Applying urinary ultrasound to predict the risk of spontaneous ureteral stone passage: a retrospective cohort study

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Abstract

Background To assess the value of urological ultrasound in predicting the risk of spontaneous passage of ureteral stones.

Methods Clinical and ultrasound data were collected consecutively from patients receiving conservative treatment for ureteral stones, and the outcome of spontaneous passage was followed up for 1 month. Ultrasound variables independently associated with the risk of spontaneous stone passage were screened. A logistic regression prediction model was constructed based on the independent risk factors, and the discriminative efficacy and clinical utility of the prediction model in inferring the risk of spontaneous passing were assessed by the receiver operating characteristic (ROC) curve, calibration curve and clinical decision curve.

Results A total of 163 patients undergoing conservative treatment for ureteral stones were included in the study, with a mean age of 45.95 ± 13.01 years. Among them, 47 cases (28.83%) experienced failure of spontaneous stone passage. Multivariable analysis revealed that stone length (OR: 2.622, $P = 0.027$), distal stone location (OR: 0.219, $P = 0.003$), and ureteral jetting frequency (OR: 6.541, $P < 0.001$) were independent risk factors for spontaneous stone passage. A prediction model incorporating stone length, stone location, and affected ureteral jetting frequency was developed to assess the risk of spontaneous stone passage. The area under the ROC curve was 0.814 (95% CI: 0.747–0.882), indicating good discriminatory power. The prediction model also demonstrated favorable net clinical benefit.

Conclusion A prediction model based on ultrasound-derived stone length, location, and ureteral jetting frequency can accurately evaluate the risk of spontaneous stone passage in patients with ureteral stones, providing a basis for optimizing the clinical decision-making on ureteral stones, and has reliable clinical application value.

Keywords Ureteral stones, Spontaneous stone passage, Urinary ultrasound, Prediction model

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Introduction

Urolithiasis is a global health issue, with a prevalence rate of 6.4% in China and a 5-year recurrence rate of 30-50%. In recent years, there has been an increasing trend in the incidence of this condition [1]. Ureteral stones are the most common urologic emergency, and procedures such as extracorporeal shock wave lithotripsy, flexible ureteroscopic lithotripsy and percutaneous nephrolithotomy achieve high stone clearance rates [2]. Conservative treatment is highly recommended by physicians and preferred by patients for stones smaller than 10 mm, as they have a higher likelihood of spontaneous passage. Approximately 50–75% of these stones can be successfully expelled with the aid of medical interventions, including the use of alpha-adrenergic blockers. These medications help facilitate self-expulsion of the stones. However, the failure of conservative treatment can lead to risks, including acute renal failure, obstructive pyelonephritis, and urosepsis [3]. Therefore, individualized and accurate assessment of the risk of conservative treatment failure in ureteral stones, along with the optimization of clinical decision-making, is of significant clinical importance in preventing complications associated with ureteral stones.

Ultrasonography, characterized by its non-ionizing radiation and real-time imaging capabilities, has become the most commonly used imaging modality for the diagnosis and follow-up of ureteral stones [4]. However, there is limited research investigating the predictive value of urological ultrasound parameters in determining the clinical outcomes of ureteral stones. This study aims to identify urological ultrasound parameters that are independently associated with the risk of spontaneous stone passage in ureteral stones and evaluate their effectiveness in predicting the risk of spontaneous stone passage. The findings of this study will provide objective evidence to optimize clinical decision-making and minimize ureteral injuries.

Methods

Study population

A retrospective study was conducted to collect data on patients with ureteral stones who underwent conservative treatment at the outpatient department of the First Affiliated Hospital of Zhengzhou University from September 2022 to April 2023. Based on the following inclusion and exclusion criteria, eligible individuals were included in this study cohort. Inclusion criteria: Patients with ureteral stones who met all of the following criteria were recruited: unilateral solitary ureteral stones confirmed by imaging; maximum stone diameter ≤ 10 mm; undergoing conservative stone expulsion therapy. Exclusion criteria: Patients with ureteral stones who met any of the following criteria were excluded from this study: age < 16 years; pregnant women; solitary

kidney; hydronephrosis with an anteroposterior diameter of the renal pelvis > 25 mm; complicated with urinary tract infection; complicated with severe liver or kidney dysfunction; those without complete ultrasonographic images of the urinary system within 2 weeks after diagnosis. This research was approved by the Ethics Committee of the First Affiliated Hospital of Zhengzhou University (2023-KY-0335-002). Informed consent to participate in the study was obtained from all participants.

