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ORIGINAL RESEARCH

Effect of lower urinary tract anatomy measured on three-dimensional reconstruction using magnetic resonance imaging on the treatment of benign prostatic hyperplasia decision

Guibing He[1,†], Rui Yu[2,†], Xingxing Li[3], Yankun Feng[4], Huiling Wu[1,*], Yi Wang[1], Kaijie Xu[1], Yong Yao[1], Junyi Lu[1], Zhisheng Hu[1]

[1]Department of Urology, Jinhua People's Hospital, 321000 Jinhua, Zhejiang, China
[2]School of Medicine, Nanchang University, 330031 Nanchang, Jiangxi, China
[3]Department of Cardiovascular Medicine, Jinhua People's Hospital, 321000 Jinhua, Zhejiang, China
[4]School of Basic Medical Sciences, Xiangnan University, 423000 Chenzhou, Hunan, China

***Correspondence**
13566782530@163.com
(Huiling Wu)

[†] These authors contributed equally.

Abstract

Background: To examine the impact of urinary tract anatomical parameters on treatment decisions for benign prostatic hyperplasia (BPH) in patients with lower urinary tract symptoms (LUTS). **Methods**: Male patients with a prostate volume (PV) greater than 25 mL, presenting with LUTS/BPH, and treated at Jinhua People's Hospital between June 2021 and May 2024 were included in this study. Patients were categorized into surgery-required (NS) and non-surgery-required (non-NS) groups based on uroflowmetry results and the International Prostate Symptom Score (IPSS). Magnetic Resonance Imaging (MRI) with three-dimensional (3D) reconstruction was utilized to accurately measure urinary tract anatomical parameters. **Results**: A total of 119 patients were included, with 51.3% requiring surgery. Binary logistic regression analysis identified bladder wall volume (BWV) Odds Ratio (OR) 1.286; 95% Confidence Internal (95% CI), 1.105 to 1.497; p = 0.001), intravesical prostatic protrusion (IPP) (OR 1.585; 95% CI, 1.165 to 2.157; p = 0.003), and prostatic urethral angle (PUA) (OR 1.158; 95% CI, 1.036 to 1.294; p = 0.01) as significant predictors of the need for surgery. Receiver operating characteristic curve analysis revealed optimal cutoff values for distinguishing the need for surgery: BWV of 47 mL (area under the curve (AUC): 0.837), PUA of 47.15° (AUC: 0.903), and IPP of 8.45 mm (AUC: 0.922). The sensitivity, specificity, and accuracy of BWV, IPP and PUA were 68.9%, 86.2% and 75.6%; 86.9%, 82.8% and 82.4%; and 82.2%, 87.9% and 81.5%, respectively. The combined area under the curve for the three parameters was 0.979. **Conclusions**: Measurements of BWV, PUA and IPP are effective in determining whether patients with LUTS/BPH require surgery.

Keywords

LUTS/BPH; Urinary tract anatomy parameters; Magnetic resonance imaging; Surgery

1. Introduction

Benign prostatic hyperplasia (BPH) is the primary cause of lower urinary tract symptoms (LUTS) experienced by men [1]. In China, the prevalence of LUTS/BPH among males aged 45 and above is 10.66%, with a higher rate of 14.76% observed in those aged 70 and older [2]. The presence of LUTS/BPH can have a substantial negative impact on the quality of life of individuals, often resulting in feelings of anxiety and depression [3]. Available treatment options encompass conservative pharmacological methods as well as surgical interventions. Surgical treatment is recommended for cases of moderate to severe LUTS that greatly compromise quality of life, recurrent urinary tract infections, visible blood in the urine, bladder stones, hydroureteronephrosis and urinary retention [4]. However, determining the need for surgery can be challenging, particularly in patients with bladder outlet obstruction (BOO) who do not present with complications.

Urodynamics (UDS) is considered the most reliable method for diagnosing voiding dysfunctions, particularly in the assessment of LUTS/BPH [5]. Viewed through the lens of fluid mechanics, BOO is closely linked to structural changes in the lower urinary tract [6–8]. Studies [6–8] have indicated that factors such as prostatic urethral angle (PUA), intravesical prostatic protrusion (IPP), bladder wall volume (BWV), and bladder wall thickness (BWT) play crucial roles as predictors of BOO in individuals with LUTS/BPH. These investigations primarily utilized cystoscopy or ultrasound techniques for these evaluations. While cystoscopy is accurate, it is an invasive procedure that can potentially modify urethral morphology, thereby impacting the precision of measurements. Ultrasound, while less invasive, is limited by its two-dimensional nature and is subject to variability based on the sonographer's technique and subjective judgment, often leading to imprecise results.

