The New Journal of Urology
eISSN 3023-6940
doi: https://doi.org/10.33719/nju1845585

RESEARCH ARTICLE

Volumetric Predictors of Stone-Free Outcomes After mini-PCNL

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***Submitted:** 2025–12–19*
***Accepted:** 2026–06–17*

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Abstract

Objective: To evaluate the predictive value of volumetric stone measurements including manually calculated stone volume and 3D software–derived volume on stone-free outcomes following mini-percutaneous nephrolithotomy (mini-PCNL), and to assess their relationship with perioperative parameters and commonly used nephrolithometry scoring systems.

Materials amd Methods: This retrospective study was conducted with patients who underwent primary mini-PCNL between January 2024 and January 2025. Preoperative non-contrast computed tomography scans were used to determine the longest stone diameter, surface area, manually calculated stone volume, and 3D software–derived stone volume. Patients were categorized into two groups according to postoperative imaging: stone-free (Group 1) and residual stone (Group 2). Demographic characteristics, stone features, operative parameters, stone complexity scores (GUY's and STONE) and complication rates were compared between groups.

Results: Of the 80 patients, 61.3% were stone-free postoperatively. Group 2 demonstrated significantly higher manually calculated stone volumes ($p = 0.02$) and S.T.O.N.E. scores ($p = 0.005$). Manually calculated and 3D-derived stone volumes both showed significant positive correlations with stone diameter, surface area, nephrolithometry scores, operative time, and laser usage parameters. ROC analysis identified a manually calculated stone volume threshold of 746.9 mm^3 for predicting residual fragments (AUC = 0.656, $p = 0.02$). In the multivariate model, manual stone volume was significantly associated with stone-free status (OR 18.71, $p = 0.042$).

Conclusion: This study demonstrates a significant association between stone volume and stone-free outcomes after mini-PCNL. While volumetric measurements may provide additional information beyond conventional parameters. Therefore, stone volume should be considered as a complementary parameter rather than a standalone predictor in clinical decision-making.

Keywords: percutaneous nephrolithotomy, stone volume, surface area, stone-free rate

Cite; Gokmen E, Altuntas T, Akay HB, Ozgur G, Senoglu Y, Sekerci CA, Sener TE. Volumetric Predictors of Stone-Free Outcomes After mini-PCNL. New J Urol. 2026;21(2):72–80. **doi:** https://doi.org/10.33719/nju1845585

INTRODUCTION

The prevalence of kidney stones varies between 10–37% in various regions and has been increasing recently (1,2). Urinary tract stone disease is a significant cause of morbidity and imposes a substantial financial burden on the healthcare system (3).

According to both the European Association of Urology (EAU) and American Urological Association (AUA) guidelines, the choice of surgical management for renal stones is chiefly guided by the stone's dimensions and its anatomical location (4,5). Guideline-recommended treatment algorithms for urolithiasis consider stone diameter as a key factor in assessing stone size (4,5). Given that a doubling of stone diameter corresponds to an eightfold increase in volume, incorporating stone volume into treatment selection is essential. This is a mathematical fact that should not be ignored. Considering the above-mentioned difference between 2-dimensional and 3-dimensional measurements, there are many publications suggesting that stone volumes should also be included in surgical planning (6,7).

Various methods can be used to calculate stone volume. Stone volumes can be determined through techniques such as manual volume calculation where diameters obtained from three slices of non-contrast CT (computed tomography) scans are inserted into formulas 3D software programs, and in vitro volume measurements by modelling and 3D printing the stones (8).

Accurate surgical planning is crucial for predicting complications. Although volumetric calculations provide more precise assessments than two-dimensional measurements, their reliability may vary, particularly in irregularly shaped stones. To predict stone-free status, we analysed stone diameter alongside surface area and volume, as advised by contemporary guidelines. Furthermore, the relationship between both two-dimensional and three-dimensional stone measurements and laser and fluoroscopy usage, as well as other perioperative parameters, was planned to be analysed.

MATERIAL AND METHODS

We carried out a retrospective study at a tertiary care center, including patients diagnosed with renal stones between January 2024 and January 2025, with ethical approval obtained from the local ethics committee (Approval No: 09.2023.1065, Date: September 9, 2024).