Echocardiography

We used ultrasound diagnostic devices (GE Logic E9 with C5-1 convex array probe, frequency: 1–5 MHz; Samsung RS85 with CA1-7 A convex array probe, frequency: 1–7 MHz) to obtain ultrasound parameters related to ureteral stones: Patients consumed 500 to 700 ml of water before examination and underwent ultrasound after 30 min [5]. Initially, both kidneys, ureters, and bladder were routinely scanned to obtain parameters such as stone location, size, and ureteral dilation. Subsequently, instruct the patients to lie in a supine position, and the probe was positioned above the pubic symphysis for transabdominal scanning, simultaneously displaying the bilateral ureteral orifices in the trigone of the bladder. Using color Doppler ultrasound, we continuously and real-time observed the number of ureteral jet occurrences from both ureteral bladder openings for 5 min, recording them simultaneously. Subsequently, based on the recorded imaging data, we retrospectively calculated the average number of urination jets within 5 min, which represents the ureteral jet frequency [6] (Fig. 1). The clinical outcomes of the enrolled patients were assessed at a 1-month follow-up. Successful spontaneous stone passage was defined as a negative finding on CT or X-ray imaging, whereas persistent evidence of stone presence on imaging indicated failed spontaneous stone passage.

Statistical analysis

The data were analyzed using R (version: 4.3.1). Normally distributed continuous variables were presented as mean ± standard deviation, and the independent samples t-test was used for between-group comparisons. Non-normally distributed continuous variables were presented as median (interquartile range), and between-group comparisons were performed using the Wilcoxon rank-sum test. Categorical variables were presented as counts (percentages), and between-group comparisons were conducted using the chi-square test or Fisher's exact test. Variables with a univariate analysis p-value < 0.10 were included in a multivariable logistic regression to identify independent associated factors. The discriminatory ability and clinical value of the relevant parameters in predicting the outcome of conservative treatment were evaluated using receiver operating characteristic (ROC)
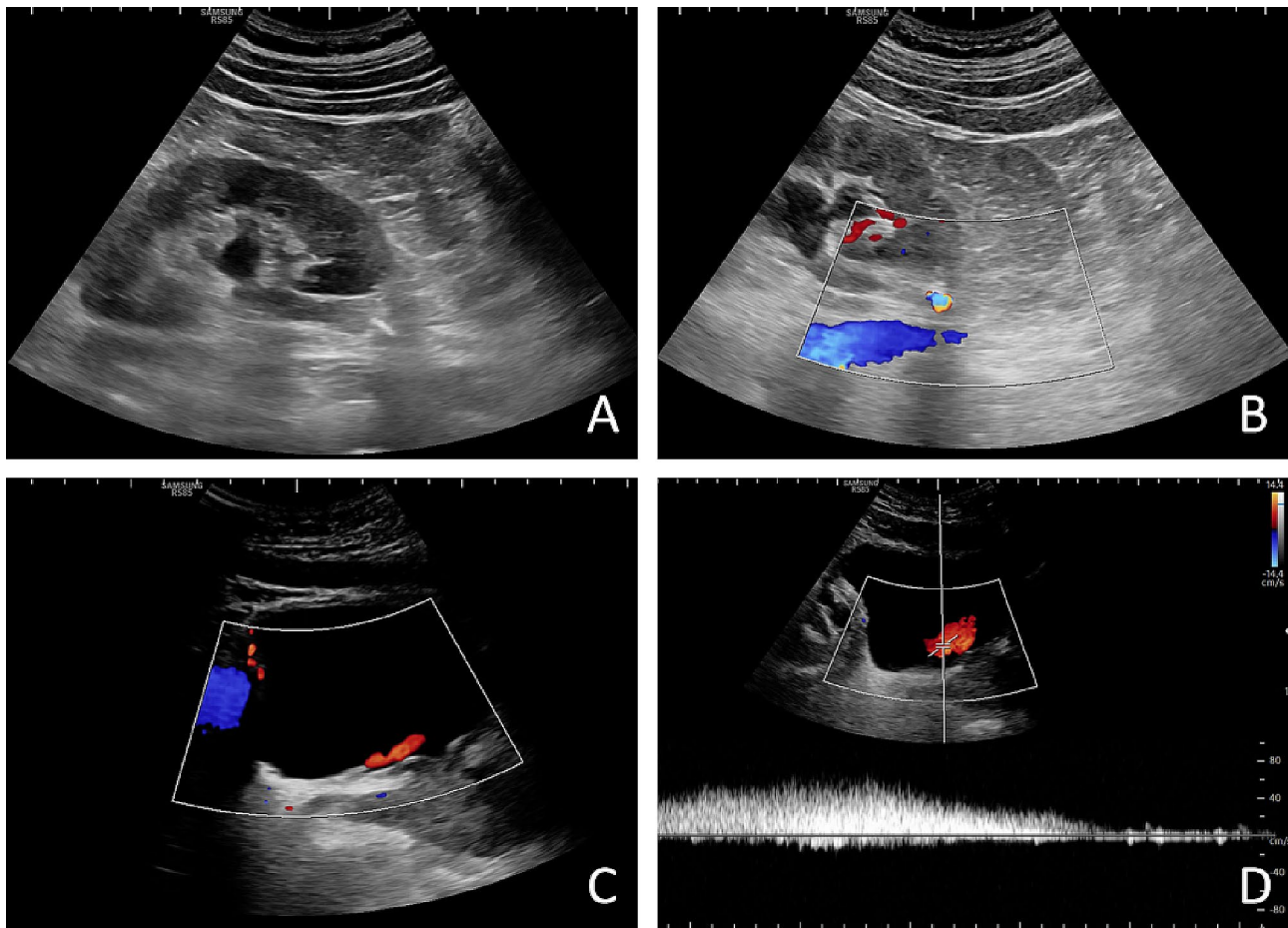
Fig. 1 Female, 57 years old, with 7.5 mm right lower ureteral stone, failed exposure. (**A**)longitudinal view of ureteral stone, (**B**) twinkle artifacts of ureteral stone, (**C**) Color Doppler image of ureteral squirt, and (**D**) spectral Doppler image of ureteral jet (jet frequency: 1.0 times/min)

