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The current status of percutaneous nephrolithotomy in the management of kidney stones

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Large kidney stones (>2 cm) is a common problem affecting all population groups across the globe and may result in significant complications if left untreated. The treatment for this condition has evolved dramatically over the past seven decades with the advent of minimally invasive treatment options. At the forefront of this paradigm shift is the development of percutaneous nephrolithotomy (PCNL). This has resulted in shorter hospital stays, reduced postoperative pain, and quicker convalescence compared with the previous criterion standard of open stone surgery. PCNL is only one of the many minimally invasive treatment options available for this condition, but remains the most efficient in all patient groups. However, it continues to be one of the more challenging urological procedures, which if not performed well, can be associated with significant complications. Refinements in techniques, improvement in equipment and increasing clinical experience have led to improved stone free rates being achieved with acceptably low patient morbidity. In this article, authors review the technical aspects, outcomes, and current role of PCNL in the treatment of large kidney stones.

Key words: **Nephrostomy, percutaneous - Kidney calculi - Surgical procedures, minimally invasive.**

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History and development

Percutaneous nephrolithotomy (PCNL) in the modern era has been the culmination of nearly seventy years of development. The foundations were laid in 1941 when Rupel and Brown first reported that renal stones could be removed through an operatively established nephrostomy tract.[1] They performed the first nephroscopy when a rigid cystoscope was passed through a nephrostomy tract and residual stones removed following open surgery. It was not until 1955 when Goodwin *et al.* created the first percutaneous tract by inserting a nephrostomy tube into an infected hydronephrotic kidney.[2] This led to the realization that a percutaneous tract could be used as access into the kidney. In 1976, Fernström and Johansson described a new extraction technique when they removed kidney stones through a percutaneous nephrostomy under radiological control.[3] Subsequently in 1977, Kurth *et al.* provided a means for removing large stones through a nephrostomy tract when they described the use of an ultrasonic lithotripsy device during PCNL to fragment a staghorn calculus.[4]

In the 1980s, PCNL underwent rapid evolution following an overall paradigm shift of stone treatment towards a more minimally invasive approach. The percutaneous technique for the creation of a nephrostomy tract was improved upon and facilitated the safe introduction of endourologic procedures through this route. Initially, conventional rigid cystoscopes were used but these were subsequently replaced with purpose built offset nephroscopes featuring a large caliber straight working channel.

The technique of PCNL gained popularity in Europe through the pioneering achievements of Alken *et al.*[5] in Germany, Marberger *et al.*[6] in Austria, and in the United Kingdom by Wickham and Kellet [7] around similar times. Subsequently, the technique gained acceptance in the United States following further development by Segura's group [8] at the Mayo Clinic, along with Clayman *et al.* at the University of Minnesota.[9] PCNL was initially reserved only for patients who were poor candidates for open surgery but with rapid developments of purpose built equipment and ancillary tools, PCNL has now become the treatment of choice for large kidney stones.[10]

Indications

Multiple factors are taken into consideration when deciding upon PCNL. These are divided into: stone, kidney, and patient factors. Individually, they each play an important role in determining the optimal approach that will render the patient stone free in the most efficacious manner.

Stone characteristics

Stone size remains important because larger stones are more efficiently treated percutaneously relative to other minimally invasive modalities. In a study comparing extracorporeal shock wave lithotripsy (SWL) and PCNL, Lingeman *et al.* showed an increased incidence of residual fragments and higher retreatment rates following SWL as stone size increased.[11] When treated with SWL alone, the stone free rate decreased from 77% for stones ≤1 cm to 29% for stones >3 cm. The number of ancillary procedures also increased from 12% to 46%, respectively. Importantly, in the only randomized, prospective trial comparing PCNL to SWL for staghorn calculi, Meretyk *et al.* showed that stone free rates for PCNL based therapy was more than three times better when compared to SWL monotherapy (74% *vs* 22%. respectively, P=0.0005).[12]

Stone composition, if known prior to treatment, should be taken into consideration in deciding between various treatment options. Stones such as cystine, calcium oxalate monohydrate, and brushite are known to fragment poorly to SWL [13] and may best be treated with either retrograde intrarenal pyeloscopic surgery or PCNL. Computed tomography (CT) has been reported to be useful in determining the stone's composition according to its Hounsfeld unit (HU) value.[14] *In vitro* studies show attenuation levels for uric acid and struvite stones to be consistently below 1 000 HU, whereas calcium oxalate and hydroxyapatite usually exceeded 1 000 HU.[15, 16] Joseph *et al.* suggested that PCNL be used more judiciously for stones with attenuation levels exceeding 1 000 HU due to poor stone clearance rates using SWL.[17] Similarly, Gupta *et al.* suggested an even lower cutoff of 750 HU above which PCNL would be a better alternative.[18] Based on these studies, better results may be achieved using PCNL for stones having high HU values comparing to SWL.

Kidney factors

Kidneys with complex or anomalous anatomy such as ureteropelvic junction obstruction, calyceal diverticulum, and benign ureteral strictures can impair renal drainage and hinder stone passage. When suitable, PCNL offers potentially better stone free rates and allows simultaneous correction of the underlying problem. Other congenital malformations such as horseshoe, malrotated, or ectopically positioned kidneys may be best treated initially by PCNL alone, or in combination with other modalities.

Kidneys containing stones in the lower

pole have always been the subject of contention as to which approach represents the best treatment option. The factors in lower pole anatomy described by Sampaio *et al.* consisting of an infundibulopelvic angle less than 90°, infundibular width less than 4 mm, and infundibular length more than 3 cm are considered unfavorable for drainage of stone fragments in the lower pole.[19] Elbahnasy *et al.* also presented similar findings although the manner of measuring the infundibulopelvic angle and critical value for infundibular width was measured differently.[20]

In 2001, a Lower Pole Study Group was convened in the United States to determine the optimal treatment of lower pole stones.[21] They performed a multicenter, prospective, randomized trial investigating the treatment of lower pole stones with PCNL or SWL. Results showed that stone free rates for lower pole PCNL treated patients was 95% compared with 37% for lower pole stones treated with SWL (P<0.001). Furthermore, when this was stratified to stone size, the stone free rates for PCNL was 100% for stones less than 10 mm and 91% for stones greater than 10 mm. In contrast, the stone free rate for SWL decreased from 63% for stones less than 10 mm, to 21% for stones between 10 and 20 mm and to 14% for stones larger than 21 mm. They concluded that stone free rates for PCNL were not dependent on stone burden and remains a more efficacious treatment for lower pole stones greater than 10 mm.

More recently, ureteroscopy (URS) has become an acceptable alternative to SWL and PCNL for lower pole stones. In 2005, a second phase of the Lower Pole Study Group was initiated to compare URS and SWL for the treatment of 1 cm or less lower pole stone.[22] The study postulated that URS would improve SWL outcomes without having significant patient morbidity. Although the URS group had better outcomes, the study was underpowered and did not show any statistically significant differences in stone free rates between the two groups. In fact, SWL showed greater patient acceptance and shorter convalescence. Consequently, URS was not recommended as an alternative to SWL for stones 1 cm or less in the lower pole.

TABLE I.—*Guidelines of the European Association of Urology.*[27-29]

Indications for PCNL
— Large stone burden >2 cm or 1.5 cm for lower calyceal stones
— Staghorn stones
— Stones that are difficult to disintegrate by ESWL (calcium-oxalate monohydrate, brushite, cystine)
— Stones refractory to ESWL or ureteroscopy
— Urinary tract obstructions that need simultaneous correction (*e.g.* UPJ obstruction)
— Malformations with reduced probability of fragment passage after ESWL (*e.g.* horseshoe or dystrophic kidneys, calyceal diverticula)
— Obesity

UPJ: urinary pelvic junction; ESWL: extracorporeal shock wave lithotripsy.

