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Stone Disease

Percutaneous Nephrolithotomy: Update, Trends, and Future Directions

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Abstract

Context: Percutaneous nephrolithotomy (PCNL) is the surgical standard for treating large or complex renal stones. Since its inception, the technique of PCNL has undergone many modifications.
Objective: To perform a collaborative review on the latest evidence related to outcomes and innovations in the practice of PCNL since 2000.
Evidence acquisition: A literature review was performed using the PubMed database between 2000 and July 2015, restricted to human species, adults, and the English language. The Medline search used a strategy including the following keywords: *percutaneous nephrolithotomy*, *PNL*, *advances*, *trends*, *technique*, and the Medical Subject Headings term *percutaneous nephrostomy*.
Evidence synthesis: Population-based studies have now provided a wealth of information regarding patient outcomes following PCNL. The complexity of the stone treated can be quantified using a variety of validated nephrolithometry classification systems. Increasing familiarity with the supine approach to PCNL has enabled simultaneous combined retrograde and antegrade surgery. Advances such as endoscopic guided percutaneous access may help urologists achieve access with less morbidity. Increasing miniaturization of equipment has led to the development of mini, micro, and ultramini techniques. The tubeless method of PCNL is now accepted practice with good evidence of safety in appropriately selected patients.
Conclusions: Modern-day PCNL allows personalized stone management tailored to individual patient and surgeon factors. Future studies should continue to refine methods to assess complexity and safety and to determine consensus on the use of miniaturized PCNL.
Patient summary: Modern-day percutaneous nephrolithotomy has transformed from an operation traditionally undertaken in one position, using one access method with one set of instrumentation and one surgeon, to one with a variety of options at each step.
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1. Introduction

It is often overlooked that the first description of percutaneous nephrolithotomy (PCNL) was a prolonged affair. In 1976, Fernström and Johansson reported on three patients who were unsuitable for open surgery and who had renal stones removed using a percutaneous technique [1]. A nephrostomy was inserted under local anesthesia and the tract dilated with a Couvelaire catheter, which was exchanged for larger catheters. Once the appropriate size was achieved, a catheter was left in place for 14 d. The stones were finally removed using fluoroscopy for intrarenal guidance.

This landmark publication led to the birth of endourology. Since 2000, PCNL has made open surgery for complex renal stones obsolete in most countries. We reviewed the latest developments in the practice of PCNL since then, including systematic efforts to assess outcomes and innovations in technique to enhance performance.

2. Evidence acquisition

A review of the literature was performed using PubMed. We identified original articles on PCNL restricted to the English language. Inclusion criteria were articles published from January 2000 to July 2015, discussing outcomes and innovations in surgical technique. All experimental and observational study designs were eligible for inclusion, including but not limited to controlled clinical trials, case series, and case–control and cohort studies. Comments, editorials, and review articles were not considered eligible. The literature search was conducted by the first author using the keywords *percutaneous nephrolithotomy OR PNL* and then restricted with the keywords *(AND) advances OR trends OR technique*. This search identified 3597 records. After excluding duplicate references, 3312 unique references were reviewed by title or abstract. A list of articles judged to be highly relevant by the junior (K.R.G.) and senior (J.dlR.) authors was circulated among the coauthors, and a final consensus was reached on the structure of this review and the articles included. Eligible studies known to the authors but not picked up by the search were also evaluated for inclusion. This resulted in an additional 22 unique records. Figure 1 shows a flowchart of the search process. A total of 134 unique references from this search were included in the qualitative synthesis. The studies included are varied (controlled clinical trials, case series, and case–control and cohort studies). Due to the likely heterogeneity of studies and the nonstandardized quality appraisal, a narrative synthesis rather than a quantified meta-analysis

