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Suction-Assisted Mini-Percutaneous Nephrolithotomy: A Comprehensive Review of Technique, Outcomes, and Patient Positioning

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Abstract

Background: Percutaneous nephrolithotomy has long been the standard surgical approach for large and complex renal stones. Over the past two decades, miniaturization of instruments has led to the development of mini-percutaneous nephrolithotomy, which uses access sheaths of 14 to 20 French, offering the potential for reduced bleeding, less postoperative pain, and shorter hospital stay compared with the standard technique. However, mini-percutaneous nephrolithotomy is associated with elevated intrarenal pressure and longer operative duration due to limited fragment evacuation through the smaller sheath. The incorporation of suction-assisted sheaths during mini-percutaneous nephrolithotomy has emerged as a promising modification, applying continuous negative pressure to aspirate stone fragments and irrigant simultaneously, thereby lowering intrarenal pressure, improving intraoperative visibility, and accelerating stone clearance. In addition, patient positioning has evolved from the traditional prone approach toward supine and flank-free modified supine techniques, which provide advantages in airway management, cardiovascular stability, and the possibility of simultaneous retrograde access.

Keywords: *mini-percutaneous nephrolithotomy; suction-assisted sheath; intrarenal pressure; stone-free rate; flank-free modified supine position; vacuum-assisted nephrostomy*

Introduction

Urolithiasis is a widespread urological condition with an increasing global prevalence attributed to dietary habits, climate changes, genetic predisposition, and metabolic disorders. The prevalence of kidney stones in the United States alone has risen from 3.8% in 1970 to more than 10% in recent years, and recurrence remains a major clinical concern, with a 50% risk within ten years of the initial episode (1).

Percutaneous nephrolithotomy was first introduced in 1976 and has since become the primary surgical modality for the management of large renal calculi, particularly those exceeding 20 millimeters in maximum diameter. International guidelines, including those of the European Association of Urology, endorse percutaneous nephrolithotomy as the first-line treatment for such stones owing to its high stone clearance rates and acceptable morbidity profile (2).

The original technique involved creating a relatively large percutaneous tract, typically 24 to 30 French in diameter, which provided excellent access for stone fragmentation and extraction but was associated with significant bleeding risk, postoperative pain, and prolonged hospitalization. These limitations prompted the development of miniaturized approaches, including mini-percutaneous nephrolithotomy, ultra-mini-percutaneous nephrolithotomy, and micro-percutaneous nephrolithotomy, all of which aim to reduce tract-related morbidity while maintaining effective stone clearance (3).

Mini-percutaneous nephrolithotomy, which uses access sheaths of 14 to 20 French, has gained particular traction over the past decade. Multiple meta-analyses have confirmed its advantages over the standard technique in terms of lower bleeding rates, fewer blood transfusions, and shorter hospital stays for stones in the moderate size range. However, the smaller sheath diameter introduces its own set of challenges, most notably elevated intrarenal pressure during irrigation and longer operative times due to the difficulty of evacuating stone fragments through the narrower channel (4).

The application of suction-assisted sheaths during mini-percutaneous nephrolithotomy has emerged as a key technical innovation aimed at overcoming these limitations. By connecting the access sheath to a negative-pressure aspirator, continuous suction evacuates stone fragments and irrigant simultaneously, thereby maintaining low intrarenal pressure, improving the surgical field, and reducing the time required for fragment retrieval. Several randomized controlled trials and meta-analyses have investigated this modification, and the accumulating evidence supports its safety and efficacy (5).

Patient positioning during percutaneous nephrolithotomy has also undergone substantial evolution. The traditional prone position, while providing excellent posterior renal access, poses well-recognized risks related to airway management, cardiovascular compromise, and positional injury, particularly in obese patients or those with significant cardiopulmonary comorbidities. The supine and flank-free modified supine positions have been developed as alternatives, offering easier anesthesia management, simultaneous retrograde access, and shorter operative times without compromising stone clearance (6).

