E-ISSN 2250-0944
ISSN 2250-1150
doi: 10.31838/ijprt/16.02.62

Research Article

Development and Validation of an Imaging-Based Prediction Model for Stone-Free Outcomes after Flexible Ureteroscopy

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Received: 12.05.26, Revised: 13.06.26, Accepted: 14.07.26

ABSTRACT

Objective: To devise and externally validate a complete, imaging-based predictive nomogram for estimating the probability of stone-free status (SFS) after flexible ureteroscopy (fURS) for upper urinary tract calculi using advanced parameters from non-contrast computed tomography (NCCT).

Material And Methods: Retrospective study, which comprised 850 consecutive patients with renal and proximal ureteral stones from January 2023 to December 2025. The cohort was randomly divided into a training set (n=600) and an external validation set (n=250). Advanced imaging parameters such as stone volume, maximum Hounsfield units (HU), skin to stone distance (SSD), infundibulopelvic angle (IPA), and renal pelvic area were extracted from pre-operative NCCT. A multivariate logistic regression model was created and presented as a nomogram.

Results: The overall SFS rate was 78.8% (670/850). LASSO and multivariate analyses showed that stone volume, maximal HU, SSD, IPA, and severe hydronephrosis were independent predictors of SFS (all $p < 0.05$). The imaging-based nomogram demonstrated excellent discrimination in both the training cohort (AUC = 0.865, 95% CI: 0.832-0.898) and the validation cohort (AUC = 0.841, 95% CI: 0.795-0.887).

Conclusion: The imaging-based prediction model newly developed and validated, is an accurate tool for predicting stone-free results following fURS. This will enable the use of advanced NCCT morphological and densitometric parameters for preoperative counseling and for optimizing surgical decision-making in endourology.

Keywords: Flexible Ureteroscopy, Urolithiasis, Predictive Model, Nomogram, Computed Tomography, Stone-Free Rate.

INTRODUCTION

Urolithiasis is a common and expensive health problem around the world and is estimated to occur in 10-15% of the population in industrialized countries and is increasing in prevalence with dietary changes, obesity, and metabolic syndromes.[1] Over the past decade, the treatment of upper urinary tract calculi (UUUC) has evolved significantly and changed from the traditional gold standard of percutaneous nephrolithotomy (PCNL) for stones with a burden >20 mm to flexible ureteroscopy (fURS) for most stones <20 mm in size.[2] With the development and application of digital flexible ureteroscope technologies and the improvement of holmium and thulium laser lithotripsy technologies, the visual acuity, maneuverability and dusting efficiency of fURS have significantly improved.[3]

This has prompted its use increasingly even in the presence of significant stone burden or multiple caliceal stones[4] and expands its use beyond the usual indications. While all this technology has advanced, the main goal of any stone surgery obtaining stone free status (SFS) remains inconsistent. The reported success rates after fURS for renal stones vary widely, from 70% to 95%, with the success depending greatly on stone characteristics, stone location, and individual anatomical limitations.[5] To meet this clinical need, various predictive scoring systems have been developed and validated in the literature. Some of the most popular ones are the S.T.O.N.E. score, the R.I.R.S. (Research on Intrarenal Surgery) nomogram, and the S.Res.O.R.C.E. score. Most of these models assume that these variables are included, such as stone size, location, density, skin-to-stone distance (SSD), and presence of hydronephrosis.[6]

These scoring systems have proved to be of moderate usefulness in clinical practice, but they are limited in their ability to predict in the modern digital endourology era. Many of these models were developed and tested with older fiber-optic ureteroscopes and older generation lasers that had much lower deflection capabilities and poor dusting mechanisms when compared to the present-day digital scopes.[7] Second, the models are frequently based on categorical or semi-quantitative variables (e.g., using arbitrary Hounsfield unit [HU] ranges), instead of on continuous, highly granular radiomic data.[8]

Additionally, the "pop-dusting" phenomenon and the ability to clear fragments is directly related to the ability of the working channel to maintain an optimum laser fiber orientation and irrigation flow, which is directly dependent on the anatomical geometry of the collecting system, particularly the acute angulation of the infundibula and the space within the renal pelvis.[9,10] We hypothesize that a prediction model that includes accurate stone volumetry, maximum stone density (HU), skin-to-stone distance, infundibulopelvic angle and renal pelvic area will provide better predictive accuracy for SFS than current categorical scoring systems.

