Application of simulated puncture in percutaneous nephrolithotomy

Y.-S. HUANG, X.-S. ZHU, G.-Y. WAN, Z.-W. ZHU, H.-P. HUANG

Department of Urology, The People's Hospital of Jiangxi Province (The People's Hospital of Nanchang University), Nanchang, China

Abstract. – OBJECTIVE: This study aimed to explore the clinical value of simulated puncture in percutaneous nephrolithotomy in the treatment of complex kidney stones.

PATIENTS AND METHODS: A total of 120 patients with complex kidney stones who were treated with percutaneous nephrolithotomy in our hospital between March 2017 and March 2020 were enrolled in this study and randomly divided into two groups: the research group and the control group (n = 60 in each). Each subject underwent a dual-source computed tomography (CT) scan of the pelvis and both kidneys before the operation. The research team imported the CT data into Mimics19 software to create a three-dimensional (3D) reconstruction of the skin, bones, kidneys, collecting system, and stones. Based on the 3D reconstruction model, the target renal calyx to be punctured was determined, the best puncture channel was designed, and puncture was simulated. Data regarding the simulated puncture were imported into 3-Matics11 software; the angle and depth of the puncture were measured, and then these data were used to guide percutaneous nephrolithotomy. 3D reconstruction and simulated puncture were not undertaken for the patients in the control group before the operation. The effects of treatment in the two groups were compared.

RESULTS: First-stage percutaneous nephrolithotomy was successfully completed in both groups of patients. The outcome was better in the research group than in the control group in terms of operation time, number of punctures required for successful establishment of a percutaneous renal channel, number of percutaneous kidney puncture channels, and intraoperative blood loss, and the differences were statistically significant ($p < 0.05$ for all). The stone clearance rate was higher in the research group than in the control group, but the difference was not statistically significant ($p = 0.471$). The incidence of penetrating kidney injury was lower in the research group than in the control group, but the difference was not statistically significant ($p = 0.154$).

CONCLUSIONS: For patients due to undergo percutaneous nephrolithotomy for the treatment of complex kidney stones, preoperative simulated puncture helps to improve the puncture accuracy and to reduce the number of punctures required for successful establishment of a percutaneous renal channel, the number of puncture channels, the operation time, and the blood loss, and therefore it is worth promoting.

Key Words:

Simulated puncture, Complex kidney stones, Percutaneous nephrolithotomy.

Introduction

Kidney stones may occur in various parts of the renal pelvis and renal calyx system. Complex kidney stone disease is mainly characterized by very large cast kidney stones or multiple stones[1]. Percutaneous nephrolithotomy (PCNL) is currently the preferred method for the treatment of large and complex kidney stones[2-5] and the establishment of an ideal percutaneous renal channel is the most critical step in the implementation of PCNL[6,7].

There is currently no uniformly accepted clinical standard for the method of establishing surgical channels for PCNL. Individualized treatment plans are required to optimize the curative effect and minimize complications in the treatment of complex kidney stones. In recent years, with the rapid development of computed tomography (CT) imaging technology and the application of related auxiliary software, it has become possible to use computers to simulate surgery and to guide surgical operations. As early as 2013, Li et al[8] applied simulated puncture in percutaneous nephrolithotomy and achieved good results. However, since then, few papers have been published in this field, possibly due to the lack of correlation between simulated puncture and percutaneous nephrolithotomy, which has limited the application of this technique. We accurately measured the angle and depth of the simulated punctures, which impro-

Corresponding Author: Haipeng Huang, MD; e-mail: huamghaipemg@21cn.com

ved the practicability of this technique in PCNL[8]. This study prospectively analyzed the application of simulated puncture in PCNL used in the treatment of 120 patients with complex kidney stones.

Patients and Methods

General Information

A total of 120 patients with complex kidney stones who were treated with PCNL in Jiangxi Provincial People's Hospital between March 2017 and March 2020 were enrolled in this study. Inclusion criteria: 1. patients with complex kidney stones confirmed by urinary tract CT (usually non-enhanced), X-ray (kidney-ureter-bladder [KUB]), ultrasound, or other related examinations; 2. in patients with bilateral complex kidney stones, the side with more severe obstruction or requiring more complex stone removal was included in the study; 3. patients with no cognitive or communication disorders; and 4. no operative contraindications. Exclusion criteria: 1. patients who had serious underlying diseases or had operative contraindications; 2. patients with renal tuberculosis or renal tumors; 3. patients with renal empyema, in whom percutaneous renal puncture and fistula drainage are required; and 4. patients with severe spinal deformity.

