Original Article

Comparative efficacy of different surgical techniques for pediatric urolithiasis—a systematic review and meta-analysis

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Background: Prior research has assessed a range of surgical treatments for pediatric urolithiasis, emphasizing the necessity of tailor-made therapeutic approaches. These studies also show the adaptability of percutaneous nephrolithotomy (PCNL), retrograde intrarenal surgery (RIRS), and shock wave lithotripsy (SWL) in managing diverse stone dimensions. The goal of this research was to examine the effectiveness of these varying surgical methods in treating pediatric urolithiasis.

Methods: Seven digital databases were explored to gather pertinent studies, following the guidelines established by the PRISMA protocol. The retrieved studies were subsequently scrutinized to draw comparisons between the stone-free rate (SFR) and the rate of complications associated with PCNL, RIRS, and SWL.

Results: The SFR evaluation revealed no notable disparity between PCNL and RIRS [odds ratio (OR) 1.43, 95% confidence interval (CI): 0.67–3.05, P=0.36]. However, it was observed that both PCNL and RIRS outperformed SWL in terms of effectiveness (OR 2.51, 95% CI: 1.19–5.29, P=0.02 and OR 2.42, 95% CI: 1.41–4.14, P=0.001 respectively). Regarding the complication rates, no significant differences were observed among the three surgical methods (OR 0.67, 95% CI: 0.49–1.59, P=0.05), albeit with various forms of complications being reported. Certain studies associated PCNL with an elevated rate of complications, specifically urinary tract infections (UTIs) and severe hematuria.

Conclusions: Though PCNL and RIRS demonstrated higher effectiveness than SWL in achieving SFR, there was no significant disparity in the rates of complications across all three procedures. The study underscores the significance of personalized treatment plans, taking into account aspects such as the dimension and location of the stone, along with patient-specific characteristics.

Keywords: Pediatric urolithiasis; stone-free rate (SFR); complication rates; percutaneous nephrolithotomy (PCNL); retrograde intrarenal surgery (RIRS); shock wave lithotripsy (SWL)

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Introduction

Pediatric urolithiasis, the occurrence of urinary stones in children, is a significant health problem with increasing incidence worldwide (1). The clinical management of urolithiasis in the pediatric population presents unique challenges due to the specific anatomical and physiological characteristics of children, and their higher tendency for metabolic abnormalities and stone recurrence compared to adults (2).

Pediatric urolithiasis presents a significant conundrum in both its diagnosis and treatment. Over the preceding quarter-century, there has been a noticeable uptick in its incidence (1-7). Adverse lifestyle and environmental factors such as high-sodium and high-protein diets, inadequate hydration, obesity, hypertension, environmental contaminants, life acceleration, and unregulated consumption of multivitamins and dietary supplements are implicated in the heightened morbidity associated with the condition (8-10). Concurrently, advancements in diagnostic precision, coupled with the rising prevalence of ultrasound and computed tomography (CT) scans in diagnosing abdominal and lumbar pain, have significantly boosted the detection rates of urolithiasis (11).

The epidemiology of pediatric urolithiasis varies significantly between low-income and high-income countries, and this divergence can influence both the approach to treatment and the outcomes reported in the literature (12). High-income countries may have a higher prevalence of certain risk factors for kidney stones, such as dietary factors and sedentary lifestyles, while in low-income countries, issues like malnutrition, infections, and dehydration are more common etiologies. The discrepancy in economic resources also affects the availability of advanced medical devices and the range of surgical options offered. High-income settings are more likely to have access to the latest technology, such as miniaturized percutaneous nephrolithotomy (PCNL) equipment, flexible ureteroscopes, and even robotic systems, and the surgeons there tend to be more proficient with these state-of-the-art tools due to better training opportunities and higher patient volumes (13).

In contrast, low-income countries may rely more on less expensive and more widely available treatments like shock wave lithotripsy (SWL) or open surgery, and the expertise in advanced endourological procedures may be limited. Furthermore, the equipment used in pediatric urology is often adapted from that designed for adults, which can present additional challenges in pediatric cases—particularly in low-income settings where the adaptation of such equipment may not always be feasible or safe (13). The learning curve for surgeons in these environments can be steep, as they might not have the same opportunities to gain experience with a broad range of devices or the most modern techniques. This disparity underscores the importance of considering the economic and educational context when interpreting the results of studies on pediatric urolithiasis from different regions, and it may also suggest the need for different treatment algorithms based on resource availability (13). Renal calculi can affect individuals across the age spectrum, with cases reported in neonates as young as 4 days old. However, the median age of pediatric patients with urolithiasis hovers around 7–8 years (11). This recurrence rate is particularly high in pediatric patients with

Highlight box

Key findings

- This manuscript provides new evidence on the comparative effectiveness of percutaneous nephrolithotomy (PCNL), retrograde intrarenal surgery (RIRS), and shock wave lithotripsy (SWL) in treating pediatric urolithiasis.
- The study found no significant difference in the stone-free rate (SFR) between PCNL and RIRS, indicating that both are similarly effective. However, both PCNL and RIRS were found to be more effective than SWL.
- In terms of complication rates, there were no significant differences identified among the three surgical options, though the types of complications varied, with PCNL being associated with higher risks of urinary tract infections and severe hematuria.

What is known and what is new?

- Prior studies have established that pediatric urolithiasis can be treated with various surgical methods, including PCNL, RIRS, and SWL. These procedures are adaptable and have been recommended based on the specific circumstances of the stone's characteristics, such as size and location, and patient factors.

What is the implication, and what should change now?

- The findings suggest that while PCNL and RIRS are superior to SWL in terms of SFR, the choice of surgical method should not be based solely on effectiveness. The complication profiles of each method must also be considered.
- Given the results, clinicians should continue to approach pediatric urolithiasis treatment on a case-by-case basis, considering both the effectiveness and the potential for complications associated with each surgical method. The decision-making process should incorporate the stone's size, location, patient-specific factors, and the family's preferences after discussing the potential risks and benefits of each procedure.

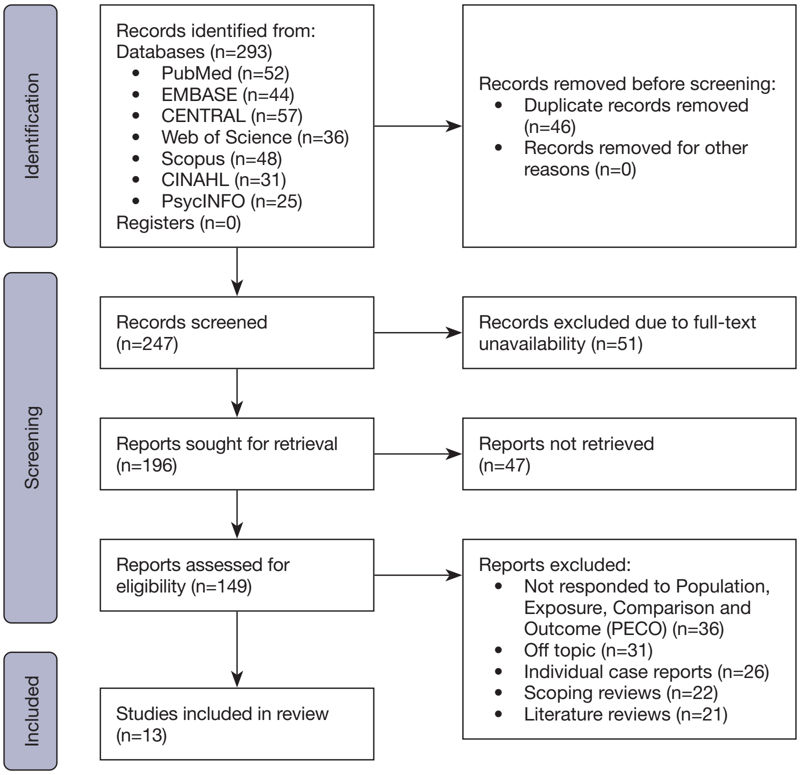

Figure 1 PRISMA protocol representation of the study selection process for this review.

metabolic disorders.

Therefore, it is crucial to select a treatment modality that ensures the least invasive yet most effective stone removal. Spontaneous elimination occurs in more than 80% of all cases, obviating the need for intervention (13). The remaining cases necessitate conservative or surgical management. The choice of treatment hinges on a multitude of factors, including the stone's location, size, and composition, the patient's age, anatomical considerations, urinary flow issues, or recurrent urinary tract infections (UTIs) (11).

A number of surgical modalities have been developed to treat pediatric urolithiasis. Due to its non-invasive nature, extracorporeal shock wave lithotripsy (ESWL), which breaks up stones into tiny fragments that can be passed in the urine by using shock waves, has been utilised extensively for pediatric urolithiasis (6). For bigger stones, PCNL, a minimally invasive surgery that entails making a small skin incision and building a tunnel into the kidney to remove the stone, has been proven to be very successful (7). Retrograde intrarenal surgery (RIRS) provides an additional minimally invasive option by using a flexible scope to identify and remove stones (9).