This study included adult patients who had a preoperative CT scan within three months prior to the procedure and underwent postoperative imaging before discharge. Only adult patients undergoing primary mini-PCNL (percutaneous nephrolithotomy) were considered. Exclusion criteria were paediatric patients, patients with multiple stones, bilateral stones, cystine stones or staghorn stones and patients with anatomical variations (such as horseshoe kidney, renal pelviectasia, or ureteropelvic junction obstruction).

All surgeries were performed by an experienced endourologist with more than 400 cases of PCNL. All procedures were carried out under general anaesthesia with the patient in the Barts flank-free modified supine position. Percutaneous access to the renal collecting system was achieved under fluoroscopic guidance, and the tract was dilated using 16/20 Amplatz dilators. No combined endourological interventions were performed, as all cases were managed solely by the antegrade route. Stone fragmentation was performed with a 30-W Quanta Cyber Ho Holmium laser, with frequency and power settings adjusted intraoperatively according to stone characteristics. Postoperative management included the routine insertion of a ureteral DJ stent, with removal scheduled at first month surgery, adhering to our institutional routine.

Surgical indications were determined based on the EAU Urolithiasis Guidelines (9). Patients were subsequently divided into subgroups based on the presence of residual stones. In the postoperative evaluation, patients who were found to be stone-free were classified as Group 1, while those with residual stones were classified as Group 2.

Subgroups were evaluated in terms of demographics, stone characteristics, operative metrics, and complication profiles. Additionally, in patients with and without residual stones, the longest stone diameters, surface areas, and measurements obtained both manually and using 3D software were compared to evaluate their predictive value for stone-free status (10,11).

A) Longest Stone Diameter (mm)

B) Surface area (SA): Calculated using the formula (longest diameter × orthogonal diameter × π) ÷ 4

C) Stone volume (SV) – manual calculation: The largest anteroposterior, mediolateral, and craniocaudal diameters were measured on CT images and used in the ellipsoid formula to estimate stone volume: SV = π × length × width × depth × 0.167

D) Volume calculation using 3D software

CT scans were carried out on a Brilliance ICT 256 Philips CT system (Philips Healthcare, Eindhoven, Germany) using a non-contrast CT protocol using a slice thickness of 2 mm. For 3D volume calculation 3D Slicer software was used. The 3D Slicer software was utilized for stone surface area calculations. Postoperative assessment of stone-free status was performed with an abdominal X-ray on day 1. At one-month, postoperative imaging consisted of either non-contrast CT or ultrasonography depending on clinical indication. The presence of stones exceeding 4 mm was considered indicative of postoperative residual stones (1). Two of the most commonly used scoring systems for predicting stone-free rates, the Guy's Stone Score and the S.T.O.N.E. score, were calculated for all patients (12). Postoperative adverse events were reviewed and assigned grades based on the Clavien–Dindo classification (13). Both of these symptom scores as well as complication rates were compared between the groups.

Statistical Analysis

Statistical analyses were performed using SPSS (version 25.0, IBM). Data normality was assessed with the Kolmogorov-Smirnov test. Numerical variables are presented as median (IQR) and categorical variables as frequency and percentage. Group comparisons for categorical data were conducted using the Chi-square or Fisher's exact test, and Spearman correlation was used to assess associations between nonparametric variables. ROC analysis was performed to determine optimal thresholds for sensitivity and specificity. Multivariate logistic regression analysis was also conducted. Variables demonstrating significance in univariate analysis were included in the multivariate regression model. A $p < 0.05$ was considered statistically significant.

RESULTS

Among the 80 patients included in the study. Of these, 56 (70%) were male and 24 (30%) were female. The median value for the longest stone diameter was 17.7 mm, the surface area was 165.15 mm^2, the manually calculated stone volume was 903 mm^3, and the stone volume measured using 3D software was 1137 mm^3.