Simulated Surgery

Each subject underwent a dual-source CT (Siemens Healthcare, Forchheim, Germany) scan of the pelvis and both kidneys before the operation; the slice thickness was 1 mm. The research team imported the CT data into Mimics 19 software (Materialise, Leuven, Belgium) to create a three-dimensional (3D) reconstruction of the skin, bones, kidneys, collecting system, and stones. After reconstruction, Mimics19 software was used to display the volume of each stone. If there were multiple stones, the volume of the stones was added together to establish the total volume of stone. On a non-enhanced CT image, there is little difference in gray level between the collecting system and the renal parenchyma because they are similar in density, and therefore, the boundary is difficult to identify. As shown in Figure 1a, 3d reconstruction cannot be directly performed. The axonometric picture was displayed in full screen, the Soft tissue structure was selected in grayscale, and the contrast was adjusted carefully. Using a combination of edit mask, 3D Livewire and other tools, the renal parenchyma and collecting system were differentiated, as shown in Figure 1b: the left renal collecting system appears yellow. Each slice containing the collecting system was treated as above, and then, the 3D reconstruction of the collecting system was created. If differentiation between the renal parenchyma and the collecting system is too difficult, it is feasible to perform dual-source kidney CT scanning + enhanced scanning + CT urography (CTU)[9]. The density of the collecting system can be seen on CTU to be higher than that of the renal parenchyma, and therefore, it can be differentiated easily.

To facilitate the examination, it is possible to rotate, scale, display or hide 3D graphics of different structures as needed, and to set the transparency of different tissues. In this way, the 3D model can be used to examine the spatial structure and correlation of the kidney, collecting system and stones through the skin to plan the operation comprehensively, determine the ideal puncture target in the renal calyces, and effectively remove the stones. Figure 1c shows translucent CT images of the collecting system that were created to display clearly the relationship between the left renal collecting system and the stones. Based on an analysis of the 3D model, in this case, the middle calyces of the posterior group and the lower calyces of the posterior group were selected as the puncture targets. Analyze software was used to create a cylinder to represent the puncture needle, with the parameters set to match those of an 18G puncture needle: the length was 200 mm and the radius was 0.95 mm. The puncture was simulated on the 3D model and was performed by moving and rotating the needle. Mimics19 can make one end of the needle immobile and move the other end, but 3-Matics11 (Materialise, Leuven, Belgium) does not have this function; therefore, it is better to complete the simulated puncture in Mimics19. The dilated posterior calyces of the target renal calyces are usually selected, as this makes it easier to perform the puncture, handle the stones, and insert the nephroscope into the ureter[10]. If it is difficult to remove the stones from one channel, multiple channels should be designed at the beginning, avoiding excessive oscillation of the nephroscope for access to the hard-to-reach renal calyces, which can cause renal parenchymal laceration and increase the risk of bleeding[11].

The criteria for success of a simulated puncture were as follows: 1. the puncture needle entered the target calyx in the ideal position, according to the predetermined puncture channel; 2. the distance that the puncture needle traversed through the re-