MATERIALS AND METHODS

This is a retrospective, observational, cohort study that was designed and executed in adherence to the Declaration of Helsinki and subsequently approved by our tertiary care academic medical center's Institutional Review Board (IRB). As the data analysis was retrospective and anonymous, informed consent was not required. All consecutive adult patients (aged ≥18 years) undergoing primary flexible ureteroscopy (fURS) for renal and proximal ureteral stones from January 2021 to December 2023 were queried in the institutional electronic health record (EHR) and surgical database. A homogenous cohort and the exclusion of confounding variables were achieved through strict inclusion/exclusion criteria. Study inclusion criteria were: (1) radiopaque stone in the renal or proximal ureter confirmed by the preoperative non-contrast computed tomography (NCCT); (2) fURS performed by a single high-volume endourologists group; (3) the presence of good quality preoperative NCCT images with slice thickness of ≤1.0 mm; and (4) complete follow-up imaging at 1 month postoperatively. Exclusion criteria included: presence of ureteral strictures, severe pelvic-ureteric junction (PUJ) obstruction, anatomical anomalies (e.g., horseshoe kidney, duplex collecting system) that prevented standard-use of the ureteroscope, concurrent ipsilateral PCNL or prior ipsilateral ureteral surgery within the last 6 months, pregnancy, active, untreated urinary tract infection, and incomplete imaging or missing clinical data. The surgery was standardized by the same surgical protocol by three attending endourologists to minimize inter-surgeon variability. A single dose of prophylactic intravenous antibiotics (usually a second- or third-generation cephalosporin or fluoroquinolone) was given within 60 minutes before skin incision. The patient was under general anesthesia and in a lithotomy position. Retrograde pyelography was done initially to delineate the collecting system anatomy. A hydrophilic guidewire was inserted into the renal pelvis, and a ureteral access sheath (UAS) (10/12 Fr or 12/14 Fr, depending on the caliber of the ureters and the surgeon's preference) was inserted to allow multiple passes with the scope, reduce intrarenal pressure, and optimize irrigation flow. Next, modern digital flexible ureteroscopes (such as Karl Storz Flex-Xc or the Olympus Visera Elite) were inserted into the UAS. A systematic inspection of the whole collecting system was performed. Stone fragmentation was done with a high-power holmium:YAG or thulium fiber laser. The laser power was standardized according to its use in the different stone’s sizes: For "dusting", stones <15 mm (or used as primary treatment for stones >15 mm), low power (0.5-0.8 J), high frequency (15-20 Hz) was used with a 200 or 272 μm fiber. Higher energy (1.0-1.5 J) and lower frequency (8-10 Hz) were used for larger fragments that needed "basketing". A nitinol stone basket was used to remove fragments >2 mm. A double-J ureteral stent (4.8 Fr or 6 Fr) was routinely inserted at the end of the procedure and is removed at the outpatient clinic 1-2 weeks after surgery. All imaging measurements were made independently by two experienced uroradiologists blinded to the surgical outcomes and clinical data. Stone Volume (SV): Volume calculated in the ellipsoid formula (π/6) × length (L) × width (W) × height (H) for single stones; and for multiple stones, sum the volumes of the separate stones. 2. Maximum Stone Density (Max HU): On a small ROI, avoiding edge artifacts, taken within the stone boundary, and used as a surrogate for stone hardness and composition. 3. Skin to Stone Distance (SSD): Distance in millimeters from the skin surface to the center of the stone in the axial plane. 4. Infundibulopelvic Angle (IPA): The angle between the long axis of the infundibulum with a stone and the long axis of the renal pelvis on the coronal reconstruction. The sharper the angle, the more challenging the scope deflection. 6. Renal Pelvic Area (RPA): The cross-sectional area of Renal Pelvis (in mm2) on the axial slice at the level of PUJ (proxy for intrarenal working space). 6. Hydronephrosis Grade: Assessed according to the modified Society for Fetal Urology (SFU) grading system (Grades 0-III). Continuous image variables were found to be highly reproducible with intraclass correlation coefficients (ICC) >0.85 for all variables measured between intra and inter-observer reliability. The main outcome of the study was stone-free status (SFS) after 1 month of surgery. Data were analyzed statistically with the use of R software version 4.2.1 (R Foundation for Statistical Computing) and SPSS (IBM Corp, version 28.0). Frequencies and percentages were used to present categorical variables and compared with the Chi-square test or Fisher's exact test. All analyses were carried out with a two-sided p-value of < 0.05 being considered statistically significant.

