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Research Article

Keywords: Percutaneous nephrolithotomy, Ultrasonic lithotripsy, Simultaneous aspiration, Miniaturized tract, Cardinality matching

Posted Date: November 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11580069/v1

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Additional Declarations: No competing interests reported.

Simultaneous Ultrasonic Lithotripsy and Aspiration Through a Miniaturized Tract: Clinical Outcomes Compared with Standard Percutaneous Nephrolithotomy

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Abstract

Background: To compare clinical outcomes of miniaturized PCNL using simultaneous ultrasonic lithotripsy and aspiration with standard PCNL.

Objective: To compare clinical outcomes of simultaneous ultrasonic lithotripsy and aspiration through a miniaturized tract with standard PCNL for renal and proximal ureteral stones.

Methods: This prospective comparative cohort included 170 patients (118 standard PCNL; 52 ultrasonic aspiration mini-PCNL). Among 168 patients with complete covariates, balance-constrained cardinality matching selected equally sized groups using ten baseline variables, followed by 1:1 Mahalanobis pairing within exact strata of stone location, hydronephrosis, and ASA class. Balance was assessed using standardized mean differences (SMDs) and distribution diagnostics. Outcomes were analyzed as matched pairs with 95% confidence intervals (CIs).

Results: In unadjusted comparisons before matching, immediate stone-free rates were 55.1% versus 78.8% (P = 0.003), 1-month rates were 59.3% versus 76.9% (P = 0.027), and median operative time was 122.5 versus 89.5 min (P <0.001), for standard PCNL and ultrasonic aspiration mini-PCNL, respectively. Matching retained 36 pairs; all categorical covariates had identical group proportions, and the maximum absolute SMD was 0.039. Immediate stone-free rates were 55.6% with standard PCNL and 75.0% with ultrasonic aspiration mini-PCNL (paired risk difference, 19.4 percentage points; 95% CI, −4.6 to 43.5). One-month rates were 61.1% and 72.2%, respectively (difference, 11.1 percentage points; 95% CI, −12.9 to 35.1). Median operative time was 120 versus 92.5 min (paired mean difference, −22.4 min; 95% CI, −42.4 to −2.4; signed-rank P = 0.018). Complication rates were 16.7% and 13.9%, respectively (P = 1.000).

Conclusion: Simultaneous ultrasonic lithotripsy and aspiration through a miniaturized tract was associated with shorter operative time in the matched cohort, with no statistically significant differences in stone clearance or complications. Integrating fragmentation and evacuation within a miniaturized instrument offers a feasible approach to renal and proximal ureteral stone treatment.

Keywords: Percutaneous nephrolithotomy; Ultrasonic lithotripsy; Simultaneous aspiration; Miniaturized tract; Cardinality matching

Introduction

Percutaneous nephrolithotomy (PCNL) is an established treatment for large and complex renal stones [1]. Miniaturization aims to reduce access-related tissue injury while preserving effective clearance. Comparative studies of mini-PCNL and standard PCNL have reported broadly similar stone-free outcomes, with differences in bleeding, pain, hospitalization, and operative duration depending on the platform and clinical setting [2–4]. These findings provide the clinical context for evaluating how stones are fragmented and evacuated through a smaller tract.

A smaller access tract constrains the space available for instruments, irrigation, and fragment removal. When fragmentation and retrieval require separate maneuvers, stone evacuation may become a limiting step. Ultrasonic lithotripsy with aspiration integrates these functions: the probe fragments the stone while aspirating debris through its lumen. This simultaneous action may reduce interruptions for fragment retrieval and help maintain endoscopic visibility.

An initial clinical series has described a miniaturized nephroscope accommodating a 2.8-mm ultrasonic probe [5]. Suction-assisted mini-PCNL has also been evaluated with other systems [6,7]. Building on this work, the present study evaluates the comparative clinical performance of simultaneous ultrasonic fragmentation and aspiration through miniaturized access. We compared this workflow with standard PCNL for renal and proximal ureteral stones, using balance-constrained matching to address measured differences in treatment selection.

Methods

Study design and participants

This was a single-center, prospective comparative cohort study that consecutively enrolled patients undergoing percutaneous nephrolithotomy (PCNL) for renal or proximal ureteral stones at Peking University People's Hospital between January 2024 and December 2025. Patients were eligible if they had radiologically confirmed renal or proximal ureteral stones for which PCNL was planned. The exclusion criteria were an active or uncontrolled urinary tract infection, severe organ dysfunction precluding anesthesia or surgery, incomplete follow-up data, and the use of combined endoscopic procedures. The surgical approach was not randomly assigned. Standard PCNL or ultrasonic aspiration mini-PCNL was selected jointly by the treating surgeon and the patient after consideration of the patient's clinical characteristics, stone burden and location, collecting-system anatomy, technical feasibility, and the patient's preference following discussion of the potential benefits and risks of each approach. All procedures were performed or directly supervised by the same senior endourologist, who had 10 years of PCNL experience and had independently performed more than 1000 PCNL procedures before the study period. A total of 170 eligible patients were included, comprising 118 patients treated with standard PCNL and 52 patients treated with ultrasonic aspiration mini-PCNL. See Figure 1 for the detailed flowchart.

The study was approved by the Ethics Committee of Peking University People’s Hospital (approval No. 2024PHB440-001). Written informed consent was obtained from all participants.