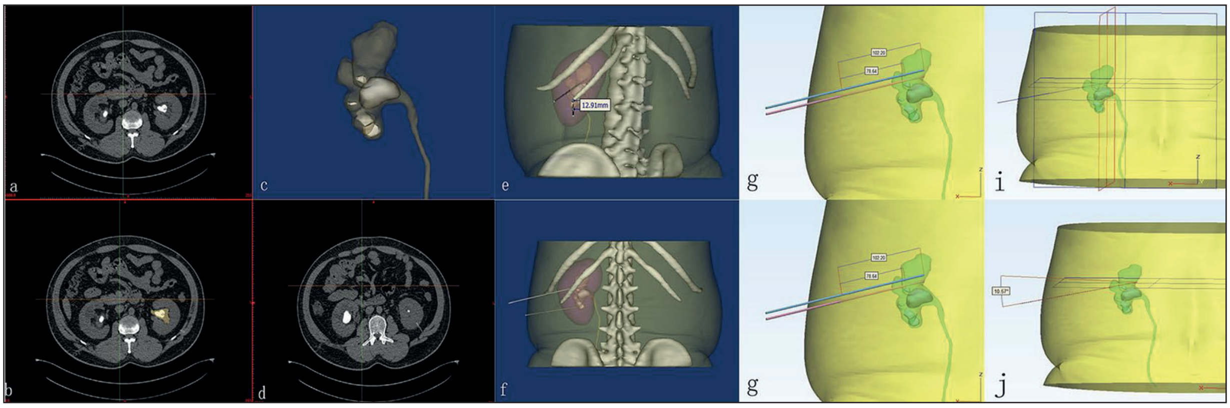

Figure 1. Images of simulated operation process. **a,** CT scan showing bilateral renal stones. **b,** The left renal collecting system is the yellow area (**c**) The anatomical structure of the left renal collecting system and the size and distribution of the stones. **d,** The path of the puncture needle in the lower calyx in the left posterior renal group. **e,** View from the direction of the puncture channel in the lower calyx. **f,** View from the back. **g,** Measurement of the distance from skin to renal calyx and from skin to needle tip. **h,** The central line of the fitted puncture needle. **i,** Three planes established through the puncture needle tip: axial plane, coronal plane, and sagittal plane. **j,** Measurement of the angles between the puncture needle and the axial plane.

nal parenchyma was short; 3. the puncture needle was close to the Brodel tangent line and avoided the large vessels; 4. the needle tip was close to the contralateral side of the collecting system; and 5. observation of the puncture needle in axial, sagittal and coronal images showed that the needle did not pass through pleura, intestines, spleen, liver or large blood vessels and did not enter the contralateral renal parenchyma. Figure 1d shows the path of the needle through the lower calyx of the left posterior renal group in the axial position. If the simulated puncture was not satisfactory, it was possible to return to the previous step and repeat the operation without causing tissue damage. In addition, when the puncture needle entered the target calyces, the angle and depth of the puncture could be adjusted until they were satisfactory.

When the simulated puncture had been successful, the puncture site for PCNL was determined by identifying bony landmarks on the skin surface through 3D graphic observation. In the case shown in Figure 1e and 1e, two percutaneous renal channels were designed to allow effective removal of the stones. The skin puncture site through which the needle entered the middle calyx was located at the midpoint of a line between the left 11^{th} rib and the tip of the left 12^{th} rib. The skin puncture site through which the needle entered the lower calyx was located beneath the tip of the left 12^{th} rib. The position was 12.91 mm below the tip of the 12^{th} rib, as measured by the measuring tool in Mimics19 software. Figure 1e shows the result as seen from the direction of the puncture channel in the lower calyx, and Figure 1f shows the result as seen from the back.

Since 3-Matics11 is superior to Mimics19 in the measurement of angles between straight lines and planes, the 3D models of skin, bone, kidney, collecting system, stone and puncture needle in the posterior group were imported into 3-Matics11. A copy of the needle was made and was moved outside the body parallel to the original needle. The position of the original needle puncture into the skin and calyx and the position of the needle tip were noted. Figure 1g shows the determination of puncture depth using measurements of the copied puncture needle: in this case, the measurements revealed that the distance from skin to calyces was 78.64 mm, and the distance from skin to tip was 102.20 mm. When the original puncture needle had entered the tissue, if a measurement had been taken directly on the original puncture needle, after rotation, it was found that the measurement reflected the distance from the body surface, not the puncture depth; therefore, only by copying a puncture needle and moving it out of the body could the depth to which the needle should enter the tissue be measured. Next, the puncture direction was determined. The center line of the puncture needle was fitted, as shown in Figure 1h. Three planes were established through the tip of the puncture needle: the axial plane, coronal plane and sagittal plane, as shown in Figure 1i. The angles between the fitted center line and the above planes, that is, the angles between the puncture needle and all planes, were measured, as shown in Figure 1j; measurement of these angles determines the puncture direction. In this case, measurement showed that the angle between the needle and the axial plane was 10.57°, the angle between the needle and the coronal plane was 33.60°, and the angle between the needle and the sagittal plane was 54.33°.

