RESEARCH PAPER

# Three-Dimensional CT Reconstruction of the Pelvicalyceal System for Preoperative Assessment in Percutaneous Nephrolithotomy

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## ABSTRACT

**Objective:** To evaluate the role of three-dimensional CT reconstruction of the pelvicalyceal system in the preoperative assessment of patients undergoing percutaneous nephrolithotomy.

**Materials and Methods:** This prospective observational study included 100 adult patients with renal calculi measuring ≥20 mm or complex renal stones who underwent PCNL. All patients underwent multidetector CT with three-dimensional reconstruction of the pelvicalyceal system before surgery. Anatomical characteristics, optimal calyceal puncture site, operative time, fluoroscopy time, number of puncture attempts, stone-free rate, and postoperative complications were recorded and analyzed using SPSS version 26.0. A p-value <0.05 was considered statistically significant.

**Results:** The mean age of the patients was 46.8 ± 13.2 years, and 62% were male. Anatomical variations of the pelvicalyceal system were identified in 32% of patients. Three-dimensional CT reconstruction accurately predicted the optimal puncture site in 92% of cases and enabled successful single-tract PCNL in 81% of patients. The mean operative time was 83.5 ± 19.7 minutes, and the mean fluoroscopy time was 3.8 ± 1.4 minutes. The overall stone-free rate after the primary procedure was 89%. Patients with anatomical variations had significantly longer operative times, more puncture attempts, and lower stone-free rates than those with normal anatomy ($p < 0.05$). Major postoperative complications occurred in 4% of patients.

**Conclusion:** Three-dimensional CT reconstruction of the pelvicalyceal system is an effective preoperative imaging modality for PCNL. It improves anatomical visualization, facilitates accurate calyceal access, enhances surgical planning, and contributes to favorable surgical outcomes with a low complication rate.

**Keywords:** Three-dimensional computed tomography, Pelvicalyceal system, Percutaneous nephrolithotomy, Renal calculi, Preoperative assessment, Multidetector computed tomography.

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## INTRODUCTION

The pelvicalyceal system (PCS) is the central collecting structure of the kidney. It is formed by minor and major calyces and renal pelvis which helps to drain the urine from the renal parenchyma into the ureter. [1] The calyceal number, orientation and branching pattern, the length and angulation of infundibula have been found to be variable among individuals in its anatomical configuration. [2] The anatomical differences have clinical implications, especially when performing endourological procedures, which require accurate access to the collecting system. Therefore, a detailed knowledge of the 3D anatomy of the pelvicalyceal system is basic for proper diagnosis, surgical planning and successful management of renal stone disease. [3]

Nephrolithiasis is one of the most prevalent urological diseases in the world and its prevalence is increasing with changing lifestyle, dietary habits, obesity, metabolic abnormalities and environmental changes. [4] If not treated properly, large or complicated renal calculi can lead to recurrent UTIs, chronic flank pain, blood in the urine (hematuria), renal hydronephrosis and progressive renal deterioration. [5] Stone size, location and anatomical features of the pelvicalyceal system have a significant impact on the selection of an effective treatment strategy and can be important factors in stone clearance and surgical accessibility. [6]

Percutaneous nephrolithotomy (PCNL) is considered the treatment of choice in patients with large renal stones, staghorn stones and complex stones not amenable to extracorporeal shock wave lithotripsy (ESWL) or ureteroscopic stones. [7] The proper establishment of a safe and accurate PCNL tract through the desired calyx is the key to a successful procedure. [8] Correct puncture of the calyceal recess ensures a lower risk of renal parenchymal injury, lower intraoperative bleeding and faster operating time and better possibility of stone removal. The exact location of the best access tract is difficult due to the very complex and variable three-dimensional anatomy of the renal collecting system. [9]

Typical imaging procedures such as ultrasonography and intravenous urography and routine axial computed tomography (CT) are useful in the diagnosis of stone burden and renal morphology. [10] However, these modalities frequently present two-dimensional views of the anatomy and the surgeon must mentally visualize the spatial relationships between the renal pelvis, calyces, infundibula and surrounding structures. [11] This may be challenging in patients with presence of staghorn calculi, congenital anomalies, distorted collecting system and previous renal procedure, which may add to the technical difficulty. [12]

