The usefulness and ergonomics of a new robotic system for flexible ureteroscopy and laser lithotripsy for treating renal stones

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Purpose: To investigate the usefulness and ergonomics of a newly developed robotic system for flexible ureteroscopy (easyUretero).

Materials and Methods: During in vitro testing, six participants performed renal stone removal four times in an artificial kidney-ureter-bladder model. Each participant manipulated a single-use digital flexible ureteroscope (LithoVue) with their hands and the robotic system, sequentially. We compared the task completion times of each participant. The ergonomics of and operational satisfaction with each procedure were assessed by questionnaires. In vivo tests evaluated the operability and safety of the robotic system in two live female pigs. We checked that all the steps of flexible lithotomy for renal stones could be completed individually.

Results: The task completion time with the robotic system during in vitro testing was significantly longer than with manual ureteroscopy regardless of the operator’s competence level (expert professors: 282.6±92.4 seconds vs. 73.6±43.3 seconds, p<0.001; fellows: 247.5±57.7 seconds vs. 95.8±43.7 seconds, p<0.001; residents: 281.3±111.0 seconds vs. 188.6±138.6 seconds, p<0.001). The residents took more time to remove the upper and mid caliceal stones with the robotic system. The ergonomic evaluation was better for the robotic system, but operational satisfaction was lower, and there was no statistical difference among the groups. In vivo tests showed that all the steps of robotic flexible ureteroscopy could be completed without difficulty. No safety issues were encountered during the procedure.

Conclusions: The robotic system (easyUretero) was ergonomic and safe for flexible ureteroscopy and laser lithotripsy for renal stones.

Keywords: Robotics; Ureteroscopy; Urolithiasis

INTRODUCTION

Medical robotic platforms can help to treat diseases and improve patients’ quality of life by providing more diverse medical services [1]. Surgical robots can be more accurately and reliably controlled than humans and have better task repeatability [2,3]. Leveraging these advantages of robots over humans can help to ease the numerous challenges...
encountered in the surgical process and can help unskilled doctors to train in surgery [3-5]. As urologists are very well aware of the advantages of robotic surgery, there are many efforts to apply robotic surgery to surgeries other than robotic prostatectomy through the Da Vinci system (Intuitive Surgical, Sunnyvale, CA, USA) [6]. Flexible endoscopic robotic surgery is one of the most promising fields in this context [7-10].

Urinary stones are a common disease, the incidence and prevalence of which are steadily increasing worldwide, including in Korea [11,12]. A recent large database study announced that the incidence and prevalence of urolithiasis has increased yearly. Jung and his colleagues [12] concluded that western dietary habits and decreased physical activity are the leading cause of this increased incidence. Flexible ureteroscopy is emerging as a major surgical modality for treating the increased number of patients with urinary stones [13].

Flexible ureteroscopy has developed remarkably over the last decade owing to the development of optical devices and improved endoscopic durability [14]. However, flexible ureteroscopic surgery requires a delicate endourologic technique and skilled assistance in handling lasers, baskets, and irrigation fluid [15]. Most urologists perform the surgery in a standing position, and as a result the repeated use of shoulder and wrist joints poses a risk for musculoskeletal disease among these expert surgeons [15-17]. In addition, the cumulative exposure of medical staff to X-rays during surgery is also an intractable problem [18,19]. Surgical tips and tricks using ultrasonography can reduce X-ray exposure, but this is not a solution in all circumstances [19,20]. The remotely controlled flexible ureteroscopic robotic system is now considered an alternative to solve numerous such issues [7-10].

Therefore, the flexible ureteroscopy robotic system has been targeted to reduce the risk for musculoskeletal disease and exposure to X-rays during surgery while maintaining the advantages of conventional flexible ureteroscopy [8,9]. In 2014, the idea, development, evaluation, assessment, and long-term (IDEAL) study framework for stages in surgical innovation was introduced, with a specific focus on ureteroscopic robotic surgery [8].