Patient characteristics

PCNL may be a better option for patients with stones who are morbidly obese, or who have musculoskeletal defects such as scoliosis and spina bifida when compared to other stone treatment modalities. Morbidly obese patients with renal stones present a therapeutic challenge because they may exceed the weight limits for SWL machines.[23] For those who do not exceed the weight limit, Pareek *et al.* found in a series of lower pole stone patients that a skin-to-stone distance (SSD) greater than 10 cm as determined on axial CT images was predictive of failure using SWL.[24] Additionally, even though body mass index (BMI) has been shown to be an independent predictor of SWL success, this study showed SSD to be a more reliable predictor than either BMI or HU measurements alone.[24] For obese patients (BMI>30) with large stone burden, treatment with PCNL may require longer instruments, but stone-free rates of up to 83% to 88% were achieved without any significant differences in morbidity compared with non-obese patients.[25, 26]

Recommendations of the EAU Guidelines Panel

The accepted indications for PCNL according to the European Urology Association guidelines panel are summarized in Table I.[27-29]

Preoperative evaluation

Patient selection and preoperative planning are important to achieve a successful outcome in PCNL. The absolute contraindications are uncorrected coagulopathy, untreated urinary tract infection (UTI), and pyonephrosis.[30] The generally accepted recommendations include actively treating UTI since patients with infected urine from the renal pelvis or infected renal stones have been shown to have a fourfold greater risk of developing urosepsis.[23] This may involve the use of prophylactic antibiotics as it has been reported to reduce the risk of infectious complications even in cases of sterile urine and noninfectious calculi.[31] Mariappan *et al.* found that a one week course of ciprofloxacin prior to PCNL significantly reduced upper urinary tract infection and urosepsis.[32] They also extended the indications to patients with stones greater than 2 cm or kidneys with associated hydronephrosis.[33] If purulent urine is found at the time of puncture, PCNL should be postponed and a nephrostomy tube inserted to avoid the risk of urosepsis.[30]

Preoperative evaluation also includes a complete blood count, coagulation profile, blood sugar determination, blood group and screen, and anesthetic review if warranted. To minimize the risk of bleeding, correctable hematological conditions should be undertaken and treated (such as withholding antiplatelet agents in conjunction with the patient's primary care physician). Kukreja *et al.* found that diabetes was one of several risk factors associated with increased blood loss during PCNL.[34] Turna *et al.* also had similar findings and suggested that arteriosclerosis with thickened basement membranes in diabetics may increase the risk for bleeding.[34, 35] For this reason, strict control and preparation of patients with diabetes is recommended prior to surgery.

Preoperative planning

Preoperative planning is essential in order to identify the position and number of stones, assess the intrarenal collecting system architecture, and to evaluate the relationship of the kidney and its surrounding organs.[36] Four modalities are in common use to image renal stones. They are plain radiograph (KUB), IVU, renal ultrasonography, and CT scan.

KUB X-ray

KUB X-ray is useful in determining if the stone is radio-opaque, which may then guide further therapy. Most calcium containing stones are visible on KUB provided they are sufficiently large, not obscured by overlying fecal matter, and not overlying any bony structures. Although KUB has the advantage of being rapidly acquired, readily available and inexpensive, it has a reported low sensitivity of 58% and low specificity of 69% for detecting kidney stones.[37] Its use in preoperative planning is limited due to its inability to delineate the kidney, the collecting system, and surrounding organs.[38]

Intravenous urogram

IVU in the past has been the standard imaging modality used in uroradiology but it is slowly becoming obsolete. It still remains valuable for the preoperative planning and evaluation of kidney stones due to its ability to demonstrate fine detail in the collecting system anatomy of the kidney.[39-41] A disadvantage is that it does not provide information on 3-dimensional relationships of the stone to the kidney, or to adjacent visceral organs. An example where this knowledge could be useful preoperatively would be in treating stones situated in an anterior calyceal diverticulum, where alternative options in treatment may be better utilized.

CT scan

CT has become the gold standard in the diagnosis and evaluation of urolithiasis.[42] Numerous studies have shown CT to be superior to IVU for evaluating patients with flank pain.[43-47] Studies have found the sensitivity and specificity of CT to range from 98-100% across all clinical scenarios [48] including in the pediatric setting where CT detects 96 to 100% of stones.[49]

Aside from being used for the diagnosis of renal stones, CT delineates the extent, orientation, and location of the stones within the kidney, which can facilitate tract selection for PCNL. It also provides detailed information on the relationship of the collecting system to adjacent organs such as the colon, liver, or spleen thereby helping the surgeon avoid injury to these structures. In addition, the proximity of an upper pole calyx to the pleural space can be ascertained by CT, and intrathoracic complications anticipated or avoided altogether when doing PCNL if the tract is carefully planned beforehand.[38]

Recently, CT urography has benefited from enhancements in newer technologies, and the development of sophisticated three-dimensional CT reconstruction software. This has led to the creation of detailed three-dimensional CT images of the renal collecting system, thereby improving preoperative planning.[50, 51] This allows accurate identification of the target calyx for safe puncture, along with the relationship to adjacent viscera to avoid complications. With three-dimensional reconstruction images, the kidney can be rotated on its axes to identify anterior and posterior calyces to provide for accurate tract placement. This information can be juxtaposed in the operating room by thoughtful evaluation of the pyelogram or ultrasound (US) images at the time of puncture.

Technique of PCNL

Many techniques have been described for PCNL, including having the patient either prone, supine or a modification of the two. A detailed description of our technique for PCNL has been described elsewhere.[52] Obtaining optimal access is the key to achieving efficient stone clearance with minimal morbidity and requiring fewer ancillary procedures.

Knowledge of the configuration of the pyelo-calyceal system, the renal blood supply as it relates to the pyelo-calyceal system and its variations are a prerequisite for successful PCNL outcome. Calyceal studies using 3-dimensional reconstructive CT by Al-Qahtani *et al.* show that the upper pole is drained by a single infundibulum in 100% of cases, the middle calyces drained by two infundibuli in 89% of cases, and the lower pole drained by either a single infundibulum (36%) or two infundibuli (64%).[53] This has previously been corroborated by Sampaio's classic study on endocast models of the human renal collecting system.[19] Therefore, when treating inferior pole stones, the inferior calyceal system can have two distinct systems and entry into one calyx may not allow access to the other lower pole calyx if required. Awareness and having a careful considered approach will help avoid this situation.

With patients in the prone position during puncture, the ideal access is one where the needle enters a posterior calyx at the fornix, traversing the smallest amount of renal parenchyma and minimizing injury to larger renal vessels.[54] In contrast, direct puncture into the anterior calyx will traverse more renal parenchyma and renders further access into the collecting system difficult without excessive tract angulation, and result in more bleeding.

When using fluoroscopy in prone PCNL, access into the desired calyx is best achieved using a "bull's eye" technique as it allows complete control and direction of the needle, and subsequent tract placement. Initially the image intensifier C-arm is in the vertical or zero degree position.[52] A slow and careful retrograde pyelogram with dilute contrast is performed to opacify the collecting system. The posterior calyces are identified by recognizing these calyces fill later and the contrast is seen as less dense. Alternatively, with the introduction of 10 cc of air using a syringe, these calyces preferentially outline with an air interface. Once the posterior calyx of interest has been identified, the image intensifier is rotated 20° to 30° towards the surgeon in the axial plane. This allows entry near Brodel's line which is relatively avascular, due to the arterial network being end-arteries in this region. A 5-10° tilt in the caudal direction for lower pole access, or cranial direction for upper pole access respectively, is added to allow for entry into the collecting system in the same direction as the