In the last few years, multidetector computed tomography (MDCT) has been used to produce high-resolution three-dimensional (3D) images of the pelvicalyceal system. These reconstructed images provide a complete picture of the orientation of the calyces, renal pelvis, stone location and their interrelationships with neighbouring anatomical structures. [13] Three-dimensional reconstruction offers a more intuitive appreciation of patient-specific anatomy to the surgeon, which aids in the planning of surgery and in choosing the best calyceal access prior to surgery, compared to conventional computed tomography (CT) images. [14]

The advantages of three-dimensional CT reconstruction in preoperation evaluation may be to enhance surgical precision, reduce the number of puncture attempts, shorten operative time and reduce the radiation of the fluoroscopy and lower the procedure-related complications. [15] Better anatomical visualization may also help achieve higher stone-free rates and preserve renal function, thus allowing for accurate access to the collecting system. Moreover, three-dimensional models are useful in educational and communication aids for the multidisciplinary management of complex renal stone disease. [16]

In endourology, three-dimensional CT reconstruction is becoming more and more recognized as a useful adjunct in the practice, however not yet commonly used in the preoperative planning for PCNL. [17] It requires further clinical data to validate its role in clinical

practice, especially in the evaluation of patients prior to an operation. Thus, the purpose of the present study is to assess the usefulness of three-dimensional CT reconstruction of the pelvicalyceal system for the preoperative evaluation in patients undergoing percutaneous nephrolithotomy (PCNL), with a focus on the ability to improve the anatomical visualization, to guide for the optimal calyceal access and to influence the surgical outcomes.

## MATERIALS AND METHODS

This was a prospective observational study conducted in the department of radiology and department of urology at the tertiary care hospitals across the Punjab, Pakistan, over a period of 12 months (from January 2025 to December 2025). All study participants were informed and written consent was obtained prior to participation and the study was approved by the Institutional Review Board of hospital. The patients included in the study were adult patients (age ≥18 years) diagnosed with renal calculi ≥20 mm or complex renal stones and planned to undergo percutaneous nephrolithotomy (PCNL). Congenital renal anomalies, previous major renal surgery causing an alteration of the collecting system anatomy, impaired renal function (which prevented the use of contrast enhanced CT), pregnancy, known allergy to iodinated contrast media and incomplete clinical or imaging information were excluded.

A total of 100 consecutive patients who fulfilled the inclusion criteria were included. A non-probability consecutive sampling technique was used. All patients were subjected to routine preoperative clinical assessment, including medical history, physical examination, laboratory investigations, urine culture, renal function tests, coagulation profile and renal, ureter and bladder ultrasonography. Non-contrast computed tomography (NCCT) was used to assess stone size, location, density and burden. In turn, a contrast enhanced multidetector computed tomography (MDCT) was performed to evaluate the pelvicalyceal system. All CT exams were done on a 64-slice multidetector CT scanner. Thin-section acquisition (0.5-1.0 mm slice thickness) from the upper poles of the kidneys to the urinary bladder provided images.

Intravenous non-ionic iodinated contrast administered per institutional protocol, delayed excretory phase images were acquired to seek to optimize opacification of the collecting system. The acquired Digital Imaging and Communications in Medicine (DICOM) data were loaded onto a special workstation for the purpose of three-dimensional image processing. For each patient, volume-rendered and multiplanar reconstructed images of the pelvicalyceal system were created. Reconstructed images were then independently assessed by an experienced radiologist as well as the operating urologist. Morphology of the collecting system, calyx number and orientation, infundibular morphology, stone location and the best calyx for puncture were recorded. The three-dimensional reconstructed images were used in the surgical planning of the patient.