curves, net reclassification improvement (NRI), integrated discrimination improvement (IDI), and decision curve analysis (DCA). The intraclass correlation coefficient (ICC) was used to assess the repeatability of the ultrasound parameters related to the stone within each group.

Results

Baseline characteristics

Among the 324 patients suspected of having ureteral stones, 196 patients with a single ureteral stone received conservative treatment. 33 patients who underwent surgery within one month after opting out of conservative treatment were excluded. Finally, a total of 163 patients with ureteral stones were included in this study, as shown in Fig. 2, illustrating the selection process. Among these 163 patients, there were 75 males (46.01%) and 88 females (53.99%), with a mean age of 45.95±13.01 years. After one month of conservative treatment, the rate of failed spontaneous stone passage was 28.83% (47/163). There were no significant differences between the successful and failed stone passage groups regarding gender,

age, height, weight, BMI, stone history, renal colic, history of diabetes, and α-blocker usage ($P \geq 0.05$) (Table 1).

Independent factors associated with failed conservative treatment of ureteral stones

Compared to the patients in the successful conservative treatment group, a higher proportion of patients in the failed conservative treatment group had the stone length < 5 mm ($P < 0.001$), the stones located in the distal ureter ($P = 0.003$), and the UJF ≥ 1.5 mm ($P < 0.001$), indicating statistically significant differences. However, there were no significant differences between the two groups in terms of the stone laterality or the ureteral dilation (all $P \geq 0.05$) (Table 2). The variables that showed statistically significant differences in the univariate analysis, namely the stone length, the stone location and the UJF, were included as independent variables in the multivariable regression analysis. The results of the multivariable analysis demonstrated that the stone length ≥ 5 mm ($P = 0.027$), the stone location ($P = 0.003$), and the UJF < 1.5 mm ($P < 0.001$) were identified as independent
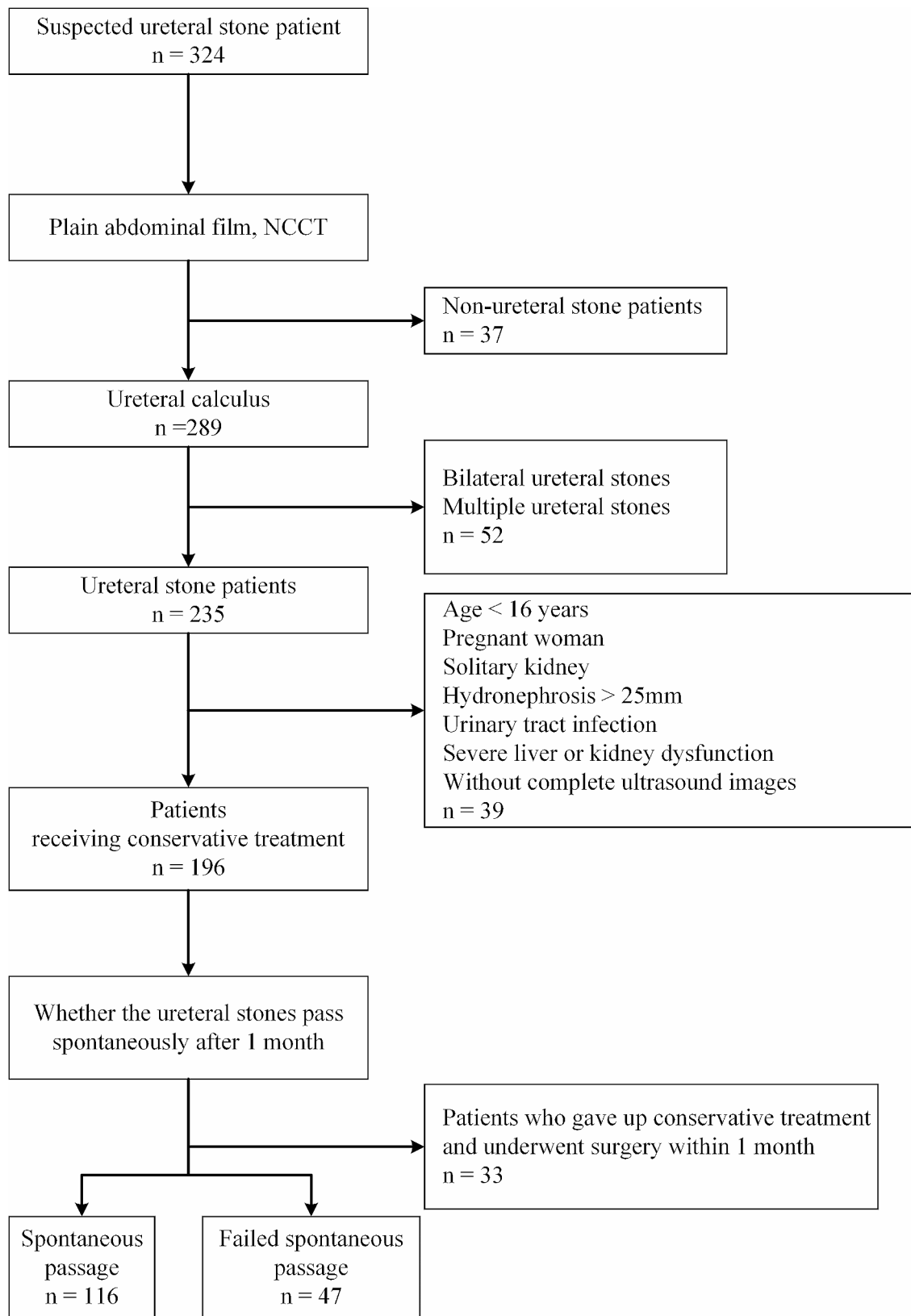
Suspected ureteral stone patient
n = 324