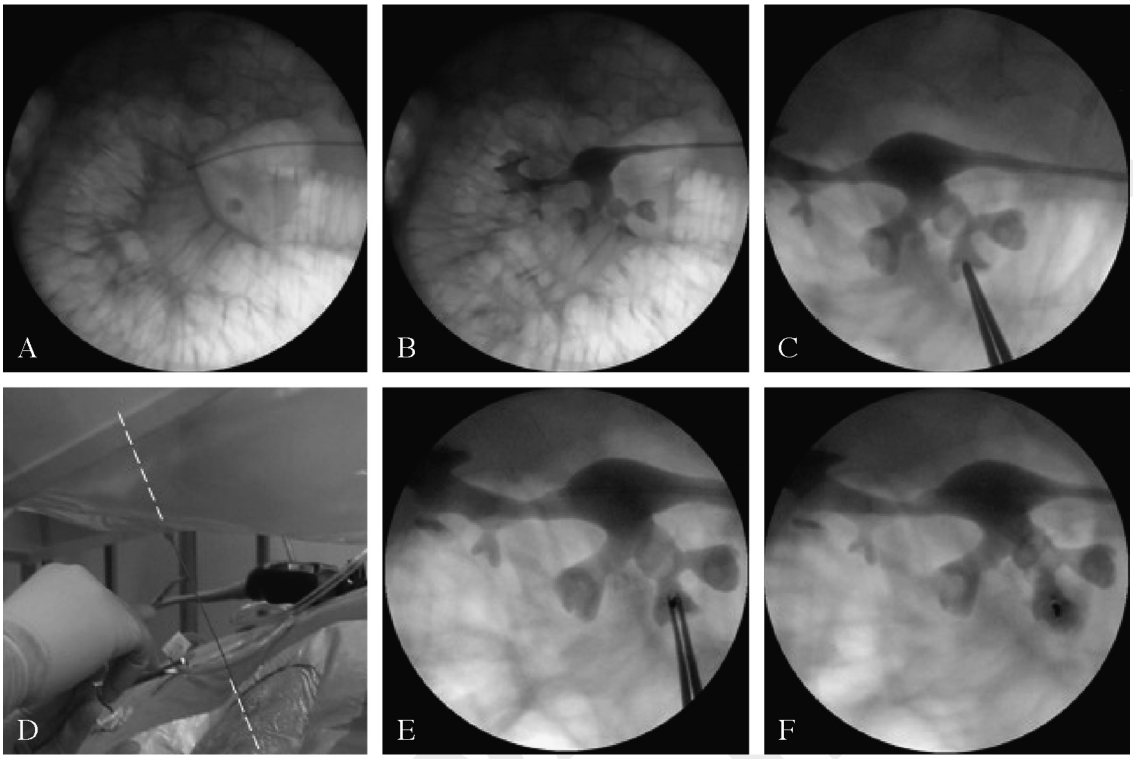

Figure 1.—The "bull's eye" effect. A) Start of PCNL. Stone at inferior pole with ureteric catheter at renal pelvis; B) retrograde pyelogram; C) tip of hemostat overlying target calyx; D) with C arm rotated 300 towards surgeon, "bull's eye" obtained when axis of fluoroscopy (dotted lines) is in direct alignment with needle and hub; E) fluoroscopic image of "bull's eye" effect during needle insertion; F) needle overlying target calyx and into renal parenchyma.

infundibular axis. This potentially causes less torque of the kidney and facilitates a near bloodless tract. The tip of a hemostat is used to mark the position on the skin overlying the selected calyx and a diamond tipped needle introduced through this point. The needle is advanced under fluoroscopic guidance using the hemostat clip as a holder, timing insertion when the patient is in full expiration and in the same trajectory as the C arm position of the fluoroscopy unit providing a "bull's eye" effect (Figure 1). This effect is seen when the hub of the needle is in direct alignment with the needle, the calyx of interest and the axis of the C-arm. Needle advancement is done in one smooth motion and is carried on until it just enters into the renal parenchyma, which is denoted by needle movement during respiration. The C-arm of the fluoroscopy unit is then tilted away from the vertical by 10° to provide depth perception (Figure 2). The surgeon will now see the needle in profile and the target calyx in front of it. The tip of the needle is then advanced along the same trajectory until it just penetrates the calyx. The stylet is removed and entry into the collecting system is achieved using an angled hydrophilic tipped guidewire.

The safest route for accessing the collecting system is directly into the fornix of a calyx and not the infundibulum, thereby avoiding the larger blood vessels that are adjacent to the infundibulum.[55] Punctures into the collecting system that are too medial have a higher risk of injury to segmental and interlobar branches of the renal artery. This has been supported by studies from Sampaio *et al.* which showed that 67% of upper pole infundibular punctures and 13% of lower pole infundibular punctures respectively had arterial injuries, whilst no arterial injury was detected when the puncture was made

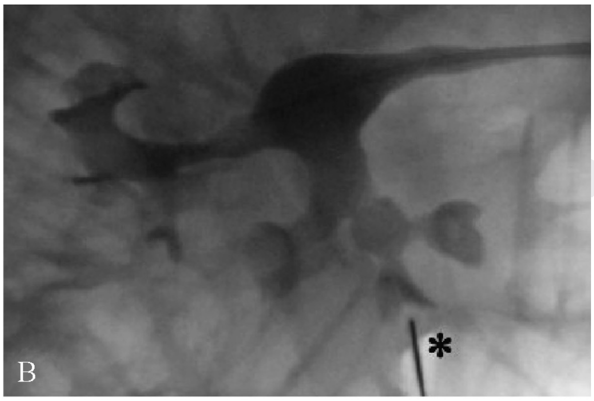

Figure 2.—Needle in profile view. A) C-arm rotated 10° away from surgeon to give needle depth perception; B) fluoroscopic image of needle (*) in profile view with C-arm in the position above. Needle is then advanced up to target calyx under fluoroscopic guidance.

through the calyceal papilla.[56] The posterior segmental artery is the most commonly injured artery during PCNL and needs to be avoided especially when performing interpolar and upper pole punctures.[57]

For most patients, the inferoposterior calyx is ideal for initial access. However, where renal anatomy and stone bulk dictates an upper pole access, puncture should be performed in full expiration to minimize pleural injury.[45, 55] Access through the upper calyx provides a straight line along the long axis of the kidney and gives excellent exposure and entry into the superior calyces, the renal pelvis, the lower calyces and proximal ureter, often without the need for significant torque on the kidney during the procedure which can result in excessive bleeding.[38, 54, 55, 58, 59]

Tract dilation

An important and integral aspect of PCNL is tract dilation, and access sheath insertion. There are currently three methods commonly used: one step balloon dilation, Alken metal reuseable telescoping dilators, and Amplatz sequential fascial dilators. In competent hands, all three methods are considered safe. However, higher blood loss has been associated with telescoping metal dilators versus Amplatz or balloon dilation.[34] Studies have shown the least amount of bleeding is associated with the use of balloon dilation when compared to Amplatz fascial dilators.[35, 58, 59] The reduced blood loss is thought to be due to the constant pressure applied on the renal parenchyma during dilation before the sheath is advanced. The disadvantages are its expense and its non-reuseable nature. With the Amplatz fascial dilating system, it has been suggested that during sequential dilator exchanges, the tamponade effect on the renal parenchymal tract is lost and this leads to more blood loss during the exchange process. However, animal studies that have been undertaken to compare the effects of balloon *vs* Amplatz fascial dilation showed no difference between the two techniques. One such study on porcine kidneys by Al-Kandari *et al.* showed that after 24 hours, Amplatz fascial dilated tracts were rounded and had more surface hemorrhage compared to balloon dilated tracts which were V shaped and had less bleeding. However, after six weeks scar formation was minimal and similar in size in both groups.[60] With regards to the Alken dilators which have the advantage of being reusable, centers using these have likewise claimed minimal bleeding complications when using this technique.[61] The findings are that all three methods of tract dilation, when used appropriately, are associated with minimal bleeding and result in minimal scar formation on healing.[54] One step balloon dilators have become popular because of its ease of use, efficacy, and safety during tract placement.

Lithotripsy devices

Presently, the four basic lithotripsy devices in use today include ultrasonic, pneumatic, laser or electrohydraulic to achieve stone fragmentation.

The ultrasonic lithotripter works by electrical energy being transferred onto a piezoelectric crystal, resulting in a strong vibrational energy directed at the tip of a hollow metal rod, which has the effect of grinding the stone into small sand like particles.[62] Suction is applied to the end of the probe to aid in particle evacuation and cooling of the probe through return flow of normal saline irrigant solution during the procedure. For staghorn calculi, the typical probe size used is 3.5 mm. Due to its rigid nature, the probe must be passed through an offset viewing nephroscope that has a straight wide caliber working channel.[63]

The pneumatic device (Swiss LithoClast®; Electro Medical Systems, Nyon, Switzerland) uses a forced air activated rigid probe containing a metal projectile that fragments the stone.[62-64] The probe sizes range from 0.8 mm to 4 mm in diameter. The fragments need to be removed manually by the surgeon using a combination of grasping forceps or stone baskets. Recently a suction feature has been built into the pneumatic device (Lithovac®; EMS, Nyon, Switzerland) to facilitate the removal of stone fragments with some success.

