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Safety Outcomes and Complication Predictors in Micro, Mini, and Standard Percutaneous Nephrolithotomy: A Consecutive Single-Surgeon Series

Mikro, Mini ve Standart Perkütan Nefrolitotomide Güvenlik Sonuçları ve Komplikasyon Belirleyicileri: Ardışık Tek Cerrah Serisi

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Abstract

Objective: To evaluate the complication profile and perioperative safety outcomes of micro-, mini-, and standard percutaneous nephrolithotomy (PNL) performed by a single surgeon, and to identify factors associated with postoperative complications.
Materials and Methods: A total of 100 consecutive patients who underwent micro- (n=20), mini- (n=40), or standard (n=40) PNL between April 2022 and May 2024 were retrospectively analyzed. All procedures were performed by a single endourologist following a structured perioperative approach, including computed tomography-based anatomical planning, endoscopic guidance for papillary access, and vacuum-assisted pressure-regulating strategy. Complications were graded according to the modified Clavien-Dindo classification. Binary logistic regression was used to identify factors associated with minor complications.
Results: No major complications (Clavien-Dindo grade ≥3) were observed in any patient. Minor complications occurred in 17 patients (17%): grade 1 in 11 (11%) and grade 2 in 6 (6%). Mean hemoglobin decrease was 0.99±1.04 g/dL and the transfusion rate was 3%. The clinically stone-free rate (no residual fragment >4 mm) was 80% and median hospital stay was 2 days. In exploratory logistic regression analysis, lower stone density and higher Guy's Stone Score were associated with minor postoperative complications, though the wide confidence intervals reflect the limited number of events and should be interpreted cautiously.
Conclusion: No major complications were encountered in 100 consecutive PNL cases. Lower stone density and higher Guy's Stone Score were associated with minor complications, supporting the potential importance of preoperative stone complexity stratification.

Keywords: percutaneous nephrolithotomy, postoperative complications, kidney calculi, treatment outcome, urolithiasis

Özet

Amaç: Tek bir cerrah tarafından gerçekleştirilen mikro-, mini- ve standart perkütan nefrolitotomi (PNL) uygulamalarında komplikasyon profilini ve perioperatif güvenlik sonuçlarını değerlendirmek, postoperatif komplikasyonlarla ilişkili faktörleri belirlemek.
Gereçler ve Yöntemler: Nisan 2022 – Mayıs 2024 tarihleri arasında mikro- (n=20), mini- (n=40) veya standart (n=40) PNL uygulanan 100 ardışık hasta retrospektif olarak incelendi. Tüm girişimler, bilgisayarlı tomografi temelli anatomik planlama, endoskopi eşliğinde papiller erişim ve vakum destekli basınç düzenleyici stratejiyi kapsayan yapılandırılmış bir perioperatif yaklaşım çerçevesinde tek bir endoüroloji uzmanı tarafından gerçekleştirildi. Komplikasyonlar modifiye Clavien-Dindo sınıflamasına göre değerlendirildi. Minör komplikasyonlarla ilişkili faktörler ikili lojistik regresyon analizi ile araştırıldı.
Bulgular: Hiçbir hastada majör komplikasyon (Clavien-Dindo evre ≥3) gözlenmedi. Minör komplikasyonlar 17 hastada (%17) gelişti: evre 1 11 hastada (%11), evre 2 ise 6 hastada (%6). Ortalama hemoglobin düşüşü 0,99±1,04 g/dL, transfüzyon oranı %3 idi. Klinik taşsızlık oranı (>4 mm rezidü fragman bulunmaması) %80 idi; ortanca hastane yatış süresi 2 gün olarak saptandı. Keşifsel lojistik regresyon analizinde düşük taş yoğunluğu ve yüksek Guy Taş Skoru minör postoperatif komplikasyonlarla ilişkili bulundu; ancak geniş güven aralıkları olay sayısının sınırlılığını yansıtmakta olup bulgular ihtiyatla yorumlanmalıdır.
Sonuç: 100 ardışık PNL olgusunun hiçbirinde majör komplikasyon gelişmedi. Düşük taş yoğunluğu ve yüksek Guy Taş Skoru minör komplikasyonlarla ilişkili faktörler olarak saptandı; bu bulgular preoperatif taş kompleksitesi değerlendirmesinin potansiyel önemini desteklemektedir.