↓

Plain abdominal film, NCCT

→ Non-ureteral stone patients
n = 37

↓

Ureteral calculus
n =289

→ Bilateral ureteral stones
Multiple ureteral stones
n = 52

↓

Ureteral stone patients
n = 235

→ Age < 16 years
Pregnant woman
Solitary kidney
Hydronephrosis > 25mm
Urinary tract infection
Severe liver or kidney dysfunction
Without complete ultrasound images
n = 39

↓

Patients
receiving conservative treatment
n = 196

↓

Whether the ureteral stones pass
spontaneously after 1 month

→ Patients who gave up conservative treatment
and underwent surgery within 1 month
n = 33

↓   ↓

Spontaneous
passage
n = 116

Failed spontaneous
passage
n = 47

Fig. 2 Flowchart of the included study subjects

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Table 1 Comparison of general clinical data between patients with different outcomes of conservative treatment

	SP Group (*n*=116)	Failed SP Group (*n*=47)	*P* value
Age, years	45.05 ± 13.28	48.17 ± 12.17	0.166
Male, n (%)	51 (43.97)	25 (53.19)	0.285
Height, cm	164.35 ± 8.04	165.72 ± 7.78	0.322
Weight, kg	65.15 ± 7.48	67.19 ± 7.90	0.123
BMI (Kg/m2)	24.26 (22.26, 26.57)	24.63 (21.93, 26.66)	0.666
History of ureteral calculi, n (%)	28 (24.14)	16 (34.04)	0.197
Renal colic, n (%)	79 (68.10)	36 (76.60)	0.281
Diabetes, n (%)	8 (6.90)	5 (10.64)	0.631
Alpha-blocker, n (%)	74 (63.79)	25 (53.19)	0.209

P < 0.05 for a significant correlation between variables

BMI = body mass index

factors associated with the failure of conservative treatment for ureteral stones (Table 2).

Construction and validation of the nomogram

We developed a nomogram based on the results of the multivariable regression analysis to predict the risk of spontaneous passage of ureteral stones. The nomogram visually represents the contribution of each independent risk factor on the likelihood of spontaneous stone passage, with the impact quantified using a point-based scoring system. By summing the points corresponding to each factor, a vertical line can be drawn from the total score axis to determine the predicted risk value for the failure of conservative treatment for the stones, as illustrated in Fig. 3. The nomogram demonstrates favorable predictive ability, with a C-index of 0.814 (95% CI 0.746–0.882).