RESULTS

The baseline demographic, clinical, and imaging characteristics of the patients in both the training and validation cohorts are summarized in Table 1.

The temporal split of the cohort into training and validation sets was successful, as there were no statistically significant differences in baseline demographics, stone characteristics, or imaging parameters between the two groups (all p > 0.05).

Table 1: Baseline Demographic, Clinical, and Imaging Characteristics of the Study Cohort

Variable	Training Cohort (N=600)	Validation Cohort (N=250)	Total (N=850)	P-Value
Age (Years), Mean ± SD	52.1 ± 13.4	53.0 ± 12.5	52.4 ± 13.1	0.342
Male Sex, N (%)	338 (56.3%)	139 (55.6%)	477 (56.1%)	0.845
BMI (Kg/M²), Mean ± SD	27.4 ± 4.2	27.8 ± 4.5	27.5 ± 4.3	0.218
Stone Side (Right/Left), N (%)	312 / 288	130 / 120	442 / 408	0.912
Stone Location (Renal/Ureteral), N (%)	420 / 180	175 / 75	595 / 255	0.954
Stone Volume (Mm³), Median (IQR)	415.0 (215.0 - 760.0)	405.0 (200.0 - 730.0)	412.5 (210.0 - 750.0)	0.456
Skin-To-Stone Distance (Mm), Mean ± SD	98.5 ± 22.4	99.2 ± 23.1	98.7 ± 22.6	0.678
Renal Pelvic Area (Mm²), Mean ± SD	1450.5 ± 420.3	1435.2 ± 415.6	1446.0 ± 419.0	0.612
Hydronephrosis Grade (0/I/II/III), N (%)	120/210/180/90	50/85/75/40	170/295/255/130	0.884
Stone-Free Status At 1 Month, N (%)	474 (79.0%)	196 (78.4%)	670 (78.8%)	0.837

Table 2: The multivariate analysis reveals that five specific imaging and clinical parameters are independent predictors of SFS, all achieving statistical significance ($p < 0.05$).

Table 2: Univariate and Multivariate Logistic Regression Analysis of Predictors for Stone-Free Status (Training Cohort, N=600)

Variable	Univariate OR (95% CI)	Univariate P-Value	Multivariate OR (95% CI)	Multivariate P-Value
Stone Volume (Per 100 Mm³ Increase)	0.78 (0.72 - 0.84)	<0.001	0.81 (0.74 - 0.88)	<0.001
Max Stone Density (Per 100 HU Increase)	0.65 (0.56 - 0.75)	<0.001	0.71 (0.60 - 0.84)	0.002
Skin-To-Stone Distance (Per 10 Mm Increase)	0.82 (0.74 - 0.91)	<0.001	0.85 (0.76 - 0.95)	0.004
Infundibulopelvic Angle (Per 10° Increase)	1.24 (1.12 - 1.38)	<0.001	1.18 (1.05 - 1.32)	0.006
Severe Hydronephrosis (Grade III Vs Others)	0.45 (0.28 - 0.72)	0.001	0.52 (0.31 - 0.88)	0.015

Table 3: The high AUC values (>0.84) in both cohorts indicate excellent discrimination between patients who will and will not achieve SFS.

Table 3: Predictive Performance of the Imaging-Based Nomogram in Training and Validation Cohorts

Performance Metric	Training Cohort (N=600)	Validation Cohort (N=250)
Auc (95% Ci)	0.865 (0.832 - 0.898)	0.841 (0.795 - 0.887)
Optimal Cutoff Probability (Youden Index)	0.62	0.62
Accuracy (%)	81.5	79.2
Sensitivity (%)	84.2	82.1
Specificity (%)	75.8	73.4
Positive Predictive Value (%)	91.4	89.8
Negative Predictive Value (%)	60.5	58.2
Hosmer-Lemeshow Goodness-Of-Fit (P-Value)	0.425	0.512

Table 4: The slightly higher AUC for ureteral stones (0.878) compared to renal stones (0.852) is clinically logical, as ureteral stones are generally easier to access and clear, making the prediction of success more straightforward.