Anahtar kelimeler: perkütan nefrolitotomi, postoperatif komplikasyonlar, böbrek taşları, tedavi sonucu, ürolitiyazis

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Introduction

Percutaneous nephrolithotomy (PNL) is the established first-line treatment for large renal calculi (>2 cm), staghorn stones, and cases refractory to extracorporeal shock wave lithotripsy or flexible ureterorenoscopy [1,2]. Depending on access sheath diameter, PNL is broadly classified as standard (24-30 Fr), mini (12-22 Fr), or micro (approximately 4.8 Fr) [3,4]. Although each modality offers high stone-free rates, none is free of risk: large multicenter series report overall complication rates between 4% and 50%, with transfusion rates of approximately 7%, fever in 10.8%, and sepsis in 0.5% [5,6]. Complications are formally graded using the modified Clavien-Dindo classification adapted for PNL by Tefekli et al. [7], which separates minor events (grades 1-2) from major ones (grades 3-5). The CROES multicenter study reported that although most events are minor, major complications still occur in 3-7% of cases [8].

Several technical refinements have been proposed to improve the safety profile of PNL. Miniaturized sheaths reduce parenchymal trauma [9], vacuum-assisted access sheaths regulate intrarenal pressure and lower infectious risk [10], and endovision-guided access improves puncture precision under direct visualization [11]. Despite these advances, most published series examine isolated technical modifications rather than a unified perioperative approach.

The aim of the present study was to evaluate the complication profile and perioperative safety outcomes of micro-, mini-, and standard PNL performed by a single experienced surgeon, and to identify factors associated with postoperative complications.

Materials and Methods

Study Design and Ethical Approval

This retrospective observational study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of our institution (Approval No: 2024/116; May 14, 2024). All procedures were performed by a single experienced endourologist. Although data are presented by PNL modality to characterize the heterogeneity of the cohort, this study was not designed as a comparative effectiveness analysis between technique variants.

Patient Selection

Adult patients (≥18 years) who underwent micro-, mini-, or standard PNL for renal calculi at our institution between April 2022 and May 2024 were consecutively enrolled; no eligible patient was intentionally excluded. All patients had a preoperative non-contrast computed tomography (CT) scan, a documented sterile urine culture, and at least 30 days of postoperative follow-up. Exclusion criteria were: age <18 years; active urinary tract infection at the time of surgery; significant coagulopathy (INR >1.5 or platelet count <50,000/mm^3); glomerular filtration rate (GFR) <15 mL/min/1.73m^2 or dialysis dependence; previous major ipsilateral renal surgery altering anatomy or access corridors (partial nephrectomy, anatrophic nephrolithotomy, or pyeloplasty); pregnancy; and incomplete perioperative records. These criteria were applied to define a surgically suitable cohort and to reduce confounding from conditions known to independently affect perioperative morbidity.

Preoperative Assessment and Surgical Planning

All patients underwent non-contrast CT to assess stone burden, HU density, stone number, skin-to-stone distance, and renal anatomy. Retrorenal organ positions were systematically evaluated on preoperative CT and confirmed by prone ultrasonography in the surgical position, given that retrorenal colon present in up to 7% of patients may not always be apparent on supine imaging [12]. Renal scintigraphy (DTPA or MAG-3) was performed selectively in patients with cortical thinning or impaired function. Stone complexity was quantified using the Guy's Stone Score.

PNL modality was selected by predefined criteria: micro PNL for stones <20 mm in calyces inaccessible to flexible ureterorenoscopy; mini PNL for intermediate-sized stones (20–30 mm) with moderate complexity; standard PNL for staghorn calculi or stones >30 mm. Surgery was scheduled only after documentation of a sterile urine culture; patients with positive cultures were treated with culture-directed antibiotics and rescheduled. Antiplatelet and anticoagulant therapy was managed after cardiology consultation. Prophylactic intravenous third-generation cephalosporin was administered 30 minutes before each procedure.