In terms of stone location, 4 patients (5%) had upper calyx stones, 58 (72.5%) had renal pelvic stones, 10 (12.5%) had mid-calyx stones, and 8 (10%) had lower calyx stones. Of the 80 patients, 44 (55%) had regularly shaped and 36 (45%) had irregular shaped stones. Postoperatively, 49 patients (61.3%) were stone-free, whereas 31 patients (38.7%) had residual stones.

Postoperative stone-free status was used to divide patients into subgroups, which were then analysed. No differences were found in terms of demographic data. Patients with residual stones had a significantly higher manually calculated stone volume compared to those who were stone-free ($p = 0.02$). For the remaining measurements, no statistically significant differences were detected between the groups. Group 2 had a significantly higher S.T.O.N.E. score compared to Group 1 ($p = 0.005$). No significant differences were found between the two groups in terms of GUY's score, laser energy dose, lasing time, Hounsfield units, fluoroscopy dose, fluoroscopy time, hospital stay, intraoperative complication rates. Postoperative complications were comparable between the two groups ($p = 0.19$). In Group 1, Clavien–Dindo grade 1 complications occurred in 1 patient (3.2%), grade 2 in 8 patients (25.8%), and grade 3a in 1 patient (3.2%), while no grade 3b complications were recorded. In Group 2, grade 1 complications were observed in 2 patients (4.1%) and grade 2 in 6 patients (12.2%), with no grade 3a or 3b complications reported (Table 1).

In univariate analysis, only stone volume and S.T.O.N.E. score demonstrated significant associations with stone-free status and were therefore included in the multivariate regression model. As shown in Table 2, manual stone volume was the only variable with a significant relationship to stone-free status in the multivariate analysis (OR 18.71, 95% CI 1.11–317.02, $p = 0.042$). Other variables, including longest diameter (OR 1.08, 95% CI 0.98–1.08, $p = 0.112$), GUYS score (OR 0.31, 95% CI 0.08–1.19, $p = 0.089$), and S.T.O.N.E score (OR 0.86, 95% CI 0.44–1.69, $p = 0.66$), were not significantly associated with stone-free rate.

Table 1. Analysis by Residual Fragment Status

	Group 1 (n:49) "Stone-Free"	Group 2 (n:31) "Residual Stone"	p value
Age (years)	56 (15.5)	52 (17)	0.33
Sex (Male/Female) n (%)	20/11 (64.5/35.5)	36/13 (73.5/26.5)	0.39
BMI (kg/m²)	31 (9.6)	26.3 (15)	0.051
Longest Diameter (mm)	16.7 (17.5)	19.9 (19.2)	0.136
Stone Location n (%)			
Renal Pelvis	20 (40.8)	11 (35.5)	0.812
Upper Pole	12 (24.5)	6 (19.4)	
Middle Pole	9 (18.4)	8 (25.8)	
Lower Pole	8 (16.3)	6 (19.4)	
Number of accesses n (%)			
1	40 (81.6)	26 (83.9)	0.761
2	7 (14.3)	3 (9.7)	
3	2 (4.1)	2 (6.5)	
Surface Area (mm²)	137 (332)	245.2 (512.2)	0.336
Stone Volume by manual calculation (mm³)	296.6 (4821.3)	2223.1 (7002.6)	**0.02**
Stone Volume by 3D software (mm³)	1004 (1734)	1157 (2128.5)	0.48
Maximum HU	1196 (433)	1249 (433)	0.61
Average HU	964 (249)	1029 (444.2)	0.22
GUYS score	1 (2)	3 (2)	0.07
S.T.O.N.E score	7 (3)	9 (1.7)	**0.005**
Operation Time (minutes)	110 (50)	120 (30)	0.21
Total Laser Energy (Joule)	66.7 (66.4)	56.1 (44.9)	0.42
Lasing Time (minutes)	20.1 (29.4)	28 (21)	0.2
Fluoroscopy Dose (DAP)	3.5 (8.2)	3.1 (3.8)	0.54
Fluoroscopy Time (minutes)	27.5 (42)	32.5 (48.5)	0.59
Intraoperative Complications n (%)	0	1 (3.1)	0.32
Hospital Stay (days)	3 (6)	2 (2)	0.13

BMI: Body Mass Index, DAP: Dose–Area Product, HU: Hounsfield Unit, IQR: Inter Quantile Range