The following perioperative variables were collected: age, sex, American Society of Anesthesiologists (ASA) class, body mass index (BMI), stone laterality, stone location, renal anatomical anomaly, hydronephrosis, cumulative stone diameter, stone CT value, stone history, previous stone surgery, preoperative nephrostomy, preoperative ureteral stenting, stone type, comorbidities, preoperative laboratory parameters, tract size, number of tracts, operative time, postoperative laboratory parameters, highest postoperative temperature, postoperative complications, tubeless status, nephrostomy-tube duration, immediate stone-free rate, 1-month stone-free rate, and hospital stay.

Outcome definitions

The primary effectiveness outcomes were the immediate and 1-month stone-free rates. The immediate stone-free rate was assessed using non-contrast computed tomography (NCCT) performed 24 hours after surgery,

whereas the 1-month stone-free rate was assessed using NCCT performed 1 month after surgery. At each time point, a patient was considered stone-free if NCCT showed no residual fragment or only residual fragments ≤2 mm, based on previous studies demonstrating an association between residual fragment size after PCNL and subsequent stone-related events [8,9]. Secondary perioperative outcomes included operative time, hemoglobin decrease, postoperative complications, nephrostomy-tube duration, tubeless status, and hospital stay. Postoperative complications were graded according to the Clavien-Dindo classification, which is widely used for surgical complication reporting and has been validated for PCNL-specific complications [10,11].

Hemoglobin and hematocrit decreases were calculated as preoperative minus postoperative day-1 values. Hematocrit differences are expressed in percentage points. Nephrostomy-tube duration included zero days for patients without a nephrostomy tube.

Simultaneous ultrasonic lithotripsy and aspiration through a miniaturized tract

The intervention is termed ultrasonic aspiration mini-PCNL in this report. A rigid mini-nephroscope with an approximately 10.5-Fr working channel accommodated a 2.8-mm ultrasonic probe. Ultrasonic lithotripsy was the primary fragmentation modality, with simultaneous aspiration of stone debris through the probe. A pneumatic probe was used when stones resisted ultrasonic fragmentation; baskets or forceps could be used when required. Irrigation and suction were maintained to support endoscopic visibility.

Access size was individualized. Recorded tract sizes in the intervention group ranged from 14 to 22 Fr, with a median of 20 [20, 22] Fr. Accordingly, the intervention is defined by its integrated fragmentation-and-aspiration workflow through miniaturized access, with variable tract diameters.

The procedural endpoint was the endoscopic and ultrasonographic absence of clinically relevant residual fragments that could be safely removed during the same session. A nephrostomy tube was placed in the presence of significant bleeding, residual stone burden, concern for obstruction, or a need for second-stage surgery. A double-J ureteral stent was placed according to intraoperative findings. Stone fragments were collected for compositional analysis when available.

Standard PCNL

Standard PCNL was performed through a conventional percutaneous tract under the same senior endourologist. After ultrasound-guided renal puncture and guidewire placement, tract dilation was selected according to stone burden, collecting-system anatomy, and intraoperative access requirements (recorded range, 20–30 Fr; median, 24 [24, 24] Fr). A rigid nephroscope was introduced through an Amplatz sheath. Stone fragmentation was performed using conventional intracorporeal lithotripsy according to stone hardness and availability, with fragment removal through the sheath using irrigation-assisted evacuation and forceps or baskets when needed. Irrigation was maintained to preserve endoscopic visibility, and outflow occurred through the sheath; no dedicated miniaturized ultrasonic suction probe was used in the standard PCNL group. At the end of the procedure, residual stones were assessed endoscopically and fluoroscopically or ultrasonographically, and a nephrostomy tube or tubeless strategy was selected according to bleeding, collecting-system injury, residual fragments, and surgeon judgment.

Statistical analysis

Analyses were performed in R 4.4.1 using MatchIt, tableone, and lpSolve. Continuous variables are presented as median [interquartile range] or mean (SD), and categorical variables as n/N (%). Descriptive overall-cohort comparisons used Wilcoxon rank-sum, chi-square, or Fisher exact tests, as appropriate.

Complete cases underwent balance-constrained cardinality matching [12] on age, sex, BMI, ASA class, cumulative stone diameter, stone density, stone type, stone location, hydronephrosis, and preoperative nephrostomy. The optimization maximized equal group sizes while requiring identical categorical marginal counts and identical joint-stratum counts for stone location, hydronephrosis, and ASA class. Continuous mean differences were constrained to 0.05 of the fixed pre-matching pooled SD, centered standardized second-moment differences to 0.10 of their fixed pooled SD, and maximum empirical cumulative distribution function (eCDF) differences to 0.20. Selected patients were paired 1:1 without replacement by Mahalanobis distance on age, BMI, cumulative stone diameter, and stone density within these exact strata. Patients with incomplete

matching covariates remained in overall-cohort summaries. Matching used baseline covariates without selecting on outcome estimates or P values.

Balance was assessed using absolute SMDs with fixed pre-matching pooled SDs or covariance matrices, including individual categorical levels and generalized multilevel measures. Diagnostic criteria were SMD <0.10, continuous-variable variance ratios of 0.5–2.0, and maximum eCDF differences ≤0.20.

Matched continuous outcomes were analyzed using paired mean differences with t-based 95% confidence intervals (CIs) and Wilcoxon signed-rank tests. Binary outcomes used paired risk differences with approximate t-based 95% CIs and exact McNemar tests; paired odds ratios with exact binomial-derived CIs were also reported. Subgroup results were descriptive. All analyses were exploratory; two-sided P <0.05 was used without multiplicity adjustment.

