number of all modalities showed inconsistent trends in different countries [7].

However, in the last two decades, the use of robotic surgery has increased in the treatment of urolithiasis. The first use of robotic surgery was in 1999, when Intuitive Surgical Inc. (Sunnyvale, CA, USA) introduced the da Vinci™ Surgical System [10]. Initially designed for telesurgery in battlefields, the da Vinci system is currently the most common surgical robot. Like most robotic systems, the da Vinci robot is a master–slave system for laparoscopic surgery with various adaptions for utilisation in different disciplines and for an increasing number of indications [11,12]. In the field of urology, robotic surgery is mostly used for laparoscopic and, recently, for RIRS. In 2013 the Roboflex Avicenna™ (Elmed Medical Systems, Ankara, Turkey) master–slave robotic system was first clinically tested for RIRS [13].

Robot-assisted surgery for urolithiasis, one of the most common diseases in urology, is rare. One reason for this is that most patients with kidney or ureteric stones are treated with modern endourological interventions or extracorporeal SWL and, therefore, only a few indications for open or laparoscopic surgical interventions in urolithiasis remain [14–17]. Only in the few cases, where minimally invasive treatment options are not applicable or particular circumstances hamper their use, do urologists have the option to perform open surgery, laparoscopic surgery, or robot-assisted stone treatment.

The present article aimed to summarise the current knowledge on the application of robotic surgery for urolithiasis treatment.

Materials and methods

We conducted a PubMed© literature search using predefined Medical Subject Headings (MeSH) terms to identify robotic stone surgery-related studies listed on Medline and published up to the present (last search performed on 06/27/2017) (Fig. 1). We also screened abstracts from the 2016 and 2017 AUA Congresses, European Association of Urology (EAU) Congresses, European section of Uro-Technology (ESUT) Meetings and EAU Section of Urolithiasis (EULIS) Meetings. Publications relevant to the subject and their cited references were retrieved and appraised independently by two authors (D.S.S. and A.M.). In the case of a disagreement, a third reviewer was consulted to reach a unanimous decision. Systematic reviews and clinical studies (randomised controlled trials, cohort studies, case-control studies, and case series) were included. Animal studies, non-systematic reviews, and publications with 'Epub ahead of print' status were also included. Non-English-language articles, case reports, publications based on expert opinion, physiology/bench research or 'first principles', epidemiological studies, cross-sectional studies, and cadaveric studies were

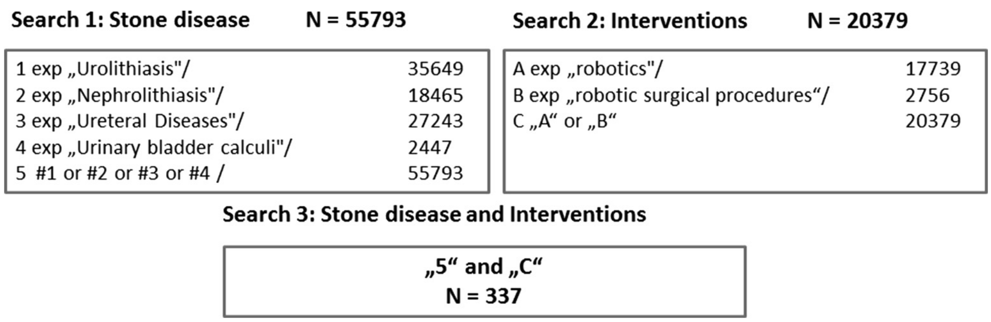

Fig. 1 Review of the literature – search terms.

excluded. The selection process comprised multiple steps. First, all references were scanned by title and abstract; full-text versions of all relevant articles were obtained and included or excluded according to the defined criteria. Where the full text was not available, the publications were excluded (Fig. 2). Two authors (P.F.M. and D.S.S.) extracted data from the selected publications, including study characteristics, information about the intervention, patient characteristics, and treatment outcomes. Extracted data were then evaluated by all participating authors. To structure all relevant data, the information was tabulated using Microsoft Excel 2013® (Microsoft, Redmond, Washington, USA). Because of the high heterogeneity of the included studies, no further analyses (subgroup analysis, sensitivity analysis, meta-regression models) were performed and data were presented in a descriptive manner.