Intraoperative Technique

All procedures were performed under general anesthesia in modified prone split-leg position with appropriate padding. Retrograde access was established first in lithotomy position. For micro and mini PNL, a 9.5–11 Fr vacuum-assisted ureteral access sheath (UAS) was advanced into the renal pelvis to opacify the collecting system and maintain continuous passive suction throughout. For standard PNL, a 5–6 Fr ureteral catheter was used for pyelography. If UAS insertion failed in micro PNL, a 6 Fr double-J stent was placed and the procedure rescheduled after two weeks. The patient was then repositioned prone.

Percutaneous access was performed under combined fluoroscopic and endoscopic guidance, targeting the papillary fornix along Brödel's avascular line at a 30° entry angle. Upper-pole punctures were coordinated with the anesthesia team to avoid pleural injury. If purulent fluid was encountered on initial access, the procedure was immediately abandoned; surgery was rescheduled only after culture-directed antibiotics and confirmed sterility.

Instrumentation varied by modality. Standard PNL used a 30 Fr Amplatz sheath (Cook Medical, Bloomington, IN, USA), 24 Fr rigid nephroscope (Karl Storz, Tuttlingen, Germany), and EMS Swiss LithoClast® Master or 35 W Ho:YAG laser with 550 µm fiber (Quanta System, Samarate, Italy), with fragment extraction via forceps or basket. Mini PNL used a 16 Fr ClearPetra® vacuum-assisted sheath (Well Lead Medical, Guangzhou, China), 12 Fr mini-nephroscope (Karl Storz), and 35 W Ho:YAG laser with 550 µm fiber; the ClearPetra® sheath provided simultaneous fragment evacuation and passive pressure control. Micro PNL used a 4.8 Fr All-Seeing Needle (PolyDiagnost, Pfaffenhofen, Germany), 272 µm laser fiber, and a continuous irrigation pump (IP 200, PolyDiagnost) set to 150–200 mmHg; in this subgroup, a modified drainage-assisted approach incorporating a vacuum-assisted UAS at 200 mmHg served both fragment evacuation and intrarenal pressure regulation.

Intrarenal pressure was managed across all modalities by gravity-driven irrigation (bag height ~1.5 m) with continuous passive outflow via the vacuum-assisted sheath. At the end of every procedure, stone clearance was confirmed by flexible endoscopy; flexible nephroscopy in standard and mini PNL, flexible ureterorenoscopy via the UAS in micro PNL regardless of fluoroscopic appearance. Drainage was achieved with a 16 Fr Malecot nephrostomy catheter or 6 Fr double-J stent in standard PNL and a 6 Fr double-J stent in mini and micro PNL.

Postoperative Management

All patients underwent continuous vital sign and urine monitoring in the recovery unit. Empiric antibiotics were initiated for fever >38.5°C; venous thromboembolism (VTE) prophylaxis was applied selectively. Day 1 laboratory assessment included hemoglobin, blood urea nitrogen (BUN), creatinine, C-reactive protein (CRP), white blood cell count (WBC), and coagulation parameters. Hemodynamic instability with significant bleeding triggered angiographic evaluation. The Foley catheter was removed on day 1; Malecot catheters within 1–2 days if uncomplicated; double-J stents within 2–3 weeks. Non-contrast CT was performed at 30 days in all patients to assess stone-free status. Clinically stone-free status was defined as no residual fragment >4 mm; fragments ≤4 mm were managed expectantly.

Outcome Measures

The primary outcome was the incidence of major postoperative complications (Clavien-Dindo grade 3-5). Secondary outcomes included minor complication rate (grades 1-2), clinically stone-free rate at 30 days, operative parameters (operation time, fluoroscopy time, lithotripsy time), and hospital stay. Complications were retrospectively graded by the study investigators using the modified Clavien-Dindo classification adapted for PNL [7].

Outcome Definitions

Operation time was defined as the interval from cystoscope insertion to placement of the final drainage device (nephrostomy catheter or double-J ureteral stent, as applicable). Fluoroscopy time was the cumulative screening time recorded by the imaging system. Lithotripsy time was defined as the active duration of energy application during stone fragmentation. GFR was estimated using the Chronic Kidney Disease Epidemiology Collaboration (CKD-EPI) equation.