Results

Overall cohort

A total of 170 patients were included in the overall cohort, including 118 patients treated with standard PCNL and 52 treated with ultrasonic aspiration mini-PCNL. Before matching, the standard PCNL group had a larger cumulative stone diameter (4.36 [3.13, 5.84] vs. 3.23 [2.19, 3.80] cm; P < 0.001) and a higher proportion of staghorn stones, whereas the ultrasonic aspiration mini-PCNL group had a different stone-location distribution, with more upper ureteral or renal + upper ureteral stones (Table 1).

In the overall cohort, immediate stone-free rates were 55.1% with standard PCNL and 78.8% with ultrasonic aspiration mini-PCNL (P = 0.003); 1-month rates were 59.3% and 76.9% (P = 0.027). Operative time was 122.50 [84.00, 148.00] versus 89.50 [64.50, 115.50] min (P <0.001). Hemoglobin decrease was 10.00 [4.00, 15.00] versus 8.50 [3.00, 13.25] g/L (P = 0.330). Overall complications occurred in 12/118 (10.2%) versus 6/52 (11.5%). Overall-cohort characteristics and outcomes are presented in Tables 1 and 2.

Matched cohort and balance

Of 168 patients with complete matching covariates, 72 were retained as 36 matched pairs; 96 were not retained (Figure 1). Renal-only stones accounted for 25/36 (69.4%) patients in each group. All categorical covariates had identical marginal proportions, and each pair had the same stone location, hydronephrosis status, and ASA class. The maximum absolute SMD was 0.039: age, 0.005; BMI, 0.037; cumulative stone diameter, 0.039; and stone density, 0.020. Continuous-variable variance ratios ranged from 0.927 to 1.205, and maximum eCDF differences from 0.083 to 0.167. No matched patient had preoperative nephrostomy (Table 3; Supplementary Table S1; Supplementary Figures S1 and S2).

Matched clinical outcomes

Immediate stone-free rates were 20/36 (55.6%) with standard PCNL and 27/36 (75.0%) with ultrasonic aspiration mini-PCNL (risk difference, 19.4 percentage points; 95% CI, −4.6 to 43.5; exact McNemar P = 0.167). One-month stone-free rates were 22/36 (61.1%) and 26/36 (72.2%) (risk difference, 11.1 percentage points; 95% CI, −12.9 to 35.1; P = 0.481). Paired odds ratios were 2.17 (95% CI, 0.77–6.95) and 1.57 (95% CI, 0.56–4.78), respectively (Table 4; Supplementary Table S2).

Median operative time was 120.00 [78.50, 143.25] min with standard PCNL and 92.50 [68.75, 112.50] min with ultrasonic aspiration mini-PCNL (paired mean difference, −22.39 min; 95% CI, −42.41 to −2.37; signed-rank P = 0.018). Hemoglobin decrease was 8.50 [4.00, 14.00] versus 8.50 [2.50, 14.00] g/L (paired mean difference, 1.72 g/L; 95% CI, −3.21 to 6.66). The paired mean difference in hematocrit decrease was 0.60 percentage points (95% CI, −1.11 to 2.30). Overall complications occurred in 6/36 (16.7%) and 5/36 (13.9%) patients, respectively (P = 1.000). Nephrostomy-tube duration, tubeless status, and hospital stay did not show statistically significant between-group differences (Table 4).

Exploratory subgroup descriptions

Among patients with cumulative stone diameter ≥4 cm, 1-month stone-free rates were 7/15 (46.7%) with standard PCNL and 6/10 (60.0%) with ultrasonic aspiration mini-PCNL. For stones ≥1000 HU, rates were 12/20 (60.0%) and 13/18 (72.2%). For upper ureteral stones with or without renal stones, rates were 9/11 (81.8%) and 8/11 (72.7%). Descriptive stone-free rates by stone burden, density, and location are presented in Table 5.

Discussion

This prospective cohort provides clinical evidence for simultaneous ultrasonic lithotripsy and aspiration through a miniaturized tract. In the 36-pair balance-constrained analysis, the integrated workflow was associated with shorter operative time, while stone-free rates and complication frequencies did not differ significantly from standard PCNL. Its clinical relevance lies in combining stone fragmentation and evacuation within a miniaturized instrument, extending ultrasonic aspiration to smaller percutaneous access.

The principal technical feature is the coupling of fragmentation and evacuation at the ultrasonic probe. Aspiration during lithotripsy allows debris to be removed as it is generated and may reduce interruptions for retrieval and improve visibility. This workflow addresses a practical challenge of miniaturized access: efficient fragment removal within a restricted working space. The observed reduction in total operative time supports further evaluation of its potential procedural efficiency.

Previous work described clinical use of a 2.8-mm ultrasonic probe through miniaturized access [5], and other studies have investigated suction-assisted percutaneous systems [6,7]. Together, these studies highlight the role of integrated evacuation in percutaneous stone surgery. Probe energy, sheath design, suction location, access size, and stone complexity are important features when comparing different platforms. The present study adds a comparison using balance-constrained matching with standard PCNL, focusing specifically on the simultaneous ultrasonic fragmentation-and-aspiration workflow.

The observed stone-free outcomes are consistent with the broader mini-PCNL literature, including randomized comparisons and meta-analyses reporting similar clearance rates to standard PCNL [2–4,13]. Both primary endpoints in this study were assessed using NCCT with a residual-fragment threshold of ≤2 mm, providing a consistent assessment of immediate and 1-month stone clearance. Reporting both time points characterizes early clearance and short-term follow-up within the same cohort.