After examining the 3D model, the researchers made a comprehensive plan for each operation: they selected the target renal calyx, designed the puncture channel, and simulated the puncture. After each successful simulated puncture, the angle and depth of insertion of the puncture needle were measured, and the data were used to guide the PCNL. The first task is to determine the puncture site, using bony landmarks as described above. In simulated puncture, these landmarks are identified by sight; in percutaneous renal puncture, they are identified by touch, and ultrasound guidance is also used. Then, following the angle and depth of the simulated puncture, the puncture was carried out under ultrasound guidance, taking account of respiratory movements. It should be noted that several factors may cause a difference between the percutaneous renal puncture and the simulated puncture: 1. The 3D reconstruction is based on data collected by CT scanning, which shows structures at a single point in the cycle of respiratory movement. During simulated puncture, the body is still, while during percutaneous renal puncture, the kidneys move up and down with respiratory movement. 2. During CT scanning, the patient is in the supine position, whereas in PCNL, the patient is in the prone position, and the abdomen is elevated. 3. Tissues and organs will deform and move during percutaneous renal puncture but will not do so during simulation surgery. During percutaneous renal puncture, the influence of these factors can be reduced by using ultrasound guidance and monitoring respiratory movement, allowing the target renal calyx to be reached accurately and quickly. Simulated puncture was not undertaken for patients in the control group before PCNL.

Percutaneous Nephrolithotomy

Epidural anesthesia was administered and the patient was placed in the lithotomy position. A 5F ureteral catheter was retrogradely inserted into the renal pelvis through the affected ureter and was fixed in position to establish indwelling catheterization. Normal saline was instilled by retrograde drip through the ureteral catheter. The patient was changed to the prone position, and the abdomen was elevated. In the research group, the puncture site was located according to bony landmarks determined by simulated surgery combined with ultrasound, whereas in the control group, the puncture site was located using ultrasound guidance combined with the CT image. An 18G puncture needle was passed through the puncture site on the body surface and inserted into the target renal calyx under ultrasound (Philips Healthcare, Eindhoven, The Netherlands) guidance. The puncture was considered successful if urine flowed out through the needle when the needle core had been removed. A safety guidewire was inserted through the puncture needle, the skin and fascia were incised, and the puncture needle was withdrawn. The tract was expanded from 8F to 18–20F using a fascial dilator over the safety guidewire, and a peel-away sheath of corresponding size was inserted to establish an operation channel. A Wolf nephroscope was inserted, and normal saline was instilled continuously to keep the visual field clear. The stones were identified and broken up with a holmium laser, and the fragments were washed out or removed. The need for a second or third channel was assessed during each operation. When no residual stones were found under a nephroscope, a 6F double J-tube was inserted into the ureter for drainage, and a 16F nephrostomy tube was inserted into the percutaneous renal channel for drainage. If the patient's condition was stable after the operation, KUB or CT images were examined on the third day. If no residual stones or residual stone fragments less than 4 mm in diameter were shown on postoperative imaging, it was considered that complete stone removal had been achieved[12]. If many residual stones were revealed on imaging, a second-stage PCNL was arranged. If there were few or no residual stones, the nephrostomy tube was removed and the patient was discharged after two days of observation; the double J-tube was removed via a cystoscope four weeks after the operation. If severe bleeding or infection occurred after the operation, the indwelling nephrostomy tube was left in place until the complications had been controlled.

Observation Indexes and Statistics

Before the operation, the patient's gender, age, and body mass index were recorded, as well as the the operation side and stone volume. After the operation, the stone clearance rate, operation time, number of punctures required for successful establishment of a percutaneous renal channel, number of percutaneous kidney puncture channels, incidence of penetrating injury, and intraoperative blood loss were recorded.

Statistical Analysis

SPSS 23.0 software was used to analyze the data (IBM Corp., Armonk, NY, USA). Measurement data were expressed as mean ± standard deviation ($\bar{x} \pm SD$) and compared using the *t*-test. Count data were expressed as a percentage and compared using the χ^2 test. $p < 0.05$ was considered statistically significant.

Results

Comparison of Patient Characteristics

Control group: There were 40 male and 20 female patients; their age range was 24-70 years, with an average of 46.48 ± 12.86 years. The operation was performed on the left side in 27 patients and on the right side in 33 patients. The range of stone volumes was 5,034-15,703 mm^3, with the average stone volume being 6,515.53 ± 1,889.24 mm^3. The body mass index range was 18.0-24.5 kg/m^2, with an average of 21.83 ± 2.42 kg/m^2.