This review aims to provide a comprehensive examination of suction-assisted mini-percutaneous nephrolithotomy, covering the evolution from standard to miniaturized techniques, the rationale and mechanism of suction-assisted sheaths, the influence of patient positioning on outcomes, and the current clinical evidence comparing suction and non-suction approaches in this setting.

Epidemiology and Burden of Renal Stones

The global burden of urolithiasis has increased substantially over the past several decades, driven by changes in dietary patterns, rising obesity rates, and environmental factors including climate warming. In the United States, the prevalence has nearly tripled from 3.8% in the early 1970s to over 10% in recent population-based surveys. Men have historically been affected more frequently than women, with a ratio of approximately two to one, although the incidence in women has been rising more rapidly. The southeastern and south-central regions of the United States, collectively known as the stone belt, carry the highest disease burden, largely attributable to climate-related dehydration and associated urinary supersaturation (1).

Stone risk increases with advancing age, peaking in men over 80 years, and has been noted to be rising among children, particularly adolescent females. Racial and ethnic disparities exist, with Black and Hispanic populations demonstrating lower overall incidence, a finding that may partly reflect differences in socioeconomic status, dietary intake, and access to healthcare rather than purely biological factors. Nephrolithiasis is now well recognized as a systemic condition associated with diabetes mellitus, hypertension, cardiovascular disease, and chronic kidney disease, further amplifying its public health significance. Projections based on current climate trends suggest that stone disease rates may increase by as much as 30% by 2050, placing considerable additional strain on healthcare systems worldwide (7).

Indications for Percutaneous Nephrolithotomy

Percutaneous nephrolithotomy is primarily indicated for the management of large or complex kidney stones that cannot be adequately treated by less invasive modalities. Stones exceeding 20 millimeters in maximum diameter are generally best managed by this technique, as extracorporeal shock wave lithotripsy and ureteroscopy often fail to achieve complete clearance for calculi of this size. Staghorn calculi, which fill a substantial portion of the renal collecting system, also carry a clear indication for percutaneous nephrolithotomy given the high risk of infection and progressive renal damage associated with incomplete removal (8).

Patients with multiple stones scattered across several calyceal groups benefit from percutaneous nephrolithotomy because it allows efficient clearance from multiple locations within a single operative session.

The technique is also the preferred option when prior attempts at extracorporeal shock wave lithotripsy or ureteroscopy have failed, or when the stone composition is particularly resistant to fragmentation, as is the case with certain cystine and calcium oxalate monohydrate stones. Anatomical variants such as horseshoe kidneys, calyceal diverticula, and pelvic kidneys may further favor percutaneous access over retrograde approaches (8).

In cases complicated by obstructive uropathy or infected stones causing pyonephrosis, percutaneous nephrolithotomy provides the dual advantage of drainage of infected urine and removal of the obstructing calculus. Proper preoperative imaging, including non-contrast computed tomography, is essential for surgical planning and for applying standardized complexity scoring systems such as the S.T.O.N.E. nephrolithometry score, which evaluates stone size, tract length, obstruction, number of involved calices, and stone density to predict operative difficulty, stone-free rates, and complication risks (9).

Evolution from Standard to Mini-Percutaneous Nephrolithotomy

The standard percutaneous nephrolithotomy technique, developed in the mid-1970s, uses access tracts of 24 to 30 French in diameter, allowing direct visualization and extraction of large stone fragments. While this approach delivers excellent stone clearance rates, particularly for complex and staghorn calculi, it is accompanied by complications related to the size of the tract, including clinically significant hemorrhage, renal parenchymal injury, and the potential need for blood transfusion, which has historically been reported in 5 to 18% of cases (10).

The drive toward miniaturization began in the early 2000s with the introduction of mini-percutaneous nephrolithotomy, which employs sheaths of 14 to 20 French. By reducing the diameter of the access tract, this modification decreases the volume of renal tissue traversed, thereby lowering the risk of vascular injury and hemorrhage. Multiple comparative studies and meta-analyses have confirmed that mini-percutaneous nephrolithotomy is associated with less blood loss, lower transfusion rates, reduced postoperative pain, and shorter hospital stays when compared with the standard technique for stones in the moderate size range (11).