A strength of this study is its prospective collection of clinical and perioperative data, combined with matching on ten clinically relevant baseline variables. Balance constraints yielded identical categorical proportions and continuous-variable SMDs below 0.05, supported by variance and distribution diagnostics. The analysis included stone burden, density, type, and location alongside patient characteristics. Matched outcome analyses accounted for pairing and reported effect estimates with confidence intervals, providing a structured comparison across stone clearance, operative time, bleeding-related measures, and complications.

Several limitations should be considered. The single-center, nonrandomized design leaves potential confounding from unmeasured anatomy, stone composition, puncture difficulty, planned staging, and temporal practice changes. The matching analysis was exploratory. The matched sample was small, and rare severe complications were insufficiently represented. Access sizes varied, and the comparison evaluated the overall workflow rather than the independent effect of aspiration. Fragmentation and evacuation times, instrument exchanges, intrarenal pressure, and aspiration performance were not measured directly. Follow-up was limited to 1 month. Larger multicenter controlled studies with standardized procedural measurements and longer follow-up would help define patient selection, procedural efficiency, and uncommon complications.

Conclusion

Simultaneous ultrasonic lithotripsy and aspiration through a miniaturized tract offers a feasible approach to integrating stone fragmentation and evacuation for renal and proximal ureteral stones. In the balance-constrained matched cohort, this workflow was associated with shorter operative time, with no statistically

significant differences in stone-free rates or complications compared with standard PCNL. The findings support its clinical potential in miniaturized percutaneous stone surgery.

Declarations

Acknowledgements
None

Ethics approval and consent to participate
The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Peking University People's Hospital (approval No. 2024PHB440-001). Written informed consent was obtained from all participants.

Consent for publication
Not applicable.

Clinical trial number:
Not applicable.

Declaration of generative AI and AI-assisted technologies in the writing process
During the preparation of this work, the authors used ChatGPT (provided by OpenAI) to improve the clarity of academic expression, logical flow, and terminological consistency. The authors subsequently reviewed and edited the manuscript and verified its scientific content in accordance with the journal's formatting requirements and take full responsibility for the accuracy, integrity, and scientific validity of the manuscript.

Conflicts of interest
The authors declare that they have no competing interests.

Funding
This project was supported by Peking University People's Hospital research and development funds (RDL2024-21 and RDE2025-09), and the Science and Technology Plan Project (Subject) of Tongzhou District, Beijing (WS2025081).

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Availability of data and materials

The de-identified data that support the findings of this study are available from the corresponding author upon reasonable request, subject to approval by the institutional ethics committee and applicable data-protection requirements.

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Table 1. Baseline characteristics in the overall cohort

Variable	Standard PCNL (n = 118)	Ultrasonic aspiration mini-PCNL (n = 52)	P value
Age, years	56.00 [48.25, 62.75]	51.50 [43.75, 60.25]	0.062
Sex: Female	45/118 (38.1%)	14/52 (26.9%)	0.157
Sex: Male	73/118 (61.9%)	38/52 (73.1%)	
ASA class: 1	6/118 (5.1%)	5/52 (9.6%)	0.094
ASA class: 2	85/118 (72.0%)	40/52 (76.9%)	
ASA class: 3	27/118 (22.9%)	6/52 (11.5%)	
ASA class: 4	0/118 (0.0%)	1/52 (1.9%)	
BMI, kg/m²	25.95 [23.44, 28.00]	26.17 [24.22, 27.73]	0.446
Cumulative stone diameter, cm	4.36 [3.13, 5.84]	3.23 [2.19, 3.80]	<0.001
Stone density, HU	1095.00 [753.00, 1356.00]	923.50 [659.75, 1267.00]	0.112
Stone type: Single	16/118 (13.6%)	15/52 (28.8%)	<0.001
Stone type: Multiple	49/118 (41.5%)	30/52 (57.7%)	
Stone type: Staghorn	53/118 (44.9%)	7/52 (13.5%)	
Stone history, months	8.50 [1.00, 60.00]	8.50 [1.00, 39.00]	0.727
Kidney side/category: Left	65/118 (55.1%)	26/52 (50.0%)	0.599
Kidney side/category: Right	52/118 (44.1%)	25/52 (48.1%)	
Kidney side/category: Transplanted kidney	1/118 (0.8%)	1/52 (1.9%)	
Stone location: Renal	99/118 (83.9%)	27/52 (51.9%)	<0.001
Stone location: Upper ureter	2/118 (1.7%)	11/52 (21.2%)	
Stone location: Renal + upper ureter	17/118 (14.4%)	14/52 (26.9%)	
Hydronephrosis: No	20/118 (16.9%)	6/52 (11.5%)	0.366
Hydronephrosis: Yes	98/118 (83.1%)	46/52 (88.5%)	
Previous stone surgery: None	75/118 (63.6%)	34/52 (65.4%)	0.525
Previous stone surgery: ESWL	8/118 (6.8%)	5/52 (9.6%)	
Previous stone surgery: PCNL	28/118 (23.7%)	8/52 (15.4%)	
Previous stone surgery: RIRS	6/118 (5.1%)	5/52 (9.6%)	
Previous stone surgery: Open/other	1/118 (0.8%)	0/52 (0.0%)	
Preoperative nephrostomy: No	105/118 (89.0%)	51/52 (98.1%)	0.066
Preoperative nephrostomy: Yes	13/118 (11.0%)	1/52 (1.9%)	
Preoperative ureteral stent: No	107/118 (90.7%)	45/52 (86.5%)	0.419
Preoperative ureteral stent: Yes	11/118 (9.3%)	7/52 (13.5%)	
Hypertension: No	67/118 (56.8%)	28/52 (53.8%)	0.723
Hypertension: Yes	51/118 (43.2%)	24/52 (46.2%)	
Diabetes: No	94/118 (79.7%)	41/52 (78.8%)	0.904
Diabetes: Yes	24/118 (20.3%)	11/52 (21.2%)	
Preoperative hemoglobin, g/L	137.50 [126.00, 149.00]	145.00 [125.75, 150.50]	0.467
Preoperative creatinine, μmol/L	78.00 [64.25, 98.25]	76.50 [65.50, 92.25]	0.533