Results

Search results

Our literature search identified 337 articles; 303 and 19 were excluded because they were not relevant based on the title and abstract, respectively. Full manuscripts were evaluated for 15 articles and based on full-text evaluation, 10 articles were included in this review. After screening the reference list of all included articles, we added three more articles to this review. We also included five abstracts from the 2016 and 2017 AUA

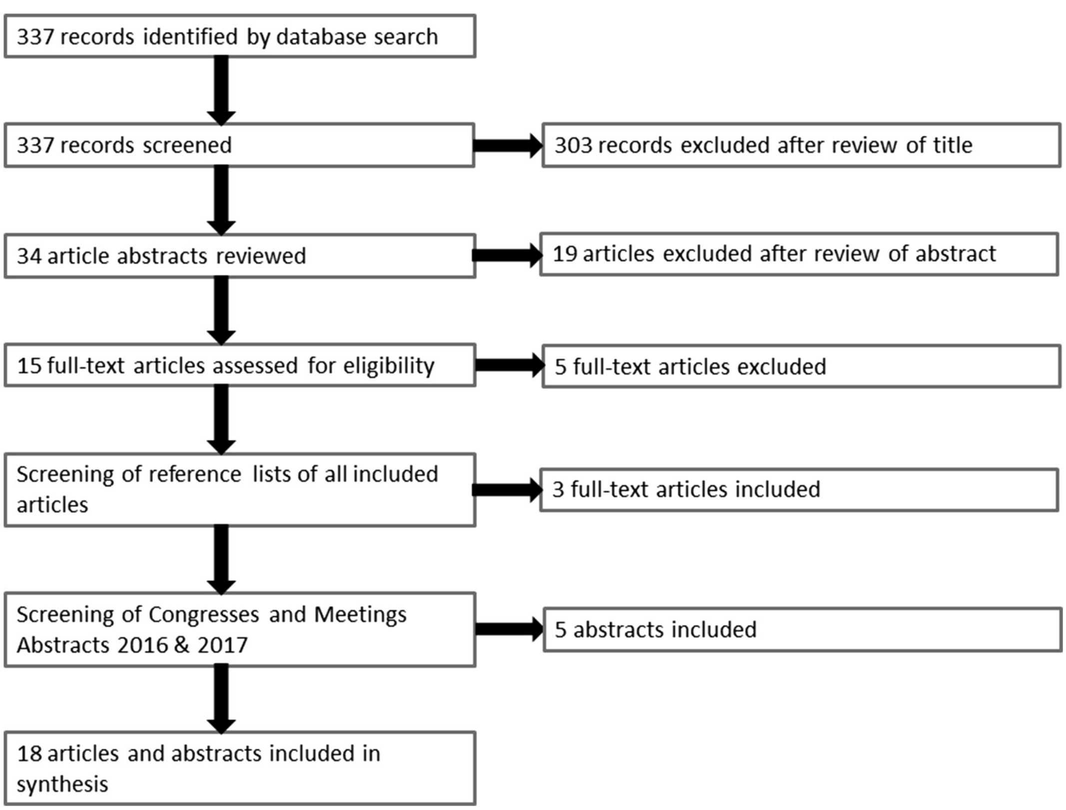

Fig. 2 Selection of included studies – adopted Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) algorithm.

Congresses, EAU Congresses, ESUT Meetings and EULIS Meetings. Of all included articles and abstracts, one was a systematic review, 16 were clinical trials, and one was an animal model study closely related to clinical work (Table 1 [13,19,20,22–27,29,36,40–46]).