The technology of three-dimensional (3D) reconstruction involves capturing three-dimensional images of real-world objects and then manipulating them for purposes such as image compression, transmission and display. Research findings suggest that the utilization of 3D reconstruction and 3D printing plays a significant role in assessing treatment options before surgery and facilitating surgical preparation [9, 10]. However, the application of 3D reconstruction in measuring lower urinary tract anatomy remains underdeveloped. Matsugasumi *et al*. [11] employed Synapse-Vincent software for MRI image reconstruction and prostate measurement, encompassing the volumes of the peripheral zone and transition zone. Their findings revealed a direct association between structural alterations in the prostatic transition zone and LUTS. In a similar vein, Anzia *et al*. [12] utilized 3D reconstruction techniques to assess BWV and maximum BWT among diverse age cohorts. Their investigation unveiled a significant positive relationship between both BWV and BWT with BOO. However, clear cutoffs for lower urinary tract anatomical parameters to guide surgical decisions have not yet been established. In this study, we used 3D reconstruction with MRI to accurately measure the anatomical parameters of the lower urinary tract and investigated the influence of these parameters on treatment decisions for BPH.

2. Methods

2.1 Study design and patient assessment

Male patients with LUTS/BPH treated at Jinhua People's Hospital between June 2021 and May 2024 were selected. Patients with a prostate volume exceeding 25 mL, as determined by ultrasound, were included in the study. Exclusion criteria were as follows: urinary retention, bladder pathology, previous lower urinary tract surgery, urethral strictures, prostate cancer, prior neurological disease, and reduced detrusor contractility due to diabetes mellitus. The study was approved by the hospital ethics committee (approval no. IRB-2021016-R), and all patients provided written informed consent before participating.

2.2 Procedure

Patient history was recorded, and blood samples were collected for prostate-specific antigen (PSA) measurement. Urine samples were obtained to rule out urinary tract infections. The International Prostate Symptom Score (IPSS) and Quality of Life Score (QoL) were assessed. Each patient received pelvic MRI and uroflowmetry. For patients demonstrating a urinary flow rate lower than 10 mL/second, urodynamics were conducted to validate the existence of BOO. There was no regulation of urine volume prior to the pelvic MRI; however, individuals with urine volumes below 50 mL or above 200 mL following 3D reconstruction were excluded. The MRI utilized a 1.5T scanner equipped with an 8-channel cardiac array. Sagittal Fast Spin Echo (FSE) T2-weighted images were acquired for analysis with the following parameters: Time of Repetition (TR) 4000–5000 ms; Echo Time (TE) 100 ms; matrix 320 $\times$ 226; Field of View (FOV) 220 $\times$ 220 mm^2; slice thickness 3 mm; true spatial resolution 0.70 $\times$ 0.70 mm; flip angle 130°; receiver bandwidth 200 kHz. Uroflowmetry, IPSS and QoL were used as reference standards for determining surgical needs. Patients, with Qmax no more than 10 mL/second and IPSS 20–35 or QoL 5–6, were considered to require surgery. Patients were classified into surgery-required (NS) and non-surgery-required (non-NS) groups.

2.3 3D reconstruction and parameter measurements

The acquired images in DICOM (Digital Imaging and Communications in Medicine) format were uploaded into Mimics version 20.0 (Materialize, Leuven, Belgium) to create virtual anatomic 3D models [12]. The bladder serosa, bladder lumen, and prostate capsule were delineated by a medical student and an author in collaboration with an experienced abdominal radiologist. Subsequently, each MRI slice was outlined to generate a mask representing the segmented anatomy, which was then transformed into a 3D model utilizing the "Calculate 3D from Mask" tool. This process was repeated for the 3D whole bladder, the 3D bladder lumen, and the 3D whole prostate to determine prostate volume (PV) (Fig. 1). The bladder wall was rendered as a 3D model by subtracting the 3D bladder lumen model from the 3D whole bladder model, thereby providing the bladder wall volume (BWV) (Fig. 2).

The bladder wall's 3D models were transferred from Mimics to 3-matic, version 11.0 (Materialize, Leuven, Belgium), for further analysis. The wall thickness evaluation tool was employed to examine the 3D models of the bladder wall. The computational median BWT for the entire bladder was collected for each patient (Fig. 3).

IPP and PUA were measured directly on sagittal MRI images. IPP was measured as the length between the internal urethral orifice and the baseline located at the bottom of the bladder. PUA was defined as the acute angle formed by a line extending from the verumontanum to the distal urethra and another line extending from the verumontanum to the proximal urethra (Fig. 4).

