RECENT ADVANCES IN PERCUTANEOUS NEPHROLITHOTOMY

***Erem Kaan Basok,[1] Serhat Donmezer,[2] Ali Erol[3]**

1. Associate Professor, Department of Urology, Bahcesehir University, School of Medicine, Istanbul, Turkey
2. MD, Department of Urology, Bahcesehir University, School of Medicine, Istanbul, Turkey
3. Professor, Department of Urology, Bahcesehir University, School of Medicine, Istanbul, Turkey
**Correspondence to erem.basok@gmail.com*

Disclosure: No potential conflict of interest.
Received: 16.01.14 **Accepted:** 03.03.14
Citation: EMJ Urol. 2014;1:83-89.

ABSTRACT

The continuous innovations in technology, instrumentations, and techniques allow urologists to perform percutaneous nephrolithotomy (PCNL) with increasing efficacy. Although recent advances have facilitated the procedure, some steps are still challenging. A thorough review of the recent urologic literature was performed to identify these improvements in PCNL technique. The newer developments mainly focused on multimodal imaging techniques, miniaturisation of instruments, tracking and navigation systems during access to the stone, and robotic systems. Further studies are necessary to better define the benefits of these new fruitful developments which remain an active research field.

Keywords: PCNL, imaging, access, microperc, robotic, augmented reality, navigation, and tracking.

INTRODUCTION

Percutaneous nephrolithotomy (PCNL) is a well set, well known, and widely accepted minimally invasive surgical procedure for stone removal within the urological procedures. As with many minimally invasive procedures, the main purpose of PCNL is the complete removal of the renal calculi, reducing mortality and morbidity without deteriorating quality of life. However, this technique is directly competing with other minimally invasive techniques such as retrograde intrarenal surgery (RIRS) and laparoscopic procedures. The indications for RIRS have expanded, and it became a viable alternative to PCNL in select cases. However, PCNL is still the gold standard for high-volume renal calculi (>2 cm), and data demonstrating utilisation of RIRS for >1 cm renal stones are still underwhelming. Nevertheless, excessive efforts have been made to reduce the morbidity and improve the efficiency of PCNL so as to make it more competitive.

In accordance with the developing technology, PCNL requires better instruments for complete stone removal, more precise stone targeting, and access to the kidney and relevant calices. The newer developments have mainly focused on imaging techniques, as well as the fusion of multiple imaging procedures, tracking and navigation systems during access to the stone, miniaturisation of the instruments, and robotic systems.[1-7] Furthermore, the debate continues over the use of the prone or supine position, tube or tubeless PCNL, and the efficiency of 'microperc'. Herein, the recent advances, primarily in imaging, instrumentation, and access techniques related to PCNL, are reviewed.

A recent internet survey among active Endourological Society members has shown that the majority of urologists would choose prone position for PCNL (prone: 86%, supine: 10%, and lateral decubitus: 4%). Additionally, more than 76% of respondents prefer a nephrostomy tube post-operatively, rather than a tubeless approach (2%).[8]

Computed tomography (CT) is mandatory for preoperative planning and appropriate percutaneous access. It shows the anatomy of kidney calices and the relation of the stone to the pelvicalyceal system, the kidney position, and its relation to other abdominal structures.[1,4,9] Angiographic CT can also be used for detailed images of blood vessels and calyceal anatomy.[1] Technological advances have also enabled the acquisition of three-dimensional (3D) images through ultrasound (US), providing volumetric measurements and 360-degree analyses of anatomic structures.[10]

After using the benefits of cone beam CT (CBCT) in neurosurgical operations, the application has been extended to percutaneous surgery. CBCT is a novel imaging modality that combines the versatility of conventional C-arm with the functionality of cross-sectional imaging to provide high-resolution, 3D, CT-like images.[9] As a result of a recent study, the authors concluded that CBCT could help for better percutaneous access using the advantages of improved imaging, which allows surgeons to have similar real-time access via high quality CT images.[11] The intraoperative availability of images may reduce the need for postoperative imaging and subsequent adjunctive procedures for clearance of residual fragments.

Multimodal Imaging

Several studies presented the combination of different imaging techniques. Among these, Li et al.[3] combined preoperative magnetic resonance imaging (MRI) with augmented intraoperative USG images, and found valuable results due to the additional advantages of high resolution, multi-planar, and 3D images. The Interactive Closest Points algorithm was used as a rigid registry process through the manual selection of pairs of points in both images from the cranial pole, caudal pole, and kidney hilum. A respiratory gating method was also used to minimise the impact of kidney deformation by using US to obtain only images at the same stages of the respiration cycles.