Robot-assisted pyelolithotomy

For most larger kidney calculi, PCNL remains the first-choice intervention [18]. There are only rare situations where laparoscopic or robot-assisted laparoscopic approaches should be considered. In most cases, robot-assisted pyelolithotomy is conducted in patients with pelvi-ureteric obstruction combined with pyeloplasty. Only a few groups have published their experiences and surgery outcomes with combined stone extraction and pyeloplasty using da Vinci robotic systems. Another indication for a robotic approach is staghorn calculi where SWL or PCNL fails. Badalato et al. [19] in 2009 reported a meta-analysis including four clinical trials with a total of 39 patients that underwent robot-assisted stone extraction from the kidney with or without pyeloplasty [20–24]. Mufarrij et al. [23] and Atug et al. [24] reported concomitant robotic pyelolithotomy and pyeloplasty in a total of 21 patients. In both studies, all patients were stone-free 3 months after surgery and showed durable radiographic resolution of the obstruction. The group in the study by Atug et al. [24] did not report intraoperative complications or conversion to open surgery. Mufarrij et al. [23] did not especially stratify for complications and conversion in patients with concomitant stone burden. Lee et al. [22] retrospectively reported a series of five adolescents undergoing robot-assisted pyelolithotomy. In one case, conversion to open surgery was required because the stone could not be removed by the robotic grasper or fragmented by electrohydraulic lithotripsy. Of the four patients with completed robotic pyelolithotomy, three were stone-free at the follow-up examination. Badani et al. [20] completed robot-assisted pyelolithotomy in 13 patients. In their series, no open conversion was necessary, and in all patients, except for one with a complete staghorn calculus, the stone could successfully be removed. The other 12 patients also showed no residual fragments on postoperative imaging. Interestingly, in both the Badani et al. [20] and Lee et al. [22] studies, the two patients with open conversion or incomplete stone extraction had complete staghorn calculi. As Badalato et al. [19] stated in their review, data presentation and follow-up were very inconsistent in the four articles included.

In 2013, Ghani et al. [25] published a study of three patients with staghorn calculi on whom they performed robot-assisted anatrophic nephrolithotomy with renal hypothermia using a da Vinci robot. They reported no intra- or postoperative complications. Complete stone clearance was achieved in one patient, the other two patients required PCNL. Renal function demonstrated no change at the 1-month follow-up.

King et al. [26], in 2014, performed a prospective study including seven patients that underwent robotic pyelolithotomy. No intraoperative complications or conversions to open surgery were reported. Only two of the seven patients were completely stone-free after the procedure. Of the five patients that were not stone free, four had complete staghorn calculi. This agrees with the results of Lee et al. [22] and Badani et al. [20], where patients with complete staghorn calculi were more difficult to operate.

Swearingen et al. [27], in 2016, reported a retrospective case series of 27 patients that underwent 28 robot-assisted pyelolithotomy and nephrolithotomy

Table 1 Summary of all included studies and abstracts.

	Reference	Robotic system	Study design	Patients
Robot-assisted pyelolithotomy	Badalato et al. [19]	da Vinci	Systematic review	39
	Atug et al. [24]	da Vinci	Retrospective	8
	Badani et al. [20]	da Vinci	Prospective	13
	Mufarrij et al. [23]	da Vinci	Retrospective	13
	Lee et al. [22]	da Vinci	Retrospective	5
	Ghani et al. [25]	da Vinci	Retrospective	3
	Swearingen et al. [27]	da Vinci	Retrospective	27
	King et al. [26]	da Vinci	Prospective	7
Robot-assisted ureterolithotomy	Dogra et al. [29]	da Vinci	Retrospective	16
Robot-assisted fURS	Desai et al. [36]	Sensei	Porcine model	/
	Desai et al. [40]	Sensei	Prospective	18
	Saglam et al. [13]	Roboflex Avicenna	Prospective	81
	Geavlete et al. [43]	Roboflex Avicenna	Prospective	51
	Geavlete et al. [41]	Roboflex Avicenna	Prospective	298 stones
	Klein et al. [45]	Roboflex Avicenna	Prospective	266
	Sarica et al. [44]	Roboflex Avicenna	Prospective	18
	Geavlete et al. [42]	Roboflex Avicenna	Prospective	200
	Klein et al. [46]	Roboflex Avicenna	Prospective	395

procedures (one bilateral approach) in five different surgical centres. No conversion to open surgery was necessary in any of the cases. In five patients, complications ranging up to Clavien-Dindo grade IIIb were reported. The complete stone-free rate (SFR) was 96% on imaging.