Recently, a Korean robotic system called “easyUretero” (ROEN Surgical Inc., Daejeon, Korea) was developed that combines conventional flexible ureteroscopes for the performance of various types of intrarenal surgery [21]. We investigated the usefulness and ergonomics of the Korean robotic system for flexible ureteroscopy and laser lithotripsy for renal stones in vitro and in vivo.
MATERIALS AND METHODS

1. Korean flexible ureteroscopy robotic system, “easyUretero”

The easyUretero robotic system consists of two elements: the master console and the slave manipulator of the flexible ureteroscope (Fig. 1A). The master console has a 32-inch touch screen for control, armrest, gimbal handle, and clutch for motion. The gimbal handle is an easy-to-hold form, like a television remote control, with a jog wheel and button for sophisticated movement and a trigger for adjusting the stone basket (Fig. 1B). The slave manipulator can be mounted on any type of flexible ureteroscope and performs all the actions that surgeons are enabled to do with the device (Fig. 1C). The manipulator can move the instrument forward and backward, can perform flexion and deflexion, and can perform rotation while equipped with a flexible ureteroscope. In addition, the manipulator can also control the delicate movement of the laser fiber and the stone basket without assistance. The console monitor displays the screen transmitted from the flexible ureteroscope to a comfortable surgeon’s view. It also provides the inserted length, flexion, and rotation degree of the flexible ureteroscope to check the status of the instrument (Fig. 1D).

2. Ethics statement and study approval

All animal experiments were approved by the Institutional Animal Care and Use Committee of Asan Institute for Life Sciences, Asan Medical Center (no. IACUC-2021-04-060). All experimental and animal care rules were obeyed according to the National Research Council publication, the Guide for Care and Use of Laboratory Animals.

3. In vitro testing

Two expert professors, two fellows, and two residents participated in this study. The two expert professors had the surgical experience of over 500 cases of flexible ureteroscopy. The two fellows had performed 50 to 100 cases of surgery and had additional experience assisting. The two residents did not have any previous experience in flexible ureteroscopy.

All participants performed renal stone removal tests four times using an artificial kidney-ureter-bladder (KUB) model (Boston Scientific Corp, Miami, FL, USA; Fig. 2A). The KUB models were made out of organosilicates to resemble the human anatomic conduit [22]. Each participant manipulated a single-use digital flexible ureteroscope (LithoVue, Boston Scientific Corp) with their hands and with the robotic system sequentially (Fig. 2B). A zero-tipped nitinol stone basket (Boston Scientific Corp) was used to remove the stones. The stone basket used in the robotic system was modified to be mounted. The participants manually removed the caliceal stones using the LithoVue Empower retrieval device (Boston Scientific Corp).

J.K., who was in charge of the robot development team, taught the robotic operation method while practicing and
### Table 1. Questionnaires for flexible robotic ureteroscopy

| Questionnaire                                      | Very good – Good – No difference – Poor – Very Poor |
|---------------------------------------------------|----------------------------------------------------|
| Pain and fatigue scores after use of flexible robotic ureteroscopy compared with the hand-assisted procedure |
| Shoulder stiffness                                 | Very good – Good – No difference – Poor – Very Poor |
| Wrist stiffness                                    | Very good – Good – No difference – Poor – Very Poor |
| Thumb fatigue                                      | Very good – Good – No difference – Poor – Very Poor |
| Hand fatigue                                       | Very good – Good – No difference – Poor – Very Poor |
| Other area (Please describe ____________)           | Very good – Good – No difference – Poor – Very Poor |

Satisfaction score after flexible robotic ureteroscopy compared with the hand-assisted procedure

| Satisfaction                                      | Very good – Good – No difference – Poor – Very Poor |
|---------------------------------------------------|----------------------------------------------------|
| Handling of the flexible scope                    | Very good – Good – No difference – Poor – Very Poor |
| Operation of stone basket                         | Very good – Good – No difference – Poor – Very Poor |

### Table 2. Checklist for flexible robotic ureteroscopy insertion and laser lithotripsy

| Step | Procedure                                                                 | Result |
|------|---------------------------------------------------------------------------|--------|
| 1    | Keeps the flexible ureteroscope in an ergonomic position                  | Pass / Fail |
| 2    | Identifies and accesses all renal calyces                                 | Pass / Fail |
| 3    | Passes the basket until the tip becomes visible (after flexible ureteroscope straightening) | Pass / Fail |
| 4    | Opens the basket and traps the stone                                     | Pass / Fail |
| 5    | Closes the basket and repositions renal stone in upper calyces            | Pass / Fail |
| 6    | Passes laser fiber until the tip is visible (after flexible ureteroscope straightening) | Pass / Fail |
| 7    | Holmium laser lithotripsy without caliceal injury (fragmentation/dusting) | Pass / Fail |
| 8    | Closes basket and removes stone fragments                                 | Pass / Fail |