We internally validated the nomogram model for predicting the failure of conservative treatment for ureteral stones using the bootstrap resampling method with 500 iterations. The validation results confirmed that the nomogram model provided reliable predictions, as evidenced by the calibration curve showing close agreement between the predicted and observed outcomes. The Hosmer-Lemeshow goodness-of-fit test demonstrated satisfactory model fit (χ^2=6.1332, *P*=0.6323), as depicted in Fig. 4A. Additionally, we evaluated the discriminative performance of the nomogram using the ROC curve. The area under the curve (AUC) values for predicting the risk of failure of conservative treatment for ureteral stones were 0.659 for the stone length≥0.5 mm, 0.646 for the stone location, and the 0.726 for the UJF<1.5 jets/min (Fig. 4B). By combining these three parameters to construct a comprehensive predictive model for assessing the risk of failure of conservative treatment for ureteral stones, the AUC of the nomogram reaches 0.814 (95% CI: 0.747–0.882) (Fig. 4C), surpassing the discriminatory performance of individual parameters such as the stone length, the location, and the UJF. The nomogram model exhibited significant NRI compared to using stone length alone, with an NRI of 0.76 (95% CI: 0.524–0.967). The NRI (+) improvement was approximately 0.255 (95% CI: 0.023–0.457), while the NRI (-) was 0.509 (95% CI: 0.402–0.609). The IDI was 0.175 (95% CI: 0.108–0.242). DCA demonstrated that the nomogram model provided greater net clinical benefit compared to using only the stone length, the location, and the UJF, underscoring its clinical utility (Fig. 4D).

Table 2 Univariate and multivariate analysis of the factors associated with failed conservative treatment of ureteral stones

Variables	SP Group (*n*=116)	Failed SP Group (*n*=47)	Univariate regression OR(95%CI)	*P* value	Multivariate regression OR(95%CI)	*P* value
Stone length, (mm)	4.59 ± 1.37	5.88 ± 1.29	2.163(1.569–2.982)	<0.001*	-	-
< 5, n (%)	64(55.17)	11(23.40)	1.000		1.000	
≥ 5, n (%)	52(44.83)	36(76.60)	4.028(1.869–8.682)	<0.001*	2.622(1.118–6.150)	0.027*
Stone Laterality, n (%)						
Left	52 (44.83)	27 (76.60)	1.000		-	-
Right	64 (55.17)	20 (42.55)	1.662(0.838–3.294)	0.146	-	-
Stone Location, n (%)						
upper segment	33 (28.45)	24(51.06)	1.000		1.000	
middle segment	35 (30.17)	14 (29.79)	0.550(0.244–1.240)	0.149	0.446(0.172–1.155)	0.096
lower segment	48 (41.38)	9 (19.15)	0.258(0.106–0.625)	0.003*	0.219(0.081–0.595)	0.003*
Ureterectasis, n (%)	77 (66.38)	37 (78.72)	0.534(0.240–1.185)	0.123	-	-
UJF, (jet/min)	1.75 ± 0.53	1.23 ± 0.41	0.098(0.039–0.245)	<0.001*	-	-
≥ 1.5, n (%)	82(70.69)	12(25.53)	1.000		1.000	
< 1.5, n (%)	34(29.31)	35(74.47)	7.034(3.264–15.16)	<0.001*	6.541(2.818–15.181)	<0.001*