The procedures were carried out by experienced consultant urologists under general anesthesia with standard operating room techniques for all the PCNL procedures. The puncture site and access tract were decided on by a preoperative three-dimensional CT reconstruction and guided by fluoroscopy and/or ultrasonographic guidance during surgery. Fragmentation of the stones was done by pneumatic or ultrasonic lithotripter depending on stone characteristics and, if possible, residual fragments were removed. The main outcome measures consisted of the accuracy of the planned access to the best calyx, the congruence of planned and actual puncture site, operating and fluoroscopy time, number of punctures and whether the stone was rendered stone-free after the procedure.

The secondary outcome measures included the intraoperative complications, postoperative complications based on the Clavien–Dindo classification, length of hospital stay and the requirement for secondary procedures. Post-operative plain radiography, ultrasonography or non-contrast computed tomography (CT) were obtained within four weeks to evaluate the presence of residual stone fragments. Those who had no stone remnant and/or stone fragments less than 4 mm in size were classified as stone-free.

Data was entered and analyzed by using Statistical Package for the Social Sciences (SPSS) version 26.0. Continuous variables were presented as mean ± SD and categorical variables were presented as frequencies and percentages. The association between categorical variables was determined by Chi square test or Fisher's exact test, as appropriate. Independent-samples t-test was used for the comparison of continuous variables. The p value $< 0.05$ was taken as statistically significant.

## RESULTS

A total of 100 patients diagnosed with renal calculi underwent preoperative three-dimensional (3D) CT reconstruction of the pelvicalyceal system before percutaneous nephrolithotomy (PCNL). The mean age of the study participants was 46.8 ± 13.2 years (range: 19–74 years). Males comprised 62% of the study population, while females accounted for 38%. The average stone size was 29.6 ± 8.4 mm, with the majority of patients presenting with non-staghorn renal calculi (72%).

**Table 1. Baseline demographic and clinical characteristics of the study population (n = 100)**

| Variable | Value |
|---|---|
| **Age (years), Mean ± SD** | 46.8 ± 13.2 |
| **Male, n (%)** | 62 (62.0) |
| **Female, n (%)** | 38 (38.0) |
| **BMI (kg/m²), Mean ± SD** | 27.4 ± 3.8 |
| **Right kidney involvement, n (%)** | 54 (54.0) |
| **Left kidney involvement, n (%)** | 46 (46.0) |
| **Stone size (mm), Mean ± SD** | 29.6 ± 8.4 |
| **Staghorn calculi, n (%)** | 28 (28.0) |
| **Non-staghorn calculi, n (%)** | 72 (72.0) |

The study population predominantly consisted of middle-aged adults, with a male predominance. Most patients presented with large renal calculi suitable for PCNL, while non-staghorn stones were more frequently encountered than staghorn calculi.

Three-dimensional CT reconstruction successfully visualized the pelvicalyceal system in all patients. Various anatomical patterns and stone locations were identified during preoperative assessment, allowing comprehensive evaluation of the collecting system before surgery.

**Table 2. Stone characteristics and pelvicalyceal system anatomy**

| Variable | n (%) |
|---|---|
| **Stone location** | |
| **Lower calyx** | 41 (41.0) |
| **Middle calyx** | 18 (18.0) |
| **Upper calyx** | 9 (9.0) |
| **Renal pelvis** | 27 (27.0) |
| **Multiple calyces** | 5 (5.0) |
| **Pelvicalyceal anatomy** | |
| **Normal anatomy** | 68 (68.0) |
| **Anatomical variation** | 32 (32.0) |
| **Elongated infundibulum** | 12 (12.0) |
| **Narrow infundibulum** | 9 (9.0) |
| **Abnormal calyceal orientation** | 8 (8.0) |
| **Duplex collecting system** | 3 (3.0) |

The lower calyx represented the most common location of renal stones, followed by the renal pelvis. Anatomical variations of the pelvicalyceal system were identified in approximately one-third of patients, demonstrating the importance of individualized preoperative anatomical assessment.

The reconstructed 3D CT images were utilized for surgical planning, enabling identification of the optimal calyx for renal access. Intraoperative findings showed good agreement with the preoperative imaging assessment.

