



FOCUS-DWI improves prostate cancer detection through deep learning reconstruction with IQMR technology

Yi Zhao¹ · Xiao-Liang Xie¹ · Xi Zhu² · Wen-Nuo Huang² · Chang-Wu Zhou¹ · Kai-Xuan Ren¹ · Run-Ya Zhai¹ · Wei Wang¹ · Jian-wei Wang³

Received: 25 May 2025 / Revised: 18 June 2025 / Accepted: 25 June 2025
© The Author(s) 2025

Abstract

Purpose This study explored the effects of using Intelligent Quick Magnetic Resonance (IQMR) image post-processing on image quality in Field of View Optimized and Constrained Single-Shot Diffusion-Weighted Imaging (FOCUS-DWI) sequences for prostate cancer detection, and assessed its efficacy in distinguishing malignant from benign lesions.

Methods The clinical data and MRI images from 62 patients with prostate masses (31 benign and 31 malignant) were retrospectively analyzed. Axial T2-weighted imaging with fat saturation (T2WI-FS) and FOCUS-DWI sequences were acquired, and the FOCUS-DWI images were processed using the IQMR post-processing system to generate IQMR-FOCUS-DWI images. Two independent radiologists undertook subjective scoring, grading using the Prostate Imaging Reporting and Data System (PI-RADS), diagnosis of benign and malignant lesions, and diagnostic confidence scoring for images from the FOCUS-DWI and IQMR-FOCUS-DWI sequences. Additionally, quantitative analyses, specifically, the peak signal-to-noise ratio (PSNR) and structural similarity index (SSIM), were conducted using T2WI-FS as the reference standard. The apparent diffusion coefficients (ADCs) of malignant and benign lesions were compared between the two imaging sequences. Spearman correlation coefficients were calculated to evaluate the associations between diagnostic confidence scores and diagnostic accuracy rates of the two sequence groups, as well as between the ADC values of malignant lesions and Gleason grading in the two sequence groups. Receiver operating characteristic (ROC) curves were utilized to assess the efficacy of ADC in distinguishing lesions.

Results The qualitative analysis revealed that IQMR-FOCUS-DWI images showed significantly better noise suppression, reduced geometric distortion, and enhanced overall quality relative to the FOCUS-DWI images ($P < 0.001$). There was no significant difference in the PI-RADS scores between IQMR-FOCUS-DWI and FOCUS-DWI images ($P = 0.0875$), while the diagnostic confidence scores of IQMR-FOCUS-DWI sequences were markedly higher than those of FOCUS-DWI sequences ($P = 0.0002$). The diagnostic results of the FOCUS-DWI sequences for benign and malignant prostate lesions were consistent with those of the pathological results ($P < 0.05$), as were those of the IQMR-FOCUS-DWI sequences ($P < 0.05$). The quantitative analysis indicated that the PSNR, SSIM, and ADC values were markedly greater in IQMR-FOCUS-DWI images relative to FOCUS-DWI images ($P < 0.01$). In both imaging sequences, benign lesions exhibited ADC values markedly greater than those of malignant lesions ($P < 0.001$). The diagnostic confidence scores of both groups of sequences were significantly positively correlated with the diagnostic accuracy rate. In malignant lesions, the ADC values of the FOCUS-DWI sequences showed moderate negative correlations with the Gleason grading, while the ADC values of the IQMR-FOCUS-DWI sequences were strongly negatively associated with the Gleason grading. ROC curves indicated the superior diagnostic performance of IQMR-FOCUS-DWI (AUC = 0.941) compared to FOCUS-DWI (AUC = 0.832) for differentiating prostate lesions ($P = 0.0487$).

Conclusion IQMR-FOCUS-DWI significantly enhances image quality and improves diagnostic accuracy for benign and malignant prostate lesions compared to conventional FOCUS-DWI.

Keywords Prostate cancer · Prostate lesions · Diffusion-weighted imaging · Intelligent quick magnetic resonance · Magnetic resonance imaging

Yi Zhao, Xiao-Liang Xie, and Xi Zhu are contributed equally to this work.

Extended author information available on the last page of the article

Introduction

Prostate cancer is a common malignancy of the male urinary and reproductive systems. It is characterized by abnormal glandular proliferation, disruption of acinar structures, and irregular nuclear morphology [1–3]. Magnetic resonance diffusion-weighted imaging (DWI) is a noninvasive MRI modality that enables the quantitative assessment of water molecule diffusion in tissues [4, 5]. Prior studies have demonstrated that DWI of the prostate is effective in visualizing changes in the tissue microstructure and can detect reduced water diffusion in lesions [6–8]. The degree of restricted diffusion correlates with histological grading, providing valuable clinical insights for diagnosis and treatment evaluation. The field of view optimized and constrained undistorted single-shot diffusion-weighted imaging (FOCUS-DWI) sequence employs two-dimensional radiofrequency (2D-RF) excitation to selectively excite imaging slices. Its incorporation of a 180-degree refocusing pulse narrows the bandwidth and suppresses unwanted signals, enabling small-field-of-view diffusion imaging [9, 10]. Feng et al. [11] reported that, compared to traditional Single-Shot Echo-Planar Imaging DWI (SS-EPI-DWI), FOCUS-DWI reduces fold-over artifacts and achieves higher spatial resolution, making it increasingly relevant in prostate MRI. The diffusion-sensitive factor, or b-value, is a crucial imaging parameter in DWI. Higher b-values increase the sensitivity to detect diffusion restriction in malignant tissue but also lead to a reduction in the signal-to-noise ratio (SNR) and increased image distortion. While high b-value FOCUS-DWI sequences improve the detection of prostate cancer, their diagnostic utility is often compromised by degraded image quality.

Intelligent Quick Magnetic Resonance (IQMR) is an advanced MRI post-processing system based on deep learning algorithms. This system consists of multiple modules, including a deep learning module, an iterative reconstruction module, and a K-space correction module, trained on a dataset of 500,000 MRI images. The deep learning module extracts high-quality semantic features and optimizes reconstruction parameters using machine learning techniques [12]. The K-space correction module performs an inverse Fourier transform to analyze the statistical distributions of signal and noise, enabling subsequent removal of noise and artifacts. The iterative reconstruction module decomposes the MRI data into 3D patches, extracting key features, predicting noise patterns, and applying multi-iteration algorithms to generate high-quality images [13–16]. IQMR operates as an intermediary between MRI scanners and the Picture Archiving and Communication System (PACS),

automatically receiving raw images, reconstructing them, and generating high-quality outputs for storage.