The choice of surgical technique is often based on factors such as the size, location, and composition of the stone, the age and overall health of the patient, and the surgeon's expertise. However, there is currently a lack of consensus regarding the most effective and safe surgical technique for pediatric urolithiasis. Therefore, the aim of this systematic review and meta-analysis was to compare the efficacy and safety of ESWL, PCNL, and RIRS for the treatment of pediatric urolithiasis. We present this article in accordance with the PRISMA reporting checklist (available at https://tau.amegroups.com/article/view/10.21037/tau-23-676/rc) (14).

Methods

Selection criteria

This review was registered in PROSPERO. A flow diagram of the study selection process is presented in *Figure 1*.

The Population, Exposure, Comparison and Outcome (PECO) protocol utilised for this review is presented as follows:

- ❖ P (Population)—children and adolescents (aged 0 to 18 years) diagnosed with urolithiasis without any restrictions on race, nationality, or health status;

- ❖ E (Exposure)—patients who had undergone ESWL, PCNL and RIRS;
- ❖ C (Comparison)—comparisons between the three surgical techniques (ESWL *vs.* PCNL, ESWL *vs.* RIRS, and PCNL *vs.* RIRS);
- ❖ O (Outcomes)—successful stone removal, defined as stone-free status and clinically insignificant residual fragments within a specified follow-up period after the surgery, and number of complications encountered during or after the procedure, including but not limited to bleeding, infection, damage to surrounding organs, need for re-intervention, and length of hospital stay. The primary outcome was the successful stone removal, defined as stone-free status, with the range of follow-up for this definition being clearly specified to ensure uniformity, drawing upon established literature for standardization (Tasian *et al.*) (2). Secondary outcomes included stratifying complications and adverse events according to the Clavien-Dindo classification to detail the severity of such events. Additionally, the number of procedures required to achieve stone-free status, the utilization of any urinary diversion methods, and the length of hospital stay were assessed separately.

Given below are different inclusion and exclusion criteria utilised for the review in terms of the PECO protocol.

Inclusion criteria

- ❖ Population: children and adolescents aged 0 to 18 years diagnosed with urolithiasis.
- ❖ Intervention: patients who underwent ESWL, PCNL, or RIRS.
- ❖ Comparator: studies that included comparisons between ESWL, PCNL, and RIRS.
- ❖ Outcomes: studies that reported on the efficacy of treatment, specifically successful stone removal and the number of complications encountered.

Exclusion criteria

- ❖ Population: studies that focused solely on adults (over 18 years old).
- ❖ Intervention: research involving surgical techniques other than ESWL, PCNL, or RIRS.
- ❖ Comparator: studies lacking a direct comparison between ESWL, PCNL, and RIRS.
- ❖ Outcomes: studies that failed to provide data on successful stone removal or the complications of the procedures.

By selecting studies within the past decade (from 2013 onwards) this review aimed to provide a more updated view on the developments across the domain of pediatric urolithiasis and the associated surgical modalities. There was no limitation placed pertaining to the language of the assessed publications. We also acknowledge the potential value of age stratification within pediatric populations to reduce heterogeneity and yield more precise conclusions. However, our decision to omit such stratification was primarily driven by the intent to include a comprehensive dataset within this systematic review and meta-analysis. The overarching aim was to assess the comparative efficacy of surgical techniques across the entire pediatric age spectrum, recognizing that the incidence of urolithiasis, although less frequent in children compared to adults, does not concentrate within a specific pediatric subpopulation.

Moreover, the literature on pediatric urolithiasis is relatively sparse, and subdividing the already limited data into narrower age groups could have resulted in a significant reduction in sample size for each stratum. This would likely compromise the statistical power of our analysis and might lead to inconclusive or biased outcomes due to the small cohorts. Consequently, the decision to evaluate the pediatric population as a single group was a methodological consideration to maximize sample size and maintain robustness in our comparative analysis.

Database search protocol

We developed a comprehensive search strategy to explore seven databases: PubMed, EMBASE, Cochrane Central Register of Controlled Trials (CENTRAL), Web of Science, Scopus, CINAHL, and PsycINFO. The search commenced on August 2023. We used a combination of MeSH terms and Boolean operators as shown in *Table 1*. MeSH terms are standardized words or phrases used to describe specific topics consistently across publications.

Variable extraction protocol

To extract the data for our systematic review and meta-analysis, we developed a standardized data extraction form that was used by two independent reviewers. The

Table 1 Search strings utilised across the databases

Database	Search strategy
PubMed (MEDLINE)	(“Urolithiasis”(Mesh) OR “kidney stone*” OR “urinary calculi” OR “bladder calculi”) AND (“Child”(Mesh) OR “Adolescent”(Mesh) OR “pediatric” OR “paediatric”) AND (“Lithotripsy, Extracorporeal Shock Wave”(Mesh) OR “ESWL” OR “Extracorporeal Shock Wave Lithotripsy”) AND (“Nephrolithotomy, Percutaneous”(Mesh) OR “PCNL” OR “Percutaneous Nephrolithotomy”) AND (“Retrograde Intrarenal Surgery” OR “RIRS”)
EMBASE	(‘urolithiasis’/exp OR ‘kidney stone*’ OR ‘urinary calculi’ OR ‘bladder calculi’) AND (‘child’/exp OR ‘adolescent’/exp OR ‘pediatric’ OR ‘paediatric’) AND (‘extracorporeal shock wave lithotripsy’/exp OR ‘ESWL’ OR ‘Extracorporeal Shock Wave Lithotripsy’) AND (‘percutaneous nephrolithotomy’/exp OR ‘PCNL’ OR ‘Percutaneous Nephrolithotomy’) AND (‘retrograde intrarenal surgery’ OR ‘RIRS’)
Cochrane Central Register of Controlled Trials (CENTRAL)	(MeSH descriptor: (Urolithiasis) explode all trees OR ‘kidney stone*’ OR ‘urinary calculi’ OR ‘bladder calculi’) AND (MeSH descriptor: (Child) explode all trees OR MeSH descriptor: (Adolescent) explode all trees OR ‘pediatric’ OR ‘paediatric’) AND (MeSH descriptor: (Lithotripsy, Extracorporeal Shock Wave) explode all trees OR ‘ESWL’ OR ‘Extracorporeal Shock Wave Lithotripsy’) AND (MeSH descriptor: (Nephrolithotomy, Percutaneous) explode all trees OR ‘PCNL’ OR ‘Percutaneous Nephrolithotomy’) AND (‘Retrograde Intrarenal Surgery’ OR ‘RIRS’)
Web of Science	(TS=(“Urolithiasis”) OR TS=(“kidney stone*”) OR TS=(“urinary calculi”) OR TS=(“bladder calculi”)) AND (TS=(“Child”) OR TS=(“Adolescent”) OR TS=(“pediatric”) OR TS=(“paediatric”)) AND (TS=(“Lithotripsy, Extracorporeal Shock Wave”) OR TS=(“ESWL”) OR TS=(“Extracorporeal Shock Wave Lithotripsy”)) AND (TS=(“Nephrolithotomy, Percutaneous”) OR TS=(“PCNL”) OR TS=(“Percutaneous Nephrolithotomy”)) AND (TS=(“Retrograde Intrarenal Surgery”) OR TS=(“RIRS”))
Scopus	(TITLE-ABS-KEY(urolithiasis OR “kidney stone*” OR “urinary calculi” OR “bladder calculi”) AND TITLE-ABS-KEY(child OR adolescent OR pediatric OR paediatric) AND TITLE-ABS-KEY(“extracorporeal shock wave lithotripsy” OR ESWL OR “Extracorporeal Shock Wave Lithotripsy”) AND TITLE-ABS-KEY(“percutaneous nephrolithotomy” OR PCNL OR “Percutaneous Nephrolithotomy”) AND TITLE-ABS-KEY(“retrograde intrarenal surgery” OR RIRS))
CINAHL	(MH “Urolithiasis” OR “kidney stone*” OR “urinary calculi” OR “bladder calculi”) AND (MH “Child” OR MH “Adolescent” OR “pediatric” OR “paediatric”) AND (MH “Lithotripsy, Extracorporeal Shock Wave” OR “ESWL” OR “Extracorporeal Shock Wave Lithotripsy”) AND (MH “Nephrolithotomy, Percutaneous” OR “PCNL” OR “Percutaneous Nephrolithotomy”) AND (“Retrograde Intrarenal Surgery” OR “RIRS”)
PsycINFO	(DE “Urolithiasis” OR “kidney stone*” OR “urinary calculi” OR “bladder calculi”) AND (DE “Child” OR DE “Adolescent” OR “pediatric” OR “paediatric”) AND (DE “Lithotripsy, Extracorporeal Shock Wave” OR “ESWL” OR “Extracorporeal Shock Wave LithotSure, here’s a table reflecting the search strategy used for different databases. Please note that each database has its own terminology and syntax, so the search strings vary accordingly

MEDLINE, Medical Literature Analysis and Retrieval System Online; MeSH, Medical Subject Headings; ESWL, extracorporeal shock wave lithotripsy; PCNL, percutaneous nephrolithotomy; RIRS, retrograde intrarenal surgery; CENTRAL, Cochrane Central Register of Controlled Trials; TS, topic search (used in Web of Science); TITLE-ABS-KEY, title, abstract, keywords (used in Scopus); MH, medical headings (used in CINAHL); DE, descriptor (used in PsycINFO).

form included sections for study characteristics, patient characteristics, intervention details, and outcome data. For the study characteristics, we extracted the year of publication, country where the study was conducted, study design (randomized controlled trial, non-randomized controlled trial, cohort study, case-control study), and sample size.