All continuous variables are presented as median (interquartile range, IQR), and categorical variables are presented as numbers and percentages

Table 2. Multivariate Regression Analyses for Stone-Free Rate

	OR	%95 CI	p value
Longest Diameter	1.079	0.983–1.084	0.112
Stone Volume by manual calculation	18.713	1.105–317.023	**0.042**
GUYS score	0.309	0.080–1.194	0.089
S.T.O.N.E score	0.859	0.437–1.689	0.66

CI: Confidence Interval, IQR: Inter Quantile Range, OR: Odds Ratio

Stone volume was categorized according to the cut-off value determined by ROC analysis.

Correlation analysis revealed a limited number of strong positive associations (r > 0.75). The manually calculated stone volume showed a strong correlation with the 3D software–derived stone volume (r = 0.854, p < 0.01), longest stone diameter (r = 0.937, p < 0.01), surface area (r = 0.937, p < 0.01), GUY's score (r = 0.828, p < 0.01), and S.T.O.N.E score (r = 0.764, p < 0.01). In addition, the 3D software–derived stone volume was strongly correlated with longest diameter (r = 0.876, p < 0.01), surface area (r = 0.886, p < 0.01), and GUY's score (r = 0.749, borderline strong association). Longest stone diameter demonstrated strong correlations with surface area (r = 0.978, p < 0.01) and GUY's score (r = 0.861, p < 0.01), while surface area was strongly correlated with GUY's score (r = 0.871, p < 0.01). Finally, a strong association was observed between total laser energy and lasing time (r = 0.898, p < 0.01).

In our study, in terms of residual fragments, ROC analysis yielded an area under the curve (AUC) of 0.656 (95% CI: 0.528–0.783), with a sensitivity of 61.2% and specificity of 61.3%. Accordingly, the optimal threshold for stone volume was identified as 746.9 mm^3 (p = 0.02) (Figure 1, Table 3).

DISCUSSION

In this study, Group 2 demonstrated significantly higher manually calculated stone volumes and STONE scores. Correlation analysis showed that both manually and 3D software–calculated stone volumes had significant positive correlations with the longest stone diameter, surface area, GUY's score, S.T.O.N.E score, operative time, total laser energy, and lasing time. Furthermore, S.T.O.N.E score was positively correlated with operative time and fluoroscopy time, while operative time showed significant positive correlations with laser energy and lasing time. While correlation analyses demonstrate associations between variables, they do not establish predictive relationships, and these findings should be interpreted accordingly.

Table 3. ROC Analysis of Manually Calculated Stone Volume for Predicting Residual Stone Formation

Risk Factor	AUC (CI %)	Threshold Value	p	Sensitivity (%)	Specificity (%)
Residual Stone	0.656 (0.528–0.783)	746.9	0.02	61.2	61.3

