

ORIGINAL RESEARCH ARTICLE

Comparison of transrectal ultrasonographic and color Doppler features of benign prostatic hyperplasia and prostate cancer in older men

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Abstract

Introduction: Benign prostatic hyperplasia (BPH) and prostate cancer (PCa) are prevalent in elderly men, yet differentiation using two-dimensional transrectal ultrasound (TRUS) remains challenging.

Objective: To compare grayscale TRUS features, color Doppler flow imaging (CDFI), and hemodynamic parameters between BPH and PCa in older men.

Methods: A total of 228 patients (132 BPH, 96 PCa) underwent TRUS from January 2022 to December 2023 at the Department of Urology at the Affiliated Hospital of Yanbian University. Two-dimensional characteristics, CDFI flow distribution, and hemodynamic parameters—including systolic blood flow velocity (Vs), diastolic blood flow velocity (Vd), and resistive index (RI)—were recorded and compared. Receiver operating characteristic (ROC) curves assessed diagnostic performance.

Results: BPH nodules were typically round/oval and located in the transition zone, whereas PCa lesions were predominantly irregular and situated in the peripheral zone. Echogenicity types differed significantly ($p = 0.013$), with hypoechoic nodules more frequent in PCa (43.8% vs. 3.7%). Pulsed Doppler measurements showed higher Vs, Vd, and RI values in the PCa group than in the BPH group (all $p < 0.01$). ROC analysis yielded areas under the curves of 0.914, 0.835, and 0.792 for Vs, Vd, and RI, respectively. PCa vessels were thicker, more tortuous, and branched, mainly in the peripheral zone, whereas BPH vessels were thinner and straighter, predominantly in the transition zone.

Conclusion: TRUS with CDFI and hemodynamic assessment may provide useful supplementary information for differentiating BPH from PCa. However, histopathological confirmation via prostate biopsy remains the definitive standard.

Keywords: Prostatic hyperplasia; Prostate cancer; Transrectal ultrasound; Color Doppler; Blood flow dynamics

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1. Introduction

According to 2021 data from the National Bureau of Statistics of China, approximately 267 million people in China were aged ≥ 60 years, accounting for 18.9% of the total

population, with approximately 147 million being male.¹ Among the diseases affecting elderly men, prostate disorders are the most common, clinically manifesting as benign prostatic hyperplasia (BPH) and prostate cancer (PCa). Currently, PCa ranks sixth among male malignancies in China,² posing a substantial threat to the health of elderly men. Globally, PCa ranks fourth in cancer incidence and eighth in cancer-related mortality, according to GLOBOCAN 2020 statistics.³ The incidence of PCa remains relatively low before age 55 but increases markedly thereafter, identifying aging as a major risk factor.⁴ With population aging in China, the burden of PCa is increasing annually, and a considerable proportion of patients in China are already at intermediate or advanced stages at initial diagnosis.

Transrectal ultrasound (TRUS) is widely recognized as one of the most effective and cost-efficient screening tools for PCa.⁵ Since its introduction, TRUS has evolved into an indispensable modality for assessing prostate size and anatomy and guiding prostate biopsy.⁶ However, conventional grayscale TRUS has inherent limitations in detecting PCa or distinguishing it from benign conditions, as many cancers may appear isoechoic and thus escape detection.⁷ Emerging TRUS modalities, including elastography, contrast-enhanced ultrasound (CEUS), and advanced Doppler techniques, have demonstrated greater sensitivity and specificity for PCa detection than conventional TRUS alone.⁸

Despite the absence of a direct causal relationship between PCa and BPH, both conditions frequently coexist clinically, rendering their differentiation difficult on two-dimensional sonograms. BPH typically presents as a uniformly enlarged prostate with relatively well-demarcated zonal architecture, whereas PCa often appears as hypoechoic lesions in the peripheral zone with ill-defined margins. Nevertheless, given the considerable overlap in sonographic appearances, grayscale TRUS alone lacks sufficient specificity for reliable differentiation.

Color Doppler flow imaging (CDFI) provides additional information by evaluating vascularity within prostatic lesions.⁹ PCa is characterized by angiogenesis with increased microvascular density, which correlates with higher pathological grade and worse prognosis.^{10,11} This increased perfusion can be detected by color Doppler ultrasound. Quantitative color Doppler and grayscale ultrasound have revealed marked differences in flow velocity, microvascular pulsatility, and resistance between malignant and benign prostatic lesions. These vascular differences, when assessed together with echogenicity, have the potential to discriminate between malignant and benign lesions.¹²

Our research team has extensively investigated urinary tract diseases in elderly men, demonstrating the advantages of TRUS for diagnosing BPH and identifying its associated risk factors in the left-behind elderly population of the Yanbian region.^{13,14} In the present study, we aimed to further examine differences in ultrasound manifestations between BPH and PCa, improve diagnostic accuracy for PCa, avoid unnecessary discomfort associated with needle biopsy, and reduce treatment delays.