We incorporated objective tools to define the severity of urolithiasis. These tools included standardized scoring systems, such as the Guy’s Stone Score or the STONE nephrolithometry score, which assesses stone burden based on size, location, and number, as well as other factors like stone density and skin-to-stone distance on CT imaging. Including such metrics in our data extraction allowed for a consistent and quantifiable measure of stone complexity across studies.

Moreover, in the section detailing intervention methods, we recognized the importance of specifying the size of the nephrostomy tract used in PCNL procedures, as this can significantly impact both outcomes and complication rates. Thus, we differentiated between mini-PCNL—where the tract size is typically less than 20 French (Fr)—and standard PCNL, which usually involves a tract size greater than 20 Fr. This distinction is crucial because mini-PCNL is often chosen for pediatric patients due to the reduced risk of complications and less postoperative pain compared to

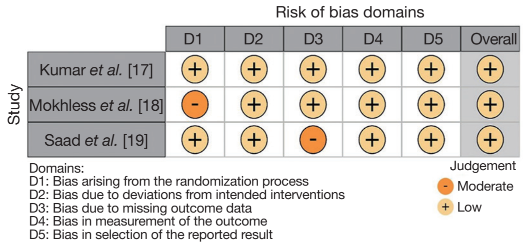

Figure 2 Risk of bias assessed across the RCTs selected for the review (17-19). RCTs, randomized control trials.

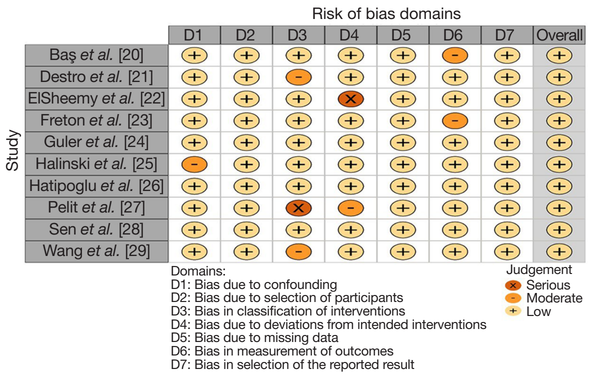

Figure 3 Risk of bias assessed across the case-cohort trials selected for the review (20-29).

standard PCNL, factors that are especially important in the delicate anatomy of children.

In terms of patient characteristics, we collected data on age, sex, stone size and location, and the severity of urolithiasis. For intervention details, we extracted data on the type of surgical technique used (ESWL, PCNL, or RIRS) and any additional treatments that were provided. We collected outcome data, specifically the efficacy of the surgical technique in terms of successful stone removal (defined as stone-free status or clinically insignificant residual fragments within a specified follow-up period) and the number of complications encountered during or after the procedure. Both reviewers independently extracted the data from each included study. Any disagreements between the reviewers were resolved through discussion until a consensus was reached. In cases where a consensus could not be reached, a third reviewer was consulted.

Bias assessment protocol

Using the RoB 2 (15) and the ROBINS-I (16) tools respectively, we evaluated the quality and risk of bias of the included studies. The findings of these analyses are shown in *Figure 2* and *Figure 3*, respectively.

Meta-analysis protocol

Our software of choice for the meta-analysis portion of our systematic review was RevMan 5.0. In treating pediatric urolithiasis, we compared the safety and effectiveness of three surgical techniques: PCNL, RIRS, and ESWL. We measured the effect size of both the number of problems and the efficacy in terms of stone removal using odds ratios (ORs). We determined or extracted the OR for both successful stone removal and complications for every combination of surgical methods for every study that was included. This was carried out in accordance with the total number of patients in each group as well as the number of events (successful stone removal and sequelae). Taking into account the anticipated variations in methodology and clinical practises among the included studies, we employed a random-effects model to compute the pooled odds ratios and associated 95% confidence intervals (CIs). For our analysis, we established a cut-off for the index of heterogeneity: an I^2 statistic value. An I^2 value of 0% indicates no observed heterogeneity, while higher values show increasing heterogeneity, with cut-offs typically set at 25% (low), 50% (moderate), and 75% (high).

Results

Article selection process

Initially, a comprehensive search was conducted in various databases and registers to identify potentially relevant studies. This search yielded a total of 293 records from databases, with no records being identified from registers. Prior to screening, duplicate records were identified and removed, totalling 46. Automated tools were also utilized to mark ineligible records, resulting in the exclusion of 51 additional records. Subsequently, 247 records were screened for potential inclusion in the review. No records were excluded at this stage, so all 247 were sought for retrieval. However, 47 of these were not retrieved, reducing the number of reports assessed for eligibility to 288.

During the eligibility assessment, several reasons led to the exclusion of numerous reports. Thirty-six studies were excluded as they did not respond to the PECO statement. An additional 51 reports were excluded due to full-text unavailability. Case reports, often excluded due to their lower level of evidence, accounted for the removal of 26

Table 2 Demographic characteristics of the selected trials

Study	Region assessed	Sample size assessed (n)	Age (years)	Gender ratio	Study protocol	Assessment period (years)	Follow-up period (years)
Baş *et al.* (20)	Turkey	81	5.62±4.50 and 8.39±4.72	38 males	Retrospective (case-cohort)	4	0.5–0.75
Destro *et al.* (21)	Italy	70	7.3±5.0	48 males	Retrospective (case-cohort)	10	4
ElSheemy *et al.* (22)	Egypt	118	4.06±0.96 and 3.84±1.44	77 males	Retrospective (case-cohort)	4	33.14±6.07 and 15.5±7.08
Freton *et al.* (23)	France	146	6.7±0.6 and 9.1±0.9	Unspecified	Retrospective (case-cohort)	14	3
Guler *et al.* (24)	Turkey	130	6.6±4.2 and 7±4.4	74 males	Retrospective (case-cohort)	4	Unspecified
Halinski *et al.* (25)	Poland	53	9.6±3.78 and 8.2±3.36	21 males	Retrospective (case-cohort)	1	Unspecified
Hatipoglu *et al.* (26)	Turkey	145	5.91±4.03 and 8.43±4.84	76 males	Retrospective (case-cohort)	2	3
Kumar *et al.* (17)	India	212	10.7±1.3 and 10.3±1.2	103 males	RCT	1	3
Mokhless *et al.* (18)	Egypt	60	2.4±1.3	40 males	RCT	Unspecified	0.25
Pelit *et al.* (27)	Turkey	77	3.71±1.89 and 3.65±1.95	41 males	Retrospective (case-cohort)	3	Unspecified
Saad *et al.* (19)	Egypt	43	6.44±4.84 and 6.93±3.55	28 males	RCT	3	Unspecified
Sen *et al.* (28)	Turkey	48	4±2.3 and 10.9±3	–	Retrospective (case-cohort)	1	0.5
Wang *et al.* (29)	China	57	19±9.9 and 21±7.8	39 males	Retrospective (case-cohort)	2	0.25

Data are presented as mean ± standard deviation. RCT, randomised control trial.

more studies. The grey literature, which is generally less reliable and harder to assess for quality and bias, led to the removal of 31 studies. Finally 22 scoping reviews and 21 literature reviews were excluded from the consideration. Consequently, the rigorous selection process resulted in the inclusion of 13 studies (17-29) in the review.

Demographic variables observed

Table 2 provides a detailed overview of the demographic characteristics across the selected trials conducted in various regions across the globe. The trials were predominantly retrospective case-cohort studies, with a few randomized control trials (RCTs) (17-19). The study sample sizes ranged from as low as 43 AME (19) to as high as 212 AME (17). These samples were drawn from diverse regions, including Turkey (20,24,26-28), Italy (21), Egypt (18,19,22), France (23), Poland (25), India (17), and China (29). The mean age of the participants varied significantly across the studies. The youngest mean age was reported to be 2.4±1.3 years (18). Some studies reported mean ages for different groups, showing variability within their samples (19,20,22-24,26-28). Gender distribution, where specified, was skewed towards males in all studies (17-22,24-27,29). However, one study did not specify the gender ratio (23). The assessment periods varied across the studies, spanning from 1 year (17,25,28,29) to as long as 14 years (23). Follow-up periods were also diverse. They ranged from short periods such as 0.25 years (18,29) to extended periods like 33.14±6.07 years (22). However, several studies did not specify the follow-up period (19,23,24,27).

