

Research Progress in Minimally Invasive Surgical Treatment for Upper Urinary Tract Stones: A Review

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Abstract: In recent years, minimally invasive techniques have made significant advancements in the management of upper urinary tract stones and have become the mainstream treatment modality. The core procedures currently routinely performed include extracorporeal shock wave lithotripsy (SWL), percutaneous nephrolithotomy (PCNL), and flexible ureteroscopy with lithotripsy (FURL). SWL is widely adopted due to its non-invasive advantage; however, its stone-free rate (SFR) can be affected by factors such as stone hardness, anatomical location, and patient body type. FURL (or RIRS) is performed through natural body cavities, resulting in minimal trauma; meanwhile, PCNL demonstrates significant efficiency advantages in managing large stone burdens. Currently, PCNL technology continues to evolve toward minimally invasive (miniaturization) and precision-oriented approaches. Concurrently, FURL technology has achieved significant breakthroughs through the integration of key innovations such as intelligent pressure control systems and flexible negative pressure suction sheaths. Therefore, systematically reviewing the latest advancements in minimally invasive surgical treatments for upper urinary tract stones and objectively evaluating their efficacy based on evidence-based medicine (such as comparing the clinical efficacy of PCNL versus FURL combined with novel negative pressure devices) will provide valuable practical guidance for clinicians in developing individualized and optimized treatment plans.

Keywords: extracorporeal shock wave lithotripsy, flexible ureteroscope lithotripsy, percutaneous nephrolithotomy

Introduction

Urinary tract stones are among the most prevalent urological conditions, with a global incidence rate that continues to rise. Upper urinary tract stones can cause acute clinical symptoms, with typical manifestations including severe renal colic (often described by patients as “knife-like” pain), often accompanied by nausea, vomiting, and profuse sweating. More concerning are the potential long-term complications, such as recurrent urinary tract infections, persistent hematuria, obstructive hydronephrosis, and even progression to renal parenchymal atrophy and progressive renal dysfunction. For patients with upper urinary tract stones unresponsive to conservative treatment, minimally invasive surgery has become the preferred treatment strategy. Current clinical practice has established an integrated treatment regimen centered on extracorporeal shock wave lithotripsy (SWL), percutaneous nephrolithotomy (PCNL), and flexible ureteroscopy with lithotripsy (FURL), with the primary goal of achieving safe and effective stone clearance while preserving renal function.

Notably, FURL technology has undergone significant innovations in recent years. Among these, the combined use of a flexible negative pressure suction sheath (eg., FANS-UAS) for continuous negative pressure suction during surgery effectively maintains intra-renal pelvic pressure (IPP) at safe levels. Existing evidence indicates that this technique significantly improves stone-free rate (SFR) and reduces reintervention rates.¹ These technological advancements not



only expand the application scope of FURL in managing larger stone burdens and more complex anatomical structures but also prompt a reevaluation of the indications for traditional PCNL. The rapid evolution of these techniques is reshaping clinical practice. PCNL continues to advance in miniaturization and precision, reducing trauma while maintaining efficacy. Concurrently, technological breakthroughs in FURL—such as intelligent pressure control and flexible suction sheaths—have significantly expanded its indications to include larger stone burdens, challenging traditional treatment paradigms. This dynamic landscape underscores the need for an updated, evidence-based synthesis to guide optimal clinical decision-making. This review summarizes the latest research progress in minimally invasive surgical treatment for upper urinary tract stones, particularly focusing on PCNL and FURL technology, with the aim of providing guidance for clinical practice.

Epidemiological Characteristics and Disease Burden

The incidence of urinary tract stones continues to rise globally, with significant regional variations.² Nephrolithiasis is a highly prevalent disease worldwide with rates ranging from 7 to 13% in North America, 5–9% in Europe, and 1–5% in Asia.³ Among all types of kidney stones, approximately 80% are composed of a mixture of calcium oxalate (CaOx) and calcium phosphate (CaP).⁴ The prevalence of kidney stones is rising globally, driven by various factors such as obesity, increasing prevalence of diabetes, high-salt, high-animal protein, and high-sugar diets, increased consumption of sugary beverages, and global warming. These factors are considered important environmental and lifestyle factors contributing to the increase in incidence.³ Additionally, the widespread application of diagnostic imaging technologies and the continuous improvement of their resolution have increased the detection rate of both asymptomatic and symptomatic kidney stones. It is worth noting that kidney stones have a high recurrence rate. Research data indicate that the recurrence rate within 5–10 years is approximately 50%, and it can reach as high as 75% within 20 years.⁵