2.4 Statistical analysis

The data were analyzed using SPSS version 26 (IBM, Armonk, NY, USA). The distribution test showed that, except for BWT and BWV, all other data were normally distributed. BWT and BWV were presented as medians with the corresponding interquartile range (IQR), and group comparisons were performed using the Mann–Whitney U-test. Other data were analyzed using an independent sample t-test and were presented as mean $\pm$ standard deviation. Binary logistic regression analysis was used to assess the significance of lower urinary tract anatomy parameters in surgical decision-making, with variable selection based on the forward method. Receiver operator characteristic curve (ROC) analysis was conducted to determine the optimal cutoff value and AUC for each parameter. Additionally, sensitivity, specificity, and accuracy were calculated. A p-value of less than 0.05 was considered statistically significant.

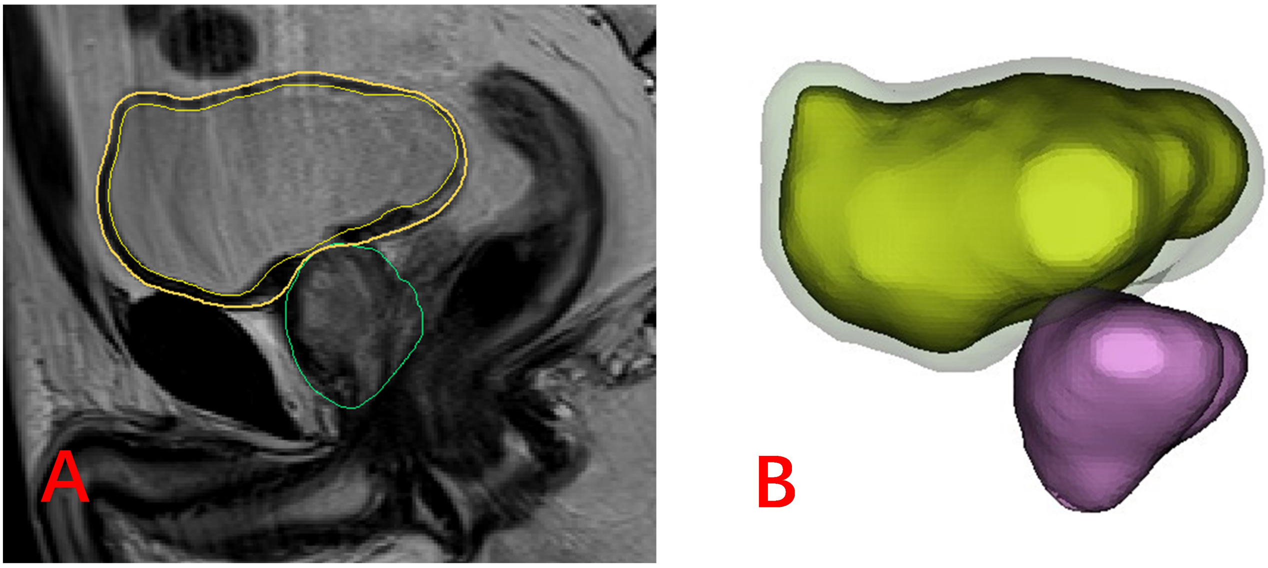

FIGURE 1. 3D reconstruction process with Mimics software using Pelvic sagittal MRI. (A) Segmentation of the bladder serosa, bladder lumen and prostate were performed. (B) Calculated 3D model of the bladder serosa, bladder lumen and prostate. Transparent represents the bladder wall, yellow represents urine and purple represents the prostate.