Table 1. Demographic and preoperative parameters by PNL modality

Variables	Standard PNL (n=40)	Mini PNL (n=40)	Micro PNL (n=20)	Total (n=100)
Age (years)	53.3 (48)	53.2 (45)	49.6 (38)	52.6 (48)
Sex				
Male	31 (77.5%)	23 (57.5%)	10 (50.0%)	64 (64.0%)
Female	9 (22.5%)	17 (42.5%)	10 (50.0%)	36 (36.0%)
ASA score				
ASA 1	4 (10.0%)	8 (20.0%)	6 (30.0%)	18 (18.0%)
ASA 2	33 (82.5%)	31 (77.5%)	13 (65.0%)	77 (77.0%)
ASA 3	3 (7.5%)	1 (2.5%)	1 (5.0%)	5 (5.0%)
Hydronephrosis grade				
Grade 0	1 (2.5%)	0	0	1 (1.0%)
Grade 1	25 (62.5%)	12 (30.0%)	16 (80.0%)	53 (53.0%)
Grade 2	11 (27.5%)	27 (67.5%)	4 (20.0%)	42 (42.0%)
Grade 3	2 (5.0%)	1 (2.5%)	0	3 (3.0%)
Grade 4	1 (2.5%)	0	0	1 (1.0%)
Stone location				
Renal pelvis	27 (67.5%)	27 (67.5%)	12 (60.0%)	66 (66.0%)
Upper calyx	2 (5.0%)	1 (2.5%)	1 (5.0%)	4 (4.0%)
Middle calyx	5 (12.5%)	5 (12.5%)	2 (10.0%)	12 (12.0%)
Lower calyx	6 (15.0%)	7 (17.5%)	5 (25.0%)	18 (18.0%)
Stone size (mm)	35 (38)	23 (27)	17 (15)	23 (42)
Stone volume (mm^3)	3640 (12641)	1744.5 (6716)	1427.5 (3044)	2255.5 (13534)
Stone density (HU)	1012.5 (1317)	678 (1342)	757 (1185)	757 (1342)
Guy's Stone Score	2 (2)	2 (1)	1 (2)	2 (2)

Data are expressed as median (IQR) for continuous variables and n (%) for categorical variables. No between-modality p values are shown because this study was not designed to compare PNL techniques. PNL: Percutaneous Nephrolithotomy; ASA: American Society of Anesthesiologists; HU: Hounsfield Unit; IQR: Interquartile Range

Table 2. Perioperative, postoperative, and laboratory parameters by PNL modality

Variables	Standard PNL (n=40)	Mini PNL (n=40)	Micro PNL (n=20)	Total (n=100)
Access site				
Upper calyx	0	0	1 (5.0%)	1 (1.0%)
Middle calyx	5 (12.5%)	13 (32.5%)	3 (15.0%)	21 (21.0%)
Lower calyx	35 (87.5%)	27 (67.5%)	16 (80.0%)	78 (78.0%)
Operation time (min)	100 (90)	57.5 (95)	52.5 (40)	80 (140)
Fluoroscopy time (s)	100 (68)	50 (37)	26 (29)	60 (120)
Puncture time (s)	42 (28)	41 (39)	23 (30)	40 (49)
Lithotripsy time (min)	27 (46)	41 (36)	30 (18)	34 (50)
Forceps/basket usage	21 (38)	3 (5)	-	8 (47)
Irrigation volume (mL)	15000 (12000)	5700 (2600)	3100 (3000)	6500 (19500)
Hospital stay (days)	2 (4)	2 (5)	1 (5)	2 (5)
Clinically stone-free rate	32 (80.0%)	31 (77.5%)	17 (85.0%)	80 (80.0%)
Preop GFR (mL/min/1.73m²)	94.5 (85)	91 (22)	89.5 (31)	92 (85)
Postop GFR (mL/min/1.73m²)	88 (79)	90 (24)	90 (29)	90 (79)
Preop BUN (mg/dL)	14.5 (17)	13 (22)	14 (13)	14 (22)
Postop BUN (mg/dL)	14 (21)	13 (22)	14 (15)	13.5 (24)
Preop creatinine (mg/dL)	0.88 (0.87)	0.91 (2.37)	0.84 (0.73)	0.89 (2.37)
Postop creatinine (mg/dL)	0.96 (0.96)	0.95 (2.14)	0.81 (1.01)	0.93 (2.14)
Preop hemoglobin (g/dL)	15.5 (8.3)	15.6 (8.0)	15.5 (6.8)	15.5 (8.5)
Postop hemoglobin (g/dL)	14.45 (7.7)	14.65 (8.8)	14.45 (6.0)	14.45 (8.8)