A combination of pneumatic and ultrasonic lithotripsy into a single handpiece with continuous suction is available (LithoClast® Ultra, EMS, Nyon, Switzerland), and has been a very successful combination.[62] Numerous authors have compared ultrasonic lithotripsy alone with the LithoClast® Ultra (or Master), and found shorter operative times in the latter group. In an *in vitro* study, Auge *et al.* found the combination device significantly more efficient, achieving complete stone fragmentation and clearance in 7.4 min as compared to 12.9 min and 23.8 min respectively for either ultrasonic or pneumatic lithotrites ($P<0.002$). In the same study, the stone fragments were significantly smaller with the combination device than with the ultrasonic or pneumatic lithotrites (1.67 mm *vs* 3.67 mm *vs* 9.07 mm, respectively, $P<0.00001$).[65] This is corroborated in a clinical study where Pietrow *et al.* demonstrated that the combination device was able to disintegrate and remove stones twice as rapidly as the standard ultrasonic lithotrite (21.1 min *vs* 43.7 min respectively, $P=0.036$).[66]

The most commonly used flexible lithotripsy device is the holmium:YAG (Ho:YAG) laser due to its efficacy in breaking all stone types,[67] whilst having a limited local effect in a fluid medium (0.4 mm) making it extremely safe to use. The tip of the laser fiber (200 or 360 microns) causes stone destruction using a photothermal effect and requires direct contact with the stone to cause fragmentation.[68] However, its use in PCNL remains limited when using rigid nephroscopes due to the better efficiency of stone fragmentation with the currently available alternative modalities. It is inefficient for stones greater than 2 cm diameter and is therefore unsuitable for the primary treatment of staghorn calculi.[64] It does have a role in flexible nephroscopy where the flexible nature of the fibres allow stone destruction to be undertaken even in difficult to reach parts of the collecting system.

Electrohydraulic lithotripsy (EHL) uses shock wave energy to treat urinary tract stones. The mechanism is a spark-gap discharge from the end of a flexible metal probe similar to HM-3 SWL (Dornier MedTech, Munich, Germany), which results in compressive forces as well as cavitatory bubbles that rapidly expand and collapse causing stone fragmentation.[62, 63] The smaller 1.9 Fr or 3Fr probes can be used *via* flexible endoscopes and results in minimal loss of endoscopic deflection. However, the disadvantage is that it causes more urothelial damage compared with Ho:YAG laser as the energy is disseminated over a longer distance up to 1 cm.[63] Because of these concerns, EHL has gone out of favor with the advent of the Ho:YAG laser. When deployed judiciously, it still remains a very effective tool in the armamentarium in stone lithotripsy.

Interventional radiologist vs urologist acquired renal access

Percutaneous access is commonly performed by either the interventional radiologist or urological surgeon. It is performed either as a single-staged procedure in the operating room or as a staged procedure where access is done at the radiology department, and the patient transferred to the operating room afterwards. A survey of urologist practice patterns in the United States revealed that only 11% of those performing PCNL routinely obtained percutaneous access themselves.[69] Reasons for this trend were cited to be inadequate training, and the belief that renal access is a radiological procedure best performed by the interventional radiologist. Lee *et al.* found that only 27% of urologists continued to perform percutaneous access despite training during their residency program.[70] Reasons given included the radiologist had better equipment (61%), better skills (44%), and the belief obtaining own access required significantly extra time (50%).[70]

In a study that compared complications and stone free rates between urologist-directed *vs* radiologist-directed renal access, Watterson *et al.* reported a three-fold increase in access related complications and clinically significant bleeding when access was placed by a radiologist.[71] This was despite the fact that 14% of patients in the urologist-directed access group required multiple tracts compared with no patients in the radiologist-directed group. In addition, stone free rates were significantly lower at 61.1% for the radiologist-directed group compared with 85.7% in the urologist-directed group ($P<0.05$). An explanation given for this discrepancy is the goal of renal access is fundamentally different; with perhaps the radiologist more intent only on gaining entry as for kidney drainage and not necessarily focusing on placing the optimal tract to best treat the stone.[54] In situations when access is achieved by the radiologist, the urologist should be closely involved regarding optimal tract selection.

Occasionally, fluoroscopy guided percutaneous puncture alone is unsafe for patients with unusual body *habitus* such as *spina bifida* or severe scoliosis since it cannot identify adjacent bowel, liver or spleen at the time of needle puncture. In these situations, CT-guided percutaneous access or US guidance is potentially safer as the tract is placed under controlled conditions. Matlaga *et al.*, reported that CT-guided access was required in 3% of patients within their series for retrorenal colon, severe vertebral deformity or stones in a transplant kidney.[72] After successful CT-guided access by an interventional radiologist, PCNL was completed safely by the urologist without undue morbidity.

Minimally invasive PCNL

Jackman *et al.* first described minimally invasive PCNL (MPCNL) and applied it on the pediatric population.[73] The technique involved dilation of the percutaneous tract to 11 F and resulted in stone free rates of 85% at three months. MPCNL has been tried on the adult population by several authors on the basis of minimizing trauma, with the use of smaller working sheaths, and hence reducing morbidity.[73-75] The technique used in these procedures is dilation of the percutaneous tract to 13-14 F, after which a standard 14 F ureteral access sheath is inserted, and nephroscopy effected with the use of an offset pediatric cystoscope, or an 8 F semirigid ureteroscope. These studies have shown good results with low morbidity, but they recommend that MPCNL was ideal in kidneys where the stone burden was under 2 cm^2. In a Chinese study, MPCNL was complimented by multiple punctures in treatment of large staghorn calculi with stone free rates of 72% after the first session and 93% after a second look procedure.[75]

There are several issues regarding MPCNL which need to be addressed. At present, the benefit of a smaller diameter tract has not been supported by published data. The renal functional effects of nephrostomy tract dilations have been described in two previous studies.[76, 77] They found that even when tract dilation was carried out to 35 F-50 F, all nephrostomy tracts healed to a fine scar at six weeks and with minimal effect on function. In an in vivo pig study, Clayman *et al.* found that the average overall amount of renal damage was only 0.15% of total measured renal cortical volume.[77] In essence, there was no clinically significant difference in terms of renal damage caused by MPCNL or traditional 30 F tract in PCNL.[77, 78] There have been no randomized studies published in the literature so far, which conclusively show a reduction in blood loss using smaller diameter tracts compared to using a 30 F tract. Overall, MPCNL appears to have the best utility in the pediatric population and stone burden limited to 2 cm.[29]

Fluoroscopy vs ultrasound guided percutaneous access

Fluoroscopy is the more commonly used imaging modality to gain needle access, however US guidance is gaining acceptance and has been popular in many centers, especially in Europe.[27] US guidance requires extra equipment but is easily performed and has been reported to be a factor in reducing potential complications during PCNL.[34, 61] It provides an extra dimension of safety by identifying overlying bowel or other viscera during needle insertion, making it especially useful for ectopic and/or transplant kidneys. For PCNL in the supine position, US guidance is an integral part of the procedure.[79] It also decreases the exposure of the patient, surgeon and operating room staff to ionizing radiation. US guidance is also useful in localizing non-opaque stones or when retrograde passage of a ureteral catheter to the renal pelvis is not performed or cannot be achieved. The limitations include difficulty in targeting a non-distended collecting system, poor image quality in obese patients and use is highly operator dependent. Regardless of modality used to gain access, fluoroscopy is still required for subsequent passage of guide wires, tract dilation, manipulation of stones and instruments within the renal tract, and overall successful completion of PCNL.[38]

Multiple punctures vs single tracts

The main drawback to multiple punctures is the belief that it can result in increased blood loss.[34, 35] Ganpule *et al.* compared studies with multiple tracts versus a single tract PCNL and concluded that when necessary, multiple tracts are safe and may be necessary especially for large stone burden.[80] Hegarty and Desai in their prospective study, noted that multiple tracts are highly effective in the treatment of staghorn and other large-volume renal calculi with blood loss and complication rates comparable to PCNL having only a single percutaneous tract.[81] These findings are further supported by Aron *et al.* who presented their results of 121 treated renal units.[82] In their series, when multiple tracts were anticipated, all punctures were made at the beginning with guide wires placed into the collecting system beforehand. They had a 15% blood transfusion rate (18 out of 121 patients), with an overall stone free rate of 84% after primary treatment. They concluded that aggressive PCNL monotherapy using multiple tracts is safe and effective, and should be the first option for very large renal staghorn calculi.