Kanemaru et al. [17] successfully applied IQMR to enhance cranial MRI image quality, particularly for morphometric analysis of T1-weighted structural images. Similarly, Yao et al. [18] demonstrated that IQMR improves image quality while reducing scanning time for lumbar spine MRI. However, the application of IQMR in functional MRI sequences, particularly for high b-value DWI of the prostate, remains largely unexplored. Here, the feasibility of applying IQMR to process high b-value FOCUS-DWI images of the prostate was evaluated. By comparing the image quality, PI-RADS scores, physician diagnostic confidence scores, and ADC-based diagnostic performance of IQMR-enhanced FOCUS-DWI with those of conventional FOCUS-DWI, these analyses sought to assess the clinical value of using IQMR in high b-value DWI for prostate imaging to diagnose and differentiate between malignant and benign lesions, thereby reducing the biopsy rate for prostate cancer.

Materials and methods

Study subjects

Men with abnormal serum levels of total PSA (TPSA, >4 ng/mL) who underwent prostate MRI, including DWI sequences, and had histopathological confirmation through surgical or biopsy procedures between August 2024 and December 2024 were enrolled in this retrospective investigation. These exclusion criteria were: (1) Patients who had undergone surgery, radiotherapy, or chemotherapy prior to MRI examination; (2) Patients for whom puncture biopsy coordinates could not be accurately matched to suspicious lesions on MRI images; (3) Patients with no clearly visible focal lesions on MRI, making it impossible to define a region of interest (ROI) for ADC value measurement; (4) Patients in whom the cross-sectional area of the largest lesion was of insufficient size (<20 mm²). In cases with multiple lesions, the lesion showing the greatest PI-RADS score was included if all lesions were within the same zone (transitional or peripheral). If lesions were present in both zones, the lesion exhibiting both the greatest PI-RADS score and the largest cross-sectional area in each zone was selected for analysis. Ultimately, 62 participants were enrolled, comprising 31 cases of benign lesions and 31 of malignant lesions. The Ethics Committee of the Hospital approved this study (Approval No. 2025-YKL02-05).

Imaging protocol

All MRI examinations were conducted with an Architect 3.0T MRI scanner (General Electric Healthcare, USA). Scanning was performed in the supine position with feet-first entry into the scanner. A 16-channel phased-array body coil was utilized for prostate imaging in the oblique axial plane. The scanning protocol included T2WI-FS and FOCUS-DWI sequences. The region from the upper edge of the pubic symphysis to the perineum was scanned, encompassing the entire prostate and seminal vesicles. The T2WI-FS sequence parameters included: Slice thickness=3 mm; spacing=0 mm; frequency field of view (FOV)=20 cm; no phase wrap=1.50; matrix=288×288; TR/TE=3210/105 ms; NEX: 2.5; Fat saturation method=Chemical saturation (Fat-Sat). The FOCUS-DWI sequence parameters included: Slice thickness=3 mm; spacing=1 mm; frequency FOV=26 cm; phase FOV=0.6; frequency=120; phase=60; TR/TE=5215/85 ms; NEX=16; b-values=0 and 2000 s/mm². The DWI images acquired with the FOCUS-DWI sequence were subsequently processed using the Intelligent Quick Magnetic Resonance (IQMR) system, which automatically generated IQMR-FOCUS-DWI images.

Image evaluation

Two independent radiologists, each with over 10 years of experience, evaluated the FOCUS-DWI and IQMR-FOCUS-DWI sequence images at a b-value of 2000 s/mm². Four parameters were qualitatively scored, namely, the noise level, geometric distortion, artifacts, and overall image quality. The FOCUS-DWI and IQMR-FOCUS-DWI sequences with b-values of 2000 s/mm² and their ADC maps of prostate lesions were scored by PI-RADS and diagnosed as benign or malignant. Lastly, the diagnostic confidence of each case was scored. The scoring criteria were adapted from previous studies [19–21], with image noise levels scored as 1 point (severe noise, with large coarse particles in images), 2 points (high levels of noise, coarse image particles), 3 points (moderate levels of noise, coarse image particles), 4 points (limited image noise, with smaller and more delicate image particles), and 5 points (no obvious noise, with small delicate image particles). Likewise, the scoring system for geometric deformation was 1 point (serious image distortion with unclear, unrecognizable anatomical structures, making it unsuitable for diagnosis), 2 points (serious image distortion, unclear anatomical structures of which some are recognizable, greatly impacting the diagnosis), 3 points (image distortion, with moderately clear anatomical structures of which all are recognizable, impacting the diagnosis), 4 points (slight image distortion,

with better anatomical clarity and all structures recognizable, resulting in no appreciable impact on diagnosis), and 5 points (no image distortion, with clear, fully recognizable anatomical structures and no impact on diagnosis). Image artifacts were assigned possible scores of 1 point (severe artifacts, unable to use for diagnosis), 2 points (moderate artifacts, some impact on diagnostic utility), 3 points (moderate artifacts, no impact on diagnostic utility), 4 points (mild artifacts, no impact on diagnostic utility), or 5 points (no artifacts). The above indices were ultimately used to assign an overall image quality score of 1 point (non-visualizable), 2 points (poor), 3 points (average), 4 points (good), or 5 points (excellent). The PI-RADS scoring criteria were 1 point (extremely unlikely to have clinically significant malignant lesions), 2 points (low likelihood of clinically significant malignant lesions), 3 points (uncertain likelihood of clinically significant malignant lesions, considered moderate risk as lesions could be benign or malignant), 4 points (likelihood of clinically significant malignant lesions being present, indicating a higher risk of prostate malignancy, and 5 points (very high likelihood of clinically significant malignant lesions, suggesting an extremely high possibility of prostate malignancy). The diagnostic confidence scoring criteria represented 1 point for extremely low confidence, 2 points for low confidence, 3 points for moderate confidence, 4 points for high confidence, and 5 points for extremely high confidence.

Quantitative assessment: DWI images (b=2000 s/mm²) of the prostate from FOCUS-DWI and IQMR-FOCUS-DWI sequences, as well as T2WI-FS images, were analyzed using MATLAB (version R2023b, MathWorks, USA). Image quality and geometric distortion were quantitatively assessed using the PSNR and SSIM [22, 23].

ADC value measurement: Two radiologists independently selected the most prominent lesion level based on T2WI-FS images. ADC values were measured by manual delineation of ROIs along the lesion contours on ADC maps from FOCUS-DWI (b=0, 2000 s/mm²) and IQMR-FOCUS-DWI sequences (b=0, 2000 s/mm²) using an AW4.7 post-processing workstation (General Electric Healthcare). Care was taken to exclude the urethra, ejaculatory ducts, and calcifications from the ROI. The final ADC value was determined by averaging the measurements from both radiologists.