Urolithiasis imposes a significant socioeconomic burden. For example, a US study predicted that if current risk factors persist, the annual medical costs associated with urolithiasis will increase by approximately \$1.24 billion by 2030,⁶ and China's large population base makes the overall economic burden of this disease even more substantial.⁷ Recent U.S. data (2011–2018) on stone disease management reveals a substantial economic burden, with total expenditures reaching \$10 billion. Notably, nonoperative management accounted for 78% of patients and the majority of costs (\$6.9 billion). Over this period, spending shifted significantly: inpatient costs decreased while outpatient and prescription expenses increased. A higher comorbidity burden was the most consistent predictor of greater healthcare spending.⁸ Therefore, optimizing treatment strategies to improve long-term outcomes and quality of life for patients is particularly critical.

Non-Surgical Treatment

Although minimally invasive surgery is currently the mainstream approach, conservative treatment remains indispensable in specific clinical scenarios. For small stones with a diameter of less than 0.5 cm, the use of α -receptor blockers (such as tamsulosin) can effectively promote their spontaneous expulsion. In terms of preventing stone recurrence, individualized drug intervention based on metabolic assessment is of critical importance. For example, in patients with calcium oxalate stones, prophylactic treatment may include thiazide diuretics, citrate preparations, allopurinol (a uric acid synthesis inhibitor), or magnesium supplements.⁹ However, it is important to note that some “stone-expelling” or “stone-dissolving” medications may increase the risk of adverse drug reactions (ADRs).¹⁰

Localization and Progress of SWL

Since its clinical application in 1980, extracorporeal shock wave lithotripsy (SWL) has been used as a non-invasive technique to fragment urinary tract stones by focusing shock waves (typically performed under fluoroscopic or ultrasound guidance). However, its stone fragmentation success rate is affected by multiple factors, including stone size, location, composition, density (measured in Hounsfield Units, HU), operational parameter settings, and the patient's pain tolerance, among others.¹¹ According to guidelines recommended by the International Association of Urology (IAU), SWL is indicated for the treatment of kidney stones with a diameter of ≤ 20 mm or ≤ 15 mm for stones in the lower calyces of the kidney.¹² For kidney stones with a diameter of >20 mm, SWL is generally not recommended as

a standalone treatment modality. Nevertheless, SWL remains valuable in specific clinical scenarios due to its non-invasive nature, repeatability, and relatively low complication rate. For example, in pediatric patients with kidney stones, SWL can still be considered a valuable alternative to more invasive procedures.¹³ In terms of technological innovation, novel lithotripsy techniques such as blast wave lithotripsy (BWL), histotripsy, and microbubble lithotripsy (ML) have demonstrated potential advantages in preclinical studies or early clinical trials,¹⁴ but their definitive clinical utility remains to be determined. Further high-quality research is needed to confirm these findings. Current evidence suggests that SWL remains a safe and effective treatment option for patients who meet the indications (including some children and special cases),^{15,16} retaining its specific role in the era of endoscopic techniques and maintaining its indispensable clinical value.

Percutaneous Nephrolithotomy (PCNL): Miniaturization and Precision

After systematically reviewing the epidemiological characteristics, disease burden, non-surgical management, and complementary techniques such as extracorporeal shock wave lithotripsy (SWL) related to urinary tract stones, this article will focus on the two core pillar technologies of the current minimally invasive treatment system for urinary tract stones: percutaneous nephrolithotomy (PCNL) and flexible ureteroscopy with lithotripsy (FURL). As the gold standard for managing high-burden (>2cm) kidney stones, PCNL has established an irreplaceable position in the treatment of complex stones due to its highly efficient stone clearance capability. The core direction of its technological development is continuously evolving toward channel miniaturization and precise puncture localization, aiming to significantly enhance surgical safety, reduce trauma, and optimize patient outcomes.