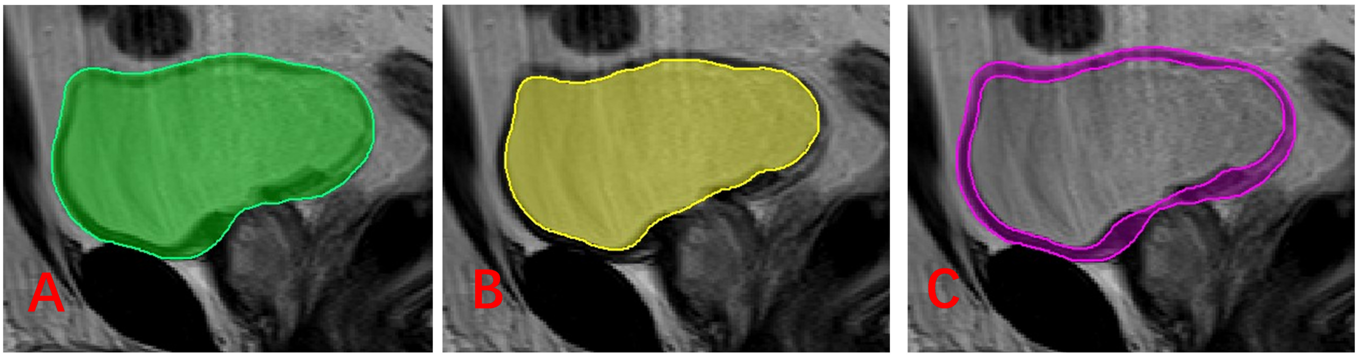

FIGURE 2. The process of delineating the bladder wall in a single MRI slice. (A) The entire bladder (lumen and wall) was contoured. (B) the bladder lumen was contoured. (C) The bladder wall was rendered by subtracting the bladder lumen (B) from the entire bladder (A) mask.

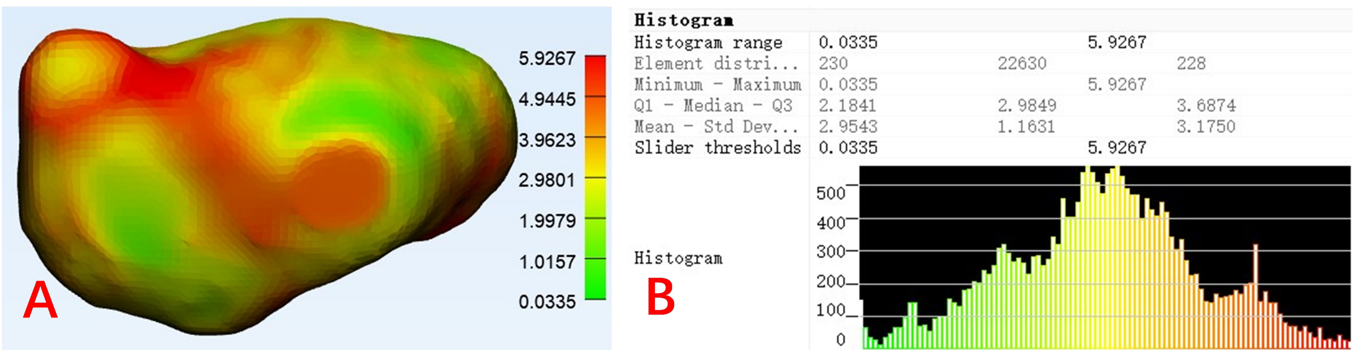

FIGURE 3. Bladder wall thickness analysis in 3-matic. (A) Bladder wall performed using 3-matic software. Gradient shows thinnest wall in green, medium wall thickness in yellow, and thickest wall in red. (B) The wall thickness analysis shows the median bladder wall thickness was 2.9849 mm.