Values are median [IQR] or n/N (%). BMI is available for 117 standard and 51 intervention patients. Transplanted kidneys are reported separately from native-kidney side. Other listed variables have complete observations. Categorical P values compare the whole variable. ASA, American Society of Anesthesiologists; BMI, body mass index; ESWL, extracorporeal shock wave lithotripsy; RIRS, retrograde intrarenal surgery.

Table 2. Perioperative outcomes in the overall cohort

Outcome	Standard PCNL (n = 118)	Ultrasonic aspiration mini-PCNL (n = 52)	P value
Operative time, min	122.50 [84.00, 148.00]	89.50 [64.50, 115.50]	<0.001*
Tract size, Fr	24.00 [24.00, 24.00]	20.00 [20.00, 22.00]	<0.001*
Number of tracts	1.00 [1.00, 1.00]	1.00 [1.00, 1.00]	0.305
Hemoglobin decrease, g/L	10.00 [4.00, 15.00]	8.50 [3.00, 13.25]	0.330
Hematocrit decrease, percentage points	2.60 [0.13, 4.77]	2.30 [0.27, 4.60]	0.563
Nephrostomy tube duration, days	4.00 [2.00, 5.00]	3.00 [0.00, 4.00]	0.131
Hospital stay, days	7.00 [5.00, 8.00]	7.00 [5.00, 8.00]	0.487
Immediate stone-free status: Residual stone	53/118 (44.9%)	11/52 (21.2%)	0.003*
Immediate stone-free status: Stone-free	65/118 (55.1%)	41/52 (78.8%)	
1-month stone-free status: Residual stone	48/118 (40.7%)	12/52 (23.1%)	0.027*
1-month stone-free status: Stone-free	70/118 (59.3%)	40/52 (76.9%)	
Clavien–Dindo grade: 0	106/118 (89.8%)	46/52 (88.5%)	0.522
Clavien–Dindo grade: 1	4/118 (3.4%)	4/52 (7.7%)	
Clavien–Dindo grade: 2	6/118 (5.1%)	2/52 (3.8%)	
Clavien–Dindo grade: 3	2/118 (1.7%)	0/52 (0.0%)	
Tubeless status: Not tubeless	98/118 (83.1%)	37/52 (71.2%)	0.099
Tubeless status: No nephrostomy tube	20/118 (16.9%)	15/52 (28.8%)	

Values are median [IQR] or n/N (%). Comparisons use Wilcoxon rank-sum, chi-square, or Fisher exact tests. Hematocrit changes are percentage-point differences. Grade 0 indicates no complication; grades 1–3 correspond to Clavien–Dindo I–III. No patient was completely tubeless.

Table 3. Baseline balance after balance-constrained matching

Variable	Standard PCNL (n = 36)	Ultrasonic aspiration mini-PCNL (n = 36)	Absolute SMD
Age, years	52.64 (10.57)	52.69 (11.35)	0.005
Sex: Female	11 (30.6)	11 (30.6)	0.000
Sex: Male	25 (69.4)	25 (69.4)	0.000
BMI, kg/m²	26.76 (3.54)	26.91 (3.88)	0.037
ASA class: 1	2 (5.6)	2 (5.6)	0.000
ASA class: 2	30 (83.3)	30 (83.3)	0.000
ASA class: 3	4 (11.1)	4 (11.1)	0.000
ASA class: 4	0 (0.0)	0 (0.0)	0.000
Cumulative stone diameter, cm	3.89 (1.75)	3.81 (1.87)	0.039
Stone density, HU	1062.33 (390.25)	1054.78 (375.68)	0.020
Stone type: Single	6 (16.7)	6 (16.7)	0.000
Stone type: Multiple	23 (63.9)	23 (63.9)	0.000
Stone type: Staghorn	7 (19.4)	7 (19.4)	0.000
Stone location: Renal	25 (69.4)	25 (69.4)	0.000
Stone location: Upper ureter	2 (5.6)	2 (5.6)	0.000
Stone location: Renal + upper ureter	9 (25.0)	9 (25.0)	0.000
Hydronephrosis: No	4 (11.1)	4 (11.1)	0.000
Hydronephrosis: Yes	32 (88.9)	32 (88.9)	0.000
Preoperative nephrostomy: No	36 (100.0)	36 (100.0)	0.000
Preoperative nephrostomy: Yes	0 (0.0)	0 (0.0)	0.000

Continuous values are mean (SD); categorical values are n (%). SMDs use fixed pre-matching complete-case pooled SDs. Every categorical level is evaluated separately; all categorical proportions are identical. Generalized multilevel SMDs are reported in Supplementary Table S1. No post-matching baseline hypothesis tests were used.