Channel Miniaturization

PCNL miniaturization is characterized by a continuous reduction in tract size. According to the consensus of the International Association of Urolithiasis (IAU), the upper limit for micro-PCNL (MPCNL) channels is 18 Fr, while the lower limit for standard PCNL (SPCNL) channels is 24 Fr.¹⁷ From traditional standard PCNL (24–30Fr) to ultra-mini channel technology (Ultra-mini PCNL, UMP, 11–13 Fr), Chinese pioneering super-mini PCNL (Super-mini PCNL, SMP, 10–14 Fr), and even finer Micro-PCNL (4.8Fr), Needle-perc (4.2Fr), the significant reduction in the outer diameter of the percutaneous channel has effectively reduced the risk of renal parenchymal injury. Clinical studies have confirmed the efficacy and safety of miniaturized channels. Zhu Jiaqi et al reported that 1–2cm kidney stones treated with UMP, the stone-free rate (SFR) reached 90.0% at 1 month postoperatively,¹⁸ with a low complication rate, showing no statistically significant difference compared to the FURL group during the same period ($P > 0.05$). SMP technology integrates negative pressure suction sheath tubes with a dual-perfusion channel design, achieving synchronized “stone fragmentation and extraction.” This enhances the single-session stone fragmentation rate (SFR) for stones ≤ 2.5 cm to over 90% and enables 93% of patients to achieve “tube-free” outcomes (eliminating the need for nephrostomy tubes and double-J stents).¹⁹ The results of a randomized controlled trial further indicate that although the average surgical time was longer in the SMP group than in the standard channel group (51.62 ± 10.17 minutes vs 35.6 ± 6.8 minutes, $P = 0.03$), the intraoperative blood loss was significantly reduced (44% less than traditional PCNL), and the postoperative pain VAS score (5.4 ± 0.7 vs 5.9 ± 0.9 , $P = 0.03$) and average hospital stay (28.38 ± 3.6 hours vs 39.84 ± 3.7 hours, $P = 0.0001$) were significantly reduced.¹⁹ For the treatment of 10–20 mm pediatric kidney stones, Micro-PCNL may have advantages over FURL.²⁰ However, it should be noted that the closed irrigation system used in Micro-PCNL has theoretical concerns about increasing renal pelvic pressure and the risk of infection.²¹ Channel miniaturization improves the safety and effectiveness of PCNL in pediatric patients, with studies showing that the stone-free rate for pediatric PCNL can reach 85%, and the complication rate is below 7%.²² Needle-perc (4.2Fr) represents the most refined PCNL endoscopic equipment currently available. It can establish percutaneous renal access under full ultrasound guidance, either in combination with standard or mini-channel PCNL for complex stones, or to assist FURL in clearing stones located in moderately unfavorable calyces. A prospective randomized study on complex solitary kidney stones showed that compared to multi-channel traditional PCNL, Needle-perc assisted endoscopic surgery (NAES) technology achieved a higher one-stage stone-free rate (90.9% vs 73.9%, $P=0.03$), while reducing hemoglobin decrease, shortening

postoperative hospital stay, and lowering the incidence of severe complications (Clavien-Dindo grade III and above), despite its longer operation time.²³

Precision Puncture Localization

Precise localization and needle placement are the cornerstones of successful PCNL. Currently, fluoroscopy and real-time ultrasound guidance remain the most commonly used and cost-effective methods in clinical practice.²⁴ However, traditional two-dimensional imaging guidance has limitations for complex kidney stones or inexperienced operators. In recent years, precision technologies have significantly improved the accuracy of needle placement in PCNL. Newly developed navigation systems (eg., the AcuSee system) applied to ultrasound-guided PCNL have demonstrated good feasibility and safety,²⁵ providing surgeons (especially beginners) with intuitive visual guidance. Three-dimensional (3D) CT reconstruction technology has been used to optimize needle insertion path planning. Haotian Tan et al reported that the 3D CT navigation group had significantly higher first-attempt puncture success rates (87.5% vs 47.8%, $P < 0.05$) and one-stage SFR (81.9% vs 64.2%, $P < 0.05$) were significantly improved, with fewer complications (91.7% vs. 74.6% with no or mild complications).²⁶

The novel percutaneous digital flexible nephroscope (Percutaneous Digital Flexible Nephroscope) has been validated in an ex vivo porcine kidney model, demonstrating its ability to smoothly enter the renal collecting system and reach more target areas of the renal calyces through bending angles,²⁷ offering superior positioning flexibility compared to traditional rigid nephroscopes. This innovation holds promise for enhancing the safety and efficiency of complex stone management. Future successful application in human trials will mark a major advancement in this field.