Further miniaturization has produced ultra-mini-percutaneous nephrolithotomy, which uses tracts smaller than 14 French, and micro-percutaneous nephrolithotomy, which employs even finer instruments. These approaches offer additional reductions in bleeding and tissue trauma and may improve cosmetic outcomes. However, the trade-off with progressively smaller sheaths is a reduced capacity for fragment evacuation, potentially leading to longer operative times and higher intrarenal pressures during irrigation. The choice among standard, mini, and ultra-mini techniques therefore depends on the balance between stone burden, patient factors, and the availability of specialized instrumentation (12).

Mini-Percutaneous Nephrolithotomy

The mini-percutaneous nephrolithotomy procedure begins with imaging-guided puncture of the target calyx, typically under fluoroscopic or ultrasonographic guidance. After establishing guidewire access to the collecting system, the tract is dilated in a single step or sequentially to the desired sheath size, usually 14 to 18 French. A miniature nephroscope is then introduced through the sheath to visualize the stone, and fragmentation is performed using holmium laser, ultrasonic, or pneumatic lithotripsy. Stone fragments are removed through the sheath by irrigation flow, basket extraction, or, in suction-equipped systems, by active aspiration (13).

Ideal candidates for mini-percutaneous nephrolithotomy are patients with renal stones measuring approximately 10 to 30 millimeters in maximum diameter, for whom the technique provides efficient clearance with a favorable safety profile. Patients at elevated risk of bleeding, including those on anticoagulant therapy, those with bleeding disorders, or those with solitary kidneys, may particularly benefit from the smaller tract size. Pediatric patients and those with a smaller body habitus are additional groups in whom mini-percutaneous nephrolithotomy offers advantages over the standard approach (14).

Conversely, very large or complex staghorn stones may be less efficiently managed by mini-percutaneous nephrolithotomy, as the smaller sheath limits the size of fragments that can be evacuated and may necessitate prolonged operative times. Careful preoperative assessment using computed tomography and validated complexity scores is essential for selecting the appropriate technique, and surgeon experience with miniaturized instruments is a further determinant of outcome (15).

Patient Positioning

The Flank-Free Modified Supine Technique

The prone position was the original standard for percutaneous nephrolithotomy and continues to provide excellent posterolateral access to the kidney. However, it carries well-documented disadvantages, including difficulty in airway management, increased risk of cardiovascular instability, potential for ocular and facial pressure injuries, and the inability to perform simultaneous retrograde ureteroscopic procedures. These limitations are particularly relevant in obese patients and those with significant respiratory or cardiac comorbidities, in whom prone positioning may increase perioperative risk (16).

Supine positioning for percutaneous nephrolithotomy was introduced as an alternative that addresses many of these concerns. With the patient lying on their back, the anesthesia team has unimpeded access to the airway, and continuous hemodynamic monitoring is straightforward. The supine approach also permits simultaneous antegrade and retrograde access, allowing combined percutaneous and ureteroscopic stone management within a single session without the need for patient repositioning, thereby reducing overall operative and anesthesia time (17).

The flank-free modified supine position is a further refinement in which the patient lies predominantly supine with the ipsilateral flank elevated and left free from compression using cushions or bolsters placed beneath the hip and back. This configuration creates an unobstructed space that allows direct posterolateral percutaneous access to the kidney while preserving all the advantages of supine positioning. The elevated flank facilitates safe needle puncture and tract dilation, and the technique has been associated with shorter operative times, improved patient comfort, and effective stone clearance comparable to that achieved in the prone position (6).