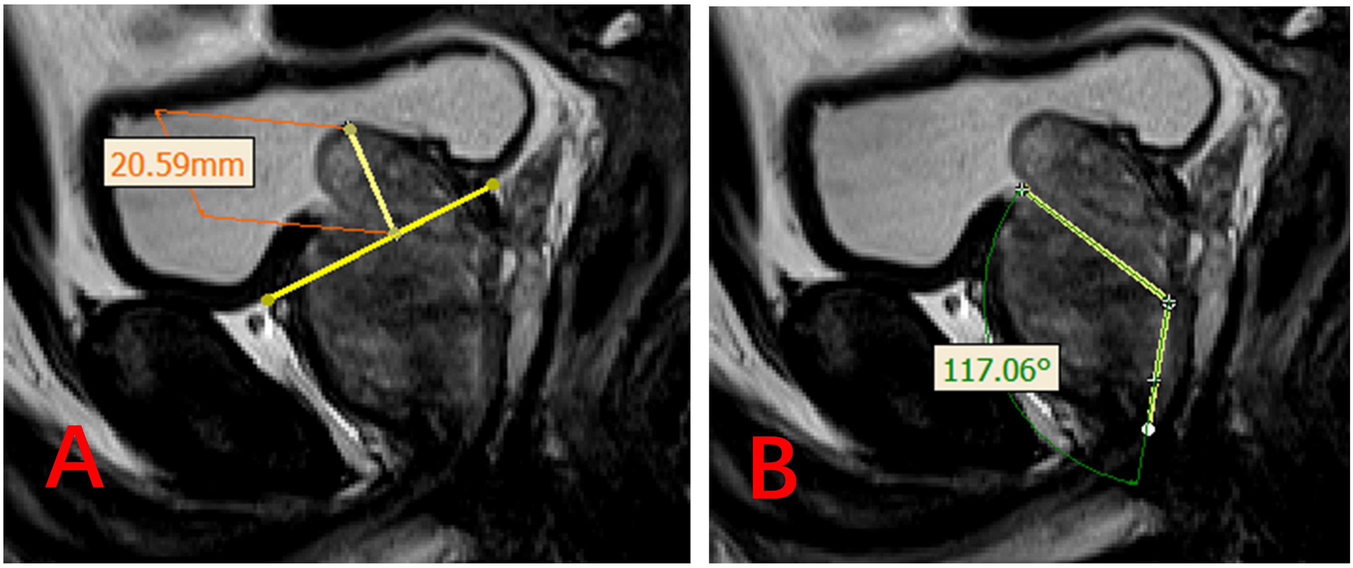

FIGURE 4. Measurement methods for IPP and PUA on Sagittal T2-weighted images. (A) Demonstrates how to measure IPP. (B) Demonstrates how to measure PUA.

3. Results

3.1 Baseline characteristics

The study included 119 patients. Urine volume was similar between the non-NS and NS groups (92.9 ± 31.2 *vs.* 101.3 ± 42.4 mL, $p = 0.22$). Significant differences were observed in age (65.0 ± 10.9 *vs.* 69.1 ± 7.9 years, $p = 0.02$), IPSS (9.2 ± 3.2 *vs.* 22.6 ± 2.9, $p < 0.01$), QoL (1.5 ± 1.2 *vs.* 4.7 ± 0.7, $p < 0.01$), and maximum flow rate (Qmax) (14.8 ± 2.3 *vs.* 6.8 ± 2.0 mL/second $p < 0.01$). The urinary tract anatomy parameters also showed significant differences: PV (45.5 ± 13.8 *vs.* 68.8 ± 22.6 mL, $p < 0.01$), IPP (4.95 ± 3.88 *vs.* 15.0 ± 6.24 mm, $p < 0.01$), PUA (39.3 ± 7.9 *vs.* 53.5 ± 8.1°, $p < 0.01$), BWT (2.69 (2.46–3.12) *vs.* 3.12 (2.54–4.03), $p < 0.01$), and BWV (40.6 (37.8–45.2) mL *vs.* 51.5 (45.0–57.9) mL, $p < 0.01$) (Table 1).

3.2 Risk factors for surgery-required

All parameters used for regression analysis do not have multicollinearity. Univariate binary regression analysis revealed that age (OR = 1.048, $p = 0.024$), PV (OR = 1.079, $p < 0.001$), BWT (OR = 3.544, $p < 0.001$), BWV (OR = 1.199, $p < 0.001$),

TABLE 1. Baseline characteristics.

	Total	non-NS group	NS group	*p*-value
No. of patients	119 (100.0%)	58 (48.7%)	61 (51.3%)	
Age (yr)	67.1 ± 9.6	65.0 ± 10.9	69.1 ± 7.9	0.020
IPSS	16.1 ± 7.4	9.2 ± 3.2	22.6 ± 2.9	<0.001
V-IPSS	9.6 ± 5.2	4.7 ± 2.0	14.3 ± 1.9	<0.001
S-IPSS	6.5 ± 2.8	4.5 ± 2.2	8.3 ± 2.0	<0.001
QoL	3.2 ± 1.9	1.5 ± 1.2	4.7 ± 0.7	<0.001
Qmax (mL/sec)	10.7 ± 4.6	14.8 ± 2.3	6.8 ± 2.0	<0.001
Urine volume (mL)	97.2 ± 37.5	92.9 ± 31.2	101.3 ± 42.4	0.222
TV (mL)	144.6 ± 41.9	134.2 ± 35.5	154.4 ± 45.4	<0.008
PV (mL)	57.5 ± 22.1	45.5 ± 13.8	68.8 ± 22.6	<0.001
IPP (mm)	10.10 ± 7.20	4.95 ± 3.88	15.00 ± 6.24	<0.001
PUA (°)	46.5 ± 10.7	39.3 ± 7.9	53.5 ± 8.1	<0.001
BWT (mm)	2.87 (2.48–3.50)	2.69 (2.46–3.12)	3.12 (2.54–4.03)	<0.001
BWV (mL)	45.4 (40.0–53.1)	40.6 (37.8–45.2)	51.5 (45.0–57.9)	<0.001

IPSS, International Prostate Symptom Score; V-IPSS, Voiding International Prostate Symptom Score; S-IPSS, Storage International Prostate Symptom Score; QoL, Quality of life score; Qmax, maximum flow rate; TV, Bladder wall volume plus Urine volume; PV, Prostate volume; IPP, intravesical prostatic protrusion; PUA, prostatic urethral angle; BWT, Bladder wall thickness; BWV, Bladder wall volume; NS, surgery-required; non-NS, non-surgery-required.