* *p* < 0.05 for a significant correlation between variables
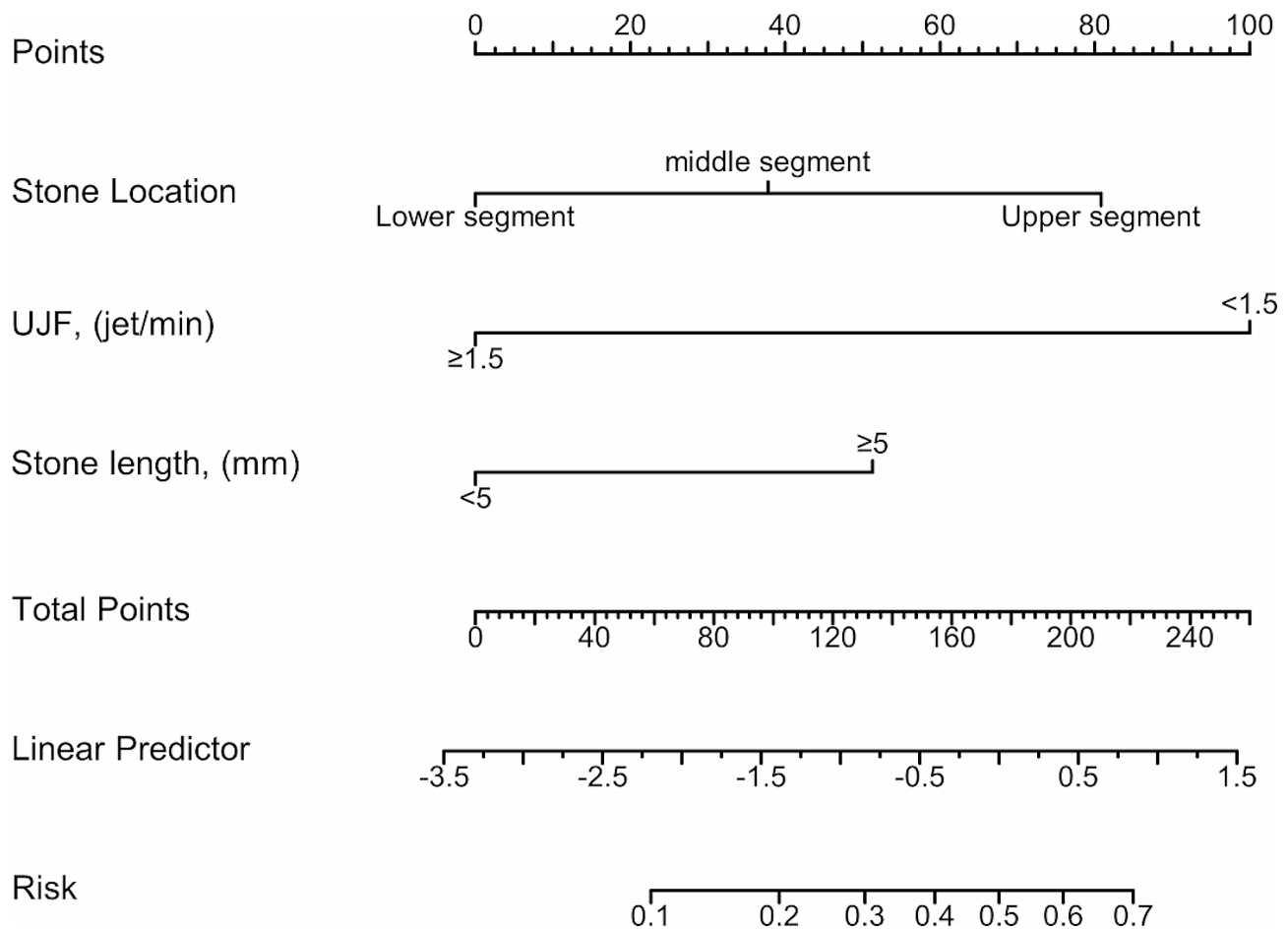
UJF, Ureteral jet frequency

Fig. 3 A nomogram based on ultrasound variables to predict the risk of failure in conservative treatment of Ureteral calculus

Repeatability analysis of parameters for ureteral calculi measured by ultrasonography

In the total study population, 79 cases underwent both urinary system ultrasonography and CT examinations with a time interval of less than 6 h. The ultrasonographically measured parameters, including the longitudinal diameter of the calculi and their locations, demonstrated good consistency with the data obtained from CT scans (longitudinal diameter of calculi: ICC=0.907, 95% CI: 0.845–0.943, $P<0.001$; stone location: ICC=0.920, 95% CI: 0.869–0.950, $P<0.001$).

Discussion

Ureteral calculi are highly prevalent worldwide. Due to the high probability of spontaneous passage for stones smaller than 10 mm, conservative treatment is widely recommended by physicians and preferred by patients. Medications such as alpha-adrenergic receptor blockers can alleviate ureteral colic, expedite ureteric stone passage, and prevent ureteral obstruction [7]. However, spontaneous stone passage can be time-consuming. Moreover, in populations affected by ureteral calculi, the proportion of middle-aged and elderly individuals is as high as 76.2%, with a higher prevalence of comorbidities such as hypertension, diabetes, and cardiovascular diseases [1]. The conservative treatment process for stones is associated with a decreased quality of life, an increased risk of infection, and an elevated risk of cardiovascular emergencies [8]. Therefore, relying solely on stone size is insufficient to determine the safety of conservative treatment.

There is an urgent need in clinical practice for accurate methods to assess the risk of spontaneous stone passage, thereby reducing the risk of complications associated with ureteral stones. Non-contrast computed tomography (NCCT) is considered the gold standard for diagnosing urolithiasis [11]. Although CT provides accurate diagnoses, it is worth noting that in the United States, approximately one-third of CT scans are performed without medical necessity. The ionizing radiation generated by CT scans is increasingly recognized as a public health concern [9].

