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PERCUTANEOUS NEPHROLITHOTRIPSY: A CONTEMPORARY MINIMALLY INVASIVE APPROACH FOR THE MANAGEMENT OF LARGE RENAL CALCULI

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ABSTRACT

Urolithiasis remains one of the most pressing problems of modern urology, affecting between 1% and 15% of the global population and demonstrating high recurrence rates. For the treatment of large (>2 cm) and staghorn renal calculi, percutaneous nephrolithotripsy (PCNL) is currently regarded as the gold standard. This review provides a comprehensive analysis of PCNL based on contemporary international literature, covering its historical evolution, indications and contraindications, preoperative work-up, principal technical variants (standard PCNL, mini-PCNL, ultra-mini PCNL, and micro-PCNL), available intracorporeal lithotripsy modalities, complication profile, and treatment efficacy. Reported stone-free rates range from 78% to 95%; however, the procedure remains associated with a non-negligible risk of major complications, including hemorrhage, sepsis, and injury to adjacent organs. These risks underscore the importance of careful patient selection, meticulous preoperative imaging, and operator expertise.

Keywords: percutaneous nephrolithotripsy, urolithiasis, renal calculi, staghorn stone, mini-PCNL, holmium laser lithotripsy, stone-free rate, Clavien-Dindo classification.

1. INTRODUCTION

Urolithiasis has accompanied humanity since ancient times and continues to represent a significant public health concern. Epidemiological data indicate that the overall prevalence of stone disease varies regionally from 1% to 15%, with the lifetime risk of stone formation reaching approximately 12% in men and 6% in women in developed countries. Over recent decades, the incidence has risen steadily, paralleling the increasing prevalence of obesity, type 2 diabetes mellitus, metabolic syndrome, and dietary changes associated with Westernized lifestyles.

The modern paradigm of stone management is rooted in minimally invasive techniques. Depending on stone size, location, composition, and patient anatomy, four principal modalities are currently available: extracorporeal shock wave lithotripsy (ESWL), retrograde intrarenal surgery (RIRS) with flexible ureteroscopy, percutaneous nephrolithotripsy (PCNL), and, in select cases, open or laparoscopic stone surgery. Among these, PCNL retains a leading role in the management of large and complex stone burdens.

The aim of this review is to summarize the contemporary status of PCNL, including its technical variants, indications and contraindications, complication spectrum, and clinical outcomes, based on a critical analysis of international literature.

2. HISTORICAL EVOLUTION

The conceptual foundation of percutaneous renal access dates back to 1955, when Goodwin and colleagues performed the first percutaneous nephrostomy. However, the first deliberate extraction of a renal stone through a percutaneous tract was reported in 1976 by the Swedish

surgeons Fernström and Johansson, an event that is universally recognized as the birth of modern PCNL.

Throughout the 1980s, the technique was substantially refined through the contributions of Wickham, Alken, Marberger, and Smith, who introduced fascial dilators, rigid nephroscopes, and ultrasonic lithotripsy. The advent and widespread adoption of ESWL during the 1990s temporarily reduced the frequency of PCNL; nevertheless, from the 2000s onward, the development of miniaturized instrumentation (mini-PCNL, ultra-mini PCNL, micro-PCNL) and high-power holmium and thulium fiber lasers has restored PCNL to a central position in contemporary endourology.

3. ANATOMICAL AND PHYSIOLOGICAL CONSIDERATIONS

Safe execution of PCNL requires a thorough understanding of the retroperitoneal anatomy and the architecture of the renal collecting system. The kidney lies between the posterior axillary and paravertebral lines, beneath or just below the twelfth rib. The pelvicalyceal system typically comprises 7 to 14 calyces grouped into upper, interpolar, and lower pole calices.

The optimal percutaneous tract traverses Brödel's avascular line along the posterolateral convex border of the kidney, allowing entry into the collecting system without damage to interlobar vessels. Upper-pole access provides superior intrarenal visualization but carries an increased risk of pleural and pulmonary injury, whereas lower-pole access is generally considered the safest entry route.