Statistical analysis

All data were analyzed using SPSS 25.0 and MedCalc (version 22.0). Kolmogorov-Smirnov tests were employed to assess the distributions of the quantitative data. Normally distributed data are shown as means±standard deviation, while data with non-normal distributions are expressed as

medians (interquartile range). Kappa analysis was employed to evaluate the consistency between the subjective ratings of the two radiologists, PI-RADS scores, diagnostic results of benign and malignant prostate lesions, and diagnostic confidence scores, as well as the consistency between benign and malignant prostate lesion assessments and pathological findings. Inter-rater agreement for ADC value measurements between the two radiologists was evaluated using the intra-class correlation coefficient (ICC). Kappa and ICC values ≤ 0.4 indicated poor agreement, while 0.4–0.6 represented moderate, 0.6–0.8 good, and >0.8 excellent agreement. Mann-Whitney tests were utilized for comparisons of qualitative scores, PI-RADS scores, and physician diagnostic confidence scores, as well as ADC values between malignant and benign lesions. Paired t-tests were utilized for comparisons of PSNR and SSIM values between the IQMR-FOCUS-DWI and FOCUS-DWI sequences, with Wilcoxon rank-sum tests used for comparing the ADC values. Spearman correlation analysis was used to evaluate the association between the diagnostic confidence scores and the diagnostic accuracy rates of the two sets of sequences, and the correlation between the malignant lesion ADC values and Gleason grades of the two sets of sequences. $|r| > 0.7$ represented a strong correlation, $0.5 < |r| \leq 0.7$ a moderate correlation, and $|r| \leq 0.5$ a weak association. The effectiveness of ADC in distinguishing lesions according to malignancy was examined with receiver operating characteristic (ROC) curves, with differences in the area under the curve (AUC) compared with the DeLong test. A p-value of <0.05 was deemed significant.

Results

Participant characteristics

Eighty patients were initially recruited. All had undergone prostate MRI (including DWI sequences), prostatectomy, or prostate biopsy with pathological confirmation. Of these, 4 patients had received surgical treatment before MRI examination, 1 patient was associated with difficulty in matching the biopsy coordinates with the MRI-detected lesions, 8 patients lacked clearly visible focal lesions on MRI, and 5 patients had lesions with a maximum cross-sectional area <20 mm². These patients were excluded, resulting in a final enrollment of 62 cases (median: 67 years old; range: 55–83 years), with a mean total serum prostate-specific antigen level of 9.7 ± 5.8 ng/ml (range: 4.7–64.8 ng/ml). Among these 62 patients, 31 had benign lesions (28 cases of benign prostatic hyperplasia, 1 case of prostatic adenoma, and 2 cases of prostatic cysts), while 31 had malignant lesions (29 cases of prostatic adenocarcinoma and 2 of intraductal

carcinoma of the prostate; Gleason's classification indicated 1 case of grade 1, 4 cases of grade 2, 20 cases of grade 3, 4 cases of grade 4, and 2 cases of grade 5). A flowchart illustrating the participant selection is presented in Fig. 1.

Consistency between qualitative image evaluation and ADC measurements

The consistency between the qualitative image evaluation by the two radiologists and the ADC measurements for IQMR-FOCUS-DWI and FOCUS-DWI is summarized in Table 1. The agreement between the radiologists for qualitative image evaluation was excellent. Similarly, the agreement for ADC value measurements was also excellent. The Bland-Altman plot illustrating inter-observer agreement for ADC values is presented in Fig. 2. For the FOCUS-DWI sequence, 96.8% (60/62) of measurements fell within the 95% limits of agreement, while for the IQMR-FOCUS-DWI sequence, 95.2% (59/62) of measurements fell within these limits.

Qualitative scoring, PSNR, SSIM, and ADC results for IQMR-FOCUS-DWI and FOCUS-DWI sequences

Regarding qualitative scores, as shown in Fig. 3, the Mann-Whitney test revealed that IQMR-FOCUS-DWI images had significantly better scores than FOCUS-DWI images in terms of noise level, geometric deformation, and overall image quality ($P < 0.001$) (Figs. 4 and 5). Although the artifact scores for IQMR-FOCUS-DWI were slightly greater than those for FOCUS-DWI, no significant difference was evident ($P = 0.0875$). For the quantitative assessment, as illustrated in Fig. 6, paired t-test results demonstrated that IQMR-FOCUS-DWI images had significantly higher PSNR and SSIM values compared to FOCUS-DWI images ($P < 0.001$). Additionally, the Wilcoxon rank-sum test indicated that the ADC values for IQMR-FOCUS-DWI were markedly greater than those for FOCUS-DWI ($P < 0.01$).

Comparison of correlations between IQMR-FOCUS-DWI and FOCUS-DWI sequences in terms of PI-RADS scores, radiologist diagnosis, radiologist diagnostic confidence scores, and ADC values and Gleason grades of malignant lesions

In terms of the PI-RADS scoring of prostate lesions, Mann-Whitney U tests indicated that the PI-RADS scores of the IQMR-FOCUS-DWI sequence were slightly lower than