2. Methods

2.1. Study population

Between January 2022 and December 2023, we retrospectively included 228 patients with histopathologically confirmed BPH and PCa who underwent TRUS at the Department of Urology, Affiliated Hospital of Yanbian University. The cohort comprised 132 patients with BPH and 96 patients with PCa. The BPH group comprised patients aged 60–74 years, with a mean age of 66.20 ± 4.80 years. They presented with lower urinary tract obstructive symptoms and had a 7–12-year history of BPH (mean: 9.29 ± 3.66 years). The mean prostate dimensions in this group were: transverse diameter 46.13 ± 14.75 mm, anteroposterior diameter 29.38 ± 9.50 mm, and craniocaudal diameter 35.61 ± 11.65 mm. The PCa group included patients aged 65–79 years, with a mean age of 68.51 ± 5.00 years. They had experienced lower urinary tract symptoms for 10–16 years (mean: 13.05 ± 4.61 years) and were all diagnosed with PCa upon this admission. Their mean prostate dimensions were: transverse diameter 48.02 ± 15.91 mm, anteroposterior diameter 30.72 ± 10.88 mm, and craniocaudal diameter 36.87 ± 12.39 mm. There was no statistically significant difference in age between the groups ($p > 0.05$); other general data (e.g., symptom duration, prostate dimensions) also showed no significant differences. All patients were in good general condition with normal diet and sleep. Inclusion criteria were as follows: (i) male patients aged ≥ 60 years residing in Yanbian Korean Autonomous Prefecture, China; (ii) histopathological confirmation of BPH or PCa by needle biopsy or surgical pathology; (iii) availability of complete clinical data; and (iv) completion of TRUS examination with complete ultrasonographic and hemodynamic measurements. Exclusion criteria were as follows: (i) a history of surgery for PCa or BPH; (ii) receipt of chemotherapy or endocrine therapy for PCa; (iii) receipt of pharmacological treatment for BPH; and (iv) serious cardiovascular disease, diabetes mellitus, or cerebrovascular disease. No significant intergroup disparities were observed in age or other general parameters ($p > 0.05$). However, detailed information regarding biopsy technique (e.g., number of cores, targeted vs. systematic approach, use of

magnetic resonance imaging [MRI] guidance), Gleason score distribution, and clinical stage was not consistently available in all cases, which we acknowledge as a limitation of this retrospective study. The study protocol received approval from the hospital's Medical Ethics Committee (approval no. IACUC-202205013-25). Despite the IACUC prefix, which typically denotes animal studies, the same committee granted ethical approval for this human clinical research within the institution's review framework. Written informed consent for the use of clinical data and ultrasound images was obtained from all participants.

2.2. Ultrasound imaging

Transrectal ultrasound was performed using an Aplio i800 color Doppler ultrasound system (Canon Medical Systems, Japan) equipped with a transrectal probe operating at a frequency of 4–13 MHz. Before the examination, the patients were informed in detail about the examination method and process, asked to empty their bladders, and given a cleansing enema when necessary. Patients were placed in the left lateral decubitus position with hips and knees flexed. The probe was coated with coupling agent and covered with a disposable probe sheath for isolation. Lubricant was applied, and the probe was inserted gently. Prostate size and shape, parenchymal echotexture, and the location, shape, margins, and internal echogenicity of nodules or lesions were observed and measured. CDFI was used to assess the distribution of blood flow within the prostate parenchyma and internal lesions. Systolic blood flow velocity (Vs), diastolic blood flow velocity (Vd), and resistive index (RI) of the lesion were measured and recorded by pulsed Doppler. Color Doppler flow signals were classified according to the Adler grading system: grade 0 (no flow signal), grade 1 (punctate or short linear blood-flow signals), grade 2 (moderate flow with visible vessels), and grade 3 (abundant flow with multiple branching vessels). For quantitative analysis, the number of visible linear blood-flow signals within the lesion was counted on a single representative scanning plane.

2.3. Statistical analysis

All statistical analyses were performed using SPSS version 26.0 (IBM Corp., United States of America). Continuous variables are presented as mean $\pm$ standard deviation, and group comparisons were evaluated using the independent-samples *t*-test. Normality was confirmed using the Shapiro–Wilk test (all $p > 0.05$). Categorical variables were compared using the chi-square test. A p -value < 0.05 was considered to indicate statistical significance. Receiver operating characteristic (ROC) curves were generated for Vs, Vd, and RI to evaluate their discriminatory ability. For each parameter, the area under

the curve (AUC) was computed, and the optimal cutoff was identified using the Youden index, at which sensitivity and specificity were subsequently estimated.

3. Results

3.1. Comparison of two-dimensional ultrasonographic features between the benign prostatic hyperplasia and prostate cancer groups

In the BPH group, the prostate was generally enlarged, most often symmetrically, although some patients showed asymmetry between the left and right lobes. The boundary between the enlarged transitioning zone and the surrounding tissue was generally well defined, and the parenchymal echotexture was homogeneous or mildly heterogeneous. Hyperplastic nodules were predominantly isoechoic or hyperechoic, located mainly in the transition zone, and were typically round or oval, with homogeneous internal echogenicity and well-defined margins (Figure 1A). In the PCa group, most prostates were enlarged, although some were normal in volume. Nodular PCa lesions were predominantly hypoechoic and located in the peripheral zone, with ill-defined margins and heterogeneous internal echogenicity (Figure 1B). Diffuse PCa was characterized by variable gland enlargement, an irregular or lobulated contour, indistinct zonal boundaries, and markedly heterogeneous parenchymal echogenicity, without a discrete peripheral-zone hypoechoic nodule (Figure 1C).