Although all authors stated encouraging results, no study compared the robotic approach to widespread minimally invasive techniques used such as URS, extracorporeal SWL, and PCNL.

Robot-assisted ureterolithotomy

To date, the treatment of ureteric stones with a diameter > 2 cm remains challenging. Most guidelines recommend URS with intracorporeal stone disintegration or extracorporeal SWL for the localisation of these stones [16]. However, laparoscopic surgery for impacted ureteric stones is considered a suitable alternative [28]. In 2013, Dogra et al. [29] published, to their knowledge, the first clinical experience with a da Vinci system for this type of stone. From 2010 to 2012, they performed robot-assisted ureterolithotomy in 16 patients and reported no conversions to open surgery. Retrospectively, they observed no major postoperative complications or the development of urinoma. They also reported a stone clearance rate of 100% and compared to classic laparoscopic surgery the hospital stay was shorter. The placed intra-abdominal drain could be removed after a mean of 18 h. In an average follow-up of 13 months, they did not report ureteric strictures after removing the JJ stent at 4 weeks after surgery. However, their study had some limitations; it was retrospective with a small number of patients. Nevertheless, the presented data showed robot-assisted ureterolithotomy to be, at least, an acceptable alternative to laparoscopic approaches. More prospective studies with a comparison with standard-of-care procedures, such as URS and SWL, are necessary to evaluate the benefits of the robotic approach.

Robot-assisted flexible URS (fURS)

Endourological treatment is the first-line treatment for most cases of urolithiasis [16]. Today, most urologists prefer fURS as a state-of-the-art procedure for urolithiasis because it has good clinical outcomes, high SFRs, and does not compromise patient safety [30–34]. However, there were few reports on approaches for implementing robotic systems in endourology before the 2000s [35].

Desai et al. [36], in 2008, first described a flexible robotic device for RIRS in a swine model. This system was based on a novel robotic catheter system (Sensei™, Hansen Medical, Mountainview, CA, USA) originally developed for intracardiac applications [37,38]. Their system consisted of a catheter sheath and an inner catheter guide combined with a custom-built passive fiberoptic flexible ureteroscope. The results of the animal study were promising, so that in 2011 the same group reported their first clinical experience with 18 patients that underwent robotic fURS [39,40]. They reported no conversion to manual URS, no intraoperative complications, few postoperative complications (transient fever in two cases, temporary limb paresis in one case), and one case of the secondary treatment of residual fragments. The complete stone-clearance rate was 89% after 3 months and all patients had stable renal function at this time point [40].

In 2013, Saglam et al. [13] first reported the Roboflex Avicenna system to be suitable and safe for robotic fURS. In this classic master–slave system, the surgeon sits at an open console and navigates, different from the adapted catheter guide used by Desai et al. [36], a commercially available flexible ureterorenoscope. The system allows manipulation of the endoscope in all dimensions and in addition, laser-technology and fluoroscopy can also be handled by the surgeon via a touchscreen and foot pedals. In particular, ergonomics showed to be improved compared to standard fURS, whilst mean operation time was acceptable and secondary URS was needed only in one of 81 patients because of a malfunction of the robotic fURS system. The first prospective data on clinical outcomes and SFRs by Geavlete et al. [41] demonstrated, at least, similar results for robotic fURS compared to classic fURS. In their study, 51 of 99 patients underwent robotic fURS and all interventions were successful without conversion to manual URS. SFRs after 3 months were comparable (89.4% vs 92.4%) and the number of required re-interventions was significantly lower in robotic fURS (9.1% vs 15.1%). At the 2017 EAU, Geavlete et al. [42] confirmed these results in more patients ($n = 200$). The same group demonstrated an increased fragmentation efficiency evaluated by fragmentation volume per minute in robotic fURS [41]. Klein et al. [45–47] reported at the 2016 ESUT Meeting and 2016 and 2017 EAU Congress a prospective case series of 395 patients undergoing robotic fURS with the Avicenna system. They demonstrated the system to be safe and easy to integrate in daily routine. Like Geavlete et al. [43], they also observed a subjectively better operation comfort for robotic fURS. At the 2016 AUA Congress Sarica et al. [44] presented the first data on a combined robotic fURS and mini PCNL in 18 patients. They stated that robotic fURS may be helpful in the combined treatment and did not report complications. Nevertheless, more studies are required to confirm that robotic fURS is beneficial to clinical outcomes and patient safety.