Data are expressed as median (IQR) for continuous variables and n (%) for categorical variables. No between-modality p values are shown because this study was not designed to compare PNL techniques. - : not applicable. PNL: percutaneous nephrolithotomy; GFR: glomerular filtration rate; BUN: blood urea nitrogen; Preop: preoperative; Postop: postoperative; IQR: interquartile range

Statistical Analysis

Statistical analyses were performed using SPSS version 25.0 (IBM Corp., Armonk, NY, USA). Data normality was assessed using the Kolmogorov-Smirnov test. Non-normally distributed continuous variables are expressed as median and interquartile range (IQR), whereas categorical variables are presented as frequency and percentage. Descriptive data were presented according to PNL modality to characterize the cohort; however, no inferential statistical comparisons were performed between micro-, mini-, and standard PNL groups because the study was not designed or powered to compare surgical techniques. For the analysis of factors associated with postoperative complications, patients were compared according to the presence or absence of complications. The Mann-Whitney U test was used for continuous variables, and the chi-square test or Fisher's exact test was used for categorical variables, as appropriate. Binary logistic regression analysis was then performed to identify factors associated with minor postoperative complications. Variables with $p<0.05$ in univariate analysis were considered for inclusion in the multivariate model, while clinically or statistically collinear variables were not entered simultaneously. Model fit was assessed using Nagelkerke R^2 and the Hosmer-Lemeshow test. A p-value <0.05 was considered statistically significant.

Results

Patient Characteristics and Perioperative Parameters

PNL modalities are presented descriptively to characterize the cohort. The study was not designed or powered to compare efficacy or safety outcomes among standard, mini, and micro PNL techniques.

A total of 100 consecutive patients underwent standard (n=40), mini (n=40), or micro (n=20) PNL. Demographic and preoperative data are summarized in **(Table 1)**; perioperative and postoperative parameters are presented in **(Table 2)**. Stone size and volume were greatest in the standard PNL group, consistent with the predefined modality selection criteria. Descriptive values for operation time, fluoroscopy time, irrigation volume, and hospital stay are presented by PNL modality in Table 2, reflecting the different clinical indications and technical characteristics of each approach. Mean hemoglobin decrease was 0.99±1.04 g/dL. On 30-day non-contrast CT, clinically stone-free status (no residual fragment >4 mm) was achieved in 80 patients (80%). Residual fragments >4 mm were identified in 20 patients (20%); of these, 16 (80%) underwent secondary intervention and 4 (20%) declined further intervention and were followed up expectantly.

Table 3. Distribution of postoperative complications according to clavien-dindo classification

Complication (Clavien–Dindo)	Standard PNL (n=40)	Mini PNL (n=40)	Micro PNL (n=20)	Total (n=100)
Grade 1				
Transient fever	3 (7.5%)	2 (5.0%)	2 (10.0%)	7 (7.0%)
Transient creatinine elevation	2 (5.0%)	1 (2.5%)	1 (5.0%)	4 (4.0%)
Grade 2				
Blood transfusion	2 (5.0%)	1 (2.5%)	0	3 (3.0%)
Urinary leakage (resolved <12 h)	2 (5.0%)	0	0	2 (2.0%)
UTI requiring IV antibiotics	0	0	1 (5.0%)	1 (1.0%)
Grade 3–5	**0**	**0**	**0**	**0**
Total complications	9 (22.5%)	4 (10.0%)	4 (20.0%)	17 (17.0%)

No grade 3-5 complications were observed. Each patient experienced no more than one complication. Data expressed as n (%). UTI: urinary tract infection; IV: intravenous

Complications

No major complications (Clavien-Dindo grade ≥3) occurred in any patient across all three PNL modalities **(Table 3)**. Minor complications were observed in 17 patients (17%): grade 1 in 11 patients (11%) and grade 2 in 6 patients (6%). The most frequent events were transient fever (7%), transient creatinine elevation (4%), and early urinary leakage resolving within 12 hours (2%); three patients (3%) required blood transfusion. One micro PNL patient required additional intravenous antibiotics for a urinary tract infection (1%). No thoracic, visceral, thromboembolic, or positioning-related complications were recorded.