Some investigators however, have advocated single punctures in the treatment of staghorn calculi and have achieved comparably high stone free rates. In 2002, Wong and Leveillee reported a stone free rate of 95% using a single tract and flexible nephroscopy during PCNL for cases of staghorn calculi, which avoided having to do multiple punctures.[83] After initial stone debulking, flexible nephroscopy with Ho:YAG laser lithotripsy or atraumatic baskets were used to fragment or reach stones not accessible with rigid instruments. Their mean operative time was 2.9 hours and the mean blood loss was only 238 mL. Thus, the choice between multiple tracts *vs* single tract access is individualized for each patient at the time of surgery. Both options are safe, but multiple punctures are associated with a slightly higher risk of bleeding.

Recently, publications have demonstrated the use of flexible pyeloscopy to visually guide needle puncture into the desired calyx.[84-86] Flexible pyeloscopy allows visualization of needle entry into the calyx, and facilitates directing the guidewire down the ureter to secure access. Its main use would be in patients who are known to be difficult in gaining access, or have previously failed PCNL due to access related problems.

Mini-nephrostomy tube PCNL

There has been considerable discussion regarding size of drainage catheters on completion of PCNL. Large bore nephrostomy tubes (NT) 16-20 F have been used traditionally and thought to be associated with significant patient discomfort requiring more analgesics, prolonged hospitalization and longer persistent urine leak from the nephrostomy site after tube removal.[87, 88] Alternative strategies to avoid these morbidities include the use of smaller caliber NT or nephrostomy tube-free PCNL.

Studies have been designed to investigate whether the size of the NT correlates with the degree of patient discomfort and persistence of urine leak from the NT site.[88, 89] Maheshwari *et al.* in their study, used 9 F pigtail NT and compared them with 28 F NT and found significantly decreased analgesic requirements and duration of urine leak after tube removal in the former group. No significant increase in complications were associated with its use.[88]

In a prospective, randomized study comparing three groups: 20 Fr NT, 9 Fr pigtail catheter (Cook Urological Inc., Spencer, IN, USA) and tubeless drainage; Desai and colleagues demonstrated that the 9 Fr pigtail catheter group had a significantly smaller requirement for analgesia compared to the group with 20 Fr large bore nephrostomy tubes (140 mg and 218 mg diclofenac sodium respectively, $P<0.05$), and had shorter duration of urine leak (13.2 hours and 21.4 hours respectively, $P<0.05$).[90] Tubeless drainage had the lowest analgesic requirement, shortest hospital stay, and the lowest duration of urine leakage from the percutaneous tract. In addition, no increase in complications was observed with the use of either pigtail catheters, or tubeless drainage. The authors suggested that the best application of small caliber catheters were in patients who could, but unlikely required further access, and who had an uncomplicated PCNL (*i.e.* no mucosal damage, single access, minimal bleeding, and no residual fragments). Conventional large bore nephrostomy drainage is reserved for procedures with significant bleeding, infected stones, or major collecting system perforations where reliable drainage is paramount, or planned second look nephroscopy during the same admission is likely to be undertaken.

Nephrostomy tube-free PCNL

The placement of a nephrostomy tube after completion of PCNL has been well recognized as a standard procedure to provide hemostasis, adequate urinary drainage and access for additional endoscopic procedures. However, some investigators have questioned the need for it when patients have had an uncomplicated PCNL and the kidney is known to be stone free. Wickham *et al.*[91] in

TABLE II.—*Inclusion criteria as reported by various Nephrostomy tube-free PCNL studies.*

Inclusion criteria for tube-free PCNL
— Patients with stones less than 3 cm in diameter [94]
— Kidneys with normal renal function [90]
— Kidneys with no previous operations [90, 95]
— No renal or obstructive anomalies [96]
— Operative time shorter than 2 hours [87, 97]
— Subcostal approach [90]
— No residual fragments [90, 96, 97]
— One to two percutaneous access [90, 94]
— No intraoperative complications [90, 94, 95]

1984 was the first to report their experience omitting the nephrostomy tube after PCNL, but the concept did not gain acceptance especially after conflicting reports resulting in prolonged hospitalization and pain.[92] In 1997, Bellman *et al.* published his results of patients undergoing tubeless PCNL and again challenged the need for requirement of a NT for drainage.[87] In their series, all patients had an indwelling ureteral stent inserted in addition to an indwelling catheter instead of an NT. Exclusion criteria for this study included an operative time of more than 2 hours, PCNL requiring two or more tracts (the main exclusion criterion), significant perforation of the collecting system, significant residual stone burden, or significant postoperative bleeding. They found no major complications using this approach.[87] Tube-free PCNL has several purported advantages including a reduced hospital stay, decreased patient discomfort, earlier return to normal activities, and decreased hospital costs.[87, 93] No consensus guidelines have been formulated in selecting patients suitable for tubeless PCNL, but the recommendations from various studies are summarized in Table II.

Recently, several investigators have tried to extend the inclusion criteria by including patients with larger stones (>3 cm), or those having moderate intraoperative bleeding. Hemostasis was initially achieved through cauterization of the bleeding points in the renal parenchyma, or the application of fibrin glue to seal the nephrostomy tract.[93, 98] If fibrin glue is used, it is instilled simultaneously at the time of removing the sheath from the collecting system.

The main disadvantage with the use of fibrin glue in the urinary tract is the unwanted formation of a cohesive mucoid gel on contact with urine, which may persist up to 5 days.[99] This raised concerns for a possible lithogenic effect of this agent, especially in light of a previous report by Eden *et al.* wherein they described a patient who developed a stone in the renal pelvis after fibrin glue was used for a retroperitoneal dismembered pyeloplasty.[100] Gelatin matrix was also evaluated in the study by Uribe *et al.* and it remained as a fine colloidal suspension for a similar period of time when also in contact with urine.[99] Because of the potential for collecting system obstruction and possible lithogenic effect, every effort must be made to prevent these materials from entering into the collecting system if used.

Nephrostomy tube-free PCNL represents an ongoing evolution in the overall improvement in the technique of PCNL. It can result in shorter hospital stays, decreased patient discomfort, earlier return to normal activities, and possibly decrease costs. The main concerns of this approach at present time include the necessity for an extra procedure for the removal of the internal ureteral stent, an increase in treatment costs associated with the use of biologic hemostatic agents, and the potential for upper urinary tract obstruction or stone formation associated with the use of these agents.

Supine versus *prone position*

PCNL has traditionally been performed with the patient in prone position. However in the literature, PCNL in the supine position is well known but has yet to gain widespread acceptance. This approach was first described by Valdivia *et al.* in 1987 and later reported their extensive experience with this technique over 11 years.[79] The purported advantages of the supine position include: safer general anesthesia, ease in positioning patients, ability to perform the procedure using local anesthesia, whilst maintaining easy access to the urethra and ureteral orifice should a retrograde procedure be required. In over 500 cases, they reported no colon perforations or hydro-pneumothoraces. Major hemorrhage requiring blood transfusion occurred in only three patients. US guided percutaneous access is helpful, and the anterior calyces are the preferred sites of puncture by these authors as they are more accessible. Direct comparison of the two techniques was evaluated by Shoma *et al.* in 2002 where they treated 53 patients supine and 77 prone and found 89% and 84% stone free rate respectively.[101] The overall complication rates were similar in both groups and none of the patients experienced injury of adjacent organs. Ng *et al.* also adopted the supine position during PCNL and reported their findings on 62 patients.[102] They achieved a primary stone-free rate of 76%. One patient with multiple tracts required an emergent nephrectomy for hemorrhage one week after the procedure due to an accidental traction on one of the nephrostomy tubes. Again, there were no colon injuries in this series. The supine position appears to be a safe alternative approach to gaining access into the collecting system. It appears to be associated with low complication rates and comparable stone free rates when performed in expert centers.

Postoperative evaluation: assessment of stone free status

The primary objectives of imaging after completion of PCNL are to identify residual stones and ensure patency in drainage of the upper urinary tract. Traditionally, KUB X-ray and plain nephrotomograms have been used to look for the presence of residual fragments. Many studies have questioned this approach because of the low sensitivities in detecting residual fragments. A study by Denstedt *et al.* in 1991 compared plain abdominal radiographs and tomograms, to flexible nephroscopy in detecting residual calculi. Using second look flexible nephroscopy as the gold standard, they found that KUB and nephrotomograms had a false negative rate of 35% and 17%, respectively.[103] They recommended second look nephroscopy as the gold standard for detecting residual calculi during the same hospital admission. They achieved this routinely on selected patients using local anesthesia in the outpatient department. Stone fragments could also be extracted at the same time using baskets placed down the instrument channel.