Bias assessed across different domains

As evident through *Figure 2*, the risk of bias was assessed for three RCTs by Kumar *et al.* (17), Mokhless *et al.* (18), and Saad *et al.* (19) using Cochrane's RoB 2.0 tool. The tool evaluated five domains: randomization process (D1), deviations from intended interventions (D2), missing outcome data (D3), measurement of the outcome (D4), and selection of the reported result (D5). Kumar *et al.* (17) had a low risk of bias across all the domains showed low risk. Mokhless *et al.* (18) had a moderate risk in D1 but low risk in D2–D5. Saad *et al.* (19) showed low risk in D1, D4, and D5, with moderate risk in D2 and D3. On an overall basis, all three studies (17-19) were judged to have a low risk of bias based on the Cochrane RoB 2.0 assessment.

Figure 3 shows the risk of bias assessment for the case-cohort studies (20-29) using the ROBINS-I tool across seven domains (D1–D7). The studies by Baş *et al.* (20), ElSheemy *et al.* (22), Freton *et al.* (23), Guler *et al.* (24), Halinski *et al.* (25), Hatipoglu *et al.* (26), Pelit *et al.* (27), Sen *et al.* (28), and Wang *et al.* (29) had an overall low risk of bias. For example, Baş *et al.* (20) and Freton *et al.* (23) had a moderate risk in D6, while ElSheemy *et al.* (22) and Pelit *et al.* (27) had a low risk in D3 and D2, respectively.

Surgical techniques and stone sizes observed

In the study by Baş *et al.* (20), PCNL and RIRS were the surgical modalities assessed, with stone sizes observed as 13.97±3.46 and 12.80±3.03 mm respectively. Destro *et al.* (21) evaluated SWL, PCNL, and RIRS, and noted a mean stone size of 12.5±5.4 mm. ElSheemy *et al.* (22) assessed SWL and PCNL with observed stone sizes of 15.09±4.22 and 16.02±4.7 mm respectively. Freton *et al.* (23) analyzed SWL and RIRS, and reported stone sizes of 12.1±0.7 and 11.9±1.1 mm respectively. In the study by Guler *et al.* (24), SWL and RIRS were used as surgical modalities and the stone size was reported as being less than or equal to 20 mm. Halinski *et al.* (25) assessed PCNL and RIRS, with stone sizes observed as 12.2±6 mm. Hatipoglu *et al.* (26) evaluated SWL and PCNL and reported stone sizes of 11.32±2.84 and 14.78±5.39 mm respectively. Kumar *et al.* (17) used PCNL and SWL as surgical modalities and observed stone sizes of 12.7±1.2 and 12.9±1.3 mm respectively. Mokhless *et al.* (18) assessed SWL and RIRS, with stone sizes ranging from 10 mm to 22 mm. Pelit *et al.* (27) evaluated PCNL and RIRS and observed stone sizes of 21.06±5.61 and 19.30±4.21 mm respectively. Saad *et al.* (19) assessed PCNL and RIRS as surgical modalities with stone sizes reported as being greater than 20 mm. Sen *et al.* (28) used PCNL and RIRS as surgical modalities, with observed stone sizes of 12.2±2.8 and 13.7±3.5 mm respectively. Wang *et al.* (29) evaluated PCNL and RIRS and reported stone sizes of 16±0.3 and 17±0.2 mm respectively.

Efficacy observed

Table 3 provides insights into the effectiveness and potential complications of different surgical approaches for treating kidney stones. According to Baş *et al.* (20), both PCNL and RIRS are quite versatile, being able to handle kidney stones of around the same size. Destro *et al.* (21) examined three methods—SWL, PCNL, and RIRS—and noted that the choice of treatment often depends on various factors, including the stone's size and location, and the patient's characteristics. ElSheemy *et al.* (22) studied SWL and PCNL and found these methods could tackle somewhat larger stones. In contrast, Freton *et al.* (23) suggested that both SWL and RIRS could handle medium-sized stones effectively. Guler *et al.* (24) and Halinski *et al.* (25) demonstrated that larger stones, up to 20mm, could be managed using SWL, RIRS, and PCNL, emphasizing the adaptability of these techniques.

Hatipoglu *et al.*'s (26) study showed both SWL and PCNL had a good success rate, with only a small number of cases requiring further treatment. Kumar *et al.* (17) compared PCNL and ESWL and found that while PCNL required more resources and time, it also had a higher initial success rate. Mokhless *et al.* (18) reported high success rates for their treatment groups, with group 2 showing slightly better results. Pelit *et al.* (27) found RIRS and PCNL to have comparable success rates, although PCNL showed a bit more success at the onset. In the studies by Saad *et al.* (19) and Sen *et al.* (28), trade-offs were found between RIRS and PCNL in terms of recovery time, radiation exposure, and success rates. Wang *et al.* (29) noted a slightly higher success rate for the micro-PCNL group, but the difference was not significant.

Complications observed

Baş *et al.* (20) showed that both PCNL and RIRS techniques presented some complications, but with no significant difference, suggesting similar levels of safety. Destro *et al.* (21)