Research group: There were 32 patients male and 28 female patients; their age range was 21-68 years, with an average of 43.90 ± 13.83 years. The operation was performed on the left side in 31 patients and on the right side in 29 patients. The range of stone volumes was 5,012-12,640 mm^3, with the average stone volume being 6,305.05 ± 989.55 mm^3. The body mass index range was 17.1-28.0 kg/m^2, with an average of 22.28 ±1.75 kg/m^2. The differences in general data between the two groups were not statistically significant ($p > 0.05$ for all). The general characteristics of the patients are detailed in Table I.

Comparison of Operation Outcomes Between Patients

All of the 120 patients with complex renal stones who were enrolled in this study underwent successful one-stage PCNL. In the research group, the stones of 51 patients were completely removed, with a clearance rate of 85% (51/60). In the control group, the stones of 48 patients were completely removed, with a clearance rate of 80% (48/60). The stone clearance rate was higher in the research group than in the control group, but the difference was not statistically significant ($p > 0.05$). The average operation time was 85.57 ± 11.69 (range: 60-121) minutes in the research group and 92.42 ± 15.05 (range: 70-140) minutes in the control group. The operation time was shorter in the research group than in the control group, and the difference was statistically significant ($p < 0.05$). The average number of puncture attempts required for successful puncture was 2.00 ± 0.52 (range: 1-4) in the research group and 3.02 ± 1.38 (range: 1-8) in the control group; thus, significantly fewer punctures were required in the research group than in the control group ($p < 0.05$). The average number of percutaneous kidney puncture channels required for successful completion of the first-stage PCNL was 1.95 ± 0.50 (range: 1-3) in the research group and 2.15 ± 0.58 (range: 1-3) in the control group; thus, fewer channels were required in the research group than in the control group, and the difference was statistically significant ($p < 0.05$). The prevalence of penetrating injury was 0% (0/60) in the research group and 3.3% (2/60) in the control group; thus, there were fewer penetrating injuries in the research group than in the control group, but the difference was not statistically significant ($p > 0.05$). This may be due to the small sample size. The average volume of intraoperative blood loss was 63.78 ± 46.21 (range: 23-313) ml in the research group and 109.80 ± 72.81 (range: 21-504) ml in the control group; thus, blood loss was significantly lower in

Table I. General data of patients.

Indicators		Research group (n = 60)	Control group (n = 60)	t/χ^2	*p*
Gender	Male (%)	32 (53.3)	40 (66.7)	2.220	0.136
	Female (%)	28 (46.7)	20 (33.3)		
Age		43.90 ± 13.83	46.48 ± 12.86	1.060	0.291
The side of the operation	Left kidney (%)	31 (51.7)	27 (45.0)	0.534	0.465
	Right kidney (%)	29 (48.3)	33 (55.0)		
Stone volume (mm^3)		6305.05 ± 989.55	6515.53 ± 1889.24	0.764	0.450
Obesity index (kg/m^2)		22.28 ± 1.75	21.83 ± 2.42	1.167	0.245

the research group than in the control group ($p < 0.05$). The patient with the largest blood loss volume, 504 ml, was in the control group. Despite blood transfusion, this patient required renal arteriography and superselective renal artery embolization to control the bleeding. One patient developed a pleural effusion after the operation and underwent closed thoracic drainage; this patient was also in the control group. No injury to the intestine, liver, spleen or abdominal vessels was found in any patient (Table II).