Later, Pearle *et al.* compared non contrast helical CT scan and KUB xray to flexible nephroscopy in looking for residual stones after PCNL.[104] They found the sensitivity and specificity in detecting residual calculi was 46% and 82% for KUB, and 100% and 62% for CT respectively. In their series, performing flexible nephroscopy only on those with positive CT findings avoided unnecessary procedures in 20% of their patients. They performed a cost analysis and found significant cost savings to the hospital if this approach was adopted.[104]

Today, the most reliable test in detecting residual stone fragments after PCNL is non contrast helical CT scan with 1 to 2 mm axial slices because of its unsurpassed sensitivity in detecting renal calculi.[86] Although the size cut off for clinically insignificant residual stones has never been firmly established, many consider this value to be 4 mm or less.[105] This could require further reevaluation since residual fragments previously considered insignificant, may often result in patient morbidity in the future with stone growth and obstruction.[105]

There have been no universal recommendations on the best postoperative surveillance regime. The guidelines adopted by our group are a consensus of the current evidence in the literature. They include meticulous and thorough flexible nephroscopy at the end of the PCNL in all patients; a large bore nephrostomy tube (18 F) is left in selected patients and a non contrast CT scan performed selectively after 24 hours to further assess for residual fragments. If the postoperative CT scan shows no fragments or only a few small fragments (*i.e.* <3 mm), the nephrostomy tube is removed. Because of the potential for edema of the ureter or ureteropelvic junction as a result of PCNL, an antegrade nephrostogram is performed after the procedure to assure adequate drainage. When antegrade drainage is confirmed, the nephrostomy tube is then removed. If the postoperative CT scan shows any fragments larger than 3 mm, then the next step is flexible nephroscopy under local anesthesia and treatment of the stones during the same admission if feasible.

Conclusions

PCNL remains a technique undergoing constant refinement which has resulted in improved patient outcomes. It remains a challenging operation requiring a good understanding of the fundamental principles. It has proven to be safe, effective and remains first line treatment in the management of large kidney stones. The most important part of the procedure is tract placement and this remains the key to having a successful outcome, denoted by having high stone-free rates and acceptably low patient morbidity. The improvements in rigid and flexible endoscopic equipment, along with the use of ultrasonic, pneumatic and Ho-YAG laser lithotripsy devices to fragment stones have been instrumental in achieving these good outcomes. The ultimate benefit of PCNL has been shorter hospital stays, greater patient comfort, and earlier return to normal activities by patients compared to earlier techniques of open stone surgery. Further improvements will continue to evolve and this will ultimately result in better patient care in the future.

Riassunto

Stato dell'arte della nefrolitotomia percutanea nel trattamento della nefrolitiasi

I calcoli renali voluminosi (>2 cm) costituiscono una patologia frequente che affligge tutti i gruppi di popolazione nel mondo e può esitare in gravi complicanze se non trattata. Il trattamento di questa patologia si è enormemente evoluto negli ultimi settanta anni con l'avvento della chirurgia mini-invasiva. Tra queste, riveste un ruolo fondamentale la nefrolitotomia percutanea (PCNL). Essa ha comportato una riduzione della degenza ospedaliera, del dolore postoperatorio, e una più rapida convalescenza, rispetto ai precedenti criteri della chirurgia tradizionale a cielo aperto. La PCNL è soltanto una delle molteplici opzioni di trattamento mini-invasivo disponibili per tale patologia, ma rimane tuttora la più efficace in tutti i gruppi di pazienti. Comunque, essa continua ad essere una delle procedure in ambito urologico più complesse, che se non effettuata in modo adeguato, può essere associata a gravi complicanze. Il perfezionamento delle tecniche, il miglioramento delle attrezzature e l'incremento dell'esperienza clinica hanno consentito di migliorare i tassi di assenza di recidiva di calcolosi delle vie urinarie con una morbilità accettabile per il paziente. In questo articolo, gli autori presentano una revisione degli aspetti tecnici, i risultati e l'attuale ruolo della PCNL nel trattamento di calcoli renali volumonosi.

Parole chiave: Nefrolitotomia, percutanea - Calcolosi renale - Chirurgia mini-invasiva.

References

1. Rupel E, Brown R. Nephroscopy with removal of stone following nephrostomy for obstructive calculus anuria. J Urol 1941;46:177-82.
2. Goodwin WE, Casey WC, Woolf W. Percutaneous trocar (needle) nephrostomy in hydronephrosis. JAMA 1955;157:891-4.
3. Fernstrom I, Johansson B. Percutaneous pyelolithotomy. A new extraction technique. Scand J Urol Nephrol 1976;10:257-9.
4. Kurth KH, Hohenfellner R, Altwein JE. Ultrasound litholapaxy of a staghorn calculus. J Urol 1977;117:242-3.
5. Alken P, Hutschenreiter G, Gunther R, Marberger M. Percutaneous stone manipulation. J Urol 1981;125:463-6.
6. Marberger M, Stackl W, Hruby W. Percutaneous litholapaxy of renal calculi with ultrasound. Eur Urol 1982;8:236-42.
7. Wickham JE, Kellett MJ. Percutaneous nephrolithotomy. Br J Urol 1981;53:297-9.
8. Segura JW, Patterson DE, LeRoy AJ, McGough PF, Barrett DM. Percutaneous removal of kidney stones. Preliminary report. Mayo Clin Proc 1982;57:615-9.
9. Clayman RV, Surya V, Miller RP, Castaneda-Zuniga WR, Smith AD, Hunter DH *et al.* Percutaneous nephrolithotomy: extraction of renal and ureteral calculi from 100 patients. J Urol 1984;131:868-71.
10. Preminger GM, Assimos DG, Lingeman JE, Nakada SY, Pearle MS, Wolf JS Jr. Chapter 1: AUA guideline on management of staghorn calculi: diagnosis and treatment recommendations. J Urol 2005;173:1991-2000.
11. Lingeman JE, Coury TA, Newman DM, Kahnoski RJ, Mertz JH, Mosbaugh PG *et al.* Comparison of results and morbidity of percutaneous nephrostolithotomy and extracorporeal shock wave lithotripsy. J Urol 1987;138:485-90.
12. Meretyk S, Gofrit ON, Gafni O, Pode D, Shapiro A, Verstandig A *et al.* Complete staghorn calculi: random prospective comparison between extracorporeal shock wave lithotripsy monotherapy and combined with percutaneous nephrostolithotomy. J Urol 1997;157:780-6.
13. Kim FJ, Rice KR. Prediction of shockwave failure in patients with urinary tract stones. Curr Opin Urol 2006;16:88-92.
14. Potretzke AM, Monga M. Imaging modalities for urolithiasis: impact on management. Curr Opin Urol 2008;18:199-204.