Table 3 Inferences assessed pertaining to different surgical techniques

Study	Surgical modalities assessed	Stone sizes observed (mm)	Efficacy observed	Complications assessed
Baş *et al.* (20)	PCNL and RIRS	13.97±3.46 and 12.80±3.03	The success rate was 80% (n=36) in the micro-perc group, with treatment failure encountered in 9 patients. In the RIRS group, the success rate was 86.2% (n=31). The main reason for residual stones was limited deflection to lower pole infundibula in all unsuccessful cases. Stone-free rates were similar between the groups (P=0.47)	Six patients (13.3%) in the micro-PERC group suffered from complications which were managed with medical treatment in 3 patients with postoperative renal colic, 1 patient with fever, and 1 patient with urinary tract infection. JJ stent insertion was needed in 1 patient due to renal colic. The mean complication rate was 16.6% (6/36) in the RIRS group. One patient suffered from renal colic, two patients had postoperative fever and two patients had urinary tract infections. One patient was treated with a JJ stent due to intractable pain following the procedure. When the complications were re-evaluated using the Modified Clavien System, there was no statistical difference between the groups (P=0.67)
Destro *et al.* (21)	SWL, PCNL and RIRS	12.5±5.4	In the MIA group, 84.3% (59/70) of patients underwent successful treatment. ESWL was done in 11.8% of cases, URS in 32.2% of subjects, RIRS in 30.5%, and other procedures, such as PCNL, stenting, and cystoscopic bladder stone removal or laser cystolithotripsy, in 25.4% of children. A significant difference in position of stones was noted according to type of surgery (P=0.001). ESWL was predominantly performed for treatment of the kidney stones (71.4%) compared to ureter and multiples locations (14.2%); URS was almost exclusively indicated for ureteral stones (73.7%), and less frequently for other localizations (26.3%); RIRS was used for kidney stones (66.7%) and less frequently in other localizations (33.3%); other procedures were considered respectively for renal (47.1%) and bladder localization (23.5%) and/or multiple localizations (29.4%). Four MIA procedures (4/59, 6.89%) for treatment of kidney and/or ureter/multiple large stones were converted to open surgery	Significant complications were recorded in 12.8% of the cases: 5 patients were kept longer for analgesic and antipyretic therapy (grade I); displacement and infection of the DJ stent were registered in 5.7% of the cases (4 patients) and required stent removal under general anesthesia (grade IIIb)
ElSheemy *et al.* (22)	SWL and PCNL	15.09±4.22 and 16.02±4.7	The average stone size was similar in both the SWL and Miniperc groups. The retreatment rate was significantly higher in the SWL group, with 46.2% of patients needing a second treatment session compared to only 7.7% in the Miniperc group (P<0.001). The stone-free rates were significantly higher in the Miniperc group after a single session (87.2% *vs.* 50% in the SWL group, P<0.001) and after two sessions (94.9% *vs.* 80.8% in the SWL group, P=0.049). However, the difference in stone-free rates after three sessions was not statistically significant (94.9% for Miniperc vs. 84.6% for SWL, P=0.17). CIRFs were found in 7.7% of patients in the SWL group and 2.6% of patients in the Miniperc group	The complication rates were similar between the groups: 15.4% (8 out of 52 patients) in the SWL group and 20.5% (8 out of 39 patients) in the Miniperc group (P=0.52). Some complications such as Steinstrasse only occurred in the SWL group, whereas RP perforation and leakage only occurred in the Miniperc group. The need for auxiliary procedures was slightly higher in the SWL group at 11.5%, compared to 2.6% in the Miniperc group, but this difference was not statistically significant (P=0.23)
Freton *et al.* (23)	SWL and RIRS	12.1±0.7 and 11.9±1.1	The stone-free rate after one procedure was almost twice higher in the F-URS (RIRS) group compared to the ESWL group (37% vs. 21%; P=0.04). Length of stay was longer in the F-URS group (1.4 *vs.* 0.9 days; P=0.02). Mean operative time was longer in the F-URS group (105.5 *vs.* 28.9 min; P<0.001). After a mean of 2.2 procedures in each group (P=0.94), the overall monotherapy stone-free rates were 76.1% and 60% in the F-URS and ESWL groups respectively (P=0.06)	Complication rates were similar (21.7% vs. 16%; P=0.31). There were three major complications (i.e., Clavien grade ≥3) in the F-URS group (two urinomas requiring ureteral stenting and one acute urinary retention due to urethral stone fragment) and one in the ESWL group (emergency placement of a double J-stent due to a renal colic refractory to analgesics; i.e., 7% in the F-URS group vs. 1% in the ESWL group; P=0.2). There were difficulties to access the upper tract in five patients. Two were managed successfully by using a ureteral access sheath and two by dilating the ureteral orifice. In the last case, a double J stent was placed for two weeks before rescheduling URS. Five ureteroscopes were damaged (i.e., 1 every 9.2 procedures)
Guler *et al.* (24)	SWL and RIRS	≤20	The average operation time was slightly longer in the micro-PCNL group (75.1±18.9 min) compared to the RIRS group (62.3±15.3 min), but this difference was not statistically significant (P>0.05). The mean fluoroscopy time was significantly shorter in the RIRS group (1.6±0.8 min) compared to the micro-PCNL group (3.1±1.1 min) (P<0.001). The stone-free rate was slightly higher in the micro-PCNL group (88.9%) compared to the RIRS group (86.7%), but this difference was not statistically significant (P=0.79)	The mean hospitalization time was similar in both groups: 2.1±0.6 days for the micro-PCNL group and 2.2±0.4 days for the RIRS group (P>0.05). All patients in the RIRS group had a pre-operative double J stent placement, compared to none in the micro-PCNL group. The complication rate was similar in both groups, with 14.8% in the micro-PCNL group and 16.7% in the RIRS group (P=0.94)
Halinski *et al.* (25)	PCNL and RIRS	12.2±6	In the Flex URS/RIRS group, stones varied in size from 1 to 1.5 cm, with the mean of 1.35 cm. The episode of inpatient care ranged from 2 to 5 days (with the mean of 3 days). The mean fluoroscopy time during the procedure was 20 s. In the MicroPERC group, the episode of inpatient care ranged from 4 to 7 days (with the mean of 4.5 days). The mean fluoroscopy time during the PCNL was 12 s. The stone free rate after a single procedure was 84.21% for flexible ureterorenoscopy and 86.7% for the MicroPERC method. According to Fisher's exact test, no significant difference between the efficacy in both groups was found (P=1.00)	No major complications were observed in any of the groups. Minor complications (hematuria, renal colic), according to the Clavien three-point grading system, were: 6% for the PCNL and 2.6% for the RIRS group
Hatipoglu *et al.* (26)	SWL and PCNL	11.32±2.84 and 14.78±5.39	The average operative time, fluoroscopy time, and hospital stay for the MicroPERC group were significantly longer compared to the SWL group. The stone-free rates were similar in both groups at different follow-up intervals: on the 1st day (75.7% for SWL, data for MicroPERC not available), 1st week (71.3% for SWL vs. 78.4% for MicroPERC), 1st month (85.2% for SWL vs. 86.5% for MicroPERC), and 3rd month (88% for SWL vs. 89.2% for MicroPERC). Three patients in the MicroPERC group had to be converted to mini-PCNL. There were 11 cases in the SWL group that required an auxiliary procedure	The complication rate was similar in both groups (18 in the SWL group and 8 in the MicroPERC group). In terms of Clavien grade I (renal colic) complications, the SWL group had 7 cases, while the MicroPERC group had 4. For Clavien grade IIIb complications, the SWL group had 11 cases of steinstrasse necessitating double-J stent insertion and 3 cases of extravasation necessitating drain placement, while the MicroPERC group had only one case of steinstrasse. The use of a preprocedural double-J stent was significantly more common in the SWL group (26 cases) compared to the MicroPERC group (2 cases), while the use of a postprocedural double-J stent was similar in both groups

Table 3 (continued)

Table 3 (continued)

Study	Surgical modalities assessed	Stone sizes observed (mm)	Efficacy observed	Complications assessed
Kumar *et al.* (17)	PCNL and SWL	12.7±1.2 and 12.9±1.3	The mean operating time, fluoroscopy time, blood transfusion rate, hospital stay and stone free rate at 3 months post-procedure were significantly higher in the PCNL group compared to the ESWL group. The mean retreatment rate and auxiliary procedure rate were significantly higher in the ESWL group. Modified EQ regarding the need for retreatment and auxiliary procedure significantly favoured miniperc compared to SWL. Stone composition was similar between the two groups. In the SWL group, the stone free rate was significantly higher in the subgroup with infundibulopelvic angle >90 compared to <90 angle group (89.6% vs. 40% respectively). Retreatment rates in SWL were higher for calcium oxalate monohydrate and cystine stones as compared to other stone composition types, although it was not statistically significant. Similarly, the stone-free rate was lower for calcium oxalate monohydrate and cystine stones as compared to other stone composition types, although it was not statistically significant	Complications, recorded as per the Clavien-Dindo classification, were higher in the PCNL group. The complications like urinary tract infection and gross hematuria were significantly higher in the PCNL group compared to the ESWL group. Overall complication was also significantly higher in PCNL patients. Bleeding complications were observed in cases with compact calyx having cystine or calcium oxalate monohydrate stones
Mokhless *et al.* (18)	SWL and RIRS	10-22	The stone-free rate after a single session treatment was 70% for group 1 and 86.6% for group 2. Nine group 1 patients needed a second shock wave lithotripsy session, of whom 2 required a third session. At 3 months the overall stone-free rate was 93.3% for group 1 and 96.6% for group 2	The mean operative time was 27.9±3.5 min for group 1 and 40±7.8 min for group 2. Mean fluoroscopy exposure time was 60±42 seconds for group 1 and 50±35 seconds for group 2. Mean hospital stay was 6±2 hours for group 1 and 12±8 hours for group 2. No major complication occurred in either group and no child in either group received blood transfusion
Pelit *et al.* (27)	PCNL and RIRS	21.06±5.61 and 19.30±4.21	The mean stone size was 19.30±4.21 mm for the RIRS group and 21.06±5.61 mm for the PCNL group (P=0.720). The SFRs after a single procedure were 84.4% in the PCNL group and 75% in the RIRS group (P=0.036). After auxiliary procedures, the overall SFRs reached 91.1% for the PCNL group and 90.6% for the RIRS group (P=0.081)	The mean operative times, fluoroscopy times, and hospitalization times were statistically higher in the PCNL group. No major complications were observed for both groups. Minor complication (Clavien 1–3) rates were 15.5% and 12.5% for the PCNL and RIRC group, respectively (P=0.38)
Saad *et al.* (19)	PCNL and RIRS	>20	The patient's average age was similar in both the RIRS and PCNL groups. The mean operative time was slightly longer in the RIRS group (79.5 min) compared to the PCNL group (69.8 min), but this difference was not statistically significant (P=0.28). However, the mean radiation time was significantly shorter in the RIRS group (1.6 min) than in the PCNL group (3.1 min) (P<0.001). The RIRS group also had a significantly lower mean hemoglobin deficit (0.53 g/dL) compared to the PCNL group (1.6 g/dL) (P=0.012), and a significantly shorter mean hospital stay (1.1 vs. 2.59 days in the PCNL group) (P<0.001). The stone-free rate, which is an important measure of treatment success, was significantly higher in the PCNL group (95.5%) than in the RIRS group (71.4%) (P=0.046)	The overall complication rate, according to the Clavien classification, was significantly higher in the PCNL group (40.9%) compared to the RIRS group (9.5%) (P=0.018). The most common complications were fever (grade 1) and bleeding (grade 2). There was one case of hydrothorax (grade 3a) in the PCNL group
Sen *et al.* (28)	PCNL and RIRS	12.2±2.8 and 13.7±3.5	The average operation time was slightly longer in the MicroPERC group (75.1±18.9 minutes) compared to the RIRS group (62.3±15.3 minutes), but this difference was not statistically significant (P>0.05). The mean fluoroscopy time was significantly shorter in the RIRS group (39.9±15.4 seconds) compared to the micro-PERC group (115±35.4 seconds) (P=0.001). The mean hospitalization time was similar in both groups: 2.1±0.6 days for the MicroPERC group and 2.2±0.4 days for the RIRS group (P>0.05). The stone-free rate, an important measure of treatment success, was similar in both groups, with 84% for the micro-PERC group and 82.6% for the RIRS group (P>0.05)	The rate of complications, categorized according to the Clavien-Dindo classification, was slightly higher in the RIRS group, with 17.3% of patients experiencing Grade I or II complications, compared to 12% in the micro-PERC group. However, there were no Grade III to V complications in either group
Wang *et al.* (29)	PCNL and RIRS	16±0.3 and 17±0.2	The stone-free rate was slightly higher in the micro-PCNL group (88.9%) compared to the RIRS group (86.7%), but this difference was not statistically significant (P=0.79). The average hospital stay was 2.3±1.0 days for the micro-PCNL group and 2.7±1.3 days for the RIRS group (P=0.24). The mean operation time was a bit longer in the micro-PCNL group (52±7 minutes) compared to the RIRS group (48±9 minutes), but the difference was not statistically significant (P=0.163). The lithotripsy time was also similar between the two groups, 21±4 minutes for micro-PCNL and 23±5 minutes for RIRS (P=0.148). Significantly less irrigation fluid was used in the micro-PCNL group (240±90 mL) compared to the RIRS group (400±120 mL) (P<0.001)	All patients in the RIRS group had a pre-operative double J stent placement, compared to none in the micro-PCNL group, which was a significant difference (P<0.001). The use of a ureteral access sheath was only reported in the RIRS group (66.7% of patients) (P<0.001). Regarding the type of drainage used, a significant difference was noted (P<0.001). In the micro-PCNL group, 44.4% had a double-J stent and 55.6% had an open-ended ureteral catheter. In the RIRS group, 70% had a double-J stent, none had an open-ended ureteral catheter, and 30% had no drainage. Patients in the RIRS group required significantly more anesthesia sessions on average (2.7±0.5) compared to the micro-PCNL group (1.4±0.5) (P<0.001). Ureteral injury (grade 1) occurred only in the RIRS group (5 cases), which was a significant difference (P<0.001). The postoperative complication rate was similar in both groups, with 14.8% in the micro-PCNL group and 16.7% in the RIRS group (P=0.94). The complications were graded according to the Clavien-Dindo classification, with Grade I including hematuria, Grade II including urinary tract infection and fever, and Grade IIIB including steinstrasse necessitating double J stent insertion. Notably, Grade IIIB complications only occurred in the micro-PCNL group (1 case)