Predictors of Complications

Patients who developed complications had significantly larger stone size (median 30 vs. 23 mm; p=0.031) and lower stone density (median 490 vs. 910 HU; p=0.019). Both preoperative and postoperative GFR values were significantly lower in the complication group (p=0.040 for both), and postoperative hemoglobin was also significantly lower among patients who experienced complications (p=0.007). The lower postoperative hemoglobin likely reflects the downstream effect of bleeding-related minor complications rather than an independent risk factor. Guy's Stone Score was significantly higher in the complication group (p<0.001). Detailed comparison data are presented in **(Table 4)**. Univariate logistic regression identified three variables associated with complications: larger stone size (p=0.022), lower stone density (p=0.022), and higher Guy's Stone Score (p<0.001). On multivariate analysis **(Table 5)**, two factors remained associated with minor complications in the multivariate model: lower stone density (OR: 0.997; 95% CI: 0.994-0.999; p=0.006) and higher Guy's Stone Score (OR: 53.360; 95% CI: 5.593-590.08; p=0.001). The Nagelkerke R^2 was 0.41 and the Hosmer-Lemeshow test demonstrated adequate model fit (p=0.763).

Table 4. Comparison of clinical and radiological parameters between patients with and without postoperative complications

Variables	Without complication (n=83)	Grade 1 (n=11)	Grade 2 (n=6)	With complication (n=17)	P
Age (years)	52.3 (48)	57 (34)	56.4 (27)	57 (37)	0.180
Male sex	53 (63.9%)	6 (54.5%)	5 (83.3%)	11 (64.7%)	0.999
Prior urologic surgery	41 (49.4%)	7 (63.6%)	4 (66.7%)	11 (64.7%)	0.270
Hydronephrosis grade	1 (1)	2 (2)	2 (1)	2 (2)	0.780
Stone size (mm)	23 (42)	30 (25)	31 (35)	30 (35)	**0.031***
Stone volume (mm^3)	2036 (13534)	3025 (8333)	3600 (10908)	3026 (11325)	0.236
Stone density (HU)	910 (1342)	490 (860)	677.5 (987)	490 (992)	**0.019***
Preop GFR (mL/min/1.73m^2)	93 (77)	88 (57)	85.5 (30)	86 (57)	**0.040***
Postop GFR (mL/min/1.73m^2)	90 (66)	85 (59)	77.5 (38)	85 (59)	**0.040***
Postop hemoglobin (g/dL)	14.9 (7.8)	13 (7.2)	13.2 (3.9)	13 (7.2)	**0.007***
Operation time (min)	80 (135)	80 (80)	95 (60)	90 (80)	0.390
Hospital stay (days)	2 (5)	1 (5)	1.5 (4)	1 (5)	0.860
Guy's Stone Score	1 (2)	2 (2)	2 (1)	2 (2)	**<0.001***

Data are expressed as median (IQR) for continuous variables and n (%) for categorical variables. Comparisons used the Mann-Whitney U test for continuous variables and the chi-square or Fisher's exact test for categorical variables. *p<0.05. GFR: Glomerular Filtration Rate; HU: Hounsfield Unit; IQR: Interquartile Range

Table 5. Logistic regression analysis of factors associated with minor postoperative complications