**Table 3. Intraoperative findings and surgical outcomes**

| Variable | Value |
|---|---|
| **Accurate prediction of puncture site, n (%)** | 92 (92.0) |
| **Successful single-tract access, n (%)** | 81 (81.0) |
| **Multiple access tracts required, n (%)** | 19 (19.0) |
| **Number of puncture attempts, Mean ± SD** | 1.3 ± 0.6 |
| **Operative time (minutes), Mean ± SD** | 83.5 ± 19.7 |
| **Fluoroscopy time (minutes), Mean ± SD** | 3.8 ± 1.4 |
| **Stone-free after first procedure, n (%)** | 89 (89.0) |
| **Residual fragments <4 mm, n (%)** | 8 (8.0) |
| **Secondary intervention required, n (%)** | 3 (3.0) |

Three-dimensional CT reconstruction accurately predicted the optimal calyceal puncture site in most patients, contributing to a high rate of successful single-tract access. Favorable operative parameters, including fewer puncture attempts and high stone-free rates, were observed following PCNL.

Postoperative outcomes were evaluated clinically and radiologically. Most patients recovered without significant complications, while only a small proportion experienced adverse events.

**Table 4. Postoperative complications**

| Complication | n (%) |
|---|---|
| **No complications** | 81 (81.0) |
| **Transient fever** | 7 (7.0) |
| **Hematuria requiring observation** | 5 (5.0) |
| **Urinary tract infection** | 3 (3.0) |
| **Blood transfusion** | 2 (2.0) |
| **Urine leakage** | 1 (1.0) |
| **Re-intervention** | 1 (1.0) |
| **Major complications (Clavien–Dindo ≥ III)** | 4 (4.0) |

The majority of patients had an uncomplicated postoperative course, with minor complications occurring more frequently than major complications. The low incidence of severe adverse events indicates satisfactory perioperative safety in patients undergoing PCNL after preoperative 3D CT evaluation.

A comparison of patients with normal pelvicalyceal anatomy and those with anatomical variations was performed to determine the impact of collecting system morphology on surgical outcomes.

**Table 5. Association between pelvicalyceal anatomical variation and surgical outcome**

| Variable | Normal Anatomy (n=68) | Anatomical Variation (n=32) | p-value |
|---|---|---|---|
| **Single-tract access** | 61 (89.7%) | 20 (62.5%) | 0.002 |
| **Multiple punctures** | 7 (10.3%) | 12 (37.5%) | 0.001 |
| **Stone-free rate** | 64 (94.1%) | 25 (78.1%) | 0.026 |
| **Operative time (minutes)** | 78.6 ± 17.4 | 94.3 ± 20.8 | 0.004 |
| **Fluoroscopy time (minutes)** | 3.2 ± 1.1 | 4.8 ± 1.5 | 0.001 |
| **Overall complications** | 8 (11.8%) | 11 (34.4%) | 0.011 |

Patients with anatomical variations of the pelvicalyceal system required significantly more puncture attempts and experienced longer

operative and fluoroscopy times than patients with normal collecting system anatomy. They also demonstrated comparatively lower stone-free rates and a higher frequency of postoperative complications, highlighting the influence of renal anatomical complexity on surgical outcomes.

**DISCUSSION**

The present study aimed to assess the usefulness of 3D CT reconstruction of the pelvicalyceal system for the preoperative evaluation of patients for percutaneous nephrolithotomy (PCNL). The data showed that 3D CT reconstruction is an effective method to clearly define the collecting system anatomy, to achieve optimal calyceal access and to achieve high stone-free rates with minimal postoperative complications. The results justify the increasing use of advanced imaging techniques in improving the safety and effectiveness of PCNL. The key to a successful PCNL is to puncture the desired calyx accurately, while sparing any surrounding structures from injury. While conventional imaging modalities offer good anatomical information, they are unable to demonstrate the complex 3D relationships of the pelvicalyceal system.

Guliev et al. showed that native three-dimensional reconstruction of the pelvis can be performed without the use of contrast dye and produce a realistic image of the pelvicalyceal anatomy, allowing accurate identification of the spatial orientation of the calyces. They found three-dimensional reconstruction aids in better understanding of individual anatomical variation, hence better preoperative planning. [18] Anatomical variations of the pelvicalyceal system were found in about one-third of the patients in the present study. The differences were linked to greater complexity of the operation, such as longer operative time and need for more punctures.