In another study, an automatic rigid registration method was used to combine CT and US images. Image contours were highlighted by using processing algorithms to improve cross-correlation of image intensity.[12] Wein et al.[13] presented a fully automatic image-based algorithm for registering 3D freehand USG sweeps with CT images. Target distance error ranged between 3.5-8.1 mm in these studies.[4]

Imaging is not only necessary to plan pelvicalyceal access, but also to evaluate treatment success and complications after PCNL. Previous studies aimed to identify possible preoperative radiological findings that predict prognostic factors. Several authors mentioned the necessity of reliable prediction models.[14] Thomas et al.[15] developed the Guy's stone score to grade PCNL complexity based on radiological findings. Lately staghorn morphometry, S.T.O.N.E. nephrolithometry, and a nephrolithometric nomogram have been developed to estimate PCNL success prior to surgery.

Staghorn Morphometry

Staghorn calculi sometimes require several renal access procedures to obtain complete clearance. Staghorn morphometry is a new prognostic tool to predict the position of access and stages for PCNL, which requires 3D CT urography assessment with volume-rendering software. Recently, a new classification of staghorn stones into three types has been proposed based on the volume of distribution of stone and the surface area. Type 1 staghorn stones have a total stone volume of <5,000 mm^3 with <5% of unfavourable calyceal stone percentile volume, whereas type 3 staghorn stones have a total volume of >20,000 mm^3 with >10% of unfavourable calyceal stone percentile volume. The type 2 staghorn stone is in between. Based on statistical models, they found that a type 1 staghorn stone would require one access in one stage, type 2 stones would require one access in more than one stage, or multiple accesses in one stage, and type 3 stones would require multiple accesses and stages.[9,16]

Nephrolithometric Nomogram

A nomogram was constituted to predict the stone-free rate using preoperative parameters, including case volume, prior treatment, stone burden and location, staghorn stones, and number of stones.[17] A high total score was significant for a higher chance of stone-free rate, while low score had a lower chance of stone-free rate. Stone burden was the best predictor of treatment outcome. In addition, nephrolithometric nomogram showed consistent but lower performance in the lower stone-free rate ranges.

The ROC AUC for predictions based on this nomogram was 0.76.

S.T.O.N.E. Nephrolithometry

In this scoring method, five variables from preoperative non-contrast enhanced CT were included; stone size, tract length, obstruction, number of involved calices, and essence or stone density. Stone-free patients had statistically significant lower scores than the patients with residual stones (p=0.002). Additionally, the score was correlated with the estimated blood loss (p=0.005), operative time (p=0.001), and length of hospital stay (p=0.001).[18]

PATIENT POSITIONING

The prone position in PCNL is frequently associated with discomfort, especially for obese patients, severe musculoskeletal deformities, and cardiovascular and respiratory problems.[19] However, it has the advantages of reduced risk of colonic injury without limitation of instrument movement and multiple posterior accesses. Recently, several reports have described various alternative positions such as the Valdivia, modified Valdivia, a flank position, prone split-leg position, and a completely supine position.[20-24]

According to Di Grazia and La Rosa,[25] prone position with split-leg is advantageous over supine position. The split-leg technique provides some benefits, especially in challenging cases, in cases with anatomical abnormalities and in multi-tract accesses. Cracco et al.[26] emphasised that the Galdakao-modified supine Valdivia position is safe, effective, and provides more advantages than the others. An easy puncture of the kidney, a reduced risk of colonic injury, and simultaneous antero-retrograde approach to the renal cavities without any requirements of intraoperative repositioning are just a few of the advantages of this position.

The main advantages of supine position are as follows: there is no need to change the position of the patient, simultaneous ureteroscopies can be performed, there is better airway control for the anaesthetist, and it facilitates easier evacuation of fragmented stones.[21] A randomised comparative study of the prone, supine, and flank positions in 150 patients showed that the supine and flank positions were as efficient as the prone position with experienced hands. They also concluded that the preference of the surgeon and proper case selection are the main factors for successful PCNL.[24] Although the supine position has been described as more attractive, there is still an argument for upper pole calyceal access, due to its medial, posterior, and concealed position in the rib cage. Recent meta-analysis showed that PCNL in the supine position was associated with a significantly shorter operative time, but lower stone-free rate than PCNL in the prone position. There was no difference between the two positions regarding hospital stay and complication rate.[27,28]