3.2. Comparison of two-dimensional ultrasonographic features of internal nodules/lesions between the benign prostatic hyperplasia and prostate cancer groups

Hyperechoic and isoechoic nodules accounted for 41.7% and 36.4% in the BPH group, respectively. However, the proportion of isoechoic and hypoechoic nodules in the PCa group was relatively high, accounting for 37.5% and 43.8%, respectively. The difference was statistically significant ($\chi^2 = 28.269$, $p = 0.013$) (Table 1).

3.3. Comparison of overall blood flow distribution on color Doppler flow imaging between the benign prostatic hyperplasia group and prostate cancer groups

In the BPH group, prostatic blood supply was normal or mildly increased, with slightly enhanced blood flow signals. Linear blood-flow signals were more frequently observed in the transition zone and less frequently in the peripheral zone. The linear flow signals were thinner and straighter, with fewer visible branches (<3 linear blood flow signals) and a normal course (Figure 2A). In

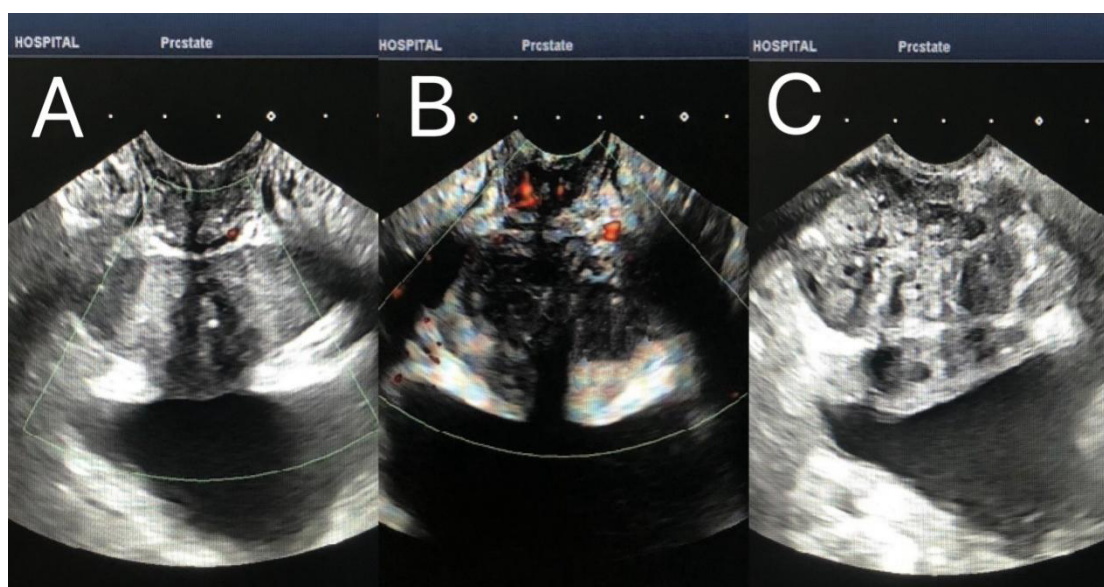


Figure 1. Ultrasonographic images of benign prostatic hyperplasia (BPH), prostate cancer (PCa) hypoechoic nodules, and diffuse PCa. (A) BPH: the prostate appears enlarged with a well-defined, round hyperplastic nodule in the transition zone. (B) Nodular PCa: a hypoechoic lesion with ill-defined margins in the peripheral zone. (C) Diffuse PCa: the gland shows irregular contour, indistinct zonal boundaries, and heterogeneous parenchymal echogenicity.

the PCa group, the prostate showed abundant vascularity and enhanced blood-flow signals. Blood flow was mainly distributed in the peripheral zone and less in the transition zone. The linear blood-flow signals were thicker and more tortuous, with ≥ 3 signals observed on the representative scanning plane and more prominent vessel branching. The vessels extended into the nodules in clustered or branching patterns, and some showed ring-like or semicircular distributions around the lesions (Figure 2B).

Table 1. Distribution of nodule status and echogenicity in the BPH and PCa groups

Group	No nodules	Hyperechoic nodules	Isoechoic nodules	Hypoechoic nodules
BPH group ($n = 132$)	24 (18.2)	55 (41.7)	48 (36.4)	5 (3.7)
PCa group ($n = 96$)	3 (3.1)	15 (15.6)	36 (37.5)	42 (43.8)
χ^2		28.269		
p		0.013		

Notes: Values are presented as n (%). Categorical variables were analyzed with the chisquare test.

Abbreviations: BPH: Benign prostatic hyperplasia; PCa: Prostate cancer.

3.4. Comparison of the number of linear blood-flow signals on color Doppler flow imaging between the benign prostatic hyperplasia and prostate cancer groups

In the BPH group, there were 69 patients with punctate blood-flow signals, 47 patients with <3 linear blood-flow signals, and 16 patients with ≥ 3 linear blood-flow signals. In the PCa group, CDFI showed punctate blood-flow signals in 12 patients, <3 linear blood-flow signals in 29 patients, and ≥ 3 linear blood-flow signals in 55 patients. The difference was statistically significant ($\chi^2 = 9.486$, $p = 0.029$) (Table 2).