**Fig. 3.** (A) Anesthetized pigs in the dorsal lithotomy position. (B) The ureteral access sheath bonded to the slave manipulator. (C) The LithoVue mounted on the slave manipulator. (D) The Lithovue introduced into the renal pelvis through the ureteral access sheath.
testing the method next to the participants. Each participant practiced for approximately 1 hour, and then had a test. The test was composed of four steps: 1) insert a flexible ureteroscope into the ureter in the KUB model; 2) confirm the stone location in each calyx in the kidney; 3) grasp the stone with the stone basket; and 4) remove the stone from the ureter. Five to 10 finely broken stones (3–5 mm) were inserted into each calyx in advance. An experimental assistant helped to

![Fig. 4. (A) The task completion time for all caliceal stones according to the surgeon’s competence level. (B) The task completion time of expert professors according to the location of stones. (C) The task completion time of fellows according to the location of stones. (D) The task completion time of residents according to the location of stones.](image-url)
measure the time taken with a watch during the test. Since the upper, mid, and lower calyx stones had to be removed with one’s hands and the robotic system, a total of six instances had to be measured each time. We compared the task completion times of each participant. The operation satisfaction and ergonomic evaluation of each procedure were assessed using questionnaires (Table 1) [23].

4. In vivo testing

The in vivo tests did not compare task completion times among participants but attempted to confirm whether actual robotic surgery could proceed stably in live pigs without difficulty [24]. We used two female pigs (Yorkshire; weight, 35–40 kg). After the first in vivo experiment, we analyzed the surgical procedures and test results. The second in vivo experiment was conducted two weeks later. All procedures were performed with the animals under general anesthesia with endotracheal intubation. The anesthetized pigs were placed in the dorsal lithotomy position. We looked for ureteral orifices using a 19-Fr cystoscope and inserted a 0.038-inch hydrophilic guidewire into the renal pelvis. Then, we inserted a ureteral access sheath (11/13 Fr, 36 cm, Navigator HD, Boston Scientific Corp.) to the level of the ureteropelvic junction to provide optimal visualization and easy access with flexible ureteroscopy [25]. About a dozen calcium oxalate stones sized 3 to 5 mm were retrogradely inserted at the renal calyces via the ureteral access sheath by using manual ureteroscopic procedures. The LithoVue mounted on the slave manipulator was introduced into the renal pelvis through the ureteral access sheath (Fig. 3). An Auriga XL Holmium laser and a 200-µm laser fiber (Boston Scientific Corp.) were used to perform dusting or fragmentation techniques. The holmium laser was set to 10 to 30 W. The laser energy was set for stone fragmentation to 1.0 to 2.0 J with 5 to 10 Hz. The laser energy was set to 0.3 to 0.8 J with 15 to 30 Hz for the dusting or pop-dusting technique. A pressure-controlled irrigation system was used to maintain an appropriate low intrarenal pressure to guarantee sufficient space to break the stones and avoid intrarenal backward flow. The fragmented stones were removed by use of the previously described modified zero-tipped nitinol stone basket. We checked that all steps of flexible robotic ureteroscopy and laser lithotripsy for renal stones could be performed (Table 2).

5. Statistical analysis

We used SPSS version 22.0 (IBM Corp., Armonk, NY, USA) for all statistical analyses. The variables are presented as means±standard deviations. In addition, we used the Kruskal–Wallis test, the Wilcoxon signed-rank test and Mann–Whitney U test for comparisons, owing to the small number of subjects in our groups. p<0.05 was considered statistically significant.

RESULTS

1. In vitro tests

Task completion in the robotic system required more time for stabilization than did manual LithoVue (Fig. 4A). The task completion time in the robotic system was significantly longer than for manual LithoVue regardless of the operator’s competence level (expert professors: 282.6±92.4 seconds vs. 73.6±43.3 seconds, p<0.001; fellows: 247.5±57.7 seconds vs. 95.8±43.7 seconds, p<0.001; residents: 281.3±111.0 seconds vs. 188.6±126.0 seconds, p<0.001; Fig. 4B–D). Among the expert professors and fellows, the location of caliceal stones did not affect the results (Fig. 4B, C). Among residents, the removal of upper and mid-caliceal stones took more time in the robotic system. Meanwhile, a similar time was taken to remove lower caliceal stones (robot vs. manual: 84.6±34.7 seconds vs. 103.2±126.0 seconds, p=0.424; Fig. 4D). The ergonomic evaluation of the robotic system was better, especially in the residents’ group. In contrast, operation satisfaction was lower with the robotic system, and there was no statistical differ-