INSTRUMENTS

The evolution of devices from their prototypes has increased the instrumentation options for urologists. Improved lithotripsy devices (Gyrus ACMI CyberWand®, Swiss LithoClast Select with Vario® and LithoPUMP®, Cook LMA StoneBreaker®), digital nephroscopes, stone retrieval and occlusion devices (PercSys Accordion®, Cook Perc N-Circle®, etc.), and haemostatic or adhesive agents for tubeless procedure can be valuable tools for successful PCNL.[29,30] New lithotripsy devices, including a combination of ultrasonic-pneumatic device, dual ultrasonic lithotripter, and pneumatic stone breaker, have the potential to enhance the efficiency of stone fragmentation.[31]

Micro PCNL (Microperc)

Endoscopic access technique has been introduced in recent years using micro-optics, which are inserted either within the needle or the working sheath. 'Microperc' is a recently described technique in which percutaneous renal access and lithotripsy are performed in a single step using a 16 gauge micro-puncture needle. The main aim of this innovation is to reduce the tract size with the intention of less morbidity. Bader et al.[32] reported a modified needle of 1.6 mm in diameter that integrates 0.9 and 0.6 mm micro-optical system. The authors concluded that the micro-optical needle appears to be helpful for confirming percutaneous access before dilatation of the tract, thus decreasing tract size, need for imaging, and multiple accesses. Desai et al.[33] further modified this concept and completed PCNL through the 'all seeing needle'. Ten patients, two of whom were children, and each having an ectopic pelvic kidney, chronic kidney disease, and obesity, were enrolled to this study. The mean stone size was 14.3 mm.

Nine patients were stone-free at the end of 1 month. A conversion to miniperc was needed due to intraoperative bleeding and obscured vision in one patient. 'Mini-microperc' is a new technical modification in which an 8 Fr sheath is used to allow insertion of ultrasonic or pneumatic lithoclast probe with suction.[34]

The advantage of the microperc is that it is a single-step renal access procedure, resulting in a shorter access time and fewer puncture attempts. The main disadvantage is the long duration of stone fragmentation. Therefore microperc is only optional for small stones less than 20 mm in size. The available evidence indicates that microperc is safe and efficient in small renal stones, especially in paediatric patients and ectopic kidneys. The high stone-free rate makes it a viable alternative to RIRS.[4,9]

ACCESS

Endoscopically Guided PCNL

Grasso et al.[35] reported first endoscopy-assisted percutaneous renal access as an alternative technique for successful access in a few patients in whom other methods failed. Later, the technique was developed as a primary access method by insertion of the needle into the collecting system under the guidance of both fluoroscopy and direct vision of flexible ureteroscope. The guidewire can be passed into the access sheath, and easily delivered via the urethral end of the access sheath. The direct visual confirmation has the advantage of a successful access in a short time with no requirement of multiple attempts. The original technique and its subsequent modifications were reported to have a success rate of 89–100%.[36-38]

Robotics

Most urological procedures are amenable for robot-assisted surgery. Different types of robotic systems are under development. These include image-guided robots that, in addition to the direct visual feedback, use medical images for guiding the intervention.[4] Recently, one centre presented three different types of medical robots. The first system (PAKY-RCM) consists of an orientation module between a needle driver and a robotic 7-degree free arm, enabling the positioning of the needle and completion of its insertion using rotational movements. Additionally, the system regulates the strength during the access. The surgeon controls all movements of the robot via a joystick under the guidance of fluoroscopic images.[6] The AcuBot robot includes previous robotic modules, but adds a bridge-like structure over the table, and a linear pre-positioning stage. This attaches to CT or fluoroscopy table of the imager. The mounted needle driver in the module is supported by a passive arm, driven by the Cartesian stage. It has 6 degrees of freedom configured for decoupled positioning, orientation, and instrument insertion.[4,6,39] The newest robot (MrBot) is introduced as a fully-actuated MRI robot for image-guided access for percutaneous interventions. The robot is customised for needle insertion and designed to be compatible with the highest field strength. It is constructed with a pneumatic stepper motor using nonmagnetic and dielectric materials. This system, with 6 degrees of freedom, has a great potential for PCNL.[4,6,40]

Lately, advances of US-guided robotic systems have been reported. The typical approach resorts to a surgical needle attached to a robotic arm that is driven automatically or controlled by the surgeon in 3D or 2D imaging volume.[41] A locator apparatus that stabilises the needle during the access was tested in a study. The authors achieved a mean access time of 225 seconds, which is much quicker than the average access time reported for traditional technique (approximately 12 minutes).[42]

Although medical robotic systems have certain benefits, supporting technology is still struggling to overcome some important problems in difficult initial setups, expensive costs, mechanical problems, absence of tactile feedback, and not fully developed motion tracking systems.[4]