3.5. Comparison of hemodynamic parameters between the benign prostatic hyperplasia group and prostate cancer group

The values of Vs, Vd, and RI were all significantly higher in the PCa group than in the BPH group. The differences for Vs and Vd were highly significant (both $p < 0.001$), while the difference for RI was also significant ($p = 0.006$) (Figure 3; Table 3).

3.6. Diagnostic performance of hemodynamic parameters

The ROC curves were generated to evaluate the utility of Vs, Vd, and RI in distinguishing PCa from BPH. The AUC values were 0.914 (95% confidence interval [CI]:

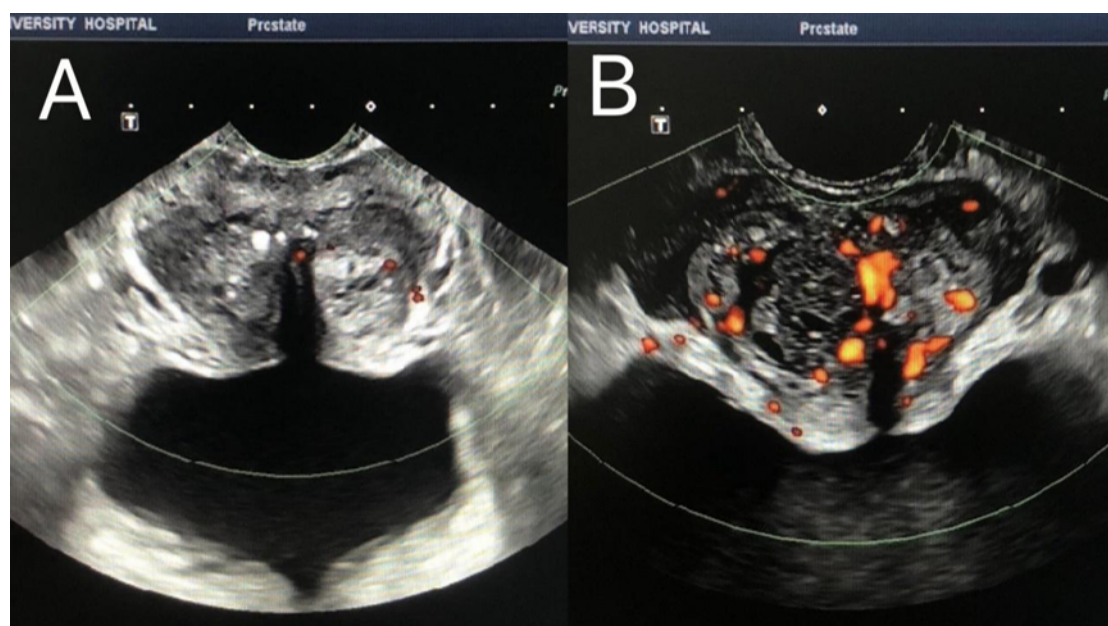


Figure 2. Color Doppler flow imaging of blood flow distribution in the BPH and PCa groups. (A) BPH: thin, straight linear blood-flow signals with limited vessel branching in the transition zone. (B) PCa: numerous thick, tortuous branching blood-flow signals in the peripheral zone.
Abbreviations: BPH: Benign prostatic hyperplasia; PCa: Prostate cancer.

0.875–0.953) for Vs, 0.835 (95% CI: 0.783–0.887) for Vd, and 0.792 (95% CI: 0.732–0.852) for RI. The optimal cutoff values derived from the Youden index were 28.5 cm/s for Vs (sensitivity: 87.5%, specificity: 84.8%), 10.3 cm/s for Vd (sensitivity: 79.2%, specificity: 78.0%), and 0.64 for RI (sensitivity: 75.0%, specificity: 73.5%) (Figure 4).

Table 2. Distribution of color Doppler flow imaging-detected blood-flow signal pattern in the BPH and PCa groups

Group	Punctate blood-flow signals	<3 linear blood-flow signals	≥3 linear blood-flow signals
BPH group (n = 132)	69 (52.3)	47 (35.6)	16 (12.1)
PCa group (n = 96)	12 (12.5)	29 (30.2)	55 (57.3)
χ^2		9.486	
p		0.029	

Notes: Values are presented as n (%). The chi-square test was applied for categorical comparisons.

Abbreviations: BPH: Benign prostatic hyperplasia; PCa: Prostate cancer.

Table 3. Hemodynamic parameters (Vs, Vd, and RI) in the BPH and PCa groups

Group	Vs (cm/s)	Vd (cm/s)	RI
BPH group (n = 132)	18.66 ± 5.90	8.87 ± 2.37	0.55 ± 0.16
PCa group (n = 96)	40.86 ± 10.33	12.78 ± 4.01	0.72 ± 0.15
t	19.011	8.120	4.210
p	<0.001	<0.001	0.006

Notes: Values are presented as mean ± standard deviation. Continuous variables were compared between groups using the independent-samples *t*-test. Normality was verified via the Shapiro–Wilk test before applying the *t*-test.