PUA (OR = 1.243, $p < 0.001$), and IPP (OR = 1.554, $p < 0.001$) were significant risk factors for requiring surgery. In multivariate binary regression analysis, BWV (OR = 1.286; 95% CI, 1.105 to 1.497; $p = 0.001$), IPP (OR = 1.585; 95% CI, 1.165 to 2.157; $p = 0.003$), and PUA (OR = 1.158; 95% CI, 1.036 to 1.294; $p = 0.01$) were identified as independent risk factors for the necessity of surgery. However, age (OR = 1.064; 95% CI, 0.958 to 1.181; $p = 0.248$), PV (OR = 0.966; 95% CI, 0.911 to 1.024; $p = 0.239$), and BWT (OR = 2.295; 95% CI, 0.567 to 9.289; $p = 0.244$) were not statistically significant in the multivariate analysis (Table 2).

TABLE 2. Association of urinary tract anatomy parameters for surgery-required.

Variable	OR	95% CI	*p*-value
Age	1.064	0.958 to 1.181	0.248
PV	0.966	0.911 to 1.024	0.239
IPP	1.585	1.165 to 2.157	0.003
PUA	1.158	1.036 to 1.294	0.010
BWT	2.295	0.567 to 9.289	0.244
BWV	1.286	1.105 to 1.497	0.001

PV, Prostate volume; IPP, intravesical prostatic protrusion; PUA, prostatic urethral angle; BWT, Bladder wall thickness; BWV, Bladder wall volume; OR, Odds Ratio; CI, Confidence Internal.

ROC analysis identified the optimal cutoff values for determining the need for surgery: 47 mL for BWV (AUC: 0.837, 95% CI: 0.767–0.907, $p < 0.001$), 8.45 mm for IPP (AUC: 0.922, 95% CI: 0.877–0.967, $p < 0.001$), and 47.15° for PUA (AUC: 0.903, 95% CI: 0.848–0.959, $p < 0.001$). The sensitivity, specificity, and accuracy for these parameters were as follows: BWV (68.9%, 86.2%, 75.6%), IPP (86.9%, 82.8%, 82.4%), and PUA (82.2%, 87.9%, 81.5%) (Fig. 5). The combined AUC for these three parameters was 0.979.

4. Discussion

Our research findings indicate that BWV, IPP and PUA serve as significant anatomical indicators in forecasting the need for surgical intervention. An escalation in BWV, IPP and PUA corresponds to a higher probability of surgery being necessary. The established threshold values stand at 47 mL for BWV, 8.45 mm for IPP, and 47.15° for PUA.

This study minimized the impact of urinary catheter indwelling on prostate morphology and avoided the influence of bladder stones and cystitis on bladder wall thickness and volume, thereby reducing the risk of selection bias. Our study offers valuable insights for surgeons making decisions for individuals with BPH/LUTS, particularly those without accompanying complications like bladder stones, urinary tract infections, or urinary retention. Our investigation not only delved into the impact of BOO on prostate morphology but also explored its effects on bladder structure. The NS group exhibited elevated BWT and BWV, which can be attributed to the compensatory thickening of the bladder muscle in response to heightened peripheral resistances observed in patients with BOO. Morphological study had shown that the thickening is a dual effect of smooth muscle hypertrophy and collagen deposition [13]. While univariate analysis showed a correlation between surgical need and prostate volume as well as bladder wall thickness, this was not supported in multivariate analysis. Therefore, we believe that prostate morphology has a greater impact on BOO than prostate size. When bladder urine volume is uncertain, bladder wall thickness is less diagnostic than bladder wall volume.