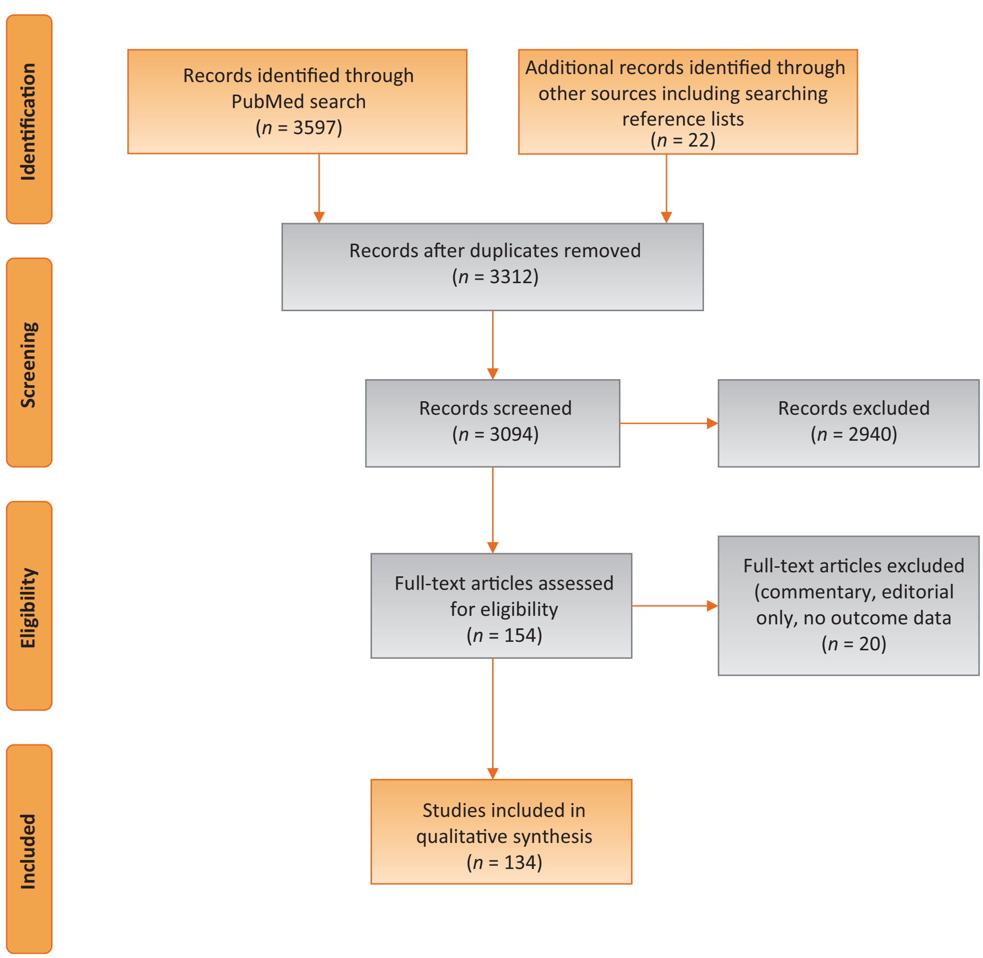

Fig. 1 – Flowchart of the literature search.

of data was performed. The limitations of using a single database for review are acknowledged [2]. In addition, outcomes may be limited by study heterogeneity and selection bias.

3. Evidence synthesis

3.1. Indications for percutaneous nephrolithotomy

The European Association of Urology guidelines recommend PCNL for the treatment of renal stones $\geq$2 cm and lower pole stones $\geq$1.5 cm [3]. The American Urological Association (AUA) guidelines recommend PCNL as the first-line treatment for staghorn calculi [4].

3.1.1. Trends in percutaneous nephrolithotomy publications

Supplementary Figure 1 demonstrates the number of publications in PubMed from 2000 to 2014 pertaining to the three most common treatment modalities for renal stones: shockwave lithotripsy (SWL), ureteroscopy (URS), and PCNL.

3.1.2. Trends in percutaneous nephrolithotomy utilization

PCNL utilization over the past decade has varied depending on the data source studied. An analysis of the Nationwide Inpatient Sample, an administrative data set containing 20% of all community hospitals in the United States, demonstrated an increase in the annual rate of PCNL during the period 1999–2009 [5]. Women saw the greatest increases compared with men. Similarly, PCNL use also increased in the United Kingdom [6]. In contrast, Lee and Bariol studied rates of stone procedures using data from the primary funder of health care in Australia [7]. Although the total number of all stone-related procedures had increased, the proportion for PCNL had decreased from 6% in 1995 to <3.5% in 2010. More recently, Ordon and colleagues studied trends for urolithiasis procedures in the Canadian province of Ontario and found PCNL use remained stable from 1991 to 2010 [8].

Local factors, availability, and expertise clearly influence the utilization of PCNL. In the United States, it accounts for 4.5% of all stone procedures [9]. In those countries more reliant on reusable instrumentation, its utilization is likely to be much higher. Although PCNL may not be as common as SWL or URS, it remains the signature piece for treating complex renal stones, a major procedure with the potential for significant morbidity.

3.2. Percutaneous nephrolithotomy outcomes

3.2.1. Administrative data

The modern era has seen a number of population-based studies assessing the prevalence and severity of complications after PCNL [5,8,10–12]. Common in-hospital complications include bleeding, urinary tract infection, fever, and sepsis [5,11]. Factors associated with an increased risk of complications include increasing patient age [5], female gender [10], operative time [10], and comorbidity [5,12]. In the United States, sepsis-related complications have increased [5]. One matter of concern is the rate of readmission following PCNL, which is as high as 15% in the United States [13], 12% in Canada [8], and 9% in the United Kingdom [11]. Increasing utilization in older and sicker patients may account for some of these findings [5]. Mortality, however, remains a rare complication at approximately 0.2% and is unchanged [5,11].

3.2.2. Registry data

Unlike administrative data, registries provide clinical details such as information on indications for surgery, stone size and location, stone clearance, and type of complications including the need for secondary procedures. Of late, data from two clinical registries have highlighted the current state of PCNL. The PCNL registry from the British Association of Urological Surgeons provided self-reported outcomes of >1000 PCNLs from 50 UK centers in 2010–2011 [14]. The overall complication rate was 21.3%; postoperative fever, sepsis, and transfusion rates were 16%, 2.4%, and 2.5%, respectively. The stone-free rate (SFR), defined as no visible stone on imaging, was 68%. Approximately a third of PCNLs were for staghorn stones.

The second registry is the PCNL Global Study Database maintained by the Clinical Research Office of the Endourology Society (CROES), the largest prospectively collected database of patients treated with PCNL. In 5724 patients undergoing PCNL in 96 centers worldwide over a 1-yr period, the overall complication rate was 20.5% [15]. In a separate analysis of outcomes for staghorn stones compared with nonstaghorn stones, frequent complications included fever (8.7–14.8%), bleeding (6.8–10.4%), collecting system perforation (2.8–4.4%), blood transfusion (4.5–9.0%), and hydrothorax (1.6–1.9%). The 30-d SFR was 69.7% [16]. This registry continues to be an important and growing source of information producing multiple studies that have helped assess the efficacy of PCNL and some of its controversies [17].