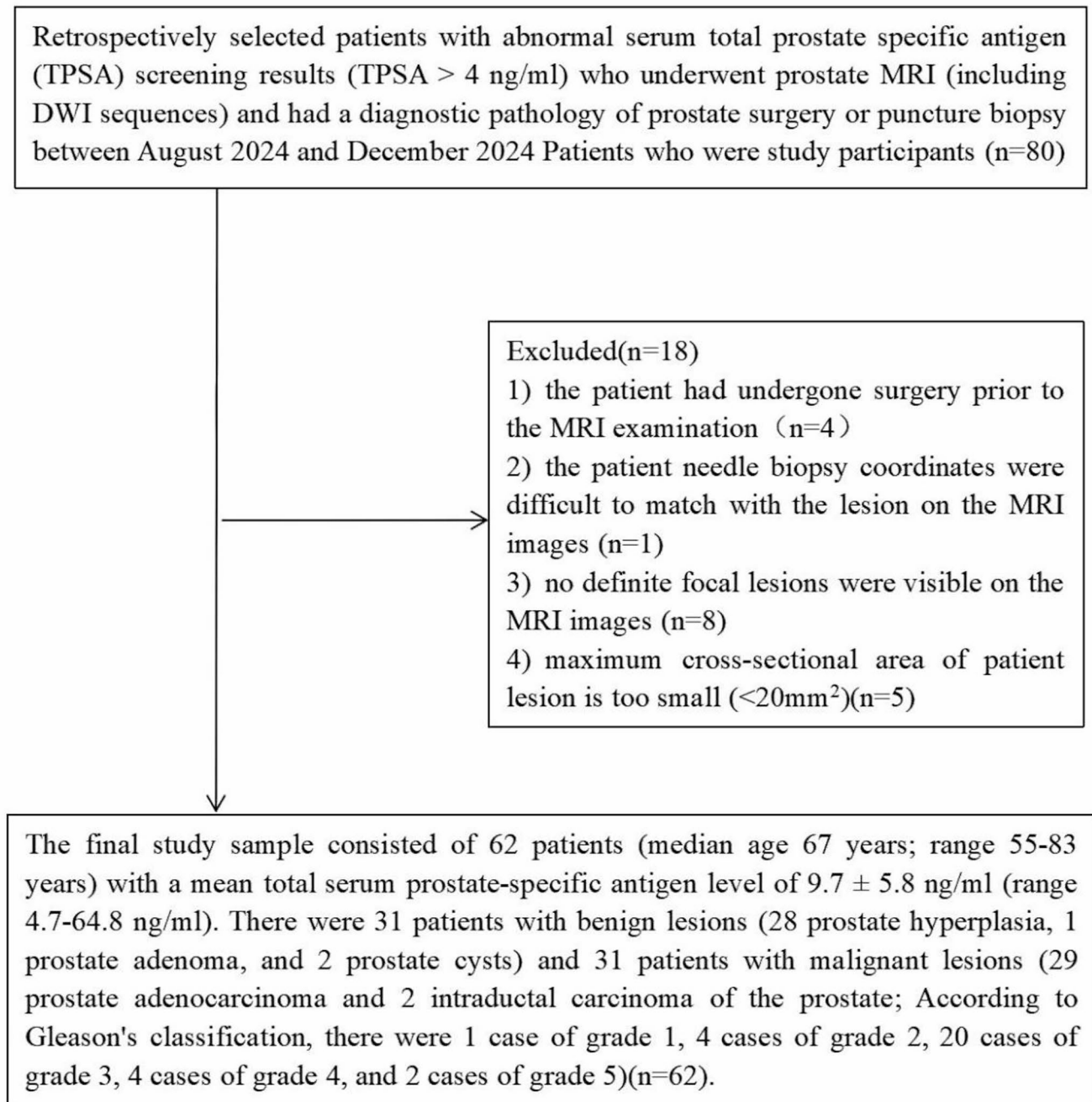


Fig. 1 Flowchart outlining participant selection

those of the FOCUS-DWI sequence, although the difference was not statistically significant ($P=0.0875$) (Fig. 7a).

Regarding the radiologists' diagnoses of benign or malignant prostate lesions and their diagnostic confidence scores, Kappa analysis indicated that the diagnostic results of prostate lesions using the FOCUS-DWI sequence showed good agreement with pathological findings (Kappa=0.677 [95% CI: 0.498–0.857], $P<0.05$), with a diagnostic accuracy of 83.9%. In contrast, the diagnostic results using the

IQMR-FOCUS-DWI sequence demonstrated excellent agreement with the pathological findings (Kappa=0.806 [95% CI: 0.660–0.953], $P<0.05$), and the diagnostic accuracy increased to 90.3%. The Mann-Whitney U test demonstrated that the diagnostic confidence scores of the same physician using the IQMR-FOCUS-DWI sequence were significantly higher than those using the FOCUS-DWI sequence ($Z = -3.757$, $P=0.0002$), with the average diagnostic confidence score increasing from 3.05 to 3.63

Table 1 Assessments of inter-observer consistency measurements between qualitative evaluations and ADC value measurements for IQMR-FOCUS-DWI and FOCUS-DWI

Items	FOCUS-DWI (b=2000s/mm ²)	IQMR-FOCUS-DWI (b=2000s/mm ²)
Noise level (Kappa)	0.910 (0.835–0.985)	0.944 (0.890–0.997)
Geometric deformation (Kappa)	0.932 (0.869–0.996)	0.913 (0.845–0.981)
Image artifacts (Kappa)	0.890 (0.798–0.983)	0.917 (0.838–0.996)
Overall image quality (Kappa)	0.876 (0.790–0.962)	0.993 (0.877–0.990)
PI-RADS score(Kappa)	0.968(0.924~1.000)	0.950(0.895~1.000)
Prostate benign and malignant diagnosis(Kappa)	0.900(0.787~1.000)	0.870(0.748~0.993)
Physician diagnostic confidence score(Kappa)	0.911(0.834~0.989)	0.916(0.842~0.990)
ADC/($\times 10^{-3}$ mm ² /s) (ICC)	0.969 (0.949–0.981)	0.995 (0.992–0.997)

Parentheses represent 95% confidence intervals

(Fig. 7b). Spearman correlation analysis further indicated that the diagnostic confidence scores of both sequences showed significant positive correlations with the diagnostic accuracy (FOCUS-DWI sequence: $r=0.327$ [95% CI: 0.085–0.534], $P=0.0094$; IQMR-FOCUS-DWI sequence: $r=0.371$ [95% CI: 0.133–0.568], $P=0.0030$).

In malignant lesions, Spearman correlation analysis showed that the ADC values of the FOCUS-DWI sequence were moderately negatively correlated with the Gleason grade ($r = -0.510$ [95% CI: -0.732 to -0.190], $P=0.003$). In contrast, the ADC values of the IQMR-FOCUS-DWI

sequence were highly negatively correlated with the Gleason classification ($r=-0.754$ [95% CI: -0.875 to -0.546], $P<0.0001$).

Evaluation of the diagnostic efficacy of IQMR-FOCUS-DWI and FOCUS-DWI ADC values in distinguishing between benign and malignant lesions

A comparison of the ADC values between benign and malignant lesions revealed that, in IQMR-FOCUS-DWI images, ADC values for benign lesions (1.35 [1.29 – 1.38]) were significantly higher than those for malignant lesions (0.93 [0.81 – 1.05]) ($Z = -5.966$, $P<0.001$). Similarly, in FOCUS-DWI images, the ADC values for benign lesions (1.08 [1.01 – 1.14]) were significantly higher than those for malignant lesions (0.92 [0.82 – 1.00]) ($Z = -4.500$, $P<0.001$).

Table 2; Fig. 8 indicate that diagnostic performance of ADC values in distinguishing between malignant and benign lesions was 0.941 (95%CI: 0.850 – 0.985) for IQMR-FOCUS-DWI and 0.832 (95%CI: 0.716 – 0.915) for FOCUS-DWI. IQMR-FOCUS-DWI demonstrated superior diagnostic performance compared to FOCUS-DWI, with the DeLong test confirming that the efficacy of the two sequences differed significantly ($P=0.0487$). For FOCUS-DWI, the optimal ADC threshold for lesion differentiation was 1.00×10^{-3} mm²/s, yielding a sensitivity of 77.4%, a specificity of 80.7%, and an accuracy of 79.0%. In contrast, for IQMR-FOCUS-DWI, the optimal ADC threshold was 1.18×10^{-3} mm²/s, achieving a sensitivity of 96.8%, a specificity of 90.3%, and an accuracy of 93.6%.