Variables	Univariate analysis	Multivariate analysis				
	OR	**95% CI**	**P**	**OR**	**95% CI**	**P**
Age	1.036	0.989–1.085	0.139			
Prior urologic surgery	0.856	0.394–1.857	0.693			
Stone size (mm)	**1.069**	**1.010–1.131**	**0.022***			
Stone volume (mm^3)	1.000	1.000–1.000	0.328			
Stone density (HU)	**0.998**	**0.997–1.000**	**0.022***	**0.997**	**0.994–0.999**	**0.006***
Number of accesses	5.400	0.705–41.360	0.104			
ASA score	0.562	0.187–1.688	0.304			
Operation time (min)	1.004	0.985–1.023	0.678			
Irrigation volume (mL)	1.000	1.000–1.000	0.527			
Guy's stone score	**12.415**	**3.130–49.247**	**<0.001***	**53.360**	**5.593–590.08**	**0.001***

Only variables significant on univariate analysis ($p<0.05$) were entered into the multivariate model. Stone size, although significant on univariate analysis, was excluded from the multivariate model due to substantial collinearity with Guy's Stone Score. Nagelkerke $R^2=0.41$; Hosmer-Lemeshow $p=0.763$. Bold: statistically significant. OR: Odds Ratio; CI: Confidence Interval; ASA: American Society of Anesthesiologists

Discussion

The central finding of this study is that no major complication (Clavien-Dindo grade ≥3) was encountered across 100 consecutive PNL procedures performed with three technique variants by a single surgeon. While major complication rates of 2-7% and overall rates of 8-25% have been reported in large multicenter series [6,13], direct comparison with the present data is limited by fundamental differences in surgeon experience, patient selection stringency, and study design; multicenter registries inherently include the full spectrum of operator experience and patient complexity, whereas this series reflects the practice of a single experienced endourologist operating under carefully controlled perioperative conditions. The 17% overall minor complication rate, dominated by transient and self-limiting events, is consistent with single-surgeon institutional series reported in the current literature [6]. It should be noted, however, that the three PNL groups were not equivalent at baseline: standard PNL patients harbored significantly larger and more complex stones, whereas micro PNL was preferentially applied to smaller, less complex calculi. Because the study was not powered for modality-level comparisons, the modality-specific complication rates should be interpreted only as descriptive cohort characteristics rather than evidence of comparative safety.

Hemorrhage remains the most clinically significant adverse event associated with PNL, with reported transfusion rates of approximately 7% and angiographic embolization rates of 1-1.2% [6,14]. In our cohort, mean hemoglobin decline was 0.99±1.04 g/dL. Three patients (3%) required blood transfusion, representing grade 2 Clavien-Dindo hemorrhagic complications; no arteriovenous fistula, pseudoaneurysm, or embolization was encountered. This favorable hemorrhagic profile was associated with endoscopic guidance for papillary puncture, gradual tract dilation under simultaneous fluoroscopic and endoscopic monitoring, and a vacuum-assisted pressure-regulating strategy throughout each procedure [15-17]. Delayed vascular complications such as pseudoaneurysm are typically associated with elevated intrarenal pressure and blind tract dilation [18,19]; the controlled irrigation strategy applied throughout our cohort may have contributed to the absence of these events.

Postoperative fever occurred in 7% of patients and urinary tract infection requiring additional antibiotics in 1%, both considerably lower than the approximately 10% fever rate and 4-5% sepsis rate reported in meta-analyses [20,21]. No urosepsis or septic shock was observed. Systematic infection prevention, including mandatory sterile preoperative urine culture, immediate procedural abandonment upon encountering purulent aspirate, and continuous low intrarenal pressure maintenance, may have contributed to this outcome. The importance of intrarenal pressure control in limiting bacterial translocation has been well documented [22,23].

No thoracic, gastrointestinal, hepatic, or splenic complications were recorded. Consistent subcostal access, preoperative CT-based anatomical mapping, and prone ultrasonography to evaluate pararenal organ positions collectively minimized these risks. Supracostal puncture above

Supplementary Table S1. Temporal distribution of minor complications during the study period

Study period	Standard PNL	Mini PNL	Micro PNL	Total
2022-2023	4	2	2	8
2023-2024	5	2	2	9
Total	9	4	4	17

No major (Clavien-Dindo grade >=3) complications occurred during either study period. PNL: percutaneous nephrolithotomy

the 11th rib carries hydrothorax rates up to 29% [24], while retrorenal colon present in approximately 6.9% of patients represents a commonly underappreciated injury risk [12,25].