Discussion

Complex renal stones usually have large volumes, and most of the patients had hydronephrosis as a complication. After importing the data of the CT scan into Mimics19 for processing, it is possible to create 3D reconstructions of the renal parenchyma, the collecting system, and the stones. By analyzing the 3D model, the surgeon gains a better understanding of the size, distribution and spatial structures of the stones and their relationship with the collecting system. On the 3D model, the various tissue structures can be examined under zoom, rotated, hidden or displayed, and different degrees of transparency can be set to allow perspective observation, which is helpful for the comprehensive planning of surgery, facilitating the identification of the target renal calyx and of an appropriate puncture channel. The 3D model is also helpful for removing stones and reducing the incidence of bleeding complications. A simulated puncture can be performed repeatedly, without causing tissue damage, unlike percutaneous renal puncture. After the simulated punctures have been performed in Mimics19, the puncture channels can be examined in axial, sagittal and coronal planes. If it is found that a puncture channel passes through the pleura, intestine, liver, spleen or large blood vessels, or enters the opposite side of the kidney, the simulated puncture channel can be redesigned in simulation, by adjusting its direction and depth, in order to avoid related organ damage during the percutaneous procedure. De la Rosette et al[13] analyzed the complications of 5,803 patients who had undergone PCNL in 96 centers around the world. Their results showed that the overall incidence of penetrating renal injury was 3.4%, and the occurrence of pleural effusion was 1.8%. In the present study, in the control group, the incidence of the above two complications was 3.3% and 1.67%, respectively, and therefore the two are similar; however, in the research group, the incidence of the above two complications was zero. After the simulated puncture had been successfully completed, the data were imported into 3-Matics11 to evaluate the angles between the puncture needle and the axial, coronal and sagittal planes and determine the puncture direction. The distances from skin to renal calyx and from skin to needle tip were measured to determine the puncture depth. In simulated puncture, bony landmarks are used to locate the appropriate puncture point on the body surface by setting the transparency of different tissues and fluoroscopy. In PCNL, the combination of bony landmarks and ultrasound guidance can be used to locate the puncture point on the body surface. The direction and depth of the puncture needle differ slightly between simulated puncture and percutaneous renal puncture, most significantly because of the movement up and down of the kidneys due to respiration. During quiet breathing, the kidneys are in the same position two to four times during each two respiratory cycles: once each at the end-expiratory point and the end-inspiratory point, and four times in other breathing phases. During percutaneous renal puncture, dynamic ultrasound real-time imaging[14] can be used to identify the point in the respiratory cycle when the puncture site on the body surface is in the same position relative to the other tissues as it is on the CT image and therefore in the 3D model. This gives the operator a brief moment

Table II. Comparisons of operation conditions between two groups of patients.

Indicators	Research group (n = 60)	Control group (n = 60)	t/χ^2	p
Stone clearance rate (%)	51 (85)	48 (80)	0.52	0.471
Operation time(min)	85.57 ± 11.69	92.42 ± 15.05	2.78	0.006
Number of punctures required for successful puncture	2 ± 0.52	3.02 ± 1.38	5.33	0
Number of percutaneous kidney puncture channels	1.95 ± 0.50	2.15 ± 0.58	2.03	0.045
The prevalence of renal penetrating injury	0 (0)	2 (3.3)	0.12	0.154
Intraoperative bleeding volume	63.78 ± 46.21	109.80 ± 72.81	4.13	0

to insert the needle in the same direction and to the same depth as were determined during the simulation. If the puncture is not ideal, the puncture needle is withdrawn and a further attempt is made to insert the needle in a subsequent respiratory cycle.

Simulated puncture and measurement are helpful to simplify the operation of percutaneous renal puncture and reduce the operation time. In the case shown in Figure 1g, if the puncture depth was less than 78.64 mm, the needle could be inserted confidently, without fear of damaging other structures. This removed the need to proceed gradually, as traditionally recommended for puncture procedures, repeatedly pulling out the needle core to look for urine outflow. If the puncture depth reached 102.20 mm, the operator would know that the needle tip was close to the opposite side of the collecting system and that the needle should not be advanced further as it would pass through the opposite side of the kidney, causing a penetrating injury and increasing the risk of bleeding and leakage of urine.

Conclusions

Simulated puncture can be used to make a detailed operation plan for PCNL. In this study, the number of punctures required for successful establishment of a percutaneous renal channel was significantly lower in the research group than in the control group. In addition, the number of percutaneous kidney puncture channels required for performing successful PCNL was lower in the research group than in the control group. Simulated puncture and measurement allowed a better understanding of the direction and depth of puncture in the research group. Penetrating renal injury did not occur in any patients in the research group, but did occur in two patients in the control group; however, the difference was not statistically significant. This may be due to the small sample size. Most researchers have found that blood loss increases as the number of puncture channels increases[15,16]. The research group had fewer punctures, fewer percutaneous kidney puncture channels and less kidney damage, and therefore lower volumes of blood loss, than the control group. A smaller volume of bleeding and a clear visual field during the operation help to improve the efficiency of lithotripsy, reduce the injury to the renal pelvis mucosa, and reduce the operation time.

Conflict of Interest
The Authors declare that they have no conflict of interests.

Ethics Approval
I confirm that I have read the Editorial Policy pages. This study was conducted with approval from the Ethics Committee of The People's Hospital of Jiangxi Province (9012). This study was conducted in accordance with the Declaration of Helsinki

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