3.2.3. Clavien-Dindo classification scheme

The diversity of complications following PCNL and the need for uniform reporting has led to interest in the Clavien-Dindo system (grades 1–5) for reporting complications [18,19]. For PCNL, the Clavien score has been shown to have high validity, with higher scores associated with longer length of stay (LOS) [20]. Use of this system, however, is not as straightforward as we expect. In a CROES study of 528 patients with complications after PCNL, agreement among urologists grading complications using the Clavien method was moderate (κ = 0.48), with the lowest agreement for complications that are grade 1 or 2 (minor complications) [18]. To improve the reliability of reporting with the Clavien system, PCNL-specific complications have now been defined [18]. More recently, an expert consensus panel defined 15 outcomes that are considered the minimum standard when reporting on PCNL [21]. Efforts such as these are much needed to reduce the heterogeneity that currently exists within the literature.

3.2.4. Stone factors affecting percutaneous nephrolithotomy outcomes

3.2.4.1. Stone size and location. Stone size and location influence the safety and success of PCNL. Compared with pelvic stones, calyceal stones are associated with an increased risk of postoperative complications [22]. Xue and colleagues assessed CROES data on 1448 solitary nonstaghorn stones, and they also found that increasing stone size, especially stones >4 cm, was associated with significantly higher rates of fever and blood transfusion [22]. In addition, stone clearance suffers as size increases; the SFR for patients with solitary stones 2–3 cm in size was 90% compared with 84.1% if stones were >4 cm. Similar trends were noted in the UK PCNL registry [14].

3.2.4.2. Staghorn stones. Staghorn stones remain the most challenging stone to treat with PCNL. A meta-analysis conducted by the AUA guidelines panel on staghorn calculi showed that PCNL alone had the highest SFR (78%) for treating staghorn stones in comparison with combination therapy with SWL (66%) or SWL monotherapy (54%) [4]. More recently, of 1466 patients with staghorn stones undergoing PCNL in the CROES database, the SFR was only 56.9% [16]. SFRs for staghorn stones were even lower in the UK registry [14]. Increasing staghorn volume and complexity may predict the need for multiple tracts and staged procedures for successful stone clearance [23]. Success rates, however, may be higher in centers that have greater experience dealing with these stones. In an evaluation of 773 patients with staghorn stones, SFRs increased from 81% to 93% over an 18-yr period [24]. Data such as these suggest that staghorn stones might be better managed in tertiary referral centers adept at dealing with these complex stones.

3.2.4.3. Hounsfield unit. In addition to stone size and location, the Hounsfield unit (HU) of the stone on computed tomography (CT) may predict the success of PCNL. In a study of 179 patients undergoing PCNL, Gucuk et al found a HU <678 significantly decreased the likelihood of stone clearance [25]. In a larger CROES study, both very high and low HU values were associated with lower SFRs and long operative times [26]. Stones with low HU are especially likely to be uric acid or struvite in composition, which are poorly visible on fluoroscopy and thus more difficult to identify during PCNL.

3.2.5. *Patient factors affecting percutaneous nephrolithotomy outcomes*

Increasing patient age and obesity are risk factors for unsatisfactory outcomes after PCNL. In a study of 334 patients ≥70 yr of age matched with younger patients, the complication rate was increased twofold in older patients, who also had a greater chance of experiencing higher grade Clavien complications [27]. In contrast, PCNL in obese patients was associated with significantly longer operative times, lower SFRs, and higher retreatment rates but not an increase in complications [28]. Another factor to consider is anticoagulation during PCNL. With careful perioperative management, PCNL can be performed safely and efficiently in properly selected patients on long-term anticoagulation [29].

3.2.6. *Surgical volume and percutaneous nephrolithotomy outcomes*

Multiple reports have confirmed a volume–outcome relationship with PCNL. An early study analyzing the US nationwide data from 1988 to 2002 demonstrated a statistically significant increase in mortality in centers that performed fewer than nine cases per year [30]. More contemporary data suggest that higher volume surgeons have lower costs and their patients have shorter LOS [31]. Similarly, Kadlec et al demonstrated that hospitals who perform >33 PCNLs per year had significantly lower LOS [12]. CROES data have revealed that high-volume centers have lower complications and LOS, as well as better SFRs [32]. The highest SFRs were achieved in centers performing >120 cases per year. It is therefore not surprising that PCNL delivery has been increasingly regionalized to these high-volume centers [20,33].

3.3. *Surgical complexity: scoring systems for percutaneous nephrolithotomy*

The desire to predict outcomes for PCNL and, in particular, the important end point of SFR has led to the development of numerous nephrolithometric scoring systems (Table 1) [34–37]. By quantifying the complexity of the stone being treated, these scoring systems allow for likewise

Table 1 – Overview of four nephrolithometric scoring systems for percutaneous nephrolithotomy

	Guy's Stone Score [34]	Nephrolithometric nomogram [36]	STONE nephrolithometry [37]	Seoul Renal Stone Complexity score [35]
Method used to develop scoring criteria	Delphi process and literature review	Multivariate analysis using CROES data	Literature review	Not reported
Information needed to determine score	Clinical	Clinical and radiologic	CT	CT
Stone location	✓	✓	✓	✓
Stone size or volume		✓	✓	
No. of stones	✓	✓		
Staghorn stone	✓	✓		
Presence of hydronephrosis			✓	
CT Hounsfield unit			✓	
Tract length			✓	
Case volume		✓		
Prior treatment		✓		
Urinary tract anatomy	✓			
Spinal deformity	✓			

CROES = Clinical Research Office of the Endourology Society; CT = computed tomography.

comparisons of PCNL. They also serve as a useful aid for patient counseling and help identify those cases that might need staged or ancillary procedures for complete stone clearance. Supplement 1 provides details of these different scoring systems (Guy's Stone Score [GSS], STONE score, Seoul National University Renal Stone Complexity, and CROES nomogram). Supplementary Table 1 summarizes studies that have validated these scoring systems [38–45]. Okhunov et al found that the STONE score was able to predict the SFR with an accuracy of 83.1%, greater than any individual component of the score [37]. Smith et al found the CROES nomogram was better at predicting treatment success and SFR compared with the GSS (area under the curve = 0.76 vs 0.69; $p < 0.001$) [36]. In contrast, in a separate study assessing the GSS and the STONE score, there were no significant differences in predictive accuracy for SFR (0.74 vs 0.63; $p = 0.06$, respectively) [41]. The problem with some of these scoring systems is that certain criteria have unclear definitions, which hinders the overall interrater reliability [38,46]. No particular scoring system has been found to be vastly superior for predicting the SFR [41,42,45].