Data are presented as mean ± standard deviation. PCNL, percutaneous nephrolithotomy; RIRS, retrograde intrarenal surgery; SWL, shock wave lithotripsy; ESWL, extracorporeal shock wave lithotripsy; MIA, minimally invasive approach; SWL, shock wave lithotripsy; Miniperc, mini percutaneous nephrolithotomy; EQ, efficacy quotient; CIRFs, clinically insignificant residual fragments; F-URS, flexible ureteroscopy; micro-PCNL, micro-percutaneous nephrolithotomy; MicroPERC, micro-percutaneous nephrolithotomy; SFRs, stone-free rates; JJ stent, double J stent; DJ stent, double J stent; RP, renal pelvis; URS, ureteroscopy.

identified significant complications in around one in eight cases that required additional treatments like extended hospital stays and stent removal. The complications were graded based on their severity. In the study by ElSheemy *et al.* (22), both SWL and Miniperc groups faced complications, with some unique to each group. The need for additional treatments was slightly higher in the SWL group, but not enough to be statistically significant, suggesting similar overall treatment profiles.

Freton *et al.* (23) noted comparable complication rates between flexible ureterorenoscopy (F-URS) and ESWL groups, with major complications slightly more common in the F-URS group. Difficulties in accessing the upper tract were managed using various methods. Guler *et al.* (24) found the average hospital stay was similar for both the micro-PCNL and RIRS groups and observed similar rates of complications, suggesting comparable safety profiles. Halinski *et al.* (25) reported no major complications for either the PCNL or RIRS groups, with only minor complications like hematuria and renal colic reported. Hatipoglu *et al.* (26) found similar complication rates in the SWL and MicroPERC groups, but the types of complications differed between groups. Kumar *et al.* (17), it was observed that complications were higher for patients undergoing PCNL compared to ESWL, with UTIs and gross hematuria particularly common in the PCNL group. Mokhless *et al.* (18) reported longer operative times and hospital stays in their second group compared to the first one. However, there were no major complications or blood transfusions reported in either group.

Pelit *et al.* (27) found that the PCNL group had longer operative times, fluoroscopy times, and hospitalization times compared to the other group. Minor complications were observed in both groups, but there was no significant difference between the two. Saad *et al.* (19) found a higher overall complication rate in the PCNL group compared to the RIRS group, with fever and bleeding being the most frequent complications. A single case of a more severe complication was reported in the PCNL group. Sen *et al.* (28) revealed a slightly higher rate of minor complications in the RIRS group compared to the MicroPERC group. However, there were no severe complications observed in either group. Wang *et al.* (29) showed that all patients in the RIRS group had a pre-operative double J stent placement, unlike the micro-PCNL group. The RIRS group required more anesthesia sessions on average, and a few cases of ureteral injury occurred only in the RIRS group. The postoperative complication rate was similar in both groups, with certain complications occurring only in the micro-PCNL group.

Statistical analysis of observed efficacy

The effectiveness of various surgical procedures for pediatric urolithiasis was assessed in terms of the SFR in the forest plot depicted in *Figure 4*. The summary odds ratio in the PCNL *vs.* RIRS comparison was 1.43. The overall effect's P value was 0.36, and the 95% CI varied from 0.67 to 3.05. The crossing of the 95% CI: above 1 and the P value exceeding 0.05 in these figures indicate that there was no significant difference in SFR between these two approaches. There was low to moderate heterogeneity among the studies, as shown by the I^2 score of 21%.

The pooled odds ratio between PCNL and SWL was 2.51. The P value for the total effect was 0.02 and the 95% CI varied from 1.19 to 5.29. The 95% CI not crossing 1 and the P value less than 0.05 in these results indicates that PCNL may be more successful than SWL in achieving an SFR. There was low to moderate heterogeneity among the studies, as shown by the I^2 score of 22%.

The cumulative odds ratio in the comparison of SWL and RIRS was 2.42. The overall effect's P value was 0.001, and the 95% CI varied from 1.41 to 4.14. These results, with the 95% CI not crossing 1 and a P value considerably below 0.05, imply that RIRS may be more successful than SWL in reaching an SFR. There was no discernible heterogeneity amongst these trials, as indicated by the I^2 value of 0%.

Statistical analysis of observed complications

The complication rates of the evaluated surgical methods for pediatric urolithiasis in this study were compared in terms of OR in the forest plot shown in *Figure 5*. There was no discernible difference in the complication rates between PCNL and RIRS, as indicated by the overall OR of 1.24 for all studies comparing the two methods. The 95% CI (0.64, 2.39) crossing 1 and the P value for the total impact (0.53) being larger than 0.05, which indicates that the difference is not statistically significant, both corroborated this. The low I^2 score of 9% indicates a low degree of heterogeneity among the research that made up this comparison, indicated that the conclusions of the studies were mostly in agreement.

Studies comparing PCNL and SWL had a pooled OR of 2.28. This suggests that compared to SWL, PCNL may have a greater rate of complications. The difference was not

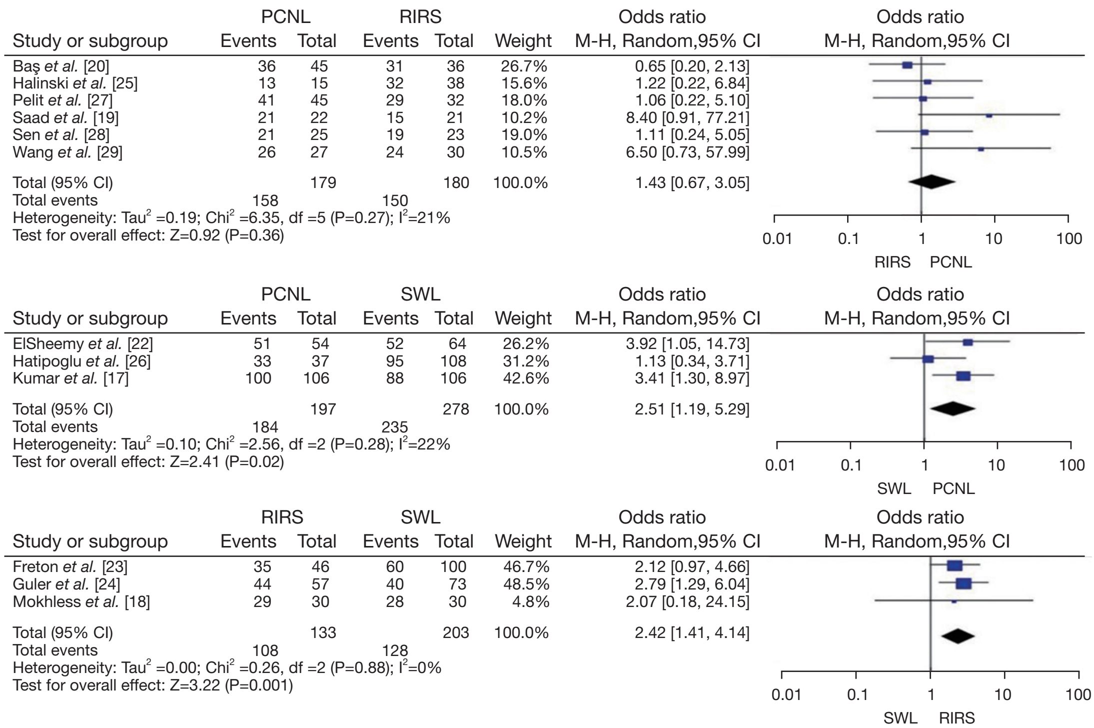

Figure 4 Efficacy of different surgical techniques observed in terms of SFR (17-20,22-29). PCNL, percutaneous nephrolithotomy; RIRS, retrograde intrarenal surgery; M-H, Mantel-Haenszel; CI, confidence interval; SWL, shock wave lithotripsy; SFR, stone-free rate.

