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ZAMENIX™ R, ROBOTIC-ASSISTED RETROGRADE INTRARENAL SURGERY SYSTEM FOR RENAL STONE REMOVAL AND ITS EFFICACY AND SAFETY EVALUATION

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ABSTRACT

We introduce Zamenix™ R, a novel robotic retrograde intrarenal surgery (RIRS) system that can remotely control a ureteroscope, laser, and stone basket. The efficacy and safety of the system were explored in an in vivo comparative pilot study using a porcine model and a multicenter, prospective, single-arm, pivotal human clinical trial. In the in-vivo test, 10 pigs were randomly divided into two groups: conventional RIRS and robotic RIRS. Three surgeons with different RIRS proficiency participated and they performed two tasks: 1) Stone retrieval test, then followed by 2) Stone fragmentation and retrieval test. In the clinical study, forty-seven adult patients who have one or more stones with a maximum size of 5-30 mm were recruited. The stone-free rate was 93.5%. The postoperative complication rate was 6.5% with three cases of Grade II urinary tract infection (Clavien-Dindo Classification). The experimental results demonstrated the feasibility and comparable safety to conventional RIRS with improved operator's fatigue and radiation exposure.

Keywords: Kidney stone, Flexible ureteroscopy, Retrograde intrarenal surgery, Robot-assisted, In-vivo study, Clinical study

1. INTRODUCTION

Retrograde intrarenal surgery (RIRS) is a minimally invasive treatment for the removal of renal kidney stones. In RIRS, a flexible ureteroscope, usually about 9 Fr in diameter, is inserted through the patient's urinary tract, then kidney stones are broken up or retrieved with a laser device or a stone basket which are introduced through the ureteroscope' channel. RIRS is a promising alternative to percutaneous nephrolithotomy (PCNL) or extracorporeal shockwave lithotripsy (ESWL). RIRS can achieve a higher stone-free rate than ESWL and provide lower morbidity than PCNL [1, 2, 3, 4]. However, RIRS is considered a challenging technique because of several difficulties such as operator's fatigue in ureteroscope manipulation, additional assistant for the use of a stone basket, risk of ureteral injury, and radiation exposure, which limit effectiveness and safety.

Robotic technology is expected to improve such difficulties as it did in laparoscopic surgery, yet only a few have been applied to the RIRS. Roboflex Avicenna (ELMED, Turkey) [5] is a CE certified robotic RIRS system that remotely controls the ureteroscope. This system has shown promising clinical results with better ergonomics and reduced radiation exposure to operators. However, as the functionality is focused only on the control of the ureteroscope and laser, stone retrieval surgical procedures using stone baskets require additional assistance which limits the potential benefit of robotic assistance.

In this paper, we introduce Zamenix™ R, a new robotic RIRS system that provides robotic assistance in the manipulation of laser, basket as well as ureteroscope. The efficacy and safety of the system are explored through an in vivo comparative pilot study using porcine model and a multicenter, prospective, single arm, pivotal human clinical trial.

2. MATERIALS AND METHODS

2.1 Robotic RIRS system, Zamenix™ R

Zamenix™ R developed by ROEN Surgical Inc. (Daejeon, Korea) is a master-slave robot system specially designed for

RIRS (Fig. 1). The slave robot can be equipped with a commercial flexible ureteroscope. A dedicated basket and a laser fiber can also be attached to the slave robot and inserted into the channel of the ureteroscope. The master console provides an enlarged ureteroscope image and a handle controller that allows the operator to remotely control the ureteroscope (deflection, rotation, and forward/backward movement), laser fiber (forward/ backward movement and firing), and basket (open/close and forward/backward movement) with only one hand in a seated position. This allows a single operator to perform the entire surgical procedure in an ergonomic and comfortable posture. Moreover, teleoperation enables the operator to be positioned behind a radiation shielding barrier, protecting the entire body from radiation exposure without wearing heavy protective equipment. The fine motion of ureteroscope can be achieved through intraoperative motion scaling. Furthermore, the robot features two advanced functions that help improve the efficiency and safety of stone retrieval: an automation function that can re-access the renal calyces that once accessed by utilizing the ureteroscope motion recording, a safety alarm that detects the grasping of an oversized stone that can collide with a ureter during extraction.