Technical Innovations and Challenges in Flexible Ureteroscopy with Lithotripsy (FURL)

Key Technological Advances in FURL

Ureteroscopy with flexible ureteroscope and lithotripsy (FURL) is a minimally invasive procedure performed through natural orifices, offering the advantages of minimally invasive surgery and rapid postoperative recovery. While traditional ureteral access sheaths (T-UAS) improve surgical field visibility and reduce intra-renal pressure, they lack active stone removal capabilities, leading to stone residue and increased risks of infection or recurrence. However, the intelligent pressure control system and flexible negative pressure suction sheath, as key technological innovations in contemporary FURL, enhance surgical safety by optimizing renal pelvic pressure dynamics and stone fragmentation efficiency.

Intelligent Pressure Control System

The system uses pressure sensors and automatic regulation to monitor and adjust irrigation pressure in real time, ensuring that intra-pelvic pressure (IPP) remains within safe thresholds. The intelligent pressure control platform on the sheath automatically detects pressure changes and triggers suction adjustment, effectively preventing high-pressure-related kidney injury and infectious complications.²⁸ Clinical studies have confirmed that this system enables precise management of IPP during surgery, improving stone-free rate (SFR) and surgical efficiency while ensuring safety.²⁹ Its core mechanisms include: dynamically regulating irrigation flow based on pressure feedback, coordinating negative pressure suction to reduce fluid absorption, and suppressing the “snowball effect” of blurred vision, thereby optimizing the surgical process.³⁰

Flexible Negative Pressure Suction Sheath

The flexible negative pressure suction sheath (eg., NP-UAS, FANS-UAS, or FV-UAS) has an additional flexible section (typically approximately 10 cm) at its distal end, which can bend along with the flexible endoscope (angle $> 90^\circ$), enabling it to better reach the target renal calyx and perform active suction in complex anatomical structures, thereby enhancing the active stone removal capability under complex anatomical conditions during FURL.³¹ The design of the negative pressure port on the sheath body enables simultaneous removal of stone fragments and dynamic stabilization of IPP. Studies have shown that it overcomes the traditional sheath-to-endoscope ratio limitations of conventional sheaths, effectively counteracting the risk of high infusion pressure through suction.^{32,33} Prospective multicenter studies have

demonstrated that FURL using FANS achieves a high stone removal rate (SFR),³⁴ with low rates of severe adverse events and reintervention.¹ The application of FANS-UAS in pediatric patients has also been confirmed to be safe and feasible, with few complications and excellent stone-free rates. This technology achieves synchronized reduction of stone residuals and recurrence risks in both adult and pediatric patients through continuous low IPP management, efficient stone fragmentation and removal, and shorter surgical times.

FURL Challenges the Therapeutic Role of PCNL

Traditional guidelines have limited the indications for FURL to kidney stones with a diameter,³⁵ which have limitations in the treatment of large stones due to insufficient stone-free rates and a high risk of infection. The emergence of technologies such as flexible negative pressure suction sheaths is gradually changing this situation.

Comparability of Stone-Free Rate (SFR)

Guanyun Deng and colleagues conducted a retrospective analysis of 2–3 cm kidney stones and found that the flexible negative pressure suction sheath FURL and microchannel PCNL (Tubeless-mini PCNL) showed no statistically significant difference in stone free rate (SFR, defined as residual stone diameter <4 mm or <2 mm) at 3 days and 1 month postoperatively.³⁶ A recent multicenter, non-inferior randomized controlled trial further confirmed that for 2–3 cm kidney stones, the FURL with a flexible suction sheath was non-inferior to MPCNL in terms of immediate SFR (84% vs 85%), with no difference in SFR at 3 months postoperatively (90% vs 92%), and patients in the FURL group showed significantly improved quality of life (QoL).³⁷ Although some studies suggest that MPCNL may be superior to FURL with a suction sheath in terms of immediate SFR,^{38–40} most evidence supports no significant difference in SFR between the two methods. This indicates that for stones measuring 2–3 cm, the flexible negative-pressure suction sheath FURL may achieve SFR outcomes comparable to those of PCNL.