Abbreviations: BPH: Benign prostatic hyperplasia; PCa: Prostate cancer; RI: Resistive index; Vd: Diastolic blood flow velocity; Vs: Systolic blood flow velocity.

4. Discussion

Prostate cancer is one of the most prevalent malignancies of the male reproductive system worldwide. According to GLOBOCAN 2020 data, PCa ranks fourth in global cancer incidence and eighth in cancer-related mortality.³

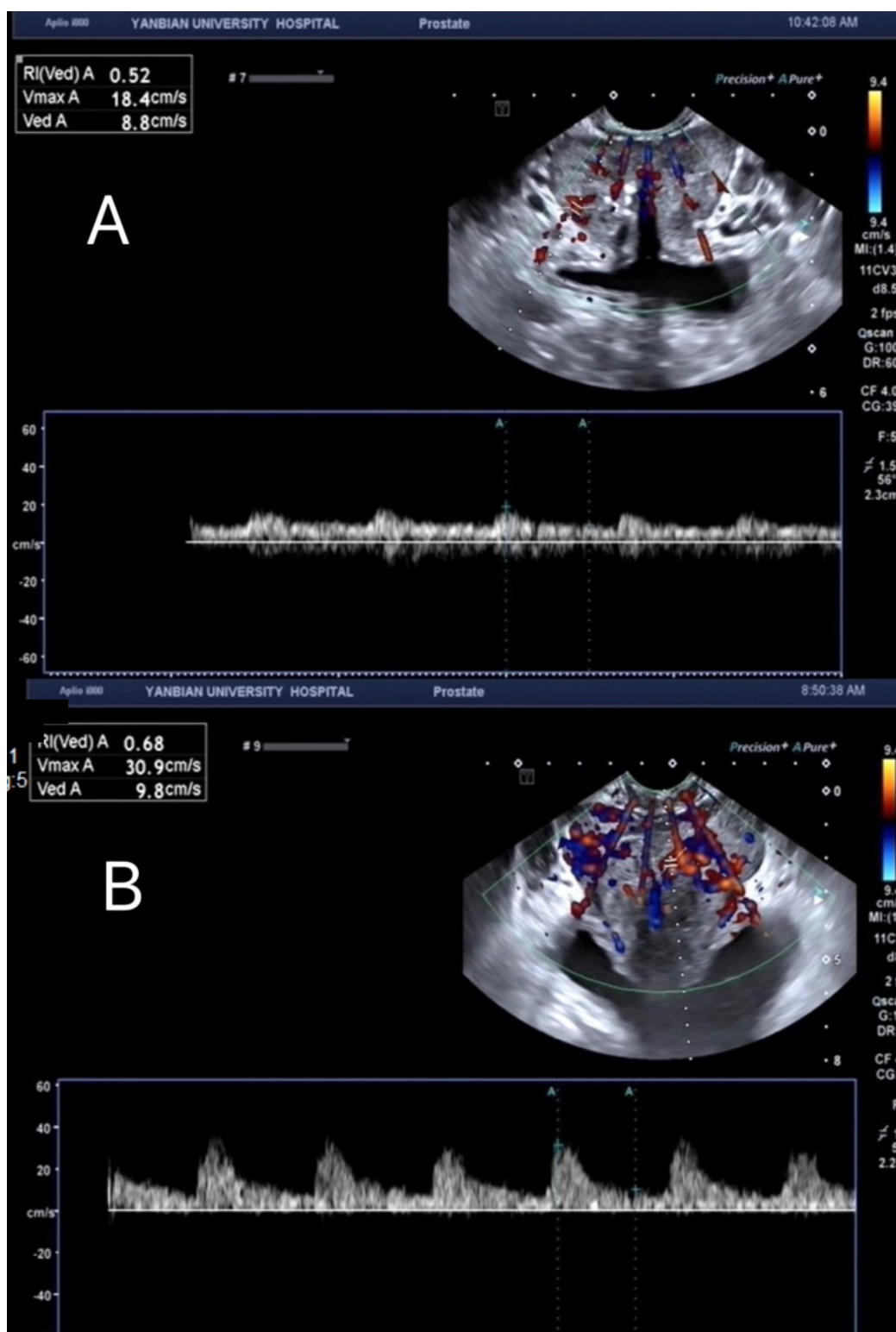


Figure 3. Representative spectral Doppler waveforms in BPH and PCa patients. (A) BPH: spectral Doppler waveform showing lower systolic and diastolic velocities and a lower resistive index. (B) PCa: spectral Doppler waveform demonstrating higher systolic and diastolic velocities and a higher resistive index.

Abbreviations: BPH: Benign prostatic hyperplasia; PCa: Prostate cancer.