Tracking and Surgery Navigation

Navigation software and augmented reality systems have recently been introduced as computer-assisted navigation systems combining imaging and tracking systems. Most of them work by obtaining the target anatomic area from preoperative data, using image segmentation algorithms or computer graphics (direct volume or surface rendering). Then, the image processed data are superimposed and registered onto a real-time intraoperative video (augmented reality) or static preoperative volume data (navigation software). The surgical tools are commonly updated using a motion tracking system.[4,43]

The use of augmented reality during surgery is challenging because of tissue deformation and respiratory movements. Therefore, many improvements are still needed for both mathematical algorithms and equipment, especially for motion tracking systems.[4,44]

Huber et al.[45] tested a navigated renal access in an *ex vivo* model. The surgical needle is guided to the renal calix according to the information retrieved by a catheter that integrates electromagnetic motion tracking sensors. The reported access time was 14 seconds with a precision of 1.7 mm. Rodrigues at al.[46] evaluated the efficiency of a new real-time electromagnetic tracking system for kidney puncture in pigs. A catheter with an electromagnetic tracking sensor was placed by ureterorenoscopy into the desired puncture site. A tracked needle with a similar electromagnetic tracking sensor was subsequently navigated into the sensor in the catheter. They described the method as highly accurate, simple, and quick.

Recently, Rassweiler et al.[47] reported iPad-assisted percutaneous access. All anatomic structures were identified and marked in preoperative CT images. Augmented virtual reality of preoperative CT 3D images could display all anatomical details of the kidney. There was no limitation of USG such as shadows caused by ribs, and the advantage of freehand needle placement without holding the US probe. The iPad was used as a camera to take a picture of the operating field. Then compressed data were transferred to a server located in a control room via Wi-Fi. The server operated the algorithm to identify the position and orientation of the navigation, and to overlay it accordingly with preoperative marked CT images, which were sent back to the iPad. The exact overlays of optical markers, which must always be visible on the iPad screen, were rigidly registered for motion tracking system.[9,47]

TUBELESS PCNL

Recently, most notably modification has been a tubeless PCNL alternative to nephrostomy tube. It appears to decrease postoperative discomfort and shorten hospital stay, without increasing complication rate in selected cases.[48] Future studies are needed to evaluate the results of tubeless PCNL in paediatric and geriatric patients, complicated cases by multiple access tracts, renal anomalies, and patients with previous renal surgery.[49-51] Although it has been used for a wide range of indications, currently, there are no sufficient data supporting the superiority of tubeless PCNL over conventional technique.[52] Therefore, tubeless PCNL can be feasible in selected patients. In order to improve outcomes of tubeless PCNL, application of haemostatic agents along the percutaneous access tract was introduced. Lipkin et al.[53] researched porcine models to depict the efficacy of haemostatic agents by using fibrin sealant Evicel and haemostatic gelatin matrix (HGM). They have found HGM more preferable than fibrin sealant, because the tract closed earlier than HGM, 10-14 days in fibrin sealant versus 30 days in HGM, post-operatively. Both forms of haemostatic agents used today, either glue or HGM, have been demonstrated to be safe and effective for tubeless procedure.[54] In a prospective cohort study published in 2013, 43 patients were randomised into two groups, with or without using autologous single donor fibrin glue after tubeless PCNL. The use of fibrin glue was found safe, though no significant role in improving results or decreasing complications was seen.[55] Gudeman et al.[56] reported their study on tubeless PCNL using fibrin sealant with 107 patients showing favourable stone-free rates, shorter hospital stays, and lower complication rates without bleeding. However, further studies are warranted with regards to its safety and histological effects on the renal tissue.[57]

Various techniques were introduced to control bleeding during or post-operative PCNL,[58] such as haemostatic sandwich technique, which was described as a successful treatment for bleeding after PCNL by Millard, and an anchoring system, which was found to be a potentially useful and safe method by Tokue et al.[59]

CONCLUSION

Urologists need to make significant efforts to improve the PCNL procedure, with the aim of further increasing stone-free outcomes and reducing morbidity. Liberal use of flexible ureteroscopy in supine position can reduce the need for multiple percutaneous accesses, but supine position alone has not demonstrated a benefit over traditional prone PCNL. A trend toward the use of tubeless PCNL improves quality of life in selected cases, but further studies are needed. The most important advancement in PCNL is the application of medical imaging modalities, smaller surgical instruments like 'microperc', robotics, and augmented reality combined with navigation and motion tracking systems. Despite all of these new developments, it remains an active and challenging research field. Future developments should focus on real-time methods supported by radiation-free imaging techniques.

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