15. Nakada SY, Hoff DG, Attai S, Heisey D, Blankenbaker D, Pozniak M. Determination of stone composition by noncontrast spiral computed tomography in the clinical setting. Urology 2000;55:816-9.
16. Zarse CA, McAteer JA, Tann M, Sommer AJ, Kim SC, Paterson RF *et al.* Helical computed tomography accurately reports urinary stone composition using attenuation values: in vitro verification using high-resolution micro-computed tomography calibrated to fourier transform infrared microspectroscopy. Urology 2004;63: 828-33.
17. Joseph P, Mandal AK, Singh SK, Mandal P, Sankhwar SN, Sharma SK. Computerized tomography attenuation value of renal calculus: can it predict successful fragmentation of the calculus by extracorporeal shock wave lithotripsy? A preliminary study. J Urol 2002;167: 1968-71.
18. Gupta NP, Ansari MS, Kesarvani P, Kapoor A, Mukhopadhyay S. Role of computed tomography with no contrast medium enhancement in predicting the outcome of extracorporeal shock wave lithotripsy for urinary calculi. BJU Int 2005;95:1285-8.
19. Sampaio FJ. Renal collecting system anatomy: its possible role in the effectiveness of renal stone treatment. Curr Opin Urol 2001;11:359-66.
20. Elbahnasy AM, Shalhav AL, Hoenig DM, Elashry OM, Smith DS, McDougall EM *et al.* Lower caliceal stone clearance after shock wave lithotripsy or ureteroscopy: the impact of lower pole radiographic anatomy. J Urol 1998;159:676-82.
21. Albala DM, Assimos DG, Clayman RV, Denstedt JD, Grasso M, Gutierrez-Aceves J *et al.* Lower pole I: a prospective randomized trial of extracorporeal shock wave lithotripsy and percutaneous nephrostolithotomy for lower pole nephrolithiasis-initial results. J Urol 2001;166:2072-80.
22. Pearle MS, Lingeman JE, Leveillee R, Kuo R, Preminger GM, Nadler RB*, et al.* Prospective, randomized trial comparing shock wave lithotripsy and ureteroscopy for lower pole caliceal calculi 1 cm or less. J Urol 2005;173:2005-9.
23. Wen CC, Nakada SY. Treatment selection and outcomes: renal calculi. Urol Clin North Am 2007;34:409-19.
24. Pareek G, Armenakas NA, Panagopoulos G, Bruno JJ, Fracchia JA. Extracorporeal shock wave lithotripsy success based on body mass index and Hounsfield units. Urology 2005;65:33-6.
25. Carson CC III, Danneberger JE, Weinerth JL. Percutaneous lithotripsy in morbid obesity. J Urol 1988;139:243-5.
26. Pearle MS, Nakada SY, Womack JS, Kryger JV. Outcomes of contemporary percutaneous nephrostolithotomy in morbidly obese patients. J Urol 1998;160: 669-73.
27. Knoll T, Michel MS, Alken P. Surgical Atlas. Percutaneous nephrolithotomy: the Mannheim technique. BJU Int 2007;99:213-31.
28. Tiselius HG, Ackermann D, Alken P, Buck C, Conort P, Gallucci M. Guidelines on urolithiasis. Eur Urol 2001;40:362-71.
29. Tiselius HG, Alken P, Buck C, Gallucci M, Knoll T, Sarica K *et al.* Guidelines on Urolithiasis. European Association of Urology 2008:1-128.
30. Skolarikos A, de la Rosette J. Prevention and treatment of complications following percutaneous nephrolithotomy. Curr Opin Urol 2008;18:229-34.
31. Inglis JA, Tolley DA. Antibiotic prophylaxis at the time of percutaneous stone surgery. J Endourol 1988;2:59-62.
32. Mariappan P, Smith G, Moussa SA, Tolley DA. One week of ciprofloxacin before percutaneous nephrolithotomy significantly reduces upper tract infection and urosepsis: a prospective controlled study. BJU Int 2006;98:1075-9.
33. Mariappan P, Smith G, Bariol SV, Moussa SA, Tolley DA. Stone and pelvic urine culture and sensitivity are better than bladder urine as predictors of urosepsis following percutaneous nephrolithotomy: a prospective clinical study. J Urol 2005;173:1610-4.
34. Kukreja RA, Desai MM, Patel SH, Bapat SD, Desai MR. Factors affecting blood loss during percutaneous nephrolithotomy: prospective study. J Endourol 2004;18:715-22.
35. Turna B, Nazli O, Demiryoguran S, Mammadov R, Cal C. Percutaneous nephrolithotomy: variables that influence hemorrhage. Urology 2007;69:603-7.
36. Michel MS, Trojan L, Rassweiler JJ. Complications in percutaneous nephrolithotomy. Eur Urol 2007;51:899-906.
37. Mutgi A, Williams JW, Nettleman M. Renal colic. Utility of the plain abdominal roentgenogram. Arch Intern Med 1991;151:1589-92.
38. Park S, Pearle MS. Imaging for percutaneous renal access and management of renal calculi. Urol Clin North Am 2006;33:353-64.
39. Mutazindwa T, Husseini T. Imaging in acute renal colic: the intravenous urogram remains the gold standard. Eur J Radiol 1996;23:238-40.
40. Weiss A, Price R, Sage M, Barratt L. The intravenous pyelogram in renal colic. Australas Radiol 1988;32:429-33.
41. Gallagher HJ, Tolley DA. 2000 AD: still a role for the intravenous urogram in stone management? Curr Opin Urol 2000;10:551-5.
42. Miller NL, Lingeman JE. Management of kidney stones. BMJ 2007;334:468-72.
43. Miller OF, Rineer SK, Reichard SR, Buckley RG, Donovan MS, Graham IR *et al.* Prospective comparison of unenhanced spiral computed tomography and intravenous urogram in the evaluation of acute flank pain. Urology 1998;52:982-7.
44. Pfister SA, Deckart A, Laschke S, Dellas S, Otto U, Buitrago C *et al.* Unenhanced helical computed tomography *vs* intravenous urography in patients with acute flank pain: accuracy and economic impact in a randomized prospective trial. Eur Radiol 2003;13:2513-20.
45. Fielding JR, Steele G, Fox LA, Heller H, Loughlin KR. Spiral computerized tomography in the evaluation of acute flank pain: a replacement for excretory urography. J Urol 1997;157:2071-3.
46. Yilmaz S, Sindel T, Arslan G, Ozkaynak C, Karaali K, Kabaalioglu A *et al.* Renal colic: comparison of spiral CT, US and IVU in the detection of ureteral calculi. Eur Radiol 1998;8:212-7.
47. Vieweg J, Teh C, Freed K, Leder RA, Smith RH, Nelson RH *et al.* Unenhanced helical computerized tomography for the evaluation of patients with acute flank pain. J Urol 1998;160:679-84.
48. Heidenreich A, Desgrandschamps F, Terrier F. Modern approach of diagnosis and management of acute flank pain: review of all imaging modalities. Eur Urol 2002;41:351-62.
49. Palmer JS, Donaher ER, O'Riordan MA, Dell KM. Diagnosis of pediatric urolithiasis: role of ultrasound and computerized tomography. J Urol 2005;174:1413-6.
50. Leder RA, Nelson RC. Three-dimensional CT of the genitourinary tract. J Endourol 2001;15:37-46.
51. Buchholz NP. Three-dimensional CT scan stone reconstruction for the planning of percutaneous surgery in a morbidly obese patient. Urol Int 2000;65:46-8.
52. Ko R, Soucy F, Denstedt JD, Razvi H. Percutaneous