A randomized clinical trial comparing flank-free modified supine ultra-mini-percutaneous nephrolithotomy with prone ultra-mini-percutaneous nephrolithotomy for medium-sized renal pelvic stones reported comparable stone-free rates between the two positions, with the flank-free modified supine group demonstrating advantages in terms of operative efficiency and patient recovery. These findings have contributed to the growing adoption of this positional technique, particularly in centers where combined antegrade and retrograde approaches are routinely employed (18).

Suction-Assisted Sheaths

Suction-assisted sheaths are modified access sheaths that incorporate a dedicated channel or side port connected to a negative-pressure aspirator, enabling continuous active evacuation of stone fragments, blood, and irrigation fluid from the renal collecting system during the procedure. The basic principle involves maintaining a constant outflow of irrigant through the sheath, which balances the inflow of fresh irrigation fluid and prevents the accumulation of pressure within the kidney. This dynamic flow ensures that intrarenal pressure remains at physiologically safe levels throughout the operation (19).

Elevated intrarenal pressure during percutaneous nephrolithotomy is a recognized cause of pyelovenous backflow, a phenomenon in which bacteria-laden urine or irrigation fluid is forced into the renal venous system and subsequently into the systemic circulation. This mechanism underlies the development of postoperative bacteremia, systemic inflammatory response, and, in severe cases, urosepsis. By continuously evacuating fluid from the collecting system, suction-assisted sheaths directly mitigate this risk, reducing the incidence of infectious complications following the procedure (20).

In addition to pressure control, the continuous aspiration of debris provides a consistently clear operative field, allowing the surgeon to visualize and target residual stone material more effectively. This improved visibility, combined with the simultaneous removal of fragments as they are generated during lithotripsy, reduces the need for repeated manual extraction passes with baskets or graspers, contributing to shorter operative times and more complete stone clearance. The suction mechanism also minimizes stone fragment migration to inaccessible locations within the collecting system, which is a recognized cause of residual stones following conventional techniques (21).

Suction Versus Non-Suction Mini-Percutaneous Nephrolithotomy

Several randomized controlled trials and comparative studies have examined the outcomes of suction-assisted mini-percutaneous nephrolithotomy compared with conventional techniques without suction. A study comparing double-sheath vacuum suction mini-percutaneous nephrolithotomy with conventional mini-percutaneous nephrolithotomy for large kidney stones demonstrated that the suction group achieved significantly shorter operative times, higher primary stone-free rates of 85.3% versus 70.3%, and lower rates of auxiliary procedures and postoperative fever compared with the conventional group (22).

A multicenter prospective randomized trial assessing vacuum-assisted nephrostomy sheaths versus conventional sheaths in minimally invasive percutaneous nephrolithotomy for stones measuring two to four centimeters reported that the vacuum-assisted group had significantly lower intrarenal pressure, shorter stone removal times, higher stone extraction rates measured in cubic millimeters per minute, and a markedly reduced need for stone extraction devices such as baskets and graspers. These findings provided strong evidence that the active aspiration mechanism directly translates into measurable improvements in operative efficiency and fragment clearance (23).

A systematic review and meta-analysis evaluating the efficacy of vacuum-assisted sheaths in minimally invasive percutaneous nephrolithotomy synthesized data from multiple studies and found that suction-assisted techniques were associated with significantly higher stone-free rates, shorter operative times, and lower postoperative infection rates compared with conventional sheaths. Notably, no significant difference was observed in blood transfusion rates between the two approaches, suggesting that the benefit of suction relates primarily to fragment clearance efficiency and pressure management rather than to a reduction in hemorrhagic risk (24).

A comparative study focusing specifically on staghorn calculi found that suctioning minimally invasive percutaneous nephrolithotomy achieved a higher stone-free rate of 78.5% versus 69.1% and a shorter operative time of approximately 106 minutes versus 132 minutes compared with the traditional non-suction approach. The suctioning group also experienced fewer postoperative infectious complications, including fever and urosepsis, further supporting the clinical value of continuous aspiration in this challenging stone subgroup (25).