Table 4. Outcomes after balance-constrained matching

Outcome	Standard PCNL (n = 36)	Ultrasonic aspiration mini-PCNL (n = 36)	Difference (95% CI)	Paired P
Operative time, min	120.00 [78.50, 143.25]	92.50 [68.75, 112.50]	-22.39 (-42.41 to -2.37)	0.018*
Hemoglobin decrease, g/L	8.50 [4.00, 14.00]	8.50 [2.50, 14.00]	1.72 (-3.21 to 6.66)	0.629
Hematocrit decrease, percentage points	2.55 [0.22, 4.07]	2.05 [0.27, 4.85]	0.60 (-1.11 to 2.30)	0.577
Nephrostomy tube duration, days	4.00 [3.00, 5.00]	3.00 [0.00, 4.00]	-0.92 (-1.94 to 0.10)	0.094
Hospital stay, days	7.00 [6.00, 8.00]	7.00 [6.00, 8.00]	-0.53 (-1.55 to 0.50)	0.383
Immediate stone-free rate	20/36 (55.6%)	27/36 (75.0%)	19.4 (-4.6 to 43.5)	0.167
1-month stone-free rate	22/36 (61.1%)	26/36 (72.2%)	11.1 (-12.9 to 35.1)	0.481
Any complication	6/36 (16.7%)	5/36 (13.9%)	-2.8 (-15.5 to 10.0)	1.000
Clavien–Dindo grade ≥II	3/36 (8.3%)	2/36 (5.6%)	-2.8 (-12.6 to 7.1)	1.000
No nephrostomy tube	7/36 (19.4%)	11/36 (30.6%)	11.1 (-11.4 to 33.7)	0.454

Continuous outcomes are median [IQR], with paired mean differences (intervention minus standard PCNL). Binary outcomes are n/N (%), with paired risk differences in percentage points. CIs use the Student-t distribution for within-pair differences; binary CIs are approximate. P values are paired Wilcoxon signed-rank tests for continuous outcomes and exact McNemar tests for binary outcomes. Signed-rank P values do not test the mean-difference estimand. Paired odds ratios are in Supplementary Table S2. All listed outcomes have 36 complete pairs.

Table 5. Descriptive subgroup stone-free rates at 1 month

Subgroup	Standard PCNL	Ultrasonic aspiration mini-PCNL
Stone diameter <4 cm	15/21 (71.4%)	20/26 (76.9%)
Stone diameter ≥4 cm	7/15 (46.7%)	6/10 (60.0%)
Non-staghorn	17/29 (58.6%)	21/29 (72.4%)
Staghorn	5/7 (71.4%)	5/7 (71.4%)
Stone density <1000 HU	10/16 (62.5%)	13/18 (72.2%)
Stone density ≥1000 HU	12/20 (60.0%)	13/18 (72.2%)
Renal only	13/25 (52.0%)	18/25 (72.0%)
Upper ureter with or without renal stones	9/11 (81.8%)	8/11 (72.7%)

Values are stone-free patients/total patients (%). Subgroups are derived from the 36-pair cohort. Size and density strata can separate members of a pair. No subgroup hypothesis tests or interaction estimates are presented.

Supplementary Table S1. Covariate balance before and after matching

Variable	Before matching (n = 168)	After matching (36 pairs)
Age, years	0.321	0.005
Sex: Female	0.263	0.000
Sex: Male	0.263	0.000
BMI, kg/m²	0.206	0.037
ASA class: 1	0.179	0.000
ASA class: 2	0.107	0.000
ASA class: 3	0.302	0.000
ASA class: 4	0.200	0.000
Cumulative stone diameter, cm	0.690	0.039
Stone density, HU	0.250	0.020
Stone type: Single	0.390	0.000
Stone type: Multiple	0.321	0.000
Stone type: Staghorn	0.738	0.000
Stone location: Renal	0.746	0.000
Stone location: Upper ureter	0.651	0.000
Stone location: Renal + upper ureter	0.321	0.000
Hydronephrosis: No	0.215	0.000
Hydronephrosis: Yes	0.215	0.000
Preoperative nephrostomy: No	0.377	0.000
Preoperative nephrostomy: Yes	0.377	0.000
ASA class (generalized)	0.388	0.000
Stone type (generalized)	0.759	0.000
Stone location (generalized)	0.822	0.000