| Variable                                      | Expert professor | Fellow | Resident | p-value |
|-----------------------------------------------|------------------|--------|----------|---------|
| Pain and fatigue scores after performance of flexible robotic ureteroscopy compared with the hand-assisted procedure | 0.50±0.84        | 0.83±0.41 | 0.40±0.55 | 0.399   |
| Shoulder stiffness                            | 0.50±1.38        | -0.50±0.55 | 1.20±0.84 | 0.053   |
| Wrist stiffness                               | 1.50±0.55        | 0.00±0.89 | 1.80±0.45 | 0.007   |
| Hand fatigue                                  | 0.83±0.41        | 0.00±0.63 | 1.60±0.55 | 0.005   |
| Satisfaction score after flexible robotic ureteroscopy compared with the hand-assisted procedure | 0.50±1.05        | -0.50±0.84 | 0.20±0.84 | 0.185   |
| Handling of the flexible scope                | -0.67±0.82       | -1.33±0.84 | 0.20±1.10 | 0.081   |

Score: Very good (2) – Good (1) – No difference (0) – Poor (-1) – Very Poor (-2).
ence among the groups (Table 3).

2. In vivo tests
   All surgeons passed all the steps of flexible ureteroscopy insertion and laser lithotripsy for renal stones in Table 2 without difficulty (Supplementary Videos 1, 2). No safety issues were encountered during the procedure. In the second in vivo testing, we tested the stone dusting procedure for over 30 minutes. Since the robotic manipulator held the flexible ureteroscope in a fixed state of motion, additional control was not required except for the laser pedal. Surgeons could comfortably perform the dusting procedure while sitting on a chair and looking at the monitor. The robotic system was also stable without any abnormalities throughout the laser operation.

DISCUSSION

The Korean flexible ureteroscopy robotic system, easyUretero, was developed to combine a conventional flexible ureteroscope to perform various types of intrarenal surgery [21]. The configuration of the flexible ureteroscope with a master console and a slave manipulator is similar to previously developed robotic systems [7-9]. These system configurations help to completely protect the technician from radiation exposure and facilitate the conduct of surgery in a comfortable position.

By comparison, Roboflex Avicenna (ELMED Medical system, Ankara, Turkey) requires assistants to work on additional lasers or basket equipment [89]. Delicate handling of lasers or baskets takes a lot of effort and time and requires another attachment to the robotic equipment and an assistant. In addition, it may be difficult to protect assistants from radiation exposure [18]. The easyUretero robotic system can reduce errors caused by inexperienced assistants and minimizes the radiation exposure of medical staff because the operator in the console can adjust both the basket and the laser. Moreover, the forward and backward movements of the laser or basket are particularly convenient because of the jogging wheels, which make fine-tuning possible.

Surgeons could hold the stone with a basket by pressing the trigger button attached to the gimbal handle. However, the basket just opened and closed in consecutive order; it could not be modified or adjusted according to the size or location of the stone. Occasionally, the stone basket needs to be opened slightly, and sometimes it needs to be opened as much as possible while pushing the walls of the calyx [25]. The easyUretero system has yet to implement these capabilities. The stiffness of the operation resulted in lower satisfaction among the professors and fellows. Residents gave neutral scores to robotic basket performance. This might have been because they had never controlled the stone basket before. The easyUretero system was expected to be better in terms of the learning curve of the resident beginners, but the manual method was superior to the robotic system. Among all the overall test procedures, stone basketing took the most time in the robotic system. As mentioned earlier, the reason mainly was that the basket did not work flexibly according to the situation.

A recent study with the easyUretero robotic system showed similar operative times for midsize renal stones (10-15 mm) in a porcine model (21). Lasering and stone retrieval times were also longer in the robotic system than in manual flexible ureteroscopy, regardless of the surgeon’s competence level. An ergonomic evaluation was not included in that study; the authors concluded that the robotic system makes less physical demands on the operator than manual flexible ureteroscopy [21].

When manipulating the flexible ureteroscope, urologists often assume uncomfortable and twisted positions to access calyceal stones in the complicated kidney anatomy [15-17]. Therefore, musculoskeletal diseases, including hand and wrist problems, are widespread among urologists who use flexible ureteroscopes [16]. The easyUretero robotic system was developed to provide user-friendly ergonomics to minimize the risk for musculoskeletal injury and maximize stone removal efficacy. However, pain and fatigue scores after use were not consistent in the current study, and it was difficult to interpret the results. Since the standard robotic operation methods were not provided, the participants could evaluate the scores differently. For example, fellows shared how to manipulate the jog dials with their thumbs, which might have reflected the relative discomfort scores for the thumbs in the questionnaire results.