In recent years, ultrasonography has gained widespread use as a simple, repeatable, and non-invasive imaging
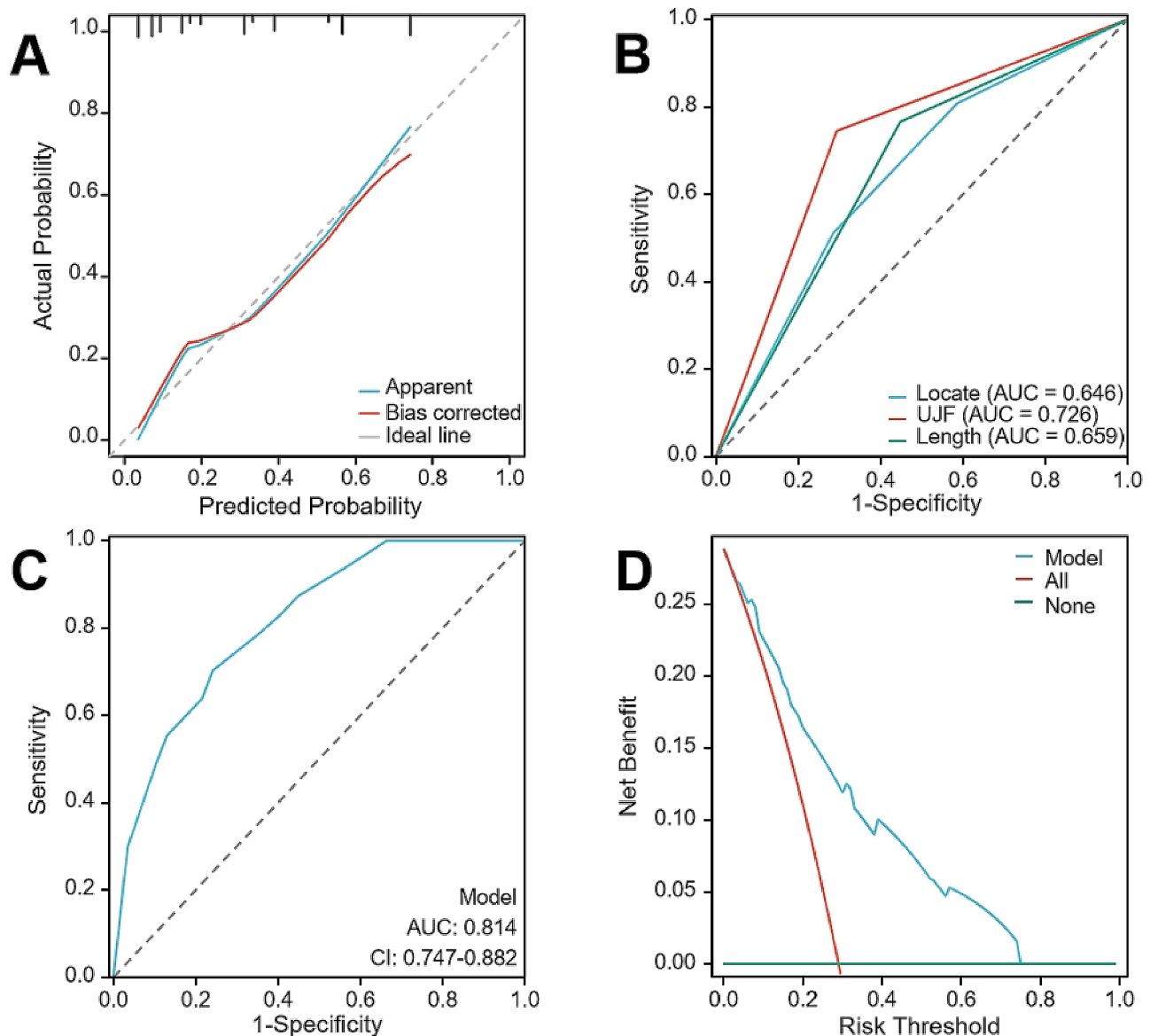
Fig. 4 Efficacy of ultrasound-related parameters in predicting the outcome of spontaneous ureteral stone expulsion. (**A**) Calibration curve (based on 500 resamplings). (**B**) ROC curves of stone length, location, and ureteral jet frequency to assess the risk of conservative treatment of ureteral stones. (**C**) ROC curves of the model. (**D**) DCA of the model

technique in the diagnosis of urological conditions. By utilizing grayscale imaging and techniques such as the visualization of stone "twinkling artifacts," ultrasonography can provide ureteral stone-related information that exhibits a high degree of consistency with CT and other imaging modalities [4, 5]. In this retrospective cohort study, the ultrasonographic measurements of ureteral stone longitudinal diameter and location showed good consistency with CT parameters. The ultrasonographic measurements of ureteral stone longitudinal diameter, stone location, and UJF on the affected side are identified as independent risk factors for the spontaneous passage outcome of ureteral stones. Constructing a predictive

model based on these three ultrasound variables can accurately assess the risk of failed spontaneous stone passage.

Currently, clinical decisions regarding ureteral stones primarily rely on size, with stones larger than 10 mm typically requiring invasive interventions such as extracorporeal shock wave lithotripsy or surgery, while stones smaller than 10 mm are often manageable through conservative treatment [10, 11]. Stone size significantly influences the likelihood of spontaneous passage, with stones smaller than 5 mm demonstrating a spontaneous passage rate of 75-89% [12]. This study demonstrates that patients in the failed spontaneous stone passage group had

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significantly larger ultrasonographically measured stone longitudinal diameters compared to the successful group, indicating it as an independent risk factor for failed spontaneous passage. Similarly, stone location plays a significant role in spontaneous passage outcomes [13, 14], with stones located in the lower ureter having a higher likelihood of passing spontaneously. The successful spontaneous passage group in this study had a significantly higher proportion of lower ureteral stones compared to the failed group.