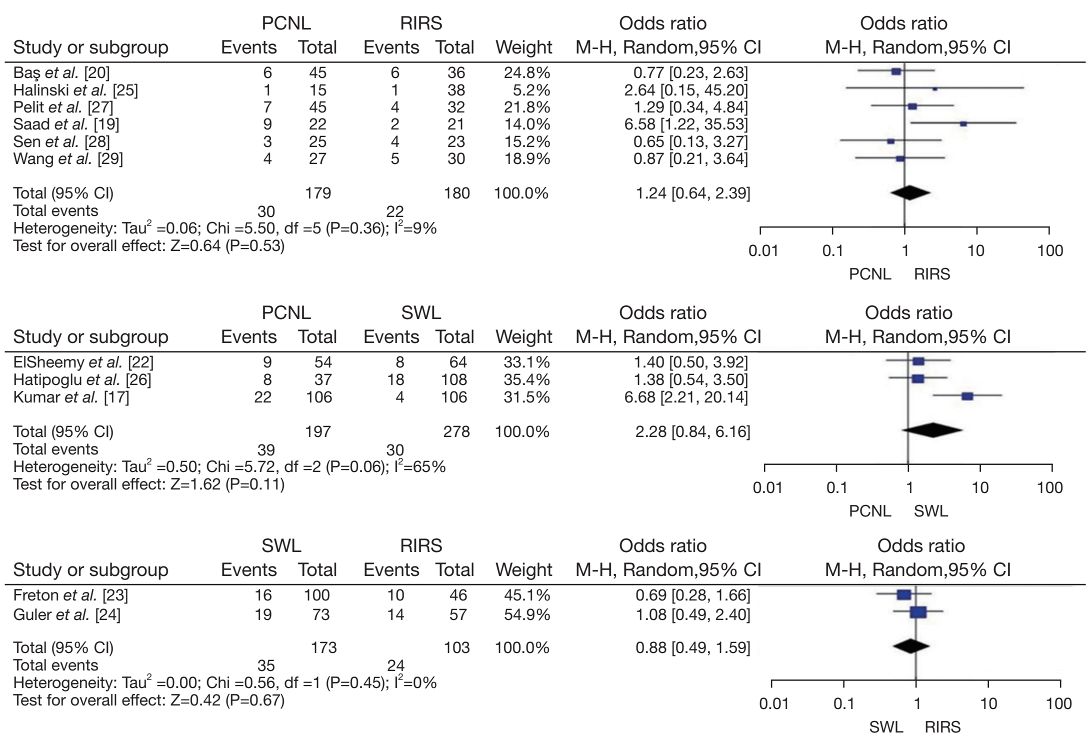

Figure 5 Complications of different surgical techniques observed (17,19,20,22-29). PCNL, percutaneous nephrolithotomy; RIRS, retrograde intrarenal surgery; M-H, Mantel-Haenszel; CI, confidence interval; SWL, shock wave lithotripsy.

statistically significant, though, as the 95% CI (0.84, 6.16) surpasses 1, and the P value for the overall effect (0.11) is more than 0.05. The studies' results differed greatly, as indicated by the considerable amount of heterogeneity indicated by the I^2 value of 65%.

There appeared to be no discernible difference in the complication rates between RIRS and SWL, as indicated by the combined OR of trials comparing these two approaches, which was 0.88. The P value for the overall effect (0.67) is greater than 0.05 and the 95% CI (0.49, 1.59) surpassed 1, further indicating that the difference was not statistically significant. The studies were consistent in their findings, as indicated by the I^2 value of 0%, which shows that there was no identified heterogeneity among them.

Discussion

The exploration of the clinical significance of the observed differences in pediatric urolithiasis treatment techniques revealed nuanced findings when applied to real-world clinical settings. Baş *et al.* (20) demonstrated comparable safety levels between PCNL and RIRS, with complication rates showing no significant difference. Similarly, Freton *et al.* (23) noted equivalent complication rates between F-URS and ESWL, though major complications were somewhat more prevalent in the F-URS group. Guler *et al.* (24) and Halinski *et al.* (25) reported analogous safety profiles and minor complications for their respective comparative groups, suggesting that in clinical practice, these treatment options could be considered relatively interchangeable in terms of safety.

Conversely, Destro *et al.* (21) and Saad *et al.* (19) observed a higher incidence of significant complications requiring additional treatment for some techniques, implying a need for cautious application in clinical practices, with readiness for additional postoperative care. The report by Kumar *et al.* (17) indicated that PCNL was associated with higher rates of UTIs and hematuria compared to ESWL highlighting the necessity for clinicians to weigh the risks of postoperative complications more heavily when considering PCNL.

In terms of treatment efficacy, the statistical analysis presented noteworthy insights. The summary odds ratio from the studies suggested no significant difference in stone-free rate (SFR) between PCNL and RIRS, as the CIs crossed the null value (20), and the P value did not indicate significance. However, PCNL might be more effective than SWL (18), as indicated by a P value below 0.05 and CIs that did not cross 1. RIRS also appeared to be more effective than SWL, supported by a significantly lower P value and non-crossing CIs (27).

When it came to complications, the forest plot analysis in *Figure 5* showed no significant difference between PCNL and RIRS, evidenced by a non-significant overall odds ratio and low heterogeneity among studies (20). The pooled odds ratio suggested a higher complication rate for PCNL compared to SWL, but with considerable heterogeneity and a non-significant P value (17), indicating that the results from different studies were not entirely consistent. The comparison of RIRS and SWL showed no significant difference in complication rates, with an odds ratio very close to 1 and no heterogeneity detected (27).

Clinically, these findings suggest that while some surgical techniques may have different complication profiles or effectiveness, the differences are not always statistically significant. This indicates a potential for a more personalized approach to treatment selection, considering patient-specific factors such as the presence of comorbidities, patient preference, and available resources. The data also highlight the importance of clinicians being well-informed about the possible outcomes and ready to manage complications associated with different treatment modalities for pediatric urolithiasis.

In line with the findings of Zeng *et al.* (6) about the proliferation of smaller PCNL methods, our analysis also revealed a growing pattern in related minimally invasive procedures including micro-PCNL and mini-micro-PCNL. These miniaturized approaches offer high rates of stone-free outcomes while lowering complication rates, as noted by Zeng *et al.* (6). This is something we also noted in our analysis, especially in studies with pediatric patients [Baş *et al.* (20), ElSheemy *et al.* (22), and Wang *et al.* (29)]. In contrast to Zeng *et al.*'s (6) suggestion that more well-designed, randomised studies should be conducted to confirm these methods as standard practises, our review found a strong positive trend regarding the safety and effectiveness of these miniaturized methods in pediatric populations, suggesting that they may already be a good substitute in this particular population.

With PCNL, including its miniaturized forms like micro-PCNL and mini-PCNL, there is a notable benefit in terms of SFR, particularly for larger stones. However, this technique often requires fluoroscopy to guide the puncture and stone removal process, potentially resulting in higher radiation exposure to the patient (30). While miniaturized versions aim to reduce the risks associated with larger tracts, including bleeding and potential damage to renal tissue, they may still utilize fluoroscopy, albeit possibly for shorter durations due to the precision of the smaller instruments (31).

RIRS, on the other hand, typically involves less radiation exposure compared to PCNL because fluoroscopy is used less intensively (32). The flexible ureteroscopes allow for direct visualization of stones, which can reduce the reliance on fluoroscopic guidance. The recovery time with RIRS is also generally shorter, with many patients able to return to normal activities relatively quickly due to the less invasive nature of the procedure (32). SWL, PCNL, and RIRS were compared by Setthawong *et al.* (30). According to their research, ESWL likely caused less problems than PCNL but may have lower treatment success rates than RIRS and PCNL. Similar findings were also obtained in our review, which showed that PCNL and RIRS were more effective in producing stone-free outcomes (17,25,27). But we also pointed out that, as Guler *et al.* (24) showed in our review, less invasive methods like F-URS showed encouraging results and could be a less dangerous substitute for PCNL, much like ESWL as proposed by Setthawong *et al.* (30).

The results of our investigation are consistent with those of Chen *et al.* (31) and He *et al.* (32), although there are some subtle variations. Both PCNL and RIRS were successful in helping pediatric patients achieve stone-free outcomes, according to the research we analysed. This is consistent with the results of Chen *et al.* (31), who discovered no appreciable variation in initial and final SFR between PCNL and RIRS. In contrast to PCNL, Chen *et al.* (31) discovered that RIRS was linked to a noticeably shorter hospital stay, a shorter fluoroscopy time, and fewer overall problems. They also observed that RIRS reduced the requirement for blood transfusions. While we did identify possible benefits linked to less invasive procedures, our review did not as clearly emphasize these findings.