Heyns and Van Gelderen confirmed that 3-D CT image reconstruction can provide a more accurate visualization of calyceal branching patterns and infundibular anatomy, allowing easier access to the kidney and avoiding complications in patients with complicated collecting system anatomy. [11] The identification of the best calyceal puncture site was one of the main results of this study, and it was successfully determined in 92% of patients. Hence, in the majority of cases, successful single tract PCNL was made possible. Tan et al. studied the clinical use of 3-D reconstruction in patients with complex renal stones who were undergoing PCNL and found that the procedure showed significant benefits in terms of the number of stones that were stone free, fluoroscopy exposure, need for multiple punctures, and operative time when compared with conventional 2-D imaging techniques. Their results are similar to the results from the present study. [19]

The overall stone-free rate of 89% in the present study was similar to that seen in the modern literature. Tan et al. showed that individual surgical planning in 3-D aids complete stone clearance because the surgeon can choose the most suitable calyx for access prior to surgery. Likewise, Durutović et al. found that the comprehensive preoperative anatomical evaluation helps in achieving better surgical precision and minimizes the risk of stone fragments remaining in the collecting system after PCNL. [20] Operative time and radiation exposure are still significant measures of procedural efficiency in PCNL. Both operative times and fluoroscopy time were relatively brief in the present study as a consequence of a thorough preoperative anatomical assessment.

Preoperative detailed computed tomography (CT) evaluation is found to significantly increase the puncture efficiency and reduce operative time by avoiding unnecessary manipulation during renal access as reported by Akand et al. Similarly, Tan et al. found that their fluoroscopy time decreased substantially after using 3-D reconstruction technology. Patients who had pelvicalyceal anatomic variations had significantly more puncture attempts and lower stone-free rate compared to those with normal anatomy. These results suggest that anatomical complexity continues to be an important factor in the difficulty of surgery even in this technologically advanced era. [19] Patient-specific 3D reconstruction can help the surgeons to anticipate these anatomical difficulties before the procedure to enhance the operative planning and decrease the uncertainty of the procedure.

The postoperative complication rates noted in the present study were favorable, with a relatively small number of patients having major complications. de la Rosette et al. found that correct calyceal puncture is one of the most important negative factors that reduce bleeding and postoperative morbidity after PCNL. [21] Likewise, Skolarikos et al. (European Association of Urology (EAU) Guidelines on

Urolithiasis) have highlighted that careful pre-operative imaging and optimal access planning are crucial to reducing stone clearance-related complications and enhancing the prospects for stone clearance. [22] Another significance of three-dimensional CT reconstruction is its educational value. Patel et al. showed that patient-specific 3D models enhance the surgeons' understanding of complex renal anatomy and preoperatively simulate the planned puncture tract. [23] The results of the current study are promising, but there are some limitations to note. This study was performed in one institution, with a relatively small number of patients, and with no control group who were only treated with conventional CT assessment.

Moreover, operating surgeons' experience may have affected the surgical outcomes. Further multi-center prospective randomized trials are needed with more patients to confirm these results and develop general guidelines for routine pre-operative evaluation with 3D CT reconstruction. In summary, the present study revealed that 3D CT reconstruction is a useful tool to help preoperatively plan PCNL procedures. It allows detailed visualization of the pelvicalyceal system and patient-specific anatomy aiding surgical planning, improving the accuracy of punctures, improving stone-free rates and enhancing safe, efficient management of renal stone disease.

## CONCLUSION

Three-dimensional CT reconstruction of the pelvicalyceal system is a valuable preoperative imaging tool for patients undergoing percutaneous nephrolithotomy. It enhances visualization of renal anatomy, facilitates accurate calyceal access, improves surgical planning and contributes to high stone-free rates with minimal complications. Incorporating 3D CT reconstruction into routine preoperative assessment may improve the safety and effectiveness of PCNL, particularly in patients with complex renal stone disease.

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