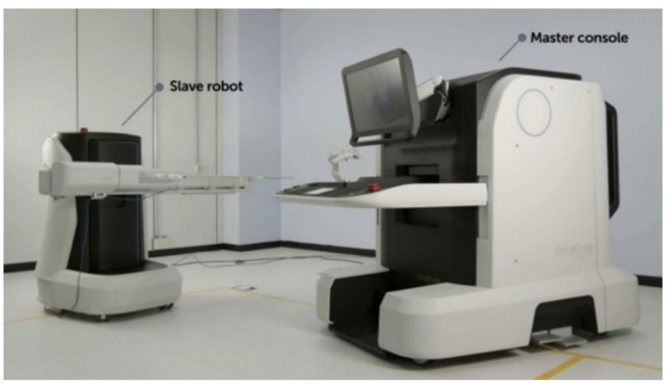

FIGURE 1: Zamenix™ R, Robotic RIRS system overview

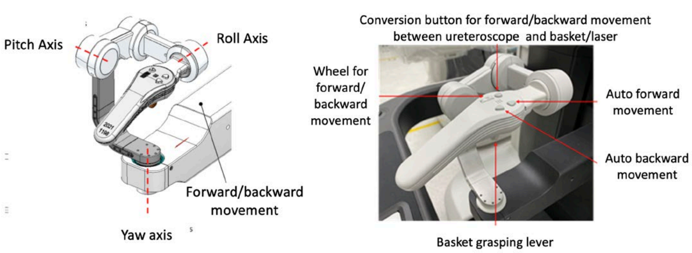

FIGURE 2: Handle controller and its movements and buttons

2.2 Design of in-vivo animal comparative study

A porcine model with the most similar urological anatomy and features to humans was used. A total of 10 female pigs (48.3 ± 0.8 kg) were randomly divided into two groups: conventional RIRS (5 pigs) and robotic RIRS (5 pigs). Three surgeons with different levels of RIRS proficiency (high, intermediate, and low) participated.

Two tasks were conducted: 1) Stone retrieval test using three pigs in each group, then followed by 2) Stone fragmentation and retrieval test using two pigs in each group. In the first task, 10 stones with a size of 0.3 cm were retrieved from an arbitrary location inside the kidney using a stone basket. In the second task, stones with a size of 1.0 to 1.5 cm were broken into fragments with a laser and the fragments were retrieved using the stone basket. As efficacy indices, success rate and procedure time, and operator's fatigue were evaluated. As safety indices, grade of ureter injury, and operator's radiation exposure were evaluated.

2.3 Design of clinical study

Forty-seven patients with one or more stones ranging in size from 5 to 30 mm in maximum size were recruited. Preoperative CT scans were used to analyze stone characteristics including maximum length, total volume, stone density (in Hounsfield units), location, and Seoul National University Renal Stone Complexity (S-ReSC) score. The primary outcome was the stone-free rate. Secondary outcomes were operation time, ureter injury rate, postoperative complication rate, and operator's musculoskeletal fatigue. The stone-free was defined as no visible stone or residual stones less than 4 mm (< 4 mm) on CT scan one month after the surgery. The postoperative complication was observed during the one-month follow-up period. Two RIRS specialist surgeons in two institutes performed the surgery.

2.4 Robot-assisted RIRS procedure

In the procedure, the slave robot is draped, and the patient is placed in the lithotripsy position under general anesthesia. An operator or assistant manually inserts a guidewire and ureteral access sheath into the patient's urinary tract. The slave robot is then docked to the ureteral access sheath. A commercial ureteroscope and a laser fiber or stone basket are mounted on the slave robot. The operator then sits at the console and operates the ureteroscope or instrument. The operator then sits at the console and operates the ureteroscope or instruments. The ureteroscope is inserted into the patient's kidney and the stone is broken up using the laser or retrieved using the stone basket as shown in Fig. 3. After the stone is removed, the ureteroscope and instruments are withdrawn from the patient and the slave robot is undocked. The operator or assistant then manually inserts the ureteral stent, and the surgery is complete.

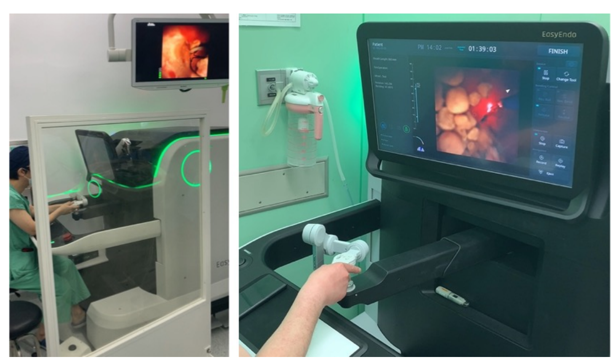

FIGURE 3: Stone fragmenting using a laser behind the radiation shielding barrier (left), stone retrieval using a stone basket (right)