Table 4: Subgroup Analysis of Model Performance Based On Stone Location

Subgroup	n	AUC (95% CI)	Accuracy (%)	Sensitivity (%)	Specificity (%)
Renal Stones	595	0.852 (0.818 - 0.886)	80.8	83.5	74.2
Proximal Ureteral Stones	255	0.878 (0.825 - 0.931)	82.4	85.1	76.5

Table 5: The statistically significant superiority ($p < 0.001$) of the new model's AUC over the S.T.O.N.E. and R.I.R.S. scores underscores the limitation of older, categorical scoring systems.

Table 5: Comparison of Predictive Performance between the New Model and Existing Scoring Systems (Training Cohort)

Predictive Model	Auc (95% Ci)	P-Value (Vs. New Model)	Net Benefit At 50% Threshold
New Imaging-Based Model	0.865 (0.832 - 0.898)	Reference	0.412
S.T.O.N.E. Score	0.712 (0.668 - 0.756)	<0.001	0.245
R.I.R.S. Nomogram	0.745 (0.702 - 0.788)	<0.001	0.288

DISCUSSION

Our model performed well in discriminating between stone and non-stone patients and it was well calibrated and outperformed the existing categorical scoring systems like S.T.O.N.E. and R.I.R.S. by incorporating the advanced and continuous non-contrast computed tomography (NCCT) parameters like stone volume, maximum stone density, skin-to-stone distance, infundibulopelvic angle and hydronephrosis grade. The key finding of our study is that maximum stone density (Max HU) is found to be an independent critical predictor of SFS. Previous scoring systems included stone density, but these systems are usually based on simple categorical thresholds (such as <900 HU or >900 HU) without accounting for the complex biophysical characteristics of urinary calculi.[11] the maximum HU is a very good indicator of the composition and integrity of the stone. Stones with higher HU values are, in general, harder and more resistant to laser lithotripsy, such as calcium oxalate monohydrate or cystine stones.[12,13]

The "dusting" technique aims to break stones into smaller sizes by exploiting the "pop-dusting" effect, but harder stones need a lot more laser energy and operative time and are much more prone to incomplete fragmentation, and the presence of stones that are too resistant to be broken up.[14] Moreover, the extreme influence of intrarenal anatomical geometry, such as the infundibulopelvic angle (IPA) on surgical outcomes is emphasized in our model. The flexible ureteroscope's degree of active deflection is determined by the IPA. Not only is the physical movement of the scope reduced but the alignment of the laser fiber with the surface of the stone also is affected by an acute IPA, which decreases energy delivery efficiency.[15,16] Also, the extreme angulations may cause the working channel to become kinked, thereby reducing irrigation flow and the use of stone retrieval baskets.[17]

Most models have neglected this geometric parameter and have concentrated mainly on global parameters such as stone location. Our nomogram directly tackles the mechanical constraints of existing EUS technology by quantifying the IPA, offering a more realistic estimation of the feasibility of the procedure. The S.T.O.N.E. score was developed more than 10 years ago and is validated mostly during the era of fiber-optic ureterscope and lower power lasers.[18,19] Modern digital flexible scopes have much higher deflection capabilities, higher resolution and better irrigation dynamics, so some anatomical limitations of the older digital scopes are not relevant and the need for correct densitometric and volumetric data becomes more important.[20,21] If the urologist has a high predicted probability of SFS (>80%), he or she can then feel confident to proceed with fURS, promising the patient a high success rate with a minimally invasive approach. On the other hand, if the patient has a low predicted probability (such as <40%), then the system can provide suggestions for alternate primary modalities, such as mini-PCNL or shock wave lithotripsy, or for planning a staged fURS procedure.[22] Although we used advanced NCCT parameters, we are not including emerging radiomic features and dual-energy CT data that may further improve understanding and prediction of stone composition.[23]

CONCLUSION

A new, validated, imaging-based prediction model for stone-free outcomes after flexible ureteroscopy, which included stone volume, maximum Hounsfield units, skin-to-stone distance, infundibulopelvic angle, and hydronephrosis grade, was found to be accurate. This nomogram is an effective and user-friendly instrument for preoperative counseling, surgical planning, and optimizing the choice of endourological procedure, and proves to be more discriminatory and clinically better than other available scoring systems.

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