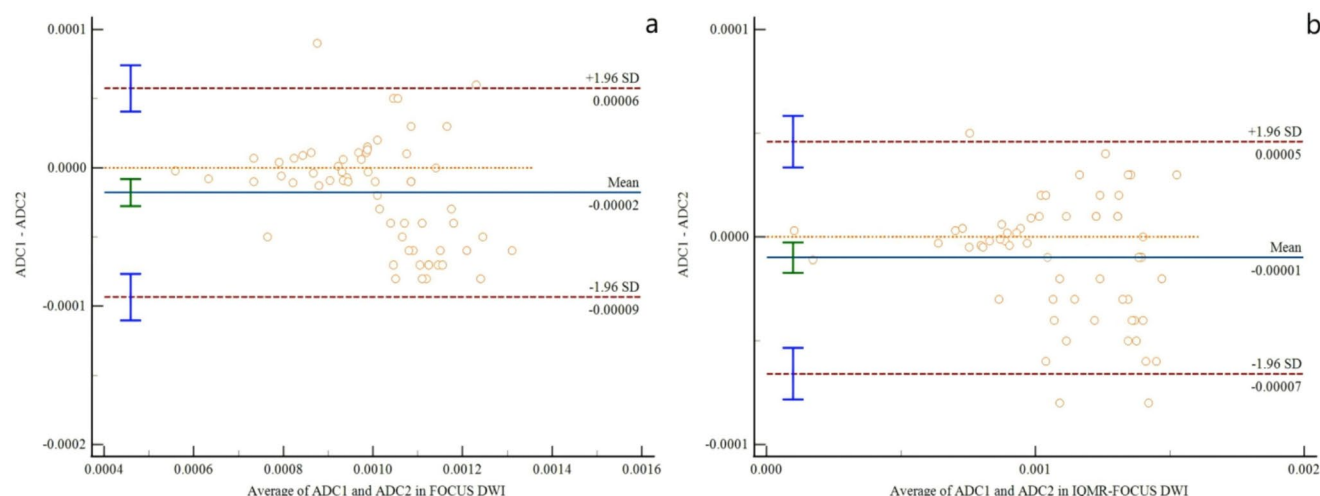


Fig. 2 Interobserver agreement on ADC values for the FOCUS-DWI (a) and IQMR-FOCUS-DWI (b) sequences. Central dashed lines represent the baseline level when the difference between observers was

zero, whereas the solid line corresponds to the mean difference, and the upper and lower dashed lines represent the 95% confidence intervals

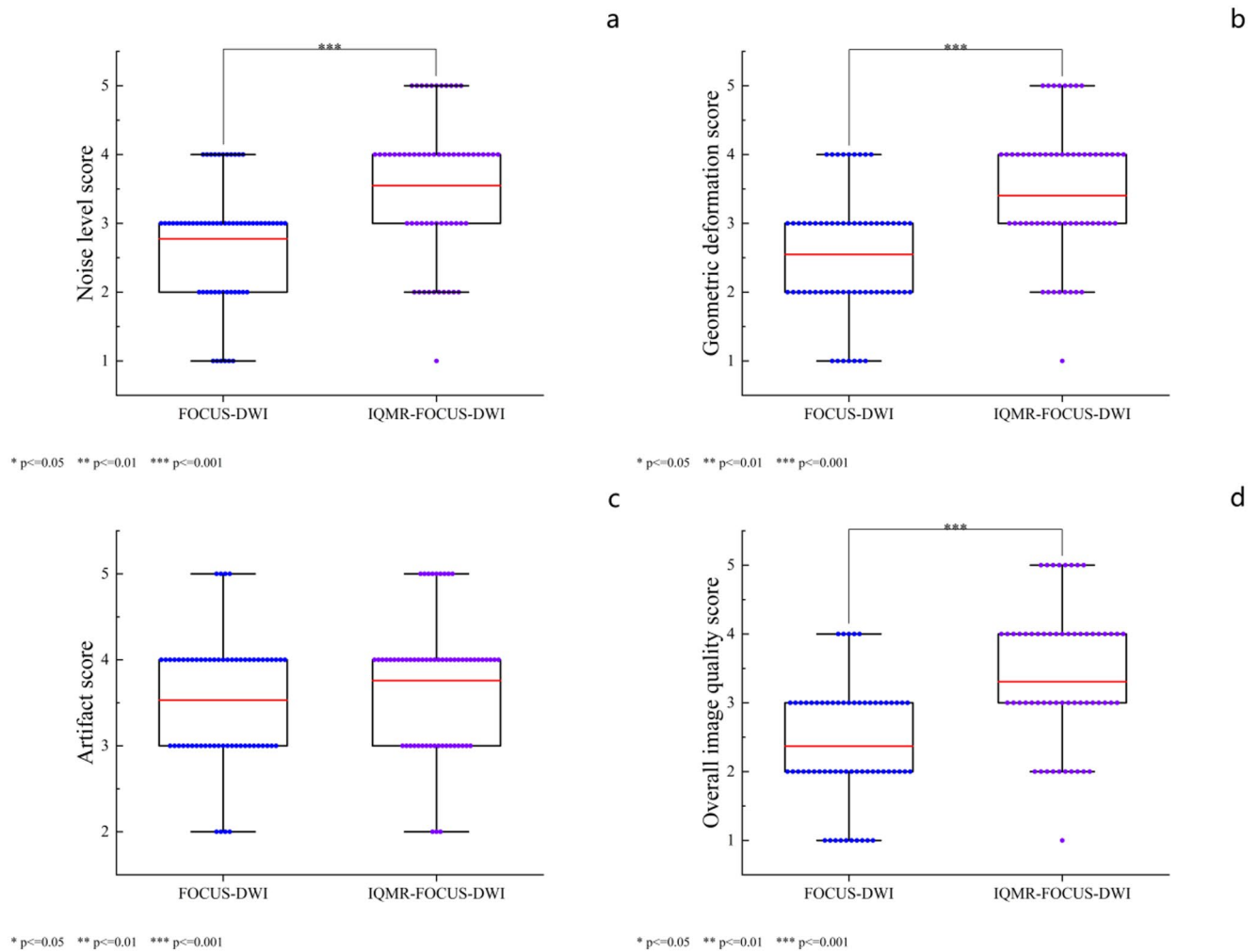


Fig. 3 Qualitative scoring results for the IQMR-FOCUS-DWI and FOCUS-DWI sequences. **a** Noise level, **b** Geometric distortion, **c** Artifact, and **d** Overall image quality ratings for IQMR-FOCUS-DWI and FOCUS-DWI. * $P < 0.05$; ** $P < 0.01$ *** $P < 0.001$

Discussion

In this study, the effects of using the IQMR technique on the image quality and quantitative parameters of prostate DWI were investigated, together with its efficacy in distinguishing benign from malignant prostate lesions. These findings indicate that, compared to FOCUS-DWI, IQMR-FOCUS-DWI significantly enhances image quality, shown by its higher PSNR, SSIM, and qualitative scores, and makes physicians have greater confidence in diagnosis. Additionally, it improves the measurement of ADC values and enhances the diagnostic accuracy when distinguishing benign from malignant lesions.