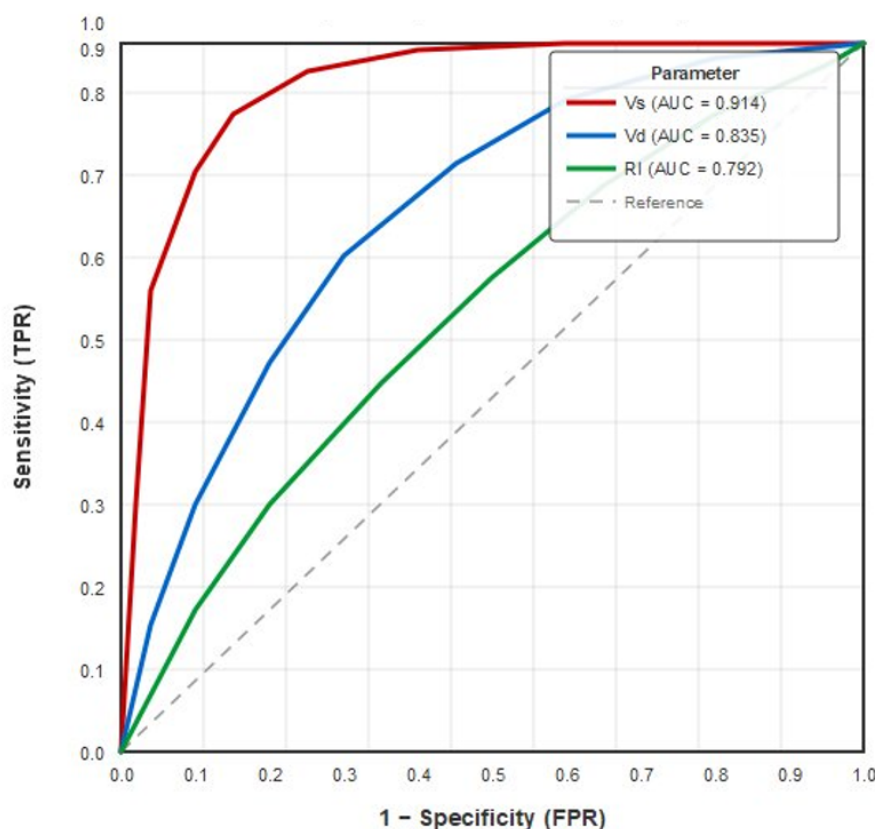


Figure 4. ROC curves of Vs, Vd, and RI for differentiating prostate cancer from benign prostatic hyperplasia. The ROC curves yielded AUCs of 0.914 (95% CI: 0.875–0.953) for Vs, 0.835 (95% CI: 0.783–0.887) for Vd, and 0.792 (95% CI: 0.732–0.852) for RI, with the diagonal dashed line indicating the reference level (AUC = 0.5).

Abbreviations: AUC: Area under the curve; CI: Confidence interval; FPR: False-positive rate; RI: Resistive index; ROC: Receiver operating characteristic; TPR: True-positive rate; Vd: Diastolic blood flow velocity; Vs: Systolic blood flow velocity.

Its incidence remains low before age 55 but rises sharply thereafter. Given the rapidly aging Chinese population, the prevalence of PCa continues to rise, underscoring the critical importance of early detection.

Transrectal ultrasound is widely regarded as one of the most effective methods for early PCa screening. Although there is no direct causal link between PCa and BPH, both conditions frequently coexist, complicating differentiation on two-dimensional sonograms. Characteristically, BPH presents with a uniformly enlarged prostate with well-demarcated transitional and peripheral zones and homogeneous or slightly heterogeneous echotexture. Hyperplastic nodules are typically isoechoic or hyperechoic, located predominantly in the transition zone, with clear, regular margins and uniform internal echogenicity. In contrast, nodular PCa typically appears as hypoechoic lesions in the peripheral zone with indistinct borders and heterogeneous echotexture. However, variations in nodule composition and location mean that BPH may occasionally

appear hypoechoic, while PCa may appear hyperechoic or mixed. Thus, two-dimensional ultrasonography alone lacks sufficient specificity for reliable differentiation.

Our findings are consistent with previous reports indicating that grayscale TRUS alone has limited diagnostic value in differentiating BPH from PCa.¹⁵ In our cohort, although hypoechoic nodules were significantly more frequent in the PCa group (43.8% vs. 3.7%), a considerable proportion of PCa cases (15.6%) appeared hyperechoic and 37.5% appeared isoechoic. This overlap underscores the necessity for supplementary imaging modalities. TRUS-guided prostate biopsy, while effective, is associated with a range of complications that require careful management.¹⁶

Diffuse PCa is characterized by an irregular, lobulated, crablike appearance of the entire gland, without distinct nodules or hypoechoic areas, indistinct zonal boundaries, highly heterogeneous parenchymal echogenicity, and

focal capsular irregularity or discontinuity. Because these findings are operator-dependent, diffuse PCa may still be difficult to recognize. The diffuse variant is particularly challenging because it can mimic advanced BPH with marked heterogeneity.¹⁷

Color Doppler flow imaging adds a functional dimension to morphological assessment by visualizing tumor vascularity. Quantitative color Doppler and grayscale ultrasound have demonstrated marked differences in flow velocity, microvascular pulsatility, and resistance between malignant and benign prostatic lesions. In our cohort, we observed significantly higher Vs, Vd, and RI values in the PCa group compared with the BPH group, which is consistent with increased downstream resistance resulting from tumor angiogenesis with abnormal, tortuous vessels and peripheral zone capsular compression. When combined with echogenicity, these vascular differences have the potential to improve lesion characterization.