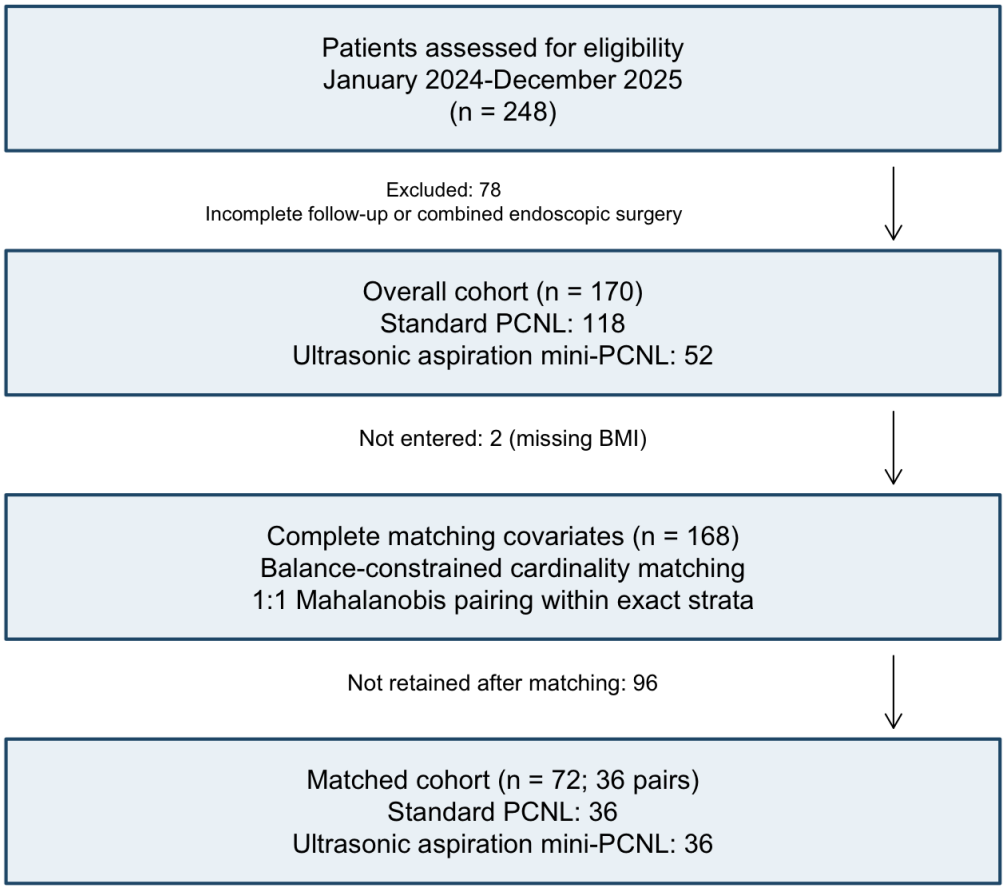
Absolute SMDs use the same pre-matching complete-case pooled SD or covariance matrix for before/after comparisons. Categorical-level denominators use pooled Bernoulli variances. Generalized SMDs summarize multilevel variables; identical distributions are displayed as zero. The final balance benchmark was 0.10.

Supplementary Table S2. Matched binary effect estimates

Outcome	Risk difference, pp (95% CI)	Paired OR (95% CI)	Exact P
Immediate stone-free rate	19.4 (-4.6 to 43.5)	2.17 (0.77 to 6.95)	0.167
1-month stone-free rate	11.1 (-12.9 to 35.1)	1.57 (0.56 to 4.78)	0.481
Any complication	-2.8 (-15.5 to 10.0)	0.67 (0.06 to 5.82)	1.000
Clavien–Dindo grade ≥II	-2.8 (-12.6 to 7.1)	0.50 (0.01 to 9.60)	1.000
No nephrostomy tube	11.1 (-11.4 to 33.7)	1.67 (0.55 to 5.58)	0.454

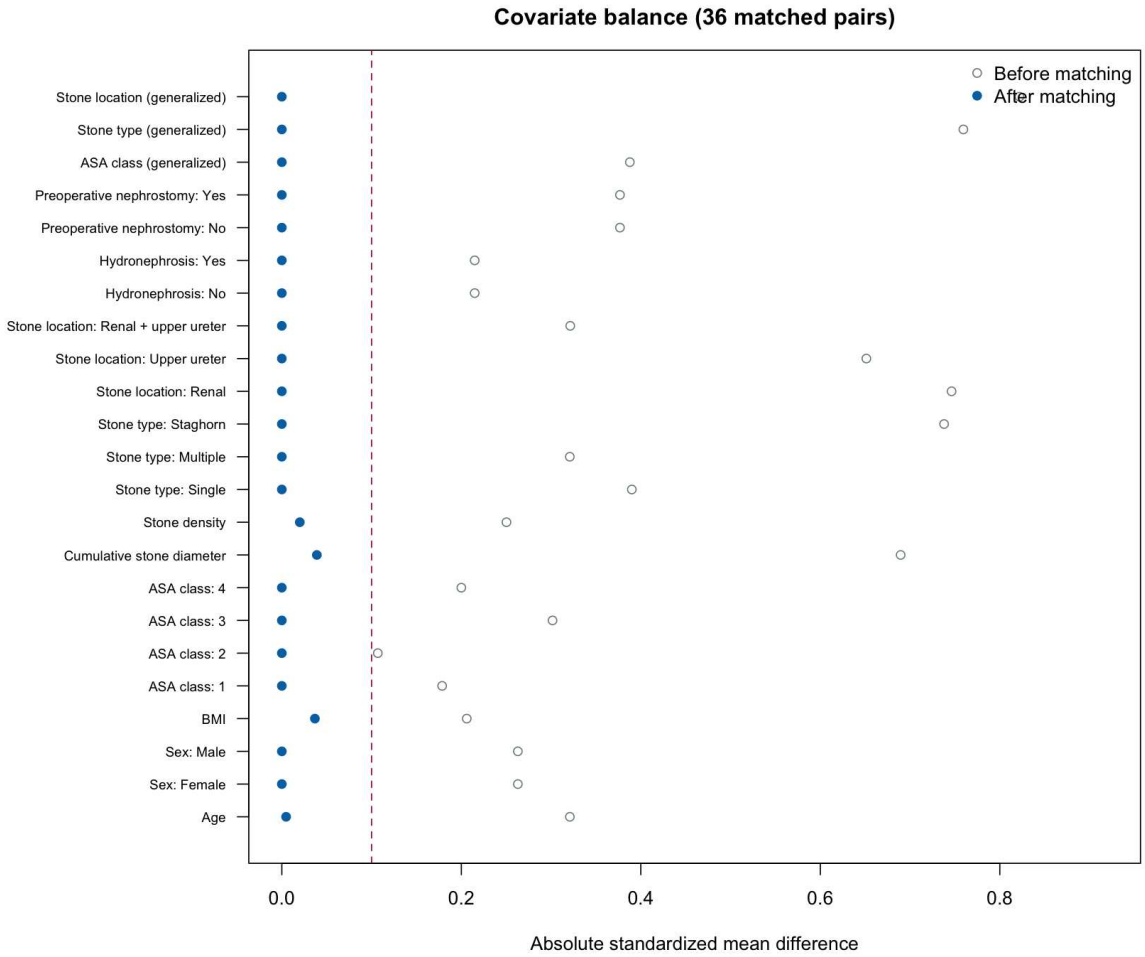
Risk differences are intervention minus standard PCNL. Paired odds ratios use discordant pairs; confidence intervals transform exact binomial limits. pp, percentage points; OR, odds ratio.