The purpose of the current flexible ureteroscopy robotic system was to make it convenient for surgeons while operating on principles similar to operations by hand [89]. However, it would be reasonable to develop future robotic ureteroscopes that can do more than surgeons can do with their hands. In other words, developing a flexible ureteroscope exclusively for robotic systems could be considered actual progress. For example, suppose the basket is built into the front of the ureteroscope. In that case, it can be operated with the robot console buttons. If the laser is embedded, the direction in which the laser instrument comes out may change periodically to 3 or 9 o’clock. In future robotic systems, a complicated movement and device operation that hands could not follow might be possible.
The limitation of the current study is that the operation was not performed on an actual human body. In vitro tests did not use irrigation fluid to keep the procedure conditions constant. It was challenging to fill the KUB model by connecting the irrigation fluid to the flexible ureteroscope. Due to the incomplete fluid filling, sometimes the air pocket in the renal calyx interfered with the endoscope’s vision, so the in vitro test was conducted without using the irrigation fluid.

In vivo tests used only two female pigs and attempted to confirm whether actual robotic surgery could proceed stably and safely without measuring task completion time. However, we inserted about a dozen calcium oxalate stones sized 3 to 5 mm in the renal calyces. Since the number of inserted stone fragments was large, depending on the manipulation method, we could have a similar experience with more than 10 times the number of surgeries. By proceeding with the repetition process of eliminating calyceal stones without any problems, we could thoroughly review the usefulness and ergonomics of the easyUretero system, which was the primary purpose of this study.

On the other hand, the size of the stones was not large, so the lasing test was also limited. Usually, one stone could be fragmented 2 to 3 times. Considering these problems, we tried the stone dusting procedure for over 30 minutes, and the results were very satisfactory. Because the robotic manipulator held the flexible ureteroscopy in a fixed state of motion, additional control was not required except for the pedal to launch the laser. Dusting techniques might be the mainstream if robotic systems are well-established and laser technology is improved a little more [26].

Because only six participants performed the tests in the study, we did not have much data to compare and analyze. However, expert professors, intermediate-level fellows, and resident beginners with prominent differences in flexible ureteroscopic surgery experience participated in the study and we compared their performances. Resident beginners had more difficulties because they had to simultaneously learn how to operate the flexible ureteroscope using manual methods and the robotic system. However, the beginners tended to get used to both ways over time. If virtual flexible ureteroscopic surgery training becomes possible in the robotic system in the future, it would be helpful to adapt to the robotic system [27].

CONCLUSIONS

The Korean robotic system easyUretero provides a safe and ergonomic surgical platform for flexible ureteroscopy and laser lithotripsy for renal stones. Thus far, the operational satisfaction and time taken by the robotic system were lower than for manipulation with hands. In the future, continuous technology development would likely improve the robotic system further.

CONFLICTS OF INTEREST

The authors have nothing to disclose.

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AUTHORS’ CONTRIBUTIONS

Research conception and design: all authors. Data acquisition: Juhyun Park, Chan Hoon Gwak, Dongwon Kim, Jung Hyun Shin, Bumjin Lim, and Hyung Keun Park. Statistical analysis: Juhyun Park, Joonhwan Kim, Dong-Soo Kwon, and Hyung Keun Park. Data analysis and interpretation: Juhyun Park, Chan Hoon Gwak, Joonhwan Kim, Byungsik Cheon, Jungmin Han, Dong-Soo Kwon, and Hyung Keun Park. Drafting of the manuscript: Juhyun Park, Chan Hoon Gwak, and Hyung Keun Park. Critical revision of the manuscript: Juhyun Park, Joonhwan Kim, Byungsik Cheon, Jungmin Han, Dong-Soo Kwon, and Hyung Keun Park. Supervision: Joonhwan Kim, Dong-Soo Kwon, and Hyung Keun Park. Approval of the final manuscript: all authors.

SUPPLEMENTARY MATERIALS

Accompanying videos can be found in the ‘Urology in Motion’ section of the journal homepage (www.icurology.org). The supplementary video clips can also be accessed by scanning a QR code, and will be available on YouTube: Supplementary Video 1, https://youtu.be/PaaNZnFQdGU; Supplementary Video 2, https://youtu.be/M_ZWi5cwtko.
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