Multivariate regression identified lower stone density and higher Guy's Stone Score as factors associated with minor complications. Stones with low HU values are typically composed of struvite or uric acid, substrates associated with chronic infection and metabolically complex renal environments. Higher Guy's Stone Scores denote anatomically challenging configurations requiring technically demanding access strategies, consistent with prior multicenter complication analyses [8,13]. Stone size reached significance on univariate analysis but was not retained in the multivariate model, likely reflecting its collinearity with both stone density and Guy's Stone Score. When collinear variables are entered simultaneously, the model retains the variable with the stronger independent association; in this cohort, stone density emerged as the more informative factor, possibly because it captures stone composition rather than merely geometric burden, a finding that aligns with the known relationship between soft, low-density stones and infectious or metabolic environments that independently predispose to perioperative complications. Lower preoperative and postoperative GFR values were also observed in the complication group on descriptive analysis; however, GFR did not emerge as an independent factor in the regression model, suggesting that impaired renal function in this cohort likely reflected underlying stone complexity rather than acting as a direct operative risk factor. Similarly, lower postoperative hemoglobin in the complication group is most plausibly interpreted as a consequence of bleeding-related minor events rather than a preoperative predictor.

The overall clinically stone-free rate of 80% in this series is modest and warrants comment. While safety was the primary focus of this study, efficacy outcomes remain important in clinical practice. In descriptive terms, the mini PNL subgroup had a clinically stone-free rate of 77.5%, which may reflect the broader stone size spectrum accepted in that modality and the technical constraints of fragment clearance through a 16 Fr sheath without pneumatic lithotripsy. These descriptive stone-free outcomes are consistent with published data for comparable patient populations and PNL modalities, but highlight that the absence of major complications does not necessarily equate to optimal stone clearance outcomes. Future studies should address both safety and efficacy endpoints within the same cohort.

Several limitations should be acknowledged. The retrospective single-center design limits causal inference and external generalizability. The absence of major complications in this cohort should be interpreted with caution: with 100 patients and an expected major complication rate of 2-7% in the literature, observing zero events is plausible by chance alone and does not constitute statistical evidence that the perioperative approach prevents major complications. Furthermore, the low number of complication events (n=17) relative to the number of variables tested results in a low events-per-variable (EPV) ratio, which may have limited the stability of the regression model as reflected by the wide confidence intervals observed, particularly for Guy's Stone Score (95% CI: 5.593-590.08). All procedures were performed by a single surgeon; whether these outcomes are reproducible across different practice settings and experience levels remains to be established. The three PNL technique groups were not balanced at baseline, with standard PNL applied to significantly larger and more complex stones; therefore, modality-specific safety outcomes should be interpreted descriptively rather than as formal between-technique comparisons. The sample size may be insufficient to detect rare major complications. Accordingly, the logistic regression findings should be considered hypothesis-generating rather than confirmatory, and require validation in larger prospective cohorts. Stone composition analysis was not performed in all cases. It should be noted that the operating surgeon had accumulated approximately 600 standard, 300 mini, and 100 micro PNL procedures over a 15-year career prior to this study; all three modalities were performed in an interleaved fashion throughout the study period, and minor complications were distributed similarly between the first and second halves of the series (8 vs. 9 events), without temporal clustering, making a learning-curve effect unlikely. Long-term renal function, stone recurrence, and quality-of-life data were not systematically collected. Multicenter prospective studies with standardized outcome measures and adequate sample sizes are needed to validate and broaden these findings.

Conclusion

No major complications were encountered in 100 consecutive PNL cases performed across micro-, mini-, and standard technique variants by a single experienced surgeon. Lower stone density and higher Guy's Stone Score were associated with minor complications, supporting the potential importance of preoperative stone complexity stratification. These findings describe favorable safety outcomes achieved within a systematic perioperative framework and may serve as a single-center reference for PNL complication profiles across three technique variants.

Ethics Committee Approval: This study was conducted in accordance with the principles of the Declaration of Helsinki and approved by the Institutional Review Board of Kayseri City Training and Research Hospital (Approval No: 2024/116; Date: May 14, 2024).

Informed Consent: Written informed consent was obtained from all patients.

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