3.4. *Technical advances*

Figure 2 provides an evolutionary timeline of the various advances in surgical techniques.

3.4.1. *Positioning*

The prone position is the conventional method for performing PCNL, and for many years this aspect of surgery did not change. The supine position, originally described by Valdivia Uria and colleagues, poses less risk on positioning-related injuries and avoids the extra time needed for turning the patient to the prone position [47]. According to CROES data, it is currently used in 20% of centers worldwide; however, its practice in North America and Australia is more limited [48]. Proponents of supine positioning have advocated it is less demanding on patients with respiratory or cardiac difficulties. In addition, the downward direction of the tract and sheath helps with spontaneous drainage of fragments, and these lower pressures may result in less fluid absorption. It may also be much easier to reach the upper calyx through a lower pole puncture in the supine position compared with the prone because of a wider angle between the lower and upper calyx axes when supine [49].

Yet these perceived advantages have not been realized into any obvious clinical superiority when compared with the traditional prone method (Table 2) [48,50–63], except in some studies where the operative times have been shorter with the supine technique [50,56,57]. More importantly, these studies tell us that supine did not expose patients to more access-related bowel injury. Nevertheless, drawbacks such as a restricted working space, difficulty in performing upper pole puncture, and awkward rigid nephroscope manipulation requiring in several cases complementary flexible nephroscopy to overcome this limitation, have limited its universal adoption [64]. In a recent study assessing patients undergoing PCNL, no differences in peak inspiratory pressure were noted when the patient was prone versus supine [65].

One significant benefit of the innovation in supine technique is that it has enabled investigators to perform combined antegrade and retrograde procedures during PCNL. Many variations in the supine position have now been

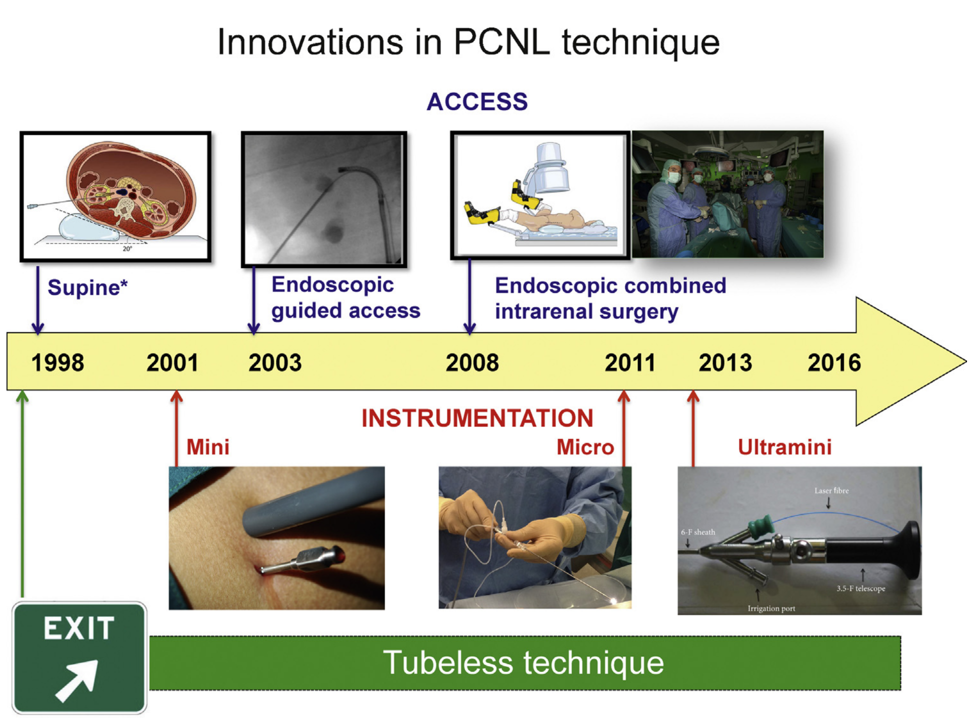

Fig. 2 – – Evolutionary timeline of recent innovations in percutaneous nephrolithotomy technique.
PCNL = percutaneous nephrolithotomy.
*** Supine PCNL first reported in 1987.**

Table 2 – Summary of studies comparing supine versus prone percutaneous nephrolithotomy