Figure 1. Participant flow



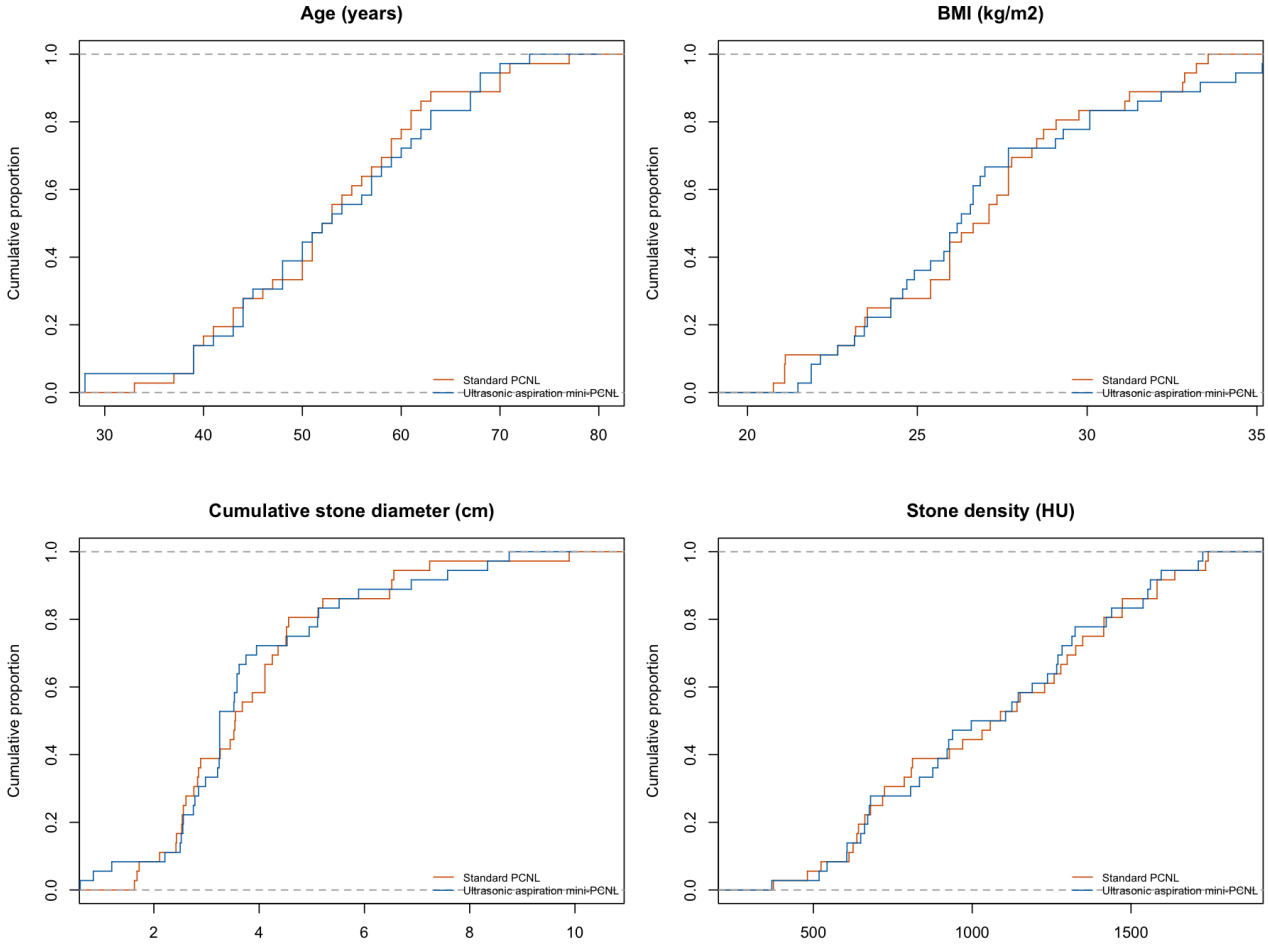
Two patients with missing BMI did not enter matching. Balance-constrained cardinality selection and within-stratum Mahalanobis pairing retained 36 matched pairs. PCNL, percutaneous nephrolithotomy.

Supplementary Figure S1. Covariate balance



Absolute SMDs before and after balance-constrained matching, using fixed pre-matching denominators. All categorical levels and generalized multilevel measures are shown. The dashed line marks 0.10.

Supplementary Figure S2. Continuous-variable distributions



Empirical cumulative distribution functions in the 36-pair cohort. Orange indicates standard PCNL and blue indicates ultrasonic aspiration mini-PCNL. Variance ratios ranged from 0.927 to 1.205 and maximum eCDF differences from 0.083 to 0.167.