nephrolithotomy made easier: a practical guide, tips and tricks. BJU Int 2008;101:535-9.
53. Al-Qahtani FN, Ali GA, Kamal BA, Taha SA. Study of pelvicaliceal anatomy by helical computerized tomography. Is it feasible? Saudi Med J 2003;24:1337-40.
54. Lee KL, Stoller ML. Minimizing and managing bleeding after percutaneous nephrolithotomy. Curr Opin Urol 2007;17:120-4.
55. Yadav R, Aron M, Gupta NP, Hemal AK, Seth A, Kolla SB. Safety of supracostal punctures for percutaneous renal surgery. Int J Urol 2006;13:1267-70.
56. Sampaio FJ, Zanier JF, Aragão AH, Favorito LA. Intrarenal access: 3-dimensional anatomical study. J Urol 1992;148:1769-73.
57. Sampaio FJB. Surgical Anatomy of the Kidney. In: Smith AD, Badlani GH, Bagley DH, Clayman RV, Docimo SG, Jordan GH *et al.*, editors. Smith's Textbook of Endourology. 2nd ed. Hamilton, ON: BC Decker; 2006. p. 79-99.
58. Safak M, Gogus C, Soygur T. Nephrostomy tract dilation using a balloon dilator in percutaneous renal surgery: experience with 95 cases and comparison with the fascial dilator system. Urol Int 2003;71:382-4.
59. Davidoff R, Bellman GC. Influence of technique of percutaneous tract creation on incidence of renal hemorrhage. J Urol 1997;157:1229-31.
60. Al-Kandari AM, Jabbour M, Anderson A, Shokeir AA, Smith AD. Comparative study of degree of renal trauma between Amplatz sequential fascial dilation and balloon dilation during percutaneous renal surgery in an animal model. Urology 2007;69:586-9.
61. Osman M, Wendt-Nordahl G, Heger K, Michel MS, Alken P, Knoll T. Percutaneous nephrolithotomy with ultrasonography-guided renal access: experience from over 300 cases. BJU Int 2005;96:875-8.
62. Lee DI, Kim I, Clayman RV. Updated approach to staghorn calculi. AUA Update Series 2005;24:305-12.
63. Razvi H, Denstedt JD, Sosa RE, Vaughan JED. Endoscopic lithotripsy devices. AUA Update Series 1995;14:290-96.
64. Noor Buchholz NP. Intracorporeal lithotripters: selecting the optimum machine. BJU Int 2002;89:157-61.
65. Auge BK, Lallas CD, Pietrow PK, Zhong P, Preminger GM. *In vitro* comparison of standard ultrasound and pneumatic lithotrites with a new combination intracorporeal lithotripsy device. Urology 2002;60:28-32.
66. Pietrow PK, Auge BK, Zhong P, Preminger GM. Clinical efficacy of a combination pneumatic and ultrasonic lithotrite. J Urol 2003;169:1247-9.
67. Johnson DE, Cromeens DM, Price RE. Use of the holmium:YAG laser in urology. Lasers Surg Med 1992;12:353-63.
68. Chan KF, Pfefer TJ, Teichman JM, Welch AJ. A perspective on laser lithotripsy: the fragmentation processes. J Endourol 2001;15:257-73.
69. Bird VG, Fallon B, Winfield HN. Practice patterns in the treatment of large renal stones. J Endourol 2003;17:355-63.
70. Lee CL, Anderson JK, Monga M. Residency training in percutaneous renal access: does it affect urological practice? J Urol 2004;171:592-5.
71. Watterson JD, Soon S, Jana K. Access related complications during percutaneous nephrolithotomy: urology versus radiology at a single academic institution. J Urol 2006;176:142-5.
72. Matlaga BR, Shah OD, Zagoria RJ, Dyer RB, Streem SB, Assimos DG. Computerized tomography guided access for percutaneous nephrostolithotomy. J Urol 2003;170:45-7.
73. Jackman SV, Docimo SG, Cadeddu JA, Bishoff JT, Kavoussi LR, Jarrett TW. The "mini-perc" technique: a less invasive alternative to percutaneous nephrolithotomy. World J Urol 1998;16:371-4.
74. Chan DY, Jarrett TW. Mini-percutaneous nephrolithotomy. J Endourol 2000;14:269-73.
75. Guohua Z, Zhong W, Li X, Wu K, Chen W, Lei M *et al.* Minimally invasive percutaneous nephrolithotomy for staghorn calculi: a novel single session approach via multiple 14-18Fr tracts. Surg Laparosc Endosc Percutan Tech 2007;17:124-8.
76. Webb DR, Fitzpatrick JM. Percutaneous nephrolithotripsy: a functional and morphological study. J Urol 1985;134:587-91.
77. Clayman RV, Elbers J, Miller RP, Williamson J, McKeel D, Wassynger W. Percutaneous nephrostomy: assessment of renal damage associated with semi-rigid (24F) and balloon (36F) dilation. J Urol 1987;138:203-6.
78. Traxer O, Smith TG III, Pearle MS, Corwin TS, Saboorian H, Cadeddu JA. Renal parenchymal injury after standard and mini percutaneous nephrostolithotomy. J Urol 2001;165:1693-5.
79. Valdivia Uria JG, Valle Gerhold J, Lopez Lopez JA, Villarroya Rodriguez S, Ambroj Navarro C, Ramirez Fabian M *et al.* Technique and complications of percutaneous nephroscopy: experience with 557 patients in the supine position. J Urol 1998;160:1975-8.
80. Ganpule AP, Desai M. Management of the staghorn calculus: multiple-tract versus single-tract percutaneous nephrolithotomy. Curr Opin Urol 2008;18:220-3.
81. Hegarty NJ, Desai MM. Percutaneous nephrolithotomy requiring multiple tracts: comparison of morbidity with single-tract procedures. J Endourol 2006;20:753-60.
82. Aron M, Yadav R, Goel R, Kolla SB, Gautam G, Hemal AK *et al.* Multi-tract percutaneous nephrolithotomy for large complete staghorn calculi. Urol Int 2005;75:327-32.
83. Wong C, Leveillee RJ. Single upper-pole percutaneous access for treatment of ?5 cm complex branched staghorn calculi: is shockwave lithotripsy necessary? J Endourol 2002;16:477-81.
84. Grasso M, Lang G, Taylor FC. Flexible ureteroscopically assisted percutaneous renal access. Tech Urol 1995;1:39-43.
85. Kidd CF, Conlin MJ. Ureteroscopically assisted percutaneous renal access. Urology 2003;61:1244-5.
86. Deane LA, Clayman RV. Advances in percutaneous nephrostolithotomy. Urol Clin North Am 2007;34:383-95.
87. Bellman GC, Davidoff R, Candela J, Gerspach J, Kurtz S, Stout L. Tubeless percutaneous renal surgery. J Urol 1997;157:1578-82.
88. Maheshwari PN, Andankar MG, Bansal M. Nephrostomy tube after percutaneous nephrolithotomy: large-bore or pigtail catheter? J Endourol 2000;14: 735-7; discussion 37-8.
89. Paul EM, Marcovich R, Lee BR, Smith AD. Choosing the ideal nephrostomy tube. BJU Int 2003;92:672-7.
90. Desai MR, Kukreja RA, Desai MM, Mhaskar SS, Wani KA, Patel SH *et al.* A prospective randomized comparison of type of nephrostomy drainage following percutaneous nephrostolithotomy: large bore versus small bore versus tubeless. J Urol 2004;172:565-7.
91. Wickham JE, Miller RA, Kellett MJ, Payne SR. Percutaneous nephrolithotomy: one stage or two? Br J Urol 1984;56:582-5.
92. Winfield HN, Weyman P, Clayman RV. Percutaneous nephrostolithotomy: complications of premature nephrostomy tube removal. J Urol 1986;136:77-9.
93. Jou YC, Cheng MC, Lin CT, Chen PC, Shen JH. Nephrostomy tube-free percutaneous nephrolithotomy for patients with large stones and staghorn stones. Urology 2006;67:30-4.

94. Goh M, Wolf JS Jr. Almost totally tubeless percutaneous nephrolithotomy: further evolution of the technique. J Endourol 1999;13:177-80.
95. Sofer M, Beri A, Friedman A, Aviram G, Mabjeesh NJ, Chen J *et al*. Extending the application of tubeless percutaneous nephrolithotomy. Urology 2007;70:412-6; discussion 16-7.
96. Aghamir SM, Hosseini SR, Gooran S. Totally tubeless percutaneous nephrolithotomy. J Endourol 2004;18: 647-8.
97. Feng MI, Tamaddon K, Mikhail A, Kaptein JS, Bellman GC. Prospective randomized study of various techniques of percutaneous nephrolithotomy. Urology 2001;58:345-50.
98. Mikhail AA, Kaptein JS, Bellman GC. Use of fibrin glue in percutaneous nephrolithotomy. Urology 2003;61: 910-4.
99. Uribe CA, Eichel L, Khonsari S, Finley DS, Basillote J, Park HK *et al*. What happens to hemostatic agents in contact with urine? An in vitro study. J Endourol 2005;19:312-7.
100. Eden CG, Sultana SR, Murray KH, Carruthers RK. Extraperitoneal laparoscopic dismembered fibrin-glued pyeloplasty: medium-term results. Br J Urol 1997;80: 382-9.
101. Shoma AM, Eraky I, El-Kenawy MR, El-Kappany HA. Percutaneous nephrolithotomy in the supine position: technical aspects and functional outcome compared with the prone technique. Urology 2002;60:388-92.
102. Ng MT, Sun WH, Cheng CW, Chan ES. Supine position is safe and effective for percutaneous nephrolithotomy. J Endourol 2004;18:469-74.
103. Denstedt JD, Clayman RV, Picus DD. Comparison of endoscopic and radiological residual fragment rate following percutaneous nephrolithotripsy. J Urol 1991;145:703-5.
104. Pearle MS, Watamull LM, Mullican MA. Sensitivity of noncontrast helical computerized tomography and plain film radiography compared to flexible nephroscopy for detecting residual fragments after percutaneous nephrostolithotomy. J Urol 1999;162:23-6.
105. Streem SB, Yost A, Mascha E. Clinical implications of clinically insignificant store fragments after extracorporeal shock wave lithotripsy. J Urol 1996;155:1186-90.