4. INDICATIONS AND CONTRAINDICATIONS

4.1. Indications

According to the guidelines of the European Association of Urology (EAU) and the American Urological Association (AUA), PCNL is recommended in the following scenarios:

- Renal calculi greater than 2 cm in diameter;
- Complete or partial staghorn calculi;
- Residual stones after failed ESWL or RIRS;
- Lower-pole calculi of 1–2 cm with dense composition (cystine, calcium oxalate monohydrate, brushite);
- Large stones in patients with anatomical anomalies (horseshoe kidney, ectopic kidney);
- Obstructive calculi of the upper urinary tract;
- Selected impacted proximal ureteral stones requiring an antegrade approach.

4.2. Contraindications

Absolute contraindications to PCNL include:

- Uncorrectable coagulopathy;
- Untreated active urinary tract infection or urosepsis;
- Pregnancy, particularly when fluoroscopic guidance is required;

- Anatomical conditions precluding safe percutaneous access.

Relative contraindications encompass disseminated malignancy, severe cardiopulmonary comorbidities, morbid obesity (BMI > 40 kg/m²), and the inability to safely discontinue antiplatelet or anticoagulant therapy.

5. PREOPERATIVE EVALUATION

Preoperative assessment combines accurate imaging with comprehensive risk stratification. Non-contrast computed tomography (NCCT) is currently the gold standard imaging modality, providing precise information on stone burden, density (measured in Hounsfield units), location, skin-to-stone distance, and renal anatomy. Stones with attenuation values exceeding 1000 HU are considered resistant to ESWL and are therefore optimal candidates for PCNL.

Laboratory work-up should include complete blood count, urinalysis, urine culture with antibiotic susceptibility testing, serum creatinine, coagulation panel, and blood typing. In patients with positive urine cultures, targeted antibiotic therapy is initiated 7–10 days prior to surgery. According to both EAU and AUA recommendations, parenteral broad-spectrum antibiotic prophylaxis (cephalosporins or fluoroquinolones) is administered at the induction of anesthesia.

6. SURGICAL TECHNIQUE

6.1. Patient positioning

Traditionally, PCNL has been performed in the prone position, which offers a wide operative field and convenient access to the collecting system. The supine position, originally proposed by Valdivia in 1998 and subsequently modified as the Galdakao-modified Valdivia position, has gained widespread adoption owing to improved anesthesiologic safety and the possibility of performing simultaneous antegrade and retrograde procedures (ECIRS — Endoscopic Combined Intrarenal Surgery).

6.2. Renal access

The most technically demanding step of the procedure is achieving accurate puncture of the appropriate calyx. Several guidance modalities are available:

- Fluoroscopy — the conventional and most widely used technique;
- Ultrasound guidance — eliminates radiation exposure and is preferred in pregnant patients;
- Combined ultrasound-fluoroscopic guidance — offers the highest accuracy;
- Endoscopically assisted puncture (ECIRS);
- CT- or MRI-guided puncture — reserved for complex anatomical scenarios.

6.3. Tract dilation

After successful puncture, a guidewire is advanced into the collecting system, followed by tract dilation. Several dilation systems are available: Amplatz telescopic dilators (reliable but associated with prolonged fluoroscopy time), balloon dilators (rapid and atraumatic but costly), and

metallic coaxial Alken dilators. The final tract caliber is typically 24–30 Fr for standard PCNL and 16–22 Fr for mini-PCNL.

6.4. Stone fragmentation and extraction

After insertion of the nephroscope through the working sheath, stones are fragmented using one or a combination of the following modalities:

- Ultrasonic lithotripsy — effective for non-rigid, echogenic stones;
- Pneumatic (ballistic) lithotripsy (e.g., Swiss LithoClast) — effective even for hard stones;
- Laser lithotripsy — holmium:YAG (Ho:YAG) and thulium fiber laser (TFL) currently represent the most versatile modern technologies;
- Combined systems integrating ultrasonic and ballistic components (Swiss LithoClast Trilogy, ShockPulse-SE).

Stone fragments are evacuated by aspiration or with the aid of grasping forceps and nitinol stone baskets. At the conclusion of the procedure, antegrade pyelography is performed to confirm clearance and to identify any residual fragments.

6.5. Conclusion of the procedure: drainage strategies

Several drainage approaches are available at the end of the procedure:

- Standard drainage — placement of a nephrostomy tube (14–24 Fr);
- "Tubeless" PCNL — no nephrostomy tube; a ureteral JJ stent is left in place;
- "Totally tubeless" PCNL — neither nephrostomy tube nor JJ stent (reserved for carefully selected patients).