3. RESULTS AND DISCUSSION

3.1 Results of in-vivo animal comparative study

All tasks were able to be completed and the success rate was 100% in both groups. In the first task, regardless of the operator's proficiency, the robot RIRS had a significantly longer procedure time (399.9±185.4, 1127.6±374.5 seconds, respectively). In the second task, the high-skilled surgeon had a significantly longer stone retrieval time in the robot RIRS (41.5±0.5, 79.3±8.1 seconds/stone, respectively). For intermediate and low-experience surgeons, the stone retrieval time was not significantly different between conventional and robotic RIRS (85 ± 30.5, 96.1 ± 32.7 seconds/seat, respectively). All surgeons responded with lower musculoskeletal fatigue in robotic RIRS.

In terms of safety, one case of Grade I ureter injury was observed in the conventional RIRS, whereas two cases of Grade I and one case of Grade II ureter injury were observed in the robotic RIRS. However, all injuries were caused by the ureter access sheath insertion unrelated to the use of a robot. The radiation exposure dose per single c-arm shot to an unprotected body part decreased from 45.5 to 0.14 μSv in robotic RIRS [7, 8].

3.2 Results of clinical study

Forty-six patients received the robotic RIRS and were included in the analysis. The surgical outcomes are shown in Table 1. The stone-free rate was 93.5%. Operation time and console time were 95.1±39.1 and 72.2±38.1 minutes, respectively. The rate of ureter injury was 6.5% for Grade I injury and 10.9% for Grade II injury, all of which were considered to have occurred during access sheath insertion prior to application of the robot-assisted device. The postoperative complication rate was 6.5% in three cases of Grade II urinary tract infection (Clavien-Dindo classification) during the one-month follow-up period. The operator's overall fatigue was 4.75 compared to the conventional RIRS (1 (very high) - 2 (high) - 3 (same) - 4 (low) - 5 (very low). All surgeons rated significantly less fatigue compared to manual RIRS.

TABLE I. SURGICAL OUTCOMES OF CLINICAL STUDY

Variables	Value (N=46)
Stone-free rate [%] (N)	93.5 (43)
Operation time [min]	95.1±39.1
Console time [min]	72.2±38.1
Ureteral injury rate, Total [%] (N)	17.4 (8)
Grade I	6.5 (3)
Grade II	10.9 (5)
Complication rate, Total [%] (N)	6.5 (3)
Grade II (Urinary tract infection)	6.5 (3)

3.3 Discussion

Zamenix™ R could complete in-vivo animal comparative study in a safe manner without device induced complications. The procedure time in the stone retrieval test was longer in a robotic case. Even though all participants received about 10 hours of basic robot training prior to the experiment, it can be said that they were still in learning stage of new robot interface. However, in the stone fragmentation and retrieval test conducted subsequently, the intermediate and low experienced surgeons showed comparable performance compared to their conventional skill. This may suggest the benefit of the robotic assistance in terms of faster improvement of surgeon's skill.

Zamenix™ R could also be successfully applied to routine RIRS clinical procedures. Robotic RIRS showed favorable stone-free rate compared to conventional RIRS. Although there were several ureter injuries in both preclinical and clinical trials, it was not caused by the robot but by the insertion of the ureter sheath. Furthermore, considering that the incidence of urinary tract infections in RIRS is 0.2-15.0% [6], the complication rate of Zamenix™ R is acceptable. All patients recovered well with medication. This result suggests that the robotic RIRS is safe with a relatively lower incidence of mild complications.

Zamenix™ R can provide surgeons with a better clinical environment with comfort and less fatigue. It also enables stable and precise laser control, which can contribute to reducing laser-induced mucosal thermal damage through compensation of respiratory movements during laser firing. Furthermore, the most prominent feature compared to the conventional RIRS is that a surgeon can perform the procedure alone through the integrated control of the basket, laser, and ureteroscope, which contributes to increasing the efficiency of the procedure. However, there is a limitation to be careful when entering the narrow and tortuous ureter because there is no force feedback.

4. CONCLUSION

The new robotic RIRS system, Zamenix™ R, featuring remote control of ureteroscope, laser, and stone basket was presented. The experiment results showed a high stone-free rate with a low risk of complications while reducing the operator's fatigue. The results also demonstrated the potential for effective and safe RIRS with Zamenix™ R. Further study will be continued to explore the clinical benefit of the robotic-assisted RIRS.

ACKNOWLEDGEMENTS

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