High b-values can improve the sensitivity of lesion detection in DWI sequences [24]. However, DWI images with high b-values often show relatively low signal-to-noise ratios (SNRs) [25]. Iima et al. [25] reported that a low SNR has a negative influence on the quantitative analysis of DWI,

thereby impairing accurate lesion characterization. Lee et al. [26] explored the use of Deep Learning Reconstruction (DLR) methods to enhance the SNR of prostate DWI images acquired with a b-value of 1400 s/mm². Their results demonstrated that the use of DLR significantly improved the SNR compared to conventional DWI reconstruction methods. When conducting image quality assessment, PSNR is an important metric, offering advantages over SNR in the objective quantification of image quality [27, 28]. In the present study, PSNR was employed as an objective indicator for comparing the quality of IQMR-FOCUS-DWI and FOCUS-DWI images. The results were consistent with those of Lee et al. [26], demonstrating that IQMR-FOCUS-DWI achieved superior PSNR at b=2000 s/mm². This improvement may be attributed to the core algorithm of IQMR. First, the deep learning module of IQMR, trained on AI-based learning, incorporates high-quality image feature parameters and optimal post-processing parameters, which serve as the foundation for the iterative reconstruction

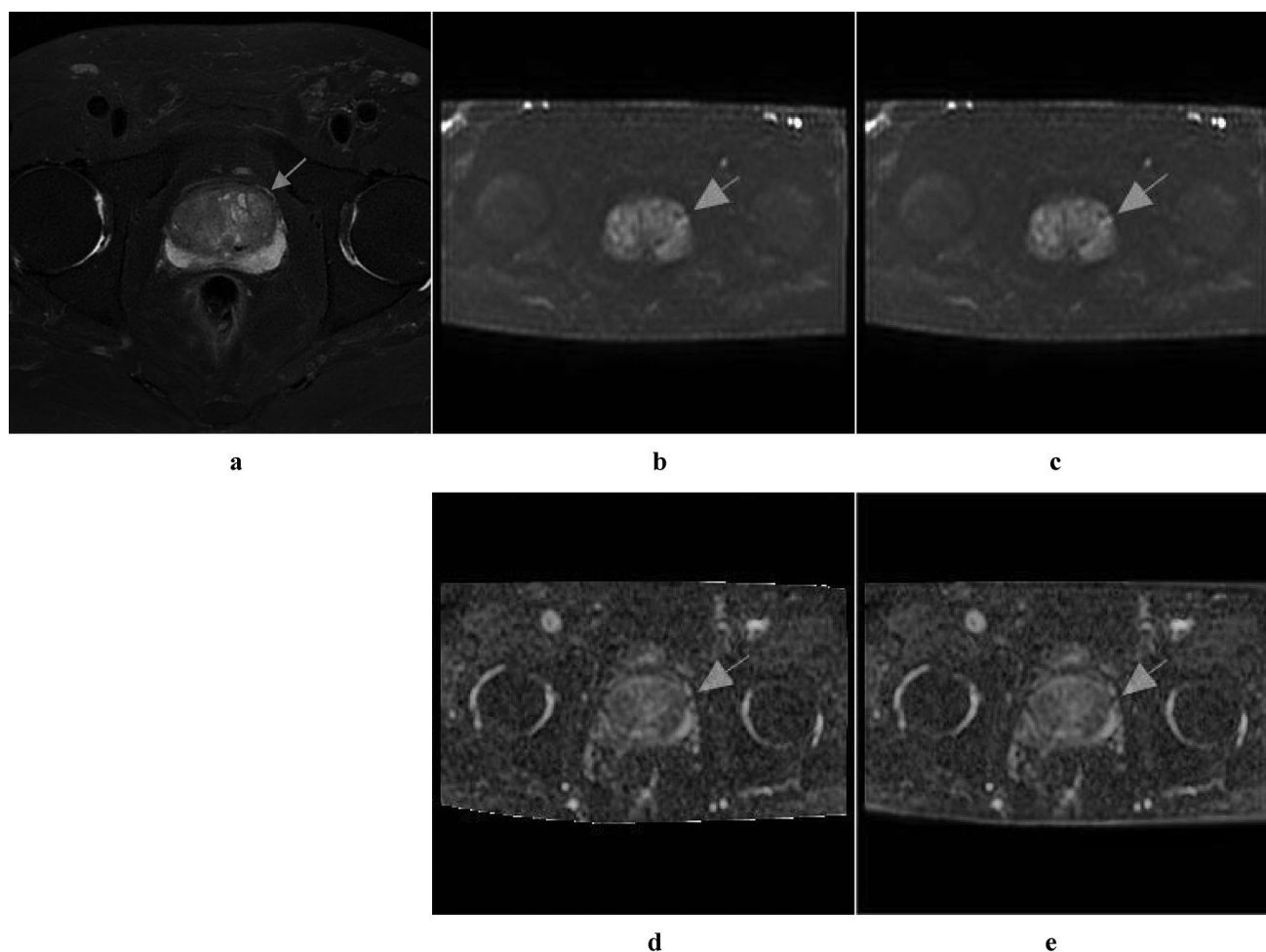


Fig. 4 Images from a 74-year-old male with a mass in the transitional zone of the prostate measuring $5.7 \times 4.2 \times 4.9$ cm that was pathologically confirmed as benign prostatic hyperplasia. (a) T2WI-FS image, (b) FOCUS-DWI sequence image, (c) IQMR-FOCUS-DWI sequence

image, (d) ADC image of the FOCUS-DWI sequence, and (e) ADC image of the IQMR-FOCUS-DWI sequence. Relative to the FOCUS-DWI sequence images, IQMR-FOCUS-DWI sequence images were less distorted, less noisy, and exhibited greater signal uniformity

module, enabling resolution enhancement [29, 30]. Second, the multiple iterative reconstruction steps in IQMR effectively filter noise and enhance contrast [13–16].