Study	Study period	Study design	Cases, n		Stone-free rate, %		Operative time, min		Hospital stay, d		Mean stone surface area, mm^2		Complication rate, %	
			PP	SP	PP	SP	PP	SP	PP	SP	PP	SP	PP	SP
Al-Dessoukey et al [51]	2011–2012	PR	102	101****	87.3	88.1	**111.7**	**86.2**	**3.4**	**2.1**	39.3*	36.8*	15.7	9.9
Wang et al [53]	2010–2011	PR	62	60	**88.7**	**73.3**	**78**	**88**	8.2	8.4	3.0**	3.1**	32.3	28.3
Karami et al [52]	2010–2011	PR	50	50	92	86	**68.7**	**54.2**	2.6	2.9	28.3	28.2	20	24
Basiri et al [54]	2009–2011	PR	46	43	65.2	79	111.3	110.2	**3**	**2.5**	345	352	**15.2**	**2.3**
Zhan et al [55]	2008–2010	PR	56	53	49	48	**86**	**56**	6	6	789.7	777.2	19.7	18.9
Falahatkar et al [56]	2008	PR	40	40	77.5	80	**106.9**	**74.7**	3.1	3.3	40.3*	40.6*	30	27.5
De Sio et al [50]	2005–2007	PR	36	39	91.6	88.7	**68**	**43**	4.1	4.3	33*	34*	13.9	20.6
Mazzucchi et al [57]	2008–2012	PN	12	30	83.3	78.1	**164.6**	**120.3**	**4.4**	**2.7**	1128	1020	12.5	3.1
McCahy et al [58]	2011	PN	41	41	65	71	**116.6**	**86.2**	2.5	2.5	**25.7***	**32.6***	–	–
Astroza et al [59]	2007–2009	PN	1079	232	**59.2**	**48.4**	**103.2**	**123.1**	5.2	5.7	402.2	446.4	**8**	**10.4**
Shoma et al [60]	1999–2000	PN	77	53	84	89	–	–	2.7	2.5	–	–	12	17
Sanguedolce et al [61]	2005–2010	MR	52	65	87.7	90.4	79	75	6.2	5.3	162	187	7.6	7.7
Valdivia et al [48]	2007–2009	MR	4637	1138	**77**	**70.2**	**82.7**	**90.1**	4.3	4.2	449.1	470.6	**23.9**	**19.4**
Wang et al [62]***	2004–2011	SR	12	6	91.7	83.3	104	128	9.1	9.2	33*	36*	0	0
Arrabal-Martin et al [63]	2000–2006	SR	32	24	75	79.2	105.3	81.2	5.2	5.4	530	510	31.3	29.2

MR = multicenter retrospective; PN = prospective nonrandomized; PP = prone positioned; PR = prospective randomized; SP = supine positioning; SR = single-center retrospective.
* Mean maximum diameter in millimeters.
** Mean stone volume in cubic centimeters.
*** Staghorn calculi.
**** Oblique supine.

reported including supine decubitus [66], Galdakao-modified Valdivia [67], and the Barts flank-free modified position [68], to name a few. Most of these modifications ease the access to the urethra, which allows for more comfortable simultaneous retrograde techniques during PCNL.

3.4.2. *Endoscopic guidance to facilitate renal access*

Obtaining safe percutaneous renal access is the hallmark of a good PCNL. Standard methods for obtaining access include fluoroscopic or ultrasound guidance that is performed either by urologists or radiologists. Dilatation techniques in standard use include Amplatz dilation, metal telescopic dilation, and balloon dilation [69]. In recent years, a minority of surgeons are performing alternative techniques such as endoscopic guided access (EGA) to facilitate retrograde or antegrade punctures [70].

3.4.2.1. Antegrade puncture: coming in. Initial reports of antegrade EGA consisted of the patient in the prone split-leg position, with URS used to confirm accurate caliceal puncture, after which it was removed following dilatation of the tract. Kidd and Conlin caught the antegrade puncture wire with a ureteroscopic basket and brought it out through the urethra, thus securing "through and through" access [71]. It was used as an aid to help for difficult cases such as complete staghorn or morbid obesity. Subsequently, Khan et al used it as a first-line procedure with combined fluoroscopic access, utilizing a ureteral access sheath and flexible URS for direct visualization of the puncture [72]. Proponents of this method cite advantages for a more accurate and safe caliceal puncture, and less utilization of radiation.

3.4.2.2. Endoscopic combined intrarenal surgery. Scoffone and coworkers broadened the scope of antegrade EGA by performing retrograde intrarenal surgery (RIRS) at the same time as PCNL in patients placed in the Galdakao-modified Valdivia position [73]. The concept extended beyond guiding a safe puncture but also used URS to improve stone clearance and treat stones that would be difficult to access through the percutaneous tract. In 127 patients, a single access was feasible in 98.4%, with an SFR of 81.9%. This technique allows for improved antegrade drainage and retrieval of fragments via the ureteral access sheath. More importantly, stones in parallel lying calyces do not necessitate a second puncture and are amenable to simultaneous RIRS [74]. Larger stones can also be basketed with the URS and relocated to the tract where they can then be retrieved via the rigid nephroscope, a maneuver known as *pass the ball* [75].

Endoscopic combined intrarenal surgery (ECIRS) is also feasible in the prone split-leg position. Isac et al compared prone EGA with standard fluoroscopic guided access and found overall operative times and bleeding were significantly reduced in patients undergoing EGA [76]. Secondary procedures to clear stones were significantly lower in these patients.

In a separate comparative study, ECIRS with a single small tract (18F) was compared with conventional PCNL. The results suggest ECIRS may be superior in SFR (81.7% vs 45.1%), with a lower incidence of bleeding, although a properly randomized study is required to confirm [77]. Although there may be distinct advantages to EGA or ECIRS, it is more costly because it requires two operating surgeons with two sets of equipment and ancillary instrumentation. In addition, if a stone occupies the target calyx, retrograde holmium laser lithotripsy is needed to clear a passage for the URS to visualize the puncture. Comprehensive value-based studies are needed to further establish the role of this method, especially in comparison with scenarios where access is obtained by radiologists instead of urologists.