Previous studies have shown that a history of ureteral stone disease is unfavorable for spontaneous passage due to the increased risk of ureteral injury [15]. Additionally, the maximum thickness of the adjacent ureteral wall is significantly associated with stone impaction [16, 17], highlighting the impact of structural and functional changes in the affected ureter on stone passage prognosis. Acquiring accurate structural information of the ureter through ultrasonography poses challenges. However, by continuously monitoring the ureterovesical junction for the ureteral jet phenomenon, changes in ureteral function can be accurately assessed using parameters such as UJF and peak flow velocity. Structural and functional impairments of the ureter, caused by factors such as congenital obstruction, stone presence, or inflammation, lead to increased pressure in the renal pelvis and ureter, reduced peristaltic function, and a decrease in the ureteral jet phenomenon. In cases of complete obstruction, the ureteral jet phenomenon may be completely absent [18, 19]. Jandaghi et al. [20] found that a UJF of less than 1.5 jets per minute can serve as a reasonable cutoff point for suspected ureteral obstruction in patients with urinary tract stones (with a sensitivity of 97.8% and specificity of 87%). Consistent with their findings, this study identifies an affected side UJF of less than 1.5 jets per minute as an independent risk factor for failed spontaneous passage of ureteral stones. A lower UJF indicates severe ureteral dysfunction, an increased risk of stone impaction, and diminishes the likelihood of spontaneous stone passage.

Unlike the existing risk models that primarily utilize CT variables, such as maximum ureteral wall thickness, to predict the spontaneous passage and risk of impaction of ureteral stones [16, 17], this study employed ultrasound-related variables to construct a nomogram. By incorporating stone longitudinal diameter, stone location, and UJF as ultrasound parameters, this predictive model utilizes information from both the stone itself and the affected ureteral function, enabling an accurate assessment of the risk of spontaneous stone passage. The model demonstrates good clinical utility and strong interpretability of the ultrasound-related parameters. Although CT is considered the gold standard for diagnosing urolithiasis [11], ultrasound information

regarding ureteral stones is more easily accessible for primary healthcare facilities and remote areas. For the primary healthcare institutions, doctors can preliminarily assess patients' stone conditions quickly and affordably through ultrasound examinations, enabling them to devise rational and personalized treatment plans, thereby reducing unnecessary referrals and medical costs. For patients with low risk of failed spontaneous passage, they can be encouraged to adopt conservative treatment to facilitate the natural excretion of stones. The predictive model proposed in this study can provide feasible alternative solutions for remote areas with relatively scarce medical resources. Local healthcare providers can analyze ultrasound parameters based on the study's findings to conduct initial assessments of patients' conditions. Additionally, through remote ultrasound image transmission technology, experts can offer consultations based on this study's conclusions, providing remote healthcare advice to patients in remote areas, thereby reducing the inconvenience and burden of travel for medical treatment. Moreover, ultrasound is radiation-free, cost-effective, easily obtainable, suitable for follow-up, and more applicable to populations such as pregnant women and children. Furthermore, the nomogram presents the predictive results in an intuitive manner, making it easily applicable in clinical practice. Therefore, it serves as an indispensable tool for clinical decision-making, allowing surgeons and patients to make better treatment choices based on this readily available scoring tool. However, this study has certain limitations. It is a retrospective cohort study conducted in a single center, and the conclusions need to be validated and optimized through multicenter prospective cohort studies.

In summary, this retrospective cohort study demonstrates that constructing a predictive model based on ultrasound measurements of ureteral stone longitudinal diameter, stone location, and UJF enables an accurate assessment of the risk of spontaneous passage of ureteral stones. The ultrasound parameters included in the model are highly interpretable and clinically accessible, providing a basis for precise clinical decision-making and reducing the risk of stone-related complications in the management of ureteral stones.

Abbreviations

ROC	Receiver Operating Characteristic
NRI	Net Reclassification Improvement
IDI	Integrated Discrimination Improvement
DCA	Decision Curve Analysis
ICC	Intraclass Correlation Coefficient
AUC	Area Under the Curve
BMI	Body Mass Index
UJF	Ureteral Jet Frequency
NCCT	Non-Contrast Computed Tomography

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Author contributions

Funding

Data availability
All data generated or analyzed during this study are included in this article. Further inquiries can be directed to the first author.

Declarations

Ethics approval and consent to participate
This research was approved by the Ethics Committee of the First Affiliated Hospital of Zhengzhou University (2023-KY-0335-002). Informed consent to participate in the study was obtained from all participants.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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