The highlight of this study is the precise measurement of BWV and the identification of a cutoff value for surgical decision-making. In prior research, the measurement of bladder weight using ultrasound (UEBW) has been utilized to evaluate variations in the bladder wall. Essentially, in practical terms, UEBW is comparable to BWV (with an approximate specific gravity of 1) [14]. Previous studies have proposed different cutoff values for BWV, such as Han *et al.* [15] at 28 g, Hironobu *et al.* [14] and Kojima *et al.* [16] at 35 g, Andrew *et al.* [17] at 48.5 g, and Zhang *et al.* [18] at 55 g. In our study, the BWV values varied. Several factors may contribute to this. To start with, UEBW is typically determined using a spherical formula. However, as the volume of the bladder increases, its form tends to transition towards a more cubic shape. Our research accurately assessed BWT regardless of variations in bladder morphology. In addition, our study did not take into account the potential impact of medication. Moreover, it is important to consider disparities in ethnicity and medical practices, given that individuals in China may delay seeking medical intervention until BOO reaches an advanced stage. As a result, we suggest broadening the criteria for surgical intervention in cases of prostatic hyperplasia. A systematic review and meta-analysis have determined that BWV demonstrates a high level of specificity in BOO diagnosis [19], a finding further supported by the 86.2% sensitivity identified in our investigation. Furthermore, BWT experiences a decline with increasing bladder volume up to 250 cm^3, beyond which it stabilizes [20]. In contrast, UEBW remains constant regardless of bladder filling. Andrew *et al.* [17] found a correlation between increased prostate volume and increased BWT. A meta-analysis [21] indicated that BWT is the most accurate non-invasive tool for evaluating BOO. In this study, BWT was greater in the NS group than in the non-NS group, but BWT did not predict the need for surgery. This may be due to the lack of strict control over urine volume. Other studies have shown that BWT is significant if urine volume is strictly controlled [22, 23]. Subgroup analyses of patients with different urine volumes could yield a cut-off value to bladder wall thickness, but this requires a larger sample size.

PUA was significantly associated with voiding symptom scores for prostate sizes $\geq$30 cm^3, while IPP was significantly correlated with Qmax [7]. Both the flow rate of urine during urination and the IPSS are factors that impact the likelihood of undergoing surgery. In our research, the mean volume of the prostate was measured at 57.5 mL. The threshold point for the IPP stood at 8.45 mm, aligning with findings from prior studies [24]. However, the cutoff for PUA (47.15°) was higher than the 35° reported in earlier studies [25], which may be due to the greater tolerance of urinary storage symptoms compared to voiding symptoms in the Chinese population.