7. CONTEMPORARY VARIANTS OF PCNL

The progressive miniaturization of instruments has given rise to multiple PCNL variants. Standard PCNL (24–30 Fr) remains the technique of choice for very large stone burdens, although it carries the highest risk of blood loss and overall complications. Mini-PCNL (16–22 Fr) has emerged as the preferred standard for moderate-sized stones, offering stone-free rates comparable to those of standard PCNL with a more favorable safety profile.

Ultra-mini PCNL (11–13 Fr) and micro-PCNL (4.85 Fr, employing the so-called all-seeing needle technology) have been developed to address smaller stones (1–2 cm) and bridge the therapeutic gap between ESWL and RIRS. These variants are particularly valuable in pediatric urology, where minimizing renal parenchymal trauma is of paramount importance.

8. COMPLICATIONS AND THEIR CLASSIFICATION

Despite its minimally invasive nature, PCNL is associated with a substantial complication rate of 15–25%. Complications are most commonly graded according to the modified Clavien-Dindo classification, which provides a standardized framework for outcome reporting.

Hemorrhage (5–10%): the most frequent complication of PCNL. Mild cases respond to conservative management, whereas major bleeding may require blood transfusion or selective renal

artery embolization. Delayed bleeding is often caused by pseudoaneurysm or arteriovenous fistula formation.

Sepsis and septic shock (0.3–4.7%): the most life-threatening complication, particularly in patients harboring multidrug-resistant organisms. Elevated intrarenal pressures during high-flow irrigation may force bacterial endotoxins into the systemic circulation, precipitating septic shock.

Pleural and pulmonary injury: associated with supracostal upper-pole access, presenting as pneumothorax, hydrothorax, or hemothorax. Most cases occur after punctures above the eleventh rib.

Adjacent organ injury: injuries to the colon (0.2–1%), duodenum, spleen, and liver have been reported. The presence of a retrorenal colon (in approximately 5% of patients) must be identified on preoperative CT.

Long-term complications: loss of functional renal parenchyma (≤1%), development of hydronephrosis, ureteral stricture formation, and stone recurrence.

9. EFFICACY AND CLINICAL OUTCOMES

The principal efficacy metric of PCNL is the stone-free rate (SFR). Reported SFR after monotherapy ranges from 78% to 95% in contemporary series. For staghorn calculi, single-session PCNL achieves an SFR of 56–80%, while staged multi-tract approaches can exceed 90%.

The global analysis conducted by the Clinical Research Office of the Endourological Society (CROES), encompassing 5,803 patients across 96 centers, identified the principal predictors of SFR as stone size and number, location (lower-pole stones being associated with reduced clearance), body mass index, and surgeon experience. The mean length of hospital stay in contemporary centers is 3–5 days, decreasing to 1–3 days with mini-PCNL and tubeless approaches.

10. DISCUSSION: COMPARATIVE ANALYSIS WITH ALTERNATIVE MODALITIES

In contemporary urological practice, the principal alternative to PCNL is RIRS performed with flexible ureteroscopy. Recent meta-analyses indicate that for stones up to 2 cm, RIRS achieves SFRs comparable to PCNL while offering a lower complication rate and shorter hospital stay. For stones exceeding 2 cm, however, PCNL maintains a clear advantage, with a significantly higher probability of single-session stone clearance.

When compared with ESWL, PCNL yields superior SFRs at the cost of greater invasiveness and the need for general anesthesia. The choice of modality is multifactorial and depends on stone characteristics, patient anatomy, comorbidities, and the technical capabilities of the institution. Current trends favor hybrid approaches, particularly ECIRS, which integrates the advantages of antegrade and retrograde access into a single procedure.

11. CONCLUSION

Percutaneous nephrolithotripsy remains the most effective minimally invasive modality for the management of large and complex renal calculi. Over four decades of continuous evolution, the

procedure has undergone substantial refinement through technical innovation, instrument miniaturization, and the introduction of advanced lithotripsy technologies. Stone-free rates of 78–95% consolidate the role of PCNL as the cornerstone of surgical stone management.

At the same time, the inherent risk of serious complications—including hemorrhage, sepsis, and adjacent organ injury—demands careful patient selection, comprehensive preoperative assessment, and a high level of operator expertise. Future directions in PCNL include artificial intelligence–assisted access planning, robotic PCNL, and next-generation laser and vacuum-aspiration systems, all of which promise to render the procedure safer, more efficient, and increasingly personalized.

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