A single-center study comparing two different suction modalities, vacuum-assisted mini-percutaneous nephrolithotomy and vacuum-cleaner minimally invasive percutaneous nephrolithotomy, in patients at high risk for infections found that the vacuum-assisted technique was associated with a lower incidence of infectious complications and shorter operative times. This comparison within suction-based systems suggests that the design and configuration of the suction mechanism itself can influence clinical outcomes, and that optimization of sheath engineering is an ongoing area of development (26).

Operative Outcomes

Time, Stone Clearance, and Complications

Operative time is consistently reported as one of the most significant advantages of suction-assisted mini-percutaneous nephrolithotomy. A meta-analysis of seven studies involving more than 1,600 patients found that suction-assisted techniques reduced operative time by a mean of approximately 17 minutes compared with conventional access sheaths. This time saving is attributed to the continuous evacuation of fragments, which eliminates the need for repeated basket passes and maintains an uninterrupted surgical workflow (5).

Stone-free rates in suction-assisted series are generally reported between 78 and 96%, depending on the stone burden, patient population, and definition of stone-free status used. The pooled analysis from multiple meta-analyses confirms a statistically significant advantage in stone-free rates favoring suction-assisted over conventional techniques, with the benefit most pronounced in larger and more complex stone burdens where fragment accumulation within the collecting system is a greater obstacle to complete clearance (24).

Postoperative complications, assessed using the Clavien-Dindo classification, are generally fewer in suction-assisted cases. The reduction in postoperative fever and systemic inflammatory responses is the most consistently reported benefit, directly attributable to the lower intrarenal pressures achieved during continuous aspiration. Operative duration exceeding 60 minutes has been identified as an independent risk factor for postoperative fever following percutaneous nephrolithotomy, and the reduction in operative time conferred by suction may therefore provide an additional indirect mechanism for lowering infectious risk (27).

Bleeding remains a concern in all forms of percutaneous nephrolithotomy, but the miniaturized tract sizes used in mini-percutaneous nephrolithotomy, with or without suction, have substantially reduced the incidence of clinically significant hemorrhage. Transfusion rates in mini-percutaneous nephrolithotomy series are consistently below 5%, and several studies of suction-assisted techniques have reported no transfusion requirements at all. The absence of a significant difference in transfusion rates between suction and non-suction groups in meta-analyses confirms that the bleeding risk is determined primarily by the tract size rather than by the aspiration mechanism (28).

Irrigation Dynamics and Intrarenal Pressure Management

The management of intrarenal pressure during percutaneous nephrolithotomy is a central concern that directly influences postoperative infectious risk. Conventional irrigation systems rely on gravity-driven or pressure-driven inflow of saline to maintain visibility and flush debris from the surgical field. However, in the absence of active outflow, irrigant can accumulate within the renal collecting system, leading to progressive elevation of intrarenal pressure and increasing the likelihood of pyelovenous backflow and bacterial translocation (20).

Suction-assisted systems address this problem by establishing a continuous outflow channel that actively removes fluid from the collecting system at a rate that matches or exceeds the inflow. The resulting dynamic equilibrium maintains intrarenal pressure at safe levels throughout the procedure, even during periods of high-flow irrigation required for optimal visibility. A prospective randomized trial demonstrated that vacuum-assisted sheaths maintained significantly lower intrarenal pressures compared with conventional sheaths across all phases of the operation, with the greatest differential observed during active lithotripsy when irrigation flow rates are highest (23).

An important consideration with suction-assisted systems is the increased total volume of irrigation fluid consumed during the procedure. Because the suction mechanism continuously draws fluid through the system, a higher throughput is required to maintain adequate inflow and visibility. Studies have reported that suction groups use significantly more irrigation bags than non-suction groups. This increased fluid consumption does not appear to translate into adverse clinical outcomes, as the actively evacuated fluid does not accumulate within the patient, but it does have implications for operative logistics and cost that should be considered in resource-limited settings (29).