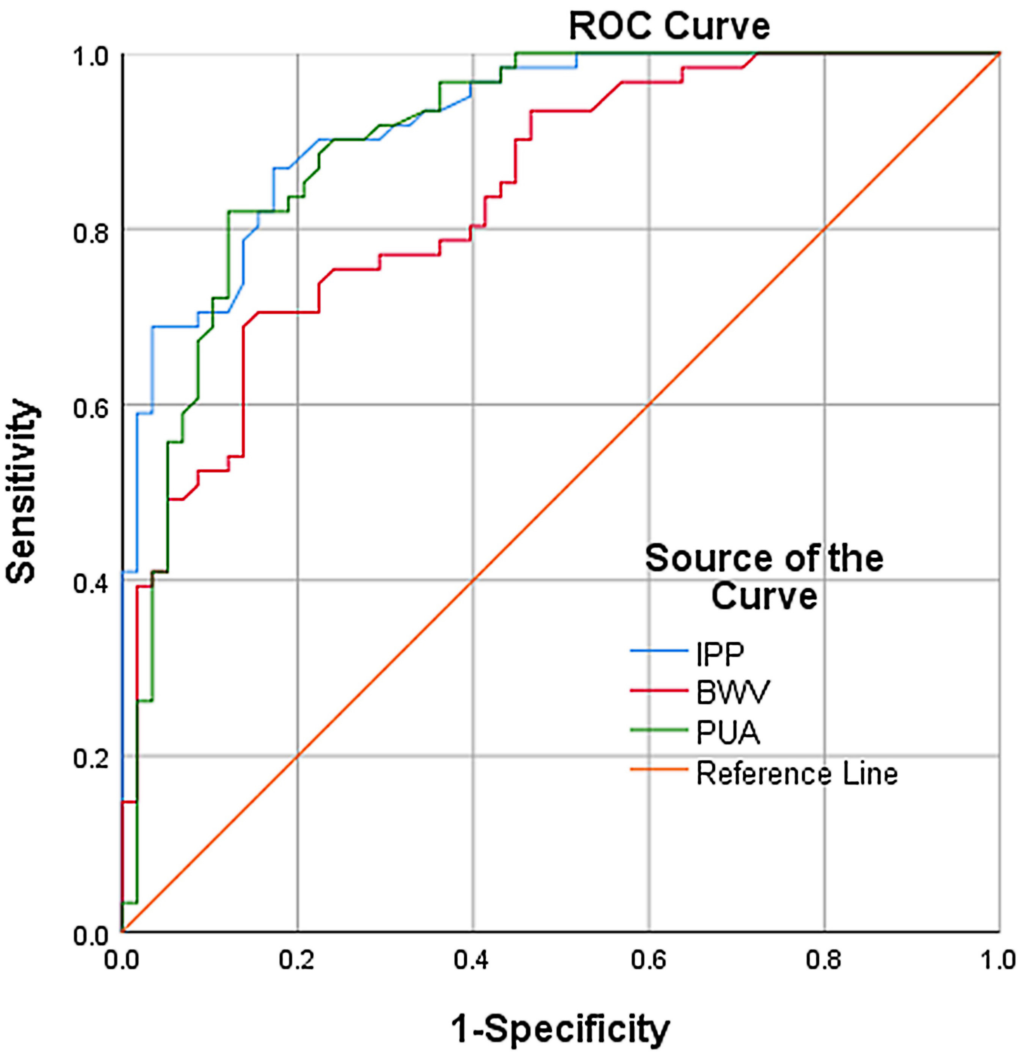

FIGURE 5. The cutoff urinary tract anatomy parameters for surgery-required. IPP, Intravesical prostatic protrusion; PUA, Prostatic urethral angle; BWV, Bladder wall volume; ROC, Receiver operator characteristic curve.

Additionally, not all patients with BOO require surgery; only those with higher PUA and more severe symptoms are likely to be selected for surgical intervention.

In prior research, ultrasound has been utilized to assess bladder wall thickness and volume. In the current study, a novel quantitative approach was adopted to evaluate anatomical characteristics of the lower urinary tract through MRI following 3D reconstruction. This technique involves slicing the bladder into sections, reconstructing them with computer technology, and creating 3D models of the bladder. Measurements taken from these 3D models are more precise than those from previous studies. Research has shown that 3D reconstruction offers more precise measurements compared to conventional two-dimensional techniques [26]. As 3D reconstruction technology develops, researchers can better focus on changes in bladder morphology caused by prostatic hyperplasia. Additionally, further research is needed to explore the pathological changes in the bladder caused by benign prostatic obstruction (BPO), which could serve as decision-making factors for prostate surgery.

Our study has some limitations. Initially, only the IPSS and Qmax scores were used to assess the surgical requirements, leading to exclusion of patients deemed unsuitable for surgery from undergoing urodynamic studies. Furthermore, the analysis focused primarily on a subset of anatomical parameters, neglecting key variables like prostatic urethral length and distal prostatic urethral angle, which were not taken into account. The measurement of these parameters without the presence of an indwelling catheter presents a significant challenge. Lastly, our research involved a cohort of 119 patients, indicating a relatively modest sample size. Future investigations should aim to conduct long-term studies on a larger scale.

5. Conclusions

IPP, PUA and BWV measurements can be used to determine whether patients with LUTS/BPH require surgery. Our findings suggest that these measurements may help in non-invasive making surgical decisions. BWT is not a predictive factor when bladder filling volume is not specifically controlled. Future studies with larger sample sizes and multi-institutional collaboration are needed, and it is also important to consider developing a model that evaluates various variables with appropriate weighting.

ABBREVIATIONS

BPH, benign prostatic hyperplasia; LUTS, lower urinary tract symptoms; IPSS, International Prostate Symptom Score; V-IPSS, Voiding International Prostate Symptom Score; S-IPSS, Storage International Prostate Symptom Score; QoL, Quality of life score; Qmax, maximum flow rate; TV, Bladder wall volume plus Urine volume; PV, Prostate volume; IPP, intravesical prostatic protrusion; PUA, prostatic urethral angle; BWT, Bladder wall thickness; BWV, Bladder wall volume; MRI, Magnetic Resonance Imaging; BOO, Bladder Outlet Obstruction; UDS, Urodynamics; 3D, three-dimensional; NS, surgery-required; non-NS, non-surgery-required; OR, Odds Ratio; 95% CI, 95% Confidence Internal; AUC, area under the curve; PSA, prostate-specific antigen; FSE, Fast Spin Echo; TR, Time of Repetition; TE, Echo Time; FOV, Field of View; DICOM, Digital Imaging and Communications in Medicine; ROC, Receiver operator characteristic curve; UEBW, bladder weight using ultrasound; BPO, benign prostatic obstruction.

AVAILABILITY OF DATA AND MATERIALS

The datasets analyzed during the current study are not publicly available due to the data involved the privacy of the person being studied, but are available from the corresponding author on reasonable request.

AUTHOR CONTRIBUTIONS

HLW—designed the research study. GBH—performed the research; analyzed the data. GBH, YKF, RY and XXL—performed 3D reconstruction and measurement. RY—wrote the manuscript. YW—Perform urodynamic testing. KJX, JYL, YY and ZSH—gather medical data. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Jinhua People's Hospital Ethics Committee (approval no. IRB-2021016-R), and all patients provided written informed consent before participating.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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