Advantages in Terms of Safety, Complications, and Recovery Period Indicators

The combination of a flexible negative pressure suction sheath and FURL demonstrates multiple advantages in terms of perioperative safety, complication rates, and postoperative recovery. In pediatric cases and patients with renal structural abnormalities (congenital renal diseases), the application of the flexible negative pressure suction sheath has been proven safe and effective, with no significant postoperative bleeding or obstruction complications, and avoids damage to the renal pelvis anastomosis site. In contrast, PCNL may carry a higher risk of invasiveness in these populations.⁴¹ The negative pressure suction sheath effectively reduces the “snowball effect” and renal pelvic fluid retention by simultaneously aspirating irrigation fluid and lithotripsy fragments, maintaining low intraoperative pressure (IPP), and lowering the risk of postoperative infection.^{33,42} In contrast, PCNL is more prone to fluid extravasation and renal pelvic venous reflux under high irrigation pressure.⁴³ In terms of postoperative pain and hospital stay, the suction sheath FURL typically offers advantages (lower VAS scores, hospital stay often 1–2 days), while even with mini-PCNL, postoperative pain and hospital stay are generally longer (average 3–5 days), and use of a modified vacuum suction sheath (Va-PCNL) can reduce this to 2–3 days.⁴⁴

Conclusion and Prospect

The core advancements in minimally invasive treatment for upper urinary tract stones are reflected in the significant innovations of FURL and PCNL technologies. The core breakthrough of FURL lies in the integration of an intelligent pressure control system and a flexible negative pressure suction sheath. The former achieves real-time dynamic adjustment of irrigation pressure, significantly reducing intra-renal pelvic pressure (IPP) during surgery and enhancing surgical safety. The latter, with its flexible distal design, enables the flexible endoscope to penetrate complex renal calyces, achieving integrated lithotripsy and simultaneous suction, effectively overcoming the stone clearance limitations of traditional FURL. Clinical studies have demonstrated that this combined technology not only expands the indications for FURL to larger stone loads (eg., 2–3 cm) but also achieves comparable stone clearance efficiency to PCNL. Its low risk of renal parenchymal injury, rapid postoperative recovery, and adaptability to special anatomical structures (eg., post-pyeloplasty) make it a preferred option for patients with complex anatomy or those at high surgical risk. Meanwhile,

PCNL technology continues to evolve along two parallel tracks: miniaturization (MPCNL, UMP, SMP, Micro-PCNL, Needle-perc) and precision (3D navigation, ultrasound-enhanced reality, digital flexible nephroscope), significantly enhancing safety and efficiency in managing large stone burdens and driving the advancement of “tubeless” practices.

The current treatment paradigm emphasizes individualized decision-making: Extracorporeal shock wave lithotripsy (SWL) remains invaluable for specific stone sizes and pediatric patients due to its non-invasive nature; percutaneous nephrolithotomy (PCNL) remains an effective method for managing large stone burdens (especially >2 cm). Flexible ureteroscopy with lithotripsy (FURL) leverages breakthroughs in intelligent pressure control and active suction technology to significantly improve stone clearance efficiency and reduce the risk of complications. Its indications have been expanded to include moderate stone burdens (2–3 cm) and certain complex stones or special populations, demonstrating promising prospects.⁴⁵ Future multicenter, large-scale clinical trials are needed to further validate the safety and efficacy of flexible negative-pressure suction sheath FURL and explore its application potential for larger stone burdens. The final choice of surgical procedure should comprehensively consider stone characteristics (size/location/density/anatomy), patient factors (comorbidities/BMI/patient preference), and technical conditions (surgeon experience/equipment availability).

Abbreviations

SWL, extracorporeal shock wave lithotripsy, FURL, flexible ureteroscopy with lithotripsy, PCNL, percutaneous nephrolithotomy, SFR, stone-free rate, RIRS, retrograde intrarenal surgery, FANS-UAS, flexible and navigable suction ureteral access sheath, IPP, intra-renal pelvic pressure, CaOx, calcium oxalate, CaP, calcium phosphate, BWL, blast wave lithotripsy, QoL, quality of life.

Data Sharing Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Disclosure

The authors have no conflicts of interest to disclose for this work.

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