A comparative investigation of PCNL, RIRS, and SWL was carried out by He *et al.* (32), and their results also included some differences from our review. He *et al.* (32) observed no significant difference between PCNL and RIRS in terms of SFR, despite our review demonstrating PCNL and RIRS's superiority in achieving stone-free outcomes. Additionally, they found no statistically significant variations in the rates of problems among the three treatments, which differs slightly from our results that suggested less issues were associated with less intrusive procedures. Interestingly, He *et al.* (32) also discovered—a characteristic we did not expressly analyse in our review—that PCNL had a greater efficiency quotient (EQ) than the other two treatments. Their findings, which are consistent with our observations that more invasive treatments such as PCNL and RIRS yield better results, indicated that while SWL offered shorter hospital stays and less operational time, it had a higher retreatment rate and a lower SFR than those procedures.

Our results further confirm the growing effectiveness of F-URS in obtaining excellent SFR for small to intermediate-sized renal stones, as reported by Knoll *et al.* (33). This agreement also includes the proposal that F-URS could replace ESWL in the future with equipment that is more advanced technically and more experienced. The possibility that F-URS could be a substitute for PCNL in the case of big renal stones was also mentioned by Knoll *et al.* (33), a fact that our review did not particularly emphasised. They further pointed out that while F-URS frequently required staged procedures and has lengthy operating durations, PCNL is still the preferred approach for treating such stones. Although PCNL was found to be beneficial, our review did not conclusively state that it should be the preferred approach for bigger stones.

The results of a comparative study between micro-PCNL and RIRS by Wicaksono *et al.* (34) both agree with and differ from those of our review. According to their research, there is no discernible difference between micro-PCNL and RIRS in terms of length of stay, incidence of UTIs, SFR, operating duration, or need for blood transfusions. This is consistent with our results, which showed that PCNL and RIRS are about equally effective. Nevertheless, Wicaksono *et al.* (34) discovered that, in contrast to RIRS, micro-PCNL had a noticeably lower need for postoperative stenting procedures; this comparison was not particularly covered in our review.

ESWL is still the main treatment option for tiny lower-pole calculi, especially when used in an outpatient clinic without the requirement for anaesthesia (35). This method has a low recurrence rate, few problems, and a satisfactory SFR (11,17). Certain prognostic criteria determine the therapy outcome for stones 1–2 cm in size (7,36). Endourological treatment, such as F-URS or PCNL, is advised if there is little chance that ESWL would be successful. This is a substantial shift in the way that the value of F-URS is seen. The revised recommendation now states that the available evidence presents a different picture, even if earlier research was unable to prove that F-URS was superior to ESWL (37). In one session, F-URS can remove stones entirely when done by skilled practitioners. Furthermore, there are situations in which ESWL may not be appropriate or effective at all, including untreated coagulopathies (although low-dose salicylate ESWL may be safe), obesity, and complicated anatomical features (38). However, PCNL is advised for bigger stones larger than 1.5 cm (26). Compared to ESWL and F-URS, it is the most effective but also the most intrusive treatment, requiring general anaesthesia, potentially resulting in serious consequences, and maybe requiring longer recovery times (38). With PCNL, the lower pole is the best target since it is easier to access and has a lower rate of complications.

SFR has been observed to be one of the most crucial metrics for evaluating how well kidney stone therapies work in young patients. High SFRs are known to be delivered by PCNL and RIRS in managing different stone sizes for all age groups. Smaller tract PCNL, like Micro-PCNL, raises questions, though, because fragment recovery is not feasible and sufficient vaporisation and pressurised irrigation are necessary for stone clearing during the process (6). There was no discernible change in SFR between patients receiving RIRS and PCNL, according to a few earlier investigations (12,14). Some authors (25,29) found consistent results, showing no discernible change in SFR between patients treated with PCNL and those treated with RIRS.

Endoscopic combined intra-renal surgery (ECIRS) is a nuanced technique in the field of urolithiasis treatment that synergizes the RIRS with the PCNL approach (39,40). This hybrid procedure allows for simultaneous antegrade and retrograde access to the kidney's urinary system, potentially improving stone clearance rates and reducing the need for multiple sessions, especially in cases of complex or large renal stones. ECIRS can be advantageous in challenging anatomical scenarios where a single approach may not suffice. By combining the two methods, ECIRS offers a comprehensive visualization of the renal system, which can facilitate the stone fragmentation process, reduce operative times, and potentially decrease the risk of residual stone fragments (39,40). The technique, however, may be associated with increased operative complexity, which could lead to longer anesthesia times and a potentially higher risk of complications if not performed by experienced hands.

Robotic-assisted URS, on the other hand, represents the cutting edge in the evolution of urolithiasis management, incorporating the dexterity and precision of robotic systems into ureteroscopic procedures (41). Robotic systems, such as the da Vinci surgical platform, provide surgeons with high-definition, three-dimensional visualization, and instruments with enhanced range of motion and stability. These features can translate into greater accuracy in stone targeting and manipulation, potentially reducing the risk of ureteral injury and improving SFR. The robotic assistance can also help decrease surgeon fatigue, particularly during lengthy procedures, which can indirectly benefit patient outcomes through consistent surgical performance (42). However, the introduction of such advanced technology also brings considerations of cost, both in terms of the initial investment in the robotic system and the operating expenses associated with its use. Additionally, the learning curve for surgeons adopting this new technology may initially affect procedure times and outcomes (42).

Limitations

The systematic review was subject to several limitations. First, the studies evaluated were not uniformly designed, with differing methodologies, objectives, and research scopes, potentially introducing heterogeneity and affecting the generalizability of the findings. The variability in the reported outcomes across the studies, such as SFR and complication rates, further compounded this issue. Second, the type and frequency of complications reported varied widely between studies. While some studies reported no major complications, others documented significant complications, including UTIs, gross hematuria, extended hospital stays, stent displacement, and infections. This inconsistency in the reporting of complications could have led to an underrepresentation or overrepresentation of certain adverse outcomes. Finally, the studies evaluated did not sufficiently discuss trade-offs in aspects such as radiation exposure, recovery time, and fluoroscopy time. Moreover, the potential advantages of newer techniques such as micro-PCNL in terms of resource utilization were not extensively explored. These gaps underscore the need for future research to provide a more comprehensive evaluation of the comparative efficacy and safety of different surgical techniques for pediatric urolithiasis.

Recommendations pertaining to clinical practice

Based on our findings, it is recommended that clinicians consider a range of surgical modalities for urolithiasis as investigated in this review given their versatility in treating kidney stones of various sizes. For larger stones, PCNL, RIRS, and SWL are suggested as potential options. The choice between RIRS and PCNL should be made based on individual patient factors and specific trade-offs associated with each technique. These may include considerations such as radiation exposure, recovery time, fluoroscopy time, and resource utilization. In certain contexts, micro-PCNL might offer advantages in terms of resource utilization.

In terms of effectiveness, while no significant difference in SFR was observed between PCNL and RIRS, both PCNL and RIRS might be more effective than SWL. When considering complications, it is crucial to understand that while the overall complication rates for PCNL, RIRS, SWL, and Miniperc were found to be comparable, the nature of the complications varied. Therefore, clinicians should be prepared for a variety of potential complications, such as UTIs, gross hematuria, extended hospital stays, stent displacement, and infections. Moreover, the recommendation is for individualized treatment strategies, taking into account not only the stone size and location but also patient-specific factors. This approach is expected to lead to better patient outcomes and more efficient resource utilization in the management of kidney stones. Further research is encouraged to continue refining the comparative effectiveness and safety profiles of these surgical techniques.

Conclusions

Our review found that PCNL and RIRS offer similar success rates in stone removal, with both tending to outperform SWL. Complication rates across PCNL, RIRS, and SWL are broadly comparable, despite differences in the nature of the complications observed, such as infections, stent issues, extended hospital stays, heavy bleeding, and urinary infections. Ultimately, each method—PCNL, RIRS, and SWL—are proved to be to be an effective intervention for pediatric kidney stones, with no single technique demonstrating superiority across all evaluated outcomes. The choice of treatment should be tailored to the individual, taking into account the characteristics of the stone, the balance of potential risks, and patient-specific factors. Further research into the relative effectiveness and safety of these surgical options is vital to refine treatment strategies and enhance care for pediatric patients with urolithiasis. All things considered, PCNL, RIRS, and SWL are all effective in treating pediatric urolithiasis; no approach stands out as being particularly better than the others in terms of all outcomes that were assessed. The properties of the stone, the potential trade-offs of each approach, and patient-specific considerations should all be carefully considered before selecting a surgical modality. The comparative effectiveness and safety of various surgical methods should be better studied in order to enhance patient outcomes and treatment plans.

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