3.4.3. *Miniaturized percutaneous nephrolithotomy*

The desire to reduce access-related complications and the morbidity related to the size of the tract has led to investigators assessing PCNL using smaller caliber instruments. This has opened the field to the increasing miniaturization of PCNL, with tracts ranging from 24F to 5F now available. The smaller instrumentation places less stress on the kidney and results in less bleeding compared with standard 30F instruments; however, to date, most studies comparing minimally invasive PCNL with standard PCNL have failed to demonstrate considerable differences in outcomes (Table 3) [78–93]. The preponderance of smaller instruments has led to calls for better labeling of PCNL, in relation to the size of the tract (ie, $PCNL^{+20}$, $PCNL^{+30}$, $PCNL^{+12}$) [94]. An alternative nomenclature that has been suggested uses XL, L, M, S, XS, and XSS to signify tract sizes (F) of $\geq$25, 20 to <25, 15 to <20, 10 to <15, 5 to <10, and <5, respectively [95].

3.4.3.1. Mini percutaneous nephrolithotomy. Mini-PCNL sets with sheath sizes are available in sizes of 15, 18, 19.5, or 24F [96]. One of the main attractions of mini-PCNL in comparison with other minimally invasive PCNLs is that it maintains the ability to use flexible nephroscopy. Regardless, superior nephron sparing has not been demonstrated when compared with standard PCNL [97], although mini-PCNL has shown a trend toward fewer complications and less bleeding, with less analgesic use. This may come at the cost of a lower SFR and longer operative times [80]. The benefit over RIRS may be a better SFR [85,87,88], avoidance of a ureteral stent, and reduced cost related to endourologic equipment such as flexible URS that may be harder to source and maintain in developing countries.

3.4.3.2. Ultramini percutaneous nephrolithotomy. Ultramini-PCNL uses a 6F inner sheath and 13F outer sheath that accommodates a 3.5F miniature nephroscope. Stones are fragmented with laser, but a side channel is used for irrigation of saline that produces an eddy of water current to evacuate the fragments. Experience with this technique is mostly limited to a single center [93] (Table 3).

3.4.3.3. Micro percutaneous nephrolithotomy. Bader et al used a 0.9-mm diameter micro-optical needle connected to a light source to perform optical puncture into the targeted calyx in 15 patients undergoing PCNL [92]. This was further

Table 3 – Studies assessing mini–percutaneous nephrolithotomy (PCNL), micro-PCNL, and ultramini-PCNL

Study	Study period	Study design	Tract size, F	Cases, *n*			Stone-free rate, %		Operative time, min		Hospital stay, d		Postoperative pain score (VAS), 0–10		Complication rate, %		Analgesics, mg	
				Non-ST	ST	RIRS												
MP vs ST							MP	ST	MP	ST	MP	ST	MP	ST	MP	ST	MP	ST
Cheng et al [78]	2004–2007	PR	16	72	115	–	**85.2**	**70**	**109.8**	**96**	7.3	7.5	4.3	4.3	23.6	35.7	88.7	94.3
Mishra et al [83]	2009–2010	PN	14–18	27	28	–	96	100	**45.2**	**31**	**3.2**	**4.8**	–	–	11.5	38.5	55.4	70.2
Knoll et al [79]	Published 2010	PN	18	25	25	–	96	92	59	49	**3.8**	**6.9**	3	4	16	32	25	37
Giusti et al [80]	1999–2004	R	14	40	67	–	77.5	94	**155.5**	**106.6**	**3.05**	**5.07**	5.53	6.36	–	–	73.8	88.1
Abdelhafez et al [81]	2007–2011	R	18	83	–	–	78.3	–	99.3	–	–	–	–	–	26.5	–	–	–
Lahme et al [82]	2000–2001	PN	15/18 and 16.5/19.5	19	–	–	100	–	99.2	–	–	–	–	–	5.2	–	–	–
MP vs RIRS							MP	RIRS	MP	RIRS	MP	RIRS	MP	RIRS	MP	RIRS	MP	RIRS
Sabnis et al [84]	2009–2011	PN	15 or 18	32	–	32	100	96.9	40.8	50.6	2.1	1.9	**2.7**	**2**	3.1	9.4	**66.1**	**28.1**
Zeng et al [85]	2012–2014	R	Up to 18	53	–	53	**71.7**	**43.4**	**43.8**	**55.4**	**6**	**2**	–	–	18.9	24.5	–	–
Kirac et al [86]	2009–2012	R	Up to 20	37	–	36	89.1	88.8	**53.7**	**66.4**	**1.8**	**1**	–	–	16.2	11.1	–	–
Pan et al [87]	2005–2011	R	18	59	–	56	**96.6**	**71.4**	**62.4**	**73.1**	**4.5**	**2**	–	–	11.9	16.1	–	–
Kruck et al [88]	2001–2007	R	15/18	172	–	108	**79.7**	**77.8**	–	–	**4.5**	**2.3**	–	–	**11.5**	**8.3**	2.7*	1.8*
Micro-PCNL							Micro	RIRS	Micro	RIRS	Micro	RIRS	Micro	RIRS	Micro	RIRS	Micro	RIRS
Sabnis et al [89]	2011–2012	PR	4.85	35	–	35	97.1	94.3	51.6	47.1	57	49	**1.9**	**1.6**	25.7	11.4	**90**	**40**
Desai et al [90]	2010	PN	4.85	10	–	–	88.9	–	–	–	2.3	–	–	–	10	–	60	–
Hatipoglu et al [91]	2011–2013	R	4.85	140	–	–	82.1	–	55.8	–	1.8	–	–	–	14.3	–	–	–
Bader et al [92]	Published 2011	Unclear	4.85	15	–	–	73.3	–	101.4	–	–	–	–	–	0	–	–	–
Ultramini-PCNL																		
Desai et al [93]	2012	R	11–13	62	–	–	97.2		59.8		3		–		16.7		–	

MP = mini-PCNL; PCNL = Percutaneous nephrolitomy; PN = prospective nonrandomized; PR = prospective randomized; R = retrospective; RIRS = retrograde internal surgery; ST = standard; VAS = visual analogue score.
All pain assessments are at postoperative day 1. Values in bold are statistically significant.
[*] Analgesic duration (days).

developed so that the whole PCNL was done through a 4.85F tract using the optical needle as camera without dilatation: micro-PCNL [90]. In a later randomized controlled trial (RCT) comparing micro-PCNL with RIRS for treating stones <1.5 cm, no differences in SFRs were found [89]; however, micro-PCNL was associated with greater blood loss, increased pain, and more analgesic use. Another drawback of micro-PCNL is the risk of conversion to standard or mini-PCNL due to bleeding obscuring vision [90,91]. In addition, stones cannot be retrieved through the small working channel but only pulverized using the holmium laser, and most importantly, there is no outflow from the scope that can cause a significant increase in intrarenal pressure [98].