AUC: Area Under Curve, CI: Confidence Interval

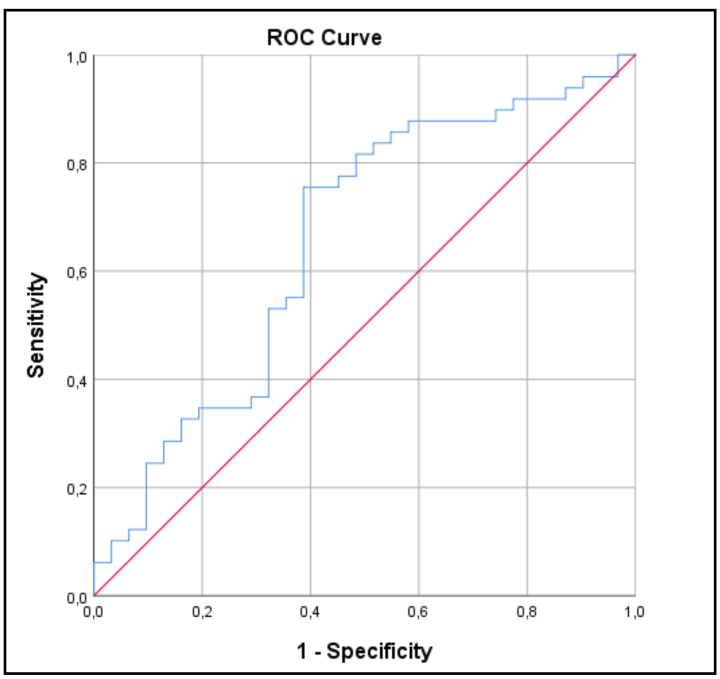

Figure 1. ROC Analysis of Stone Volume with Manual Calculation

According to the ROC analysis, the threshold value for predicting the presence of residual stones was determined to be 746.9 mm^3 (AUC: 0.656, 95% CI: 0.528–0.783, sensitivity: 61.2%, specificity: 61.3%). Multivariate logistic regression identified manually calculated stone volume as the only factor significantly associated with stone-free rate. The discrepancy between manual and 3D-derived volumes may be attributed to methodological differences, including assumptions of geometric shape in manual calculations and segmentation variability in 3D analysis. Additionally, the absence of reproducibility assessment for 3D segmentation represents a limitation. Interestingly, manual volume showed stronger predictive value, which may be related to its consistency and closer alignment with simplified clinical measurements.

When the literature is reviewed, numerous studies can be found that examine the factors influencing stone-free rates in patients undergoing PCNL. Atalay et al. conducted a retrospective review of 164 patients treated with PCNL and reported that 53% achieved complete stone clearance. Unlike our study, their analysis included measurements of both stone volume and the volume of the renal collecting system. The predictive value of the ratio of these two volumes in terms of stone-free status was investigated. It was found that the stone volume/renal collecting system volume ratio was statistically superior in predicting stone-free status compared to stone surface area and stone volume measurements (14). The stronger predictive value of the stone volume to renal collecting system volume ratio may be explained by several practical points. Unlike conventional measurements based solely on stone size, this ratio indicates the extent to which the collecting system is occupied by the stone burden. This offers a more realistic understanding of the surgical challenge. The advantage becomes even clearer in patients with complex or staghorn stones, where irregular shapes make surface area or volume measurements less reliable. By accounting for individual anatomical differences and showing the true proportion of the system filled by the stone, this ratio provides a more consistent and meaningful indicator of stone-free outcomes. We think that these factors likely contributed to its superior performance in predicting postoperative results.

Another study designed by Tailly et al., the data of 313 patients who underwent PCNL were analysed. In this study, the stone-free rate was found to be 69.6%. In our study, this rate was 61.3%. Similar to our study, this publication also found that stone volume had a significant predictive value for surgical outcomes. However, in that study, only stone volumes measured using 3D software were used. Additionally, in the same study, stone diameter and surface area were also found to be significant predictors of stone-free rates (11).

In a prospective cohort of 142 patients undergoing retrograde intrarenal surgery, Treigny et al. found that 64% had no residual stones postoperatively. For stone analysis, stone diameters and manual stone volume calculations were performed using two different measurement methods (Ackermann's and Sphere). The stones were also subdivided based on whether their diameter was below or above 20 mm and re-evaluated. While all three measurement methods accurately predicted the absence of residual stones for stones smaller than 20 mm, only volume-based measurements were effective for stones exceeding 20 mm (15).

In the study designed by Canat et al. using stone data from 27 patients who underwent PCNL, stone volumes were calculated using both the ellipsoid formula (also used in our study) manually and 3D software. These stones were then 3D printed, and their in vitro volumes were calculated using the water displacement method. The results of the study showed that volume calculations made using 3D software were more correlated with the volumes of the 3D-printed stones. A statistically significant difference was observed between the manually calculated volumes and those of the 3D-printed stones (8). Based on our study results, manually calculated stone volume was more predictive of stone-free status than volumes obtained using 3D software.

There are also similarly designed studies for other stone treatment modalities besides PCNL. In the study conducted by Bandi et al., which included 94 patients who underwent ESWL, 58 patients (62%) were found to be stone-free after the procedure, while 36 patients (38%) had residual stones. A statistically significant difference was found in stone volume between these two groups. Consistent with our study, stone volume was identified as the strongest predictor of stone-free status (16).