Our data indicate that BPH and PCa exhibit specific differences in CDFI blood flow distribution and hemodynamic parameters. The PCa group had a significantly greater proportion of patients with ≥ 3 linear blood-flow signals ($p < 0.05$), as well as higher Vs, Vd, and RI values, than the BPH group. These results align with those of Ashi *et al.*,⁹ who reported that median microvascular flow velocity was 1.25 cm/s in malignant lesions versus 0.36 cm/s in benign lesions, with significant intergroup differences in pulsatility and RIs. It is important to emphasize that while TRUS and other imaging modalities provide valuable information for risk stratification and lesion targeting, the definitive diagnosis of PCa still relies on histopathological confirmation via prostate biopsy. Imaging findings should be interpreted as adjunctive evidence rather than diagnostic proof.

The underlying mechanisms are as follows: During chronic BPH, increased arterial oxygen supply is required to support expansile growth of the transition zone. Accordingly, CDFI shows thin, straight linear blood-flow signals with limited vessel branching in the transition zone of BPH. However, as BPH advances, compression by the peripheral zone and capsule leads to vascular compromise, fibrosis, and reduced vascular wall elasticity, resulting in increased resistance within a certain range.^{18,19}

Conversely, rapid growth and peripheral expansion in PCa require an adequate nutritional supply. Neovascularization plays a crucial role in this process. Tumor growth and progression within the prostate are typically accompanied by angiogenesis, which may substantially increase microvessel density. Increased microvascular density in PCa is associated with higher pathological grade and worse prognosis. Even at a tumor

diameter of 1–2 mm, numerous new vessels form within and around the tumor under the influence of various growth factors. Arteriovenous fistulas and high-velocity turbulent flow have been observed in tumors.^{20,21} On CDFI, this manifests as multiple tortuous, branching vessels within the lesion, arranged in clustered or branching patterns, or annular/semi-annular flow signals surrounding the lesion.²²

Multiparametric TRUS—integrating grayscale, color Doppler, elastography, and CEUS—has emerged as a promising approach for PCa detection. Chen *et al.*¹² developed multiparametric TRUS scoring systems that improved the identification of peripheral-zone PCa and clinically significant PCa, with performance comparable to PI-RADS version 2. The PCa score, based on margin characteristics, Adler grade, enhancement pattern, and strain ratio, achieved an AUC of 0.879 in the validation cohort. These findings underscore the potential of multimodal ultrasound integration for enhancing diagnostic accuracy.

Contrast-enhanced ultrasound further improves PCa detection by visualizing microvascular perfusion.¹⁷ Machine learning models combining B-mode TRUS and CEUS radiomic features have demonstrated improved detection of peripheral-zone PCa.²³ The pooled sensitivity and specificity of CEUS for detecting PCa were 0.73 and 0.78, respectively. When CEUS is combined with biparametric MRI, diagnostic performance can be further enhanced.²⁴ The quantitative perfusion analysis of CEUS also provides valuable information for distinguishing benign from malignant prostate diseases.²⁵

Shear-wave elastography (SWE) provides additional tissue characterization by quantifying tissue stiffness. Studies have evaluated transrectal SWE for differentiating benign from malignant tissue in patients with suspected PCa. The mean strain index of malignant lesions was significantly higher than that of benign lesions.²⁶ Both strain and SWE have been shown to aid in PCa detection.²⁷ Two-dimensional SWE has also demonstrated utility in predicting PCa in preliminary studies.²⁸

Micro-ultrasound is a newer modality that can identify and target suspicious areas with higher resolution than conventional ultrasound. A systematic review indicated that micro-ultrasound may further increase the diagnostic yield of prostate biopsy.²⁹ In MRI-guided confirmatory biopsy, micro-ultrasound demonstrated a sensitivity of 94.1% and a negative predictive value of 88.9% for detecting clinically significant PCa.³⁰ Micro-ultrasound and multiparametric magnetic resonance imaging (mpMRI) are valuable imaging tools for patient management, with ongoing advances expanding their clinical horizons.³¹

Three-dimensional power Doppler ultrasound with virtual organ computer-aided analysis (VOCAL) has shown favorable performance in PCa detection. Zeng *et al.*²² demonstrated that 3D-PD-VOCAL discriminated malignant from benign foci, with optimal cutoff values of 27.4% for vascularization index, 38.2 for flow index, and 8.6 for vascularization-flow index. All parameters had higher AUC values for lesions in the peripheral zone than in the transition zone. The AUC, sensitivity, specificity, and accuracy for detecting clinically significant PCa were 95%, 86%, 87%, and 87% for vascularization index, and 95%, 94%, 76%, and 85% for vascularization-flow index, respectively.

The role of Doppler RIs in prostatic evaluation has been explored in various clinical contexts. Studies have correlated prostatic Doppler RI with the severity of lower urinary tract symptoms, prostate volume, and concomitant diabetes mellitus.³² The effect of systemic hypertension on prostatic artery RI in patients with benign prostatic enlargement has also been investigated, revealing that hypertensive patients had significantly higher RIs than normotensive patients.³³ These findings suggest that hemodynamic parameters may be influenced by multiple factors beyond the presence of malignancy.