Management of Residual Stones and Follow-Up

Despite the high stone-free rates achievable with modern percutaneous nephrolithotomy techniques, residual stone fragments following the procedure are not uncommon and require structured management. Small fragments measuring less than four millimeters, often termed clinically insignificant residual fragments, can frequently be managed conservatively with adequate hydration, dietary modification, and medical therapies aimed at preventing stone growth. Many of these fragments remain stable or pass spontaneously without causing symptoms. However, the concept of clinical insignificance has been increasingly questioned, as studies have demonstrated that a proportion of these fragments do grow or cause subsequent complications over time (30).

Larger residual fragments or those causing symptoms such as pain, obstruction, or recurrent infection generally require additional intervention. The choice of auxiliary procedure depends on the size, location, and composition of the residual stones, as well as patient factors and preferences. Options include repeat percutaneous nephrolithotomy for substantial or difficult-to-access fragments, flexible ureteroscopy for smaller or favorably positioned stones, and extracorporeal shock wave lithotripsy as a less invasive alternative for amenable fragment characteristics (31).

Follow-up imaging is essential for assessing stone clearance and guiding subsequent management decisions. Non-contrast computed tomography is the most sensitive modality for detecting residual fragments and accurately defining their size, location, and density, and is typically performed four to twelve weeks after surgery.

Ultrasonography may be preferred in specific populations such as children or pregnant women to minimize radiation exposure, although its sensitivity for small fragments is lower. Long-term surveillance with periodic imaging is particularly important in patients with metabolic risk factors or recurrent stone disease, as early detection of new stone formation or growth of residual fragments allows timely intervention and reduces the risk of progression to more complex disease (32).

Safety Considerations and Complication Prevention

Infectious complications following percutaneous nephrolithotomy range from transient postoperative fever, which occurs in up to 30% of cases in some series, to life-threatening urosepsis requiring intensive care. The principal mechanism involves bacterial translocation during the procedure, facilitated by elevated intrarenal pressure and the manipulation of infected or colonized stones. Preoperative urine culture with targeted antibiotic treatment for positive results, appropriate perioperative antibiotic prophylaxis, and intraoperative pressure management through suction-assisted irrigation are the cornerstones of infection prevention (33).

Bleeding during percutaneous nephrolithotomy can occur at any stage of the procedure, from initial puncture through tract dilation, lithotripsy, and nephrostomy placement. Careful image-guided puncture targeting the posterior calyx along the avascular plane of Brodel minimizes the risk of significant vascular injury. The use of miniaturized tracts in mini-percutaneous nephrolithotomy has substantially reduced the incidence and severity of hemorrhagic complications. In rare instances of severe or persistent bleeding, selective renal artery embolization provides an effective treatment option without the need for open surgical intervention (10).

The Clavien-Dindo classification provides a standardized framework for reporting and comparing surgical complications across studies, facilitating quality improvement and benchmarking. In the context of mini-percutaneous nephrolithotomy, the majority of reported complications fall within Grades I and II, including transient fever, minor pain requiring analgesics, and urinary tract infections managed with antibiotics. Grade III complications requiring additional intervention are less common, and Grade IV and V complications are rare, reflecting the overall safety of the technique when performed by experienced surgeons with appropriate patient selection (34).

Conclusion

The flank-free modified supine position further enhances the benefits of this technique by providing optimal airway management, cardiovascular stability, and the possibility of simultaneous retrograde access. While stone-free rates and major complication profiles are broadly comparable between suction and non-suction techniques in the available literature, the operational advantages of continuous aspiration are clinically meaningful, particularly for larger or more complex stone burdens where prolonged operative times and elevated intrarenal pressures pose greater risks. Future large-scale, multicenter randomized trials incorporating direct intrarenal pressure measurement, long-term follow-up, and cost-effectiveness analysis are needed to definitively establish the place of suction-assisted mini-percutaneous nephrolithotomy in the urological armamentarium and to guide evidence-based recommendations regarding its routine adoption across different patient positions and stone complexities. (32,33,34).

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