In general, it has yet to be seen whether micro and ultramini approaches will have a routine place in our armamentarium and overtake RIRS, which is less invasive and does not necessitate percutaneous access skills. They could have a unique role in treating 1- to 1.5-cm lower pole stones that are inaccessible to flexible URS but not big enough for a standard PCNL. Moreover, innovations in these instruments are likely to benefit percutaneous surgery in children.

3.4.4. *Exit strategy: tubeless*

Nephrostomy tubes traditionally are placed at the end of PCNL with the intended purpose of tamponading bleeding from the tract, promoting urinary drainage in the event of ureteral obstruction, and maintaining access in case of the need for a second-look procedure. Multiple comparative studies over the last decade have confirmed that in selected cases, outcomes are not compromised if patients are managed with a ureteral stent and no nephrostomy tube (tubeless), or even without [99,100] a stent or nephrostomy tube (totally tubeless) [101].

The tubeless technique for PCNL has been extensively studied with at least 19 RCTs examining the efficacy of this approach (Table 4) [99,100,102–118]. The main reasons for using a tubeless technique are to reduce postoperative pain, analgesic requirements, and LOS. Multiple studies have shown that in the uncomplicated case, tubeless does not lead to an increase in complications [119]. Other options for a tubeless method are to use open-ended ureteral catheters that are removed the following day or tethered stents coming out of the tract that are removed in the office [102]. The attraction of the totally tubeless method is avoidance of a second procedure to remove the ureteral stent, as well as stent-related morbidity.

Contraindications for a tubeless technique include significant bleeding, major collecting system perforation, infection stones, and where multiple tracts have been undertaken. Relative contraindications include staghorn stones and patients with a reconstructed urinary tract. Investigators have assessed the role of hemostatic and biologic sealants in preventing bleeding from the tract or urinary leakage from the flank, but the routine use of these agents is unnecessary and costly [120]. Even in the best of hands, not all PCNLs are feasible for a tubeless approach [121]. If a tube is to be placed, a larger tube may result in lower bleeding and fewer complications [122], although larger tubes are associated with increased postoperative pain [116,123].

3.5. *Postprocedure: imaging and residual fragments*

Recent work utilizing CT in the follow-up of patients has evaluated the long-term significance of residual fragments (RFs) after PCNL. Raman and coworkers followed 42 patients with CT-detected RFs over a median of 32 mo and found that 43% experienced a stone-related event [124]. On multivariate analysis, RFs >2 mm were the only independent predictor of a stone event. In a larger study of 75 patients with CT follow-up, Osman et al found that RFs >3 mm significantly predicted stone growth and secondary interventions [125]. In contrast, in 129 patients followed after PCNL for a median of 5.4 yr, the cumulative retreatment rates were equivalent for patients with RFs <2 and >2 mm (30–33%) [126]; however, patients who were completely stone free had a retreatment rate of only 4%.

Steps to maximize stone clearance at PCNL include routine use of flexible nephroscopy, high-resolution fluoroscopy [127], and perioperative CT to assess the need for intervention in the same admission. Second-look procedures in patients with RFs >4 mm were found to be cost effective when compared with an observational strategy [128]. Even in expert hands, obtaining completely stone-free outcomes can be challenging [127]. However, not all RFs are equal. Those located in the lower pole, renal pelvis, infection stones, or associated with a previous intervention, renal failure, and metabolic abnormalities may have greater clinical consequences [129]. In particular, non–calcium-based stones such as struvite and uric acid have a far greater risk of retreatment [126].

3.6. *Future directions*

What will PCNL look like in 5–10 yr? First, the quest for the perfect access technique will continue. Preoperative planning might routinely incorporate three-dimensional (3D) CT planning [130] including the use of easy to engineer 3D models for navigation [131]. Access may incorporate augmented technology using tablet computers to superimpose CT images [132] or rely on tracking systems [133]. In terms of instrumentation, it is possible we may do more mini-PCNLs because with mini-PCNL one can rely on the suction effect of the increased flow. The question remains though, what size? This may eventually be somewhere between 16 and 22F. As such, energy sources will become tailored to the size of the tract. Larger sized stones, however, may be more suited for combined ultrasound/ballistic devices, and advances in ancillary instrumentation will be crucial [134]. For smaller size tracts, developments in holmium laser technology and in particular the dusting technique may prove significant. Multipuncture, multitract PCNL might become rare. ECIRS with PCNL could become the standard of care in specialist centers—where a team of surgeons will facilitate EGA, to reduce both access-related morbidity and increase the SFR. In addition, the ambulatory approach may become more feasible as the PCNL technique

Table 4 – Summary of randomized controlled trials assessing tubeless percutaneous nephrolithotomy