Discussion

Urolithiasis remains one of the most frequent urological diseases worldwide and its treatment has undergone several paradigm changes. After the introduction of minimally invasive endourological surgery in the last century, robotic systems are now emerging.

Several robotic devices, such as the widely available da Vinci system, were introduced in treatment guidelines regarding various stone localisations. The da Vinci master–slave system may replace conventional laparoscopic and open surgery for their rare indications for stone disease in the future [19]. Most studies, to date, show the robot system to be safer and with, at least, similar clinical outcomes. New robotic systems entering the market such as Avatera© (Avateramedical GmbH, Jena, Germany) or the TELELAP ALF-X robotic system© (SOFAR SpA, Milan, Italy), which have new features such as motion feedback and eye tracking, might further improve the usability and outcomes associated with robot systems [35,48]. Nevertheless, all currently existing robotic devices have their known limitations with respect to availability and cost-effectiveness [49]. Furthermore, indications for non-endourological approaches for the treatment of urinary calculi are decreasing. With the improvement of endoscopes and with robotics emerging, this development seems irreversible.

For urolithiasis, new robot endourological approaches, such as the Roboflex Avicenna system for fURS, are possibly the most innovative techniques currently on the market. These robotic systems for RIRS have already shown their potential in early clinical trials [13,43,44]. Whilst patient safety is not compromised, SFRs are equal to those in manual URS and surgeons comfort is significantly increased [54]. Likewise the surgeon can operate outside the radiation exposure area and first results indicate less endoscope breakage [41,51]. However, Avicenna remains in an early stage of implementation in daily clinical practice. Bigger prospective multicentre studies are currently being conducted and should show whether this technique can add value to existing open and endourological treatment options.

Various new technical improvements, such as real-time three-dimensional visualisation increase safety and usability in percutaneous interventions for stone treatment (i.e., PCNL) [50]. To date, there is no master–slave system commercially available for this type of stone treatment. Research and development are still necessary to improve (robotic) assistance devices in this field.

In the distant future, the use of nano-robots in the urogenital tract could also be an option for the treatment of urolithiasis. Miniaturised mechanic devices would make the endoscopic application nearly atraumatic and improve treatment precision and quality. Recent technical progress has made this former science-fiction scenario a potential reality. Nanomotors, -pumps, and -electromechanical manipulation devices are being developed for future use in the human body [52,53]. These techniques should comprise next-generation treatment approaches for urolithiasis.

The data on robotic surgery for urolithiasis still need improvement and our review was limited by the small number of published studies. However, the data to date and the ongoing development of new robotic devices are encouraging for robotic stone surgery in the near future. Therefore, in the authors' opinion, especially regarding the field of endourological surgery, there will be a shift towards the use of robotic (assistance) devices.

Conclusion

Robotic systems are continuously replacing classic laparoscopy and open surgical operations in stone surgery. They are also used in endourological interventions. The evidence for the increased benefit of robotic stone surgery compared to existing treatment options is increasing, but data are insufficient regarding this topic to draw a final conclusion. More prospective randomised controlled studies are necessary to verify the benefit of this novel technology for the treatment of urolithiasis. The ensuing years will see an increase in new technologies and robots in the field of urology and surgery in general. Improved and newly designed master–slave systems should change the current field of robotic surgery. Nanotechnology will also be part of next-generation treatment options and is of great interest to scientists and surgeons.

Conflict of interest

None.

Author contributions

Müller: Protocol/project development, data analysis, manuscript and figure writing/editing.

Schlager: Manuscript editing, data analysis.

Hein: Protocol development, manuscript editing.

Bach: Manuscript editing and supervision.

Miernik: Protocol/project development, data analysis, manuscript and figure writing/editing, supervision.

Schoeb: Protocol/project development, data analysis, manuscript, figure writing/editing.

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