The combination of transrectal CDFI with risk-stratification nomograms has been shown to reduce unnecessary prostate biopsies in patients with suspected PCa.³⁴ Additionally, the integration of rectal CDFI features with clinical indicators has demonstrated value in constructing nomograms for differentiating benign and malignant prostatic lesions.³⁵

Current clinical guidelines advocate for mpMRI before prostate biopsy to enhance the detection of clinically meaningful PCa. Pepe *et al.*³⁶ demonstrated that mpMRI-targeted biopsy, combined with systematic biopsy, significantly increases the diagnostic yield for clinically meaningful PCa, particularly in patients with suspicious MRI lesions. This approach reduces the risk of underdiagnosing clinically relevant tumors while minimizing unnecessary sampling.

The integration of mpMRI with TRUS has further advanced TRUS's diagnostic capabilities. Fusion imaging-guided TRUS examination can help avoid unnecessary mpMRI-guided targeted biopsies.³⁷ Prospective single-center studies have compared fusion-guided mpMRI-TRUS with systematic biopsy for detecting clinically significant PCa, showing promising results.³⁸ In addition, machine learning models integrating transrectal multimodal ultrasound data with prostate-specific antigen (PSA)-related indicators have demonstrated utility for identifying clinically significant PCa.³⁹ In patients with

primary negative conventional biopsy and persistently elevated PSA, ultrasound/MRI-targeted biopsy has been compared with standard TRUS-guided biopsy in prospective randomized clinical trials.⁴⁰

The higher Vs, Vd, and RI values observed in PCa can be attributed to the fact that PCa typically develops in the peripheral zone, where it is subject to greater capsular compression than BPH. The elevated RI in PCa reflects increased downstream resistance resulting from tumor angiogenesis with abnormal, tortuous vessels and arteriovenous shunting. The significantly higher Vs indicates enhanced systolic flow driven by the high metabolic demands of rapidly proliferating tumor cells.

In addition to imaging-based approaches, circulating and liquid biopsy biomarkers are increasingly being investigated as non-invasive tools for PCa diagnosis, prognosis, and treatment monitoring. Matuszczak *et al.*⁴¹ reviewed the clinical utility of liquid biopsy biomarkers in PCa and highlighted their potential to complement conventional diagnostic pathways, including TRUS-guided biopsy and mpMRI. Biomarkers such as exosomal RNA, cell-free DNA, and circulating tumor cells may help reduce diagnostic uncertainty and improve risk stratification, particularly in patients with indeterminate imaging findings or elevated PSA levels with negative biopsy. Future diagnostic strategies may benefit from integrating TRUS-based vascular parameters with PSA-derived indices, mpMRI findings, and molecular biomarkers to achieve more accurate and individualized PCa detection.

5. Conclusion

In conclusion, TRUS with CDFI and hemodynamic assessment provides useful adjunctive information for differentiating BPH from PCa, particularly in resource-limited settings where advanced imaging is not readily available. Nevertheless, mpMRI provides enhanced diagnostic performance for detecting and characterizing PCa. Current guidelines therefore recommend its use prior to biopsy to optimize the detection of clinically meaningful disease. TRUS may serve as a complementary first-line screening tool, but mpMRI should be preferred for definitive pre-biopsy evaluation when accessible. The significantly higher Vs, Vd, and RI values in PCa compared with BPH, along with the characteristic pattern of increased, tortuous vascularity in the peripheral zone, remain valuable objective criteria to guide clinical decision-making, especially when used in combination with mpMRI findings.

Future studies with larger sample sizes and correlation with radical prostatectomy specimens are needed to further validate these findings and establish

standardized cutoff values for hemodynamic parameters. Integration of multiparametric TRUS approaches—including elastography and CEUS—may further improve diagnostic accuracy and reduce unnecessary biopsies.⁴² The combination of population aging and the escalating burden of PCa in China underscores the urgent need for cost-effective, non-invasive screening tools.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Guangming Jin

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Formal analysis: Guangming Jin, Ming Jin

Investigation: Guangming Jin, Ming Jin

Methodology: Guangming Jin, Ming Jin

Project administration: Baoding Shan

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Software: Guangming Jin

Supervision: Baoding Shan

Validation: Ming Jin

Writing—original draft: Guangming Jin

Writing—review & editing: Ming Jin, Baoding Shan

Ethics approval and consent to participate

This study was reviewed and approved by the Medical Ethics Committee of Yanbian University Hospital (approval number: IACUC-202205013-25). Written informed consent to participate was obtained from all patients prior to the study.

Consent for publication

Written informed consent for publication of clinical data and ultrasound images was obtained from all participants. Identifying information has been anonymized.

Availability of data

The datasets generated and/or analyzed during the current study are not publicly available due to confidentiality and privacy concerns, as well as institutional data privacy policies, but are available from the corresponding author on reasonable request.

Further disclosure

During the preparation of this work, the authors used no artificial intelligence (AI) tools for data analysis, writing, or language polishing. The authors take full responsibility for the content and originality of the manuscript.

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