Study	Size of tube, F	Cases, *n*		Mean stone size		Stone-free rate, %		Operative time, min		Hospital stay, d		Analgesic requirement, mg		Complication rate, %	
	TL	TL	ST	TL	ST	TL	ST	TL	ST	TL	ST	TL	ST	TL	ST
Agrawal et al [102]	12	83	83	3.6 cm^2	3.8 cm^2	100	100	–	–	**0.9**	**2.3**	**81.3**	**128.0**	–	–
Cormio et al [103]	16	50	50	30.2 mm	32.2 mm	87.8	87.2	83.7	88.4	**2.8**	**5.2**	1.2[*]	1.2[*]	**2.0**	**25.5**
Lu et al [104]	16	16[†]	16[†]	3.3 cm	3.1 cm	No difference		59.7	65.2	**3**	**4**	–	–	25.1	12.5
Shoma and Elshall [105]	22	50	50	1004 mm^2	1226 mm^2	92	84	60	Overall	2.7	3.3	**96**	**194**	14.0	20.0
Yun et al [106]	20	30	27	13.6 cm^3	17.4 cm^3	77.8	73.3	128.7	148.5	**3.92**	**8.25**	**30.3**	**69.5**	10	15
Chang et al [107]	20	58	60	24.9 mm	24.7 mm	–	–	31.7	33.1	**3.4**	**4.2**	**61.5**	**75.5**	8.3	5.6
Marchant et al [99]	18	45	40	7.8 cm^2	6.4 cm^2	–	–	–	–	**3.2**	**5.0**		**Higher for ST PCNL**	5.0	2.2
Kara et al [100]	18	30	30	22.3 mm	25.6 mm	86.0	83.0	41	45	**1.5**	**3.2**	**0.5**[**]	**1.4**[**]	13.3	13.3
Li et al [108]	10	11	20[††]	2.15 cm	2.52 cm	48.0	10.0	161.1	137.2	1.6	2.0	24.0	24.3	–	–
Istanbulluoglu et al [109]	14	45	45	453.4 mm^2	448.9 mm^2	–	–	52.6	64.1	**2.1**	**3.5**		**Higher for ST PCNL**	**4.4**	**13.3**
Mishra et al [110]	20	11	11	–	–	72.7	90.9	–	–	2.9	3.0	68.2	72.7	54.5	18.2
Agrawal et al [111]	16	101	101	3.6 cm^2	3.8 cm^2	100	100	–	–	**0.9**	**2.3**	**81.7**	**126.5**	5.0	10.9
Crook et al [112]	26	25	25	21.6 mm	17.5 mm	96.0	84.0	–	–	**2.3**	**3.4**	16.9	34.7	12.0	24.0
Shah et al [113]	8	32	33	495.9 mm^2	535.4 mm^2	87.9	87.5	50.6	46.9	1.4	1.8	**150.0**	**246.1**	18.2	21.9
Choi et al [114]	8.2	12	12	26.8 mm	28.5 mm	–	–	82.1	79.5	1.6	1.6	9.1	10.7	–	–
Tefekli et al [115]	14	18	17	3.3 cm^2	3.0 cm^2	100	100	59.6	67.3	**1.6**	**2.8**	**110.3**	**224.3**	0	0
Desai et al [116][***]	20	10	10	249.1 mm^2	263.7 mm^2	–	–	45.5	45	**4.4**	**3.4**	217.5	87.5	–	–
	9		10	243 mm^2	–	–	–	–	44.5	–	**4.3**	–	140.0	–	–
Karami et al [117]	ND	30	30	–	–	90	90	106.9	74.7	1.5	3.0	30	90	6.6	3.3
Feng et al [118]	22	8	10	4.4 cm^3	8.4 cm^3	71.4	37.5	128	129	**1.9**	**4.1**	**5.3**	**52.0**	0.0	10.0

ND = not defined; PCNL = percutaneous nephrolithotomy; ST = standard; TL = tubeless.
Values in boldface are statistically significant.
[*] No. of doses during first 24 postoperative hours.
[†] Mini-PCNL.
[**] Milligrams per kilogram.
[††] 50% FloSeal, 50% fascial stitch.
[***] Incorporated both 20F and 9F nephrostomy tubes.

is further refined [135]. Finally, collaboration among urologists will grow, with development of real-time clinical registries that provide patients and providers with information that feeds further improvements in quality and patient safety.

4. Conclusions

Our understanding of PCNL has vastly improved through the study of population-based data sources and registries that have provided a wealth of outcome information. Adopting the Clavien-Dindo system provides a consistent framework for improving the quality of PCNL reporting. Of the different nephrolithometry classification systems, although the GSS is the most studied, no single system has been shown to be superior. Further studies and modifications may change that in the future. Increasing familiarity with the supine approach has opened the door for ECIRS and single-tract surgery. Obtaining optimal renal access is a crucial step in the learning curve of PCNL, and it is possible that EGA could shorten this curve. The propagation of minimally invasive refinements has been spurred by the desire to reduce access-related complications and bleeding. In particular, micro and ultramini techniques are in their infancy and require further investigation. During PCNL, efforts for initial stone clearance should be maximized to avoid the risk of retreatment from RFs. Postprocedure, even RFs <2 mm may have significant consequences. It is increasingly clear that the exit strategy does not have to be a nephrostomy tube in every single patient.

In this era in which surgical techniques are easily shared around the world, PCNL has been transformed from an operation traditionally undertaken in one position, using one access method with one set of instrumentation and one surgeon, to one with a variety of options at each step. Consequently, we can offer personalized stone management tailored to the local environment and individual patient.

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Study concept and design: Ghani, de la Rosette.
Acquisition of data: Ghani.
Analysis and interpretation of data: Ghani, Giusti, de la Rosette, Bultitude, Okhunov, Andonian.
Drafting of the manuscript: Ghani, de la Rosette.
Critical revision of the manuscript for important intellectual content: Ghani, Giusti, de la Rosette, Bultitude, Okhunov, Andonian, Preminger, Desai.
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