In the study by Ito et al., unlike our study, 314 patients who underwent ureteroscopy were evaluated to determine whether stone diameter or stone volume better predicted stone-free status. Stone volumes were manually calculated, similar to our study. In this study, the predictive value of diameter and volume was assessed by dividing the stones into subgroups based on size. For stones smaller than 20 mm, diameter and volume had a similar level of predictive value. However, for stones larger than 20 mm, stone volume was found to be a more successful predictor, consistent with the findings of our study (17).

From a clinical perspective, the identified threshold of 746.9 mm^3 may serve as a practical parameter in preoperative surgical planning. In our cohort, stone volumes exceeding this cutoff were associated with a markedly increased likelihood of requiring more complex intervention. Therefore, for patients with stone volumes above 746.9 mm^3, surgeons may consider a more cautious approach, including planning for standard PCNL rather than less invasive alternatives, anticipating longer operative times, or the potential need for staged procedures. Conversely, patients with smaller stone volumes may be more suitable candidates for less invasive strategies. However, this threshold should not be interpreted as an absolute decision-making criterion but rather as a supportive tool to be integrated with other clinical factors such as stone location, anatomy, and surgeon experience. In the present study, the discriminative ability of manual stone volume was found to be modest (AUC: 0.656), with sensitivity and specificity values of approximately 61%. These findings suggest that stone volume alone may not be sufficiently robust as a standalone predictor for clinical decision-making. Rather, its clinical utility may be enhanced when used in combination with established nephrolithometry scoring systems such as S.T.O.N.E. score and Guy's stone score, which incorporate additional anatomical and procedural factors. Integrating stone volume into such multifactorial models may improve risk stratification, surgical planning, and prediction of procedural outcomes. Therefore, we believe that future studies should focus on validating combined predictive models to better define the additive value of stone volume in clinical practice.

When discussing the limitations of the study, we must acknowledge the inherent constraints of retrospective studies. We believe that the design and execution of prospective, randomized studies would contribute more meaningfully to the literature. In such prospective studies, conducting a power analysis for sample size calculation would also help obtain statistically more robust results. The use of different imaging modalities with varying sensitivity for detecting residual fragments may have introduced detection bias. Another limitation is that the postoperative stone-free rate assessment was conducted solely at the first postoperative month. We believe that future studies should incorporate longer-term outcomes, such as evaluations at the third and sixth postoperative months, to provide a more comprehensive clinical perspective. Furthermore, the wide CI associated with the OR for manual stone volume indicates substantial uncertainty around the effect size, likely due to the limited sample size and potential sparsity in the data. Therefore, while the observed association is noteworthy, it should be interpreted cautiously. Additionally, we believe that not performing routinely non-contrast-enhanced CT for postoperative residual fragment evaluation may have led to the oversight of some small residual stones. However, since current guidelines recommend postoperative CT imaging only for symptomatic patients, it was not routinely performed. In addition, preoperative imaging was primarily based on non-contrast computed tomography rather than contrast-enhanced imaging, which may have limited detailed assessment of the collecting system anatomy in selected cases.

CONCLUSIONS

This study demonstrates a significant association between stone volume and stone-free outcomes after mini-PCNL. While volumetric measurements may provide additional information beyond conventional parameters, their predictive performance remains moderate. Therefore, stone volume should be considered as a complementary parameter rather than a standalone predictor in clinical decision-making. Integrating these parameters into clinical practice could enhance risk assessment, guide surgical planning, and improve urolithiasis outcomes.

Acknowledgments: None

Conflict of Interest: None

Funding: None

Ethical Approval: This study was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Ethics Committee (Approval No: 09.2023.1065, Date: September 9, 2024).

Informed Consent: The requirement for informed consent was waived by the Institutional Ethics Committee due to the retrospective nature of the study.

Author Contributions:
- Concept and Design: CAS, TES, EG
- Supervision: CAS, TES, EG
- Data Collection and/or Analysis: HBA, GO, YS
- Analysis and/or Interpretation: EG, TA
- Literature Search: EG, TA
- Writing: EG, TA
- Critical Review: EG, TA, CAS, TES

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