In this study, the b-value of DWI was set at 2000 s/mm^2 . Although this improved the sensitivity for detecting prostatic lesions, it also led to an increase in geometric distortion of DWI images. Ming et al. [31] evaluated the effect of DLR on reducing geometric distortion in breast DWI images (b-value = 1000 s/mm^2) using subjective assessment methods. Their results showed that the use of DLR significantly reduced distortion in the images. Similarly, our qualitative assessment indicated that IQMR-FOCUS-DWI reduced geometric distortion in prostate DWI images, achieving higher qualitative scores. However, subjective assessment methods are susceptible to observer bias. Structural Similarity Index Measurement (SSIM) is widely used as an objective metric for evaluating image quality and provides a more reliable assessment than subjective evaluations

[32, 33]. The findings demonstrated that SSIM values were significantly higher for IQMR-FOCUS-DWI than for FOCUS-DWI, further confirming its ability to enhance image quality. Additionally, qualitative evaluations in our study showed that IQMR-FOCUS-DWI not only achieved higher scores for geometric distortion reduction but also for noise suppression and overall image quality compared to FOCUS-DWI.

Comparisons of the ADC values showed that the ADC values obtained with IQMR-FOCUS-DWI were markedly greater than those from FOCUS-DWI. This result is consistent with those of previous investigations of the use of DLR in prostate [26] and liver imaging [34]. The observed difference may be due to the influence of noise on ADC value calculations, as the lower PSNR of FOCUS-DWI may lead to an underestimation of the ADC values [25]. In terms of distinguishing benign from malignant lesions, the present results confirmed that ADC values were markedly

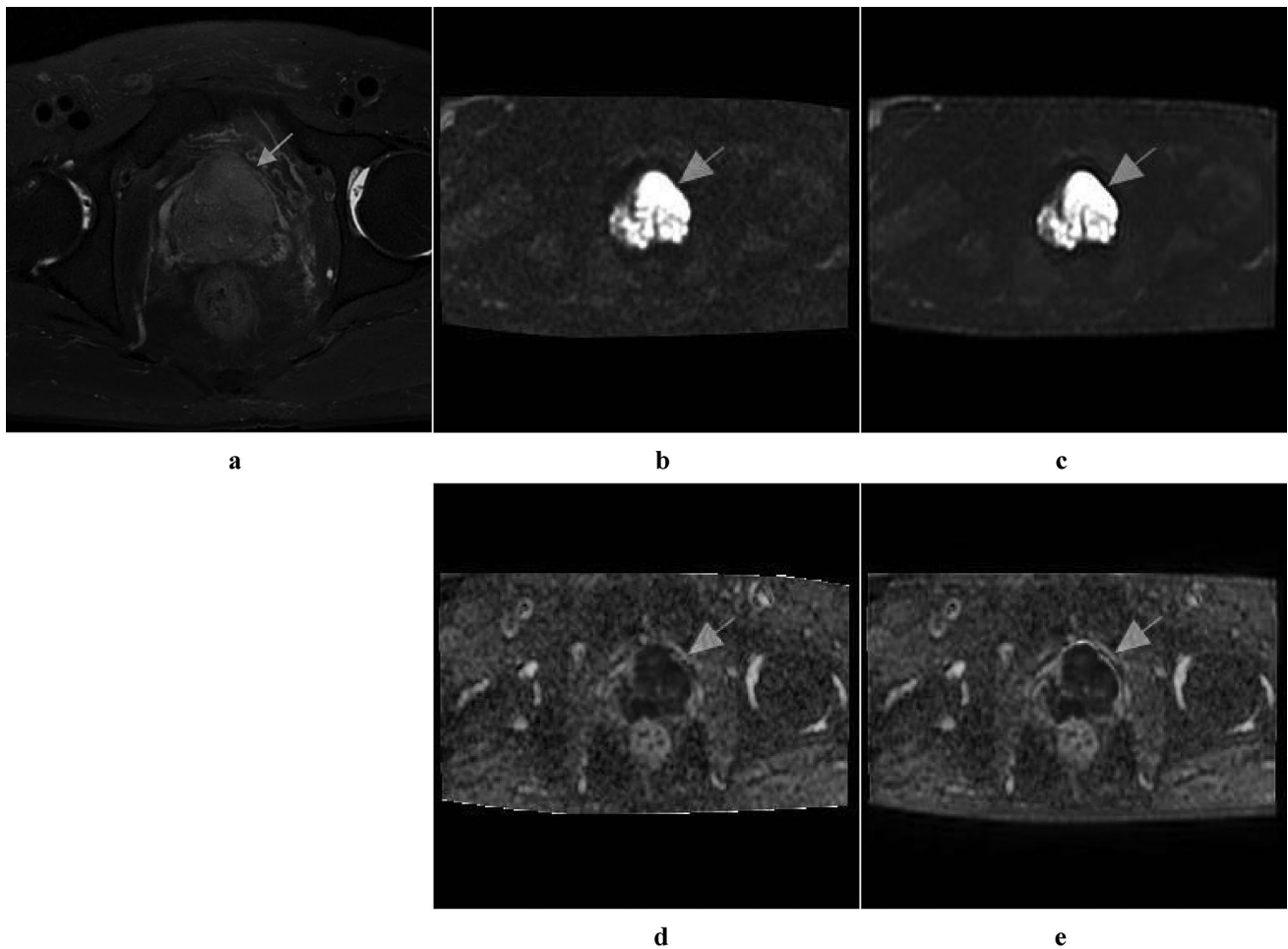


Fig. 5 Images from a 70-year-old male with a mass in the transitional zone of the prostate measuring $5.9 \times 5.1 \times 5.5$ cm that was pathologically confirmed as prostate adenocarcinoma. **a** T2WI-FS image, **b** FOCUS-DWI sequence image, **c** IQMR-FOCUS-DWI sequence

image, **d** ADC image of the FOCUS-DWI sequence, and **e** ADC image of the IQMR-FOCUS-DWI sequence. Relative to the FOCUS-DWI sequence images, IQMR-FOCUS-DWI sequence images were less distorted, less noisy, and exhibited greater signal uniformity

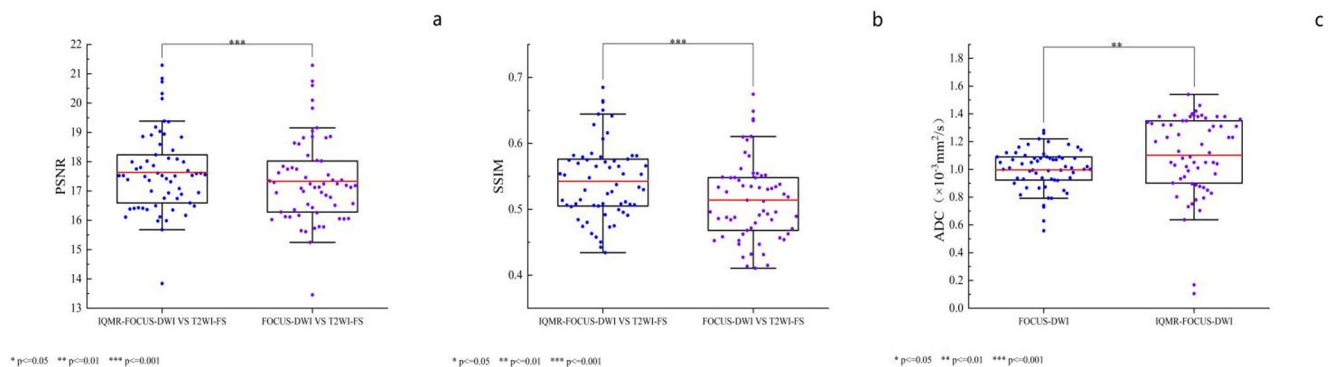


Fig. 6 Comparisons of PSNR, SSIM, and ADC values between IQMR-FOCUS-DWI and FOCUS-DWI sequences **a** PSNR, **b** SSIM, and **c** ADC value comparisons between IQMR-FOCUS-DWI and FOCUS-DWI. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

greater for benign lesions relative to malignant lesions in both IQMR-FOCUS-DWI and FOCUS-DWI, aligning with the findings of previous studies [35–37]. ADC values are inversely correlated with diffusion restriction, and malignant

prostate lesions, characterized by higher cellular density and more restricted water diffusion, typically exhibit lower ADC values than benign tissues. Furthermore, the study compared the diagnostic efficacy of IQMR-FOCUS-DWI

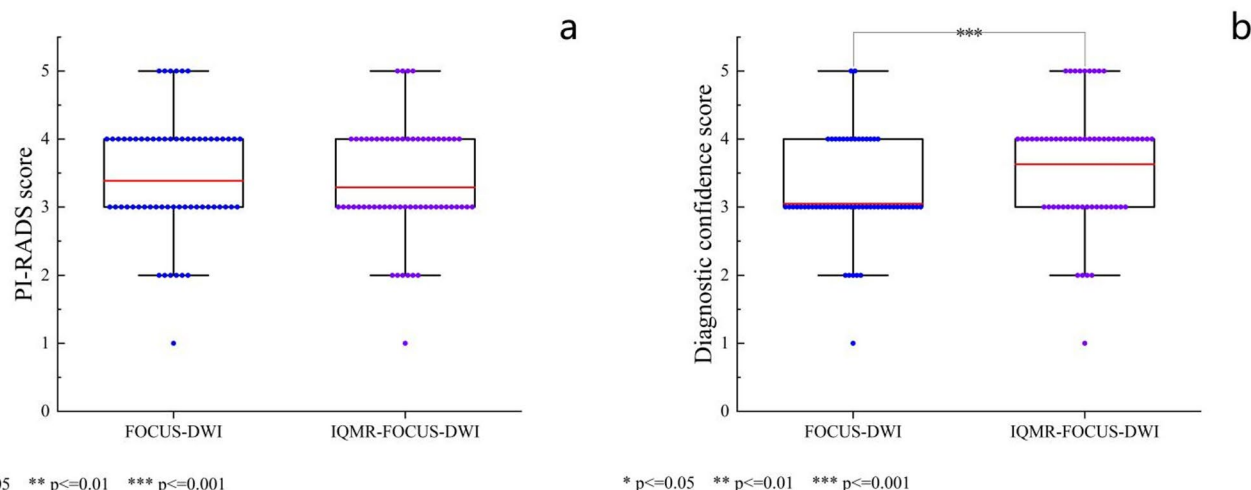


Fig. 7 Comparison of PI-RADS and diagnostic confidence scores between the IQMR-FOCUS-DWI and FOCUS-DWI sequences. **a** and **b** show the comparison of physician PI-RADS and physician diagnostic confidence scores, respectively. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

Table 2 Evaluation of the effectiveness of IQMR-FOCUS-DWI and FOCUS-DWI ADC values in differentiating between benign and malignant lesions

Groups	AUC (95%CI)	<i>P</i>	<i>Z</i>	Threshold of ADC/($\times 10^{-3}$ mm ² /s)	sensitivity/%	specificity/%	accuracy/%
IQMR-FOCUS-DWI	0.941 (0.850–0.985)	<0.001	12.108	1.18	96.8	90.3	93.6
FOCUS-DWI	0.832 (0.716–0.915)	<0.001	6.338	1.00	77.4	80.7	79.0

AUC area under the curve, CI confidence interval, ADC apparent diffusion coefficient

and FOCUS-DWI for distinguishing between benign and malignant lesions, demonstrating similar diagnostic performance to previously reported results on prostate DWI (AUC=0.720–0.958) [38, 39]. Notably, it was found that IQMR significantly improved the discriminative power of the ADC value in distinguishing benign from malignant prostate lesions ($P=0.0487$). This enhancement is likely due to the increased PSNR and SSIM provided by IQMR, which improves image quality and enhances the stability of ADC measurements. The results of the qualitative assessments of diagnostic efficacy in this study also confirmed the above observations. The diagnostic results from the IQMR-FOCUS-DWI sequence were more consistent with pathological findings than those of the FOCUS-DWI sequence, and the use of IQMR increased the radiologist's diagnostic confidence score from 3.05 to 3.68 points.

Despite these promising results, this study has some limitations. First, the sample size was small, and this, together with the single-center design, may have introduced selection bias. Therefore, this study represents an exploratory preliminary investigation before large-scale case verification. Second, due to the retrospective nature of the study, it was not possible to compare the findings with other deep-learning sequences or reconstruction methods. It has been reported that DL reconstruction techniques may lead to

image smoothing or a reduction in edge sharpness. However, this phenomenon was not observed in the present study. The authors believe that this may be due to differences in the sequence analyzed and the deep learning algorithm used. In addition, possible regulatory or integration challenges when introducing IQMR between scanners and PACS systems and how to ensure the stability of diagnostic information during image transmission when introducing IQMR between scanners and PACS systems will be assessed in the future.

Conclusion

Compared with the FOCUS-DWI sequence, the use of the IQMR technique can significantly improve the image quality of prostate FOCUS-DWI without increasing the scanning time, thereby enhancing the confidence of the physician in differentiating between benign and malignant lesions of the prostate. Moreover, the use of IQMR was found to have a notable impact on the quantitative ADC values of DWI, thereby improving diagnostic accuracy as a means of distinguishing between benign and malignant prostate lesions. These findings suggest that the IQMR technique holds significant potential for the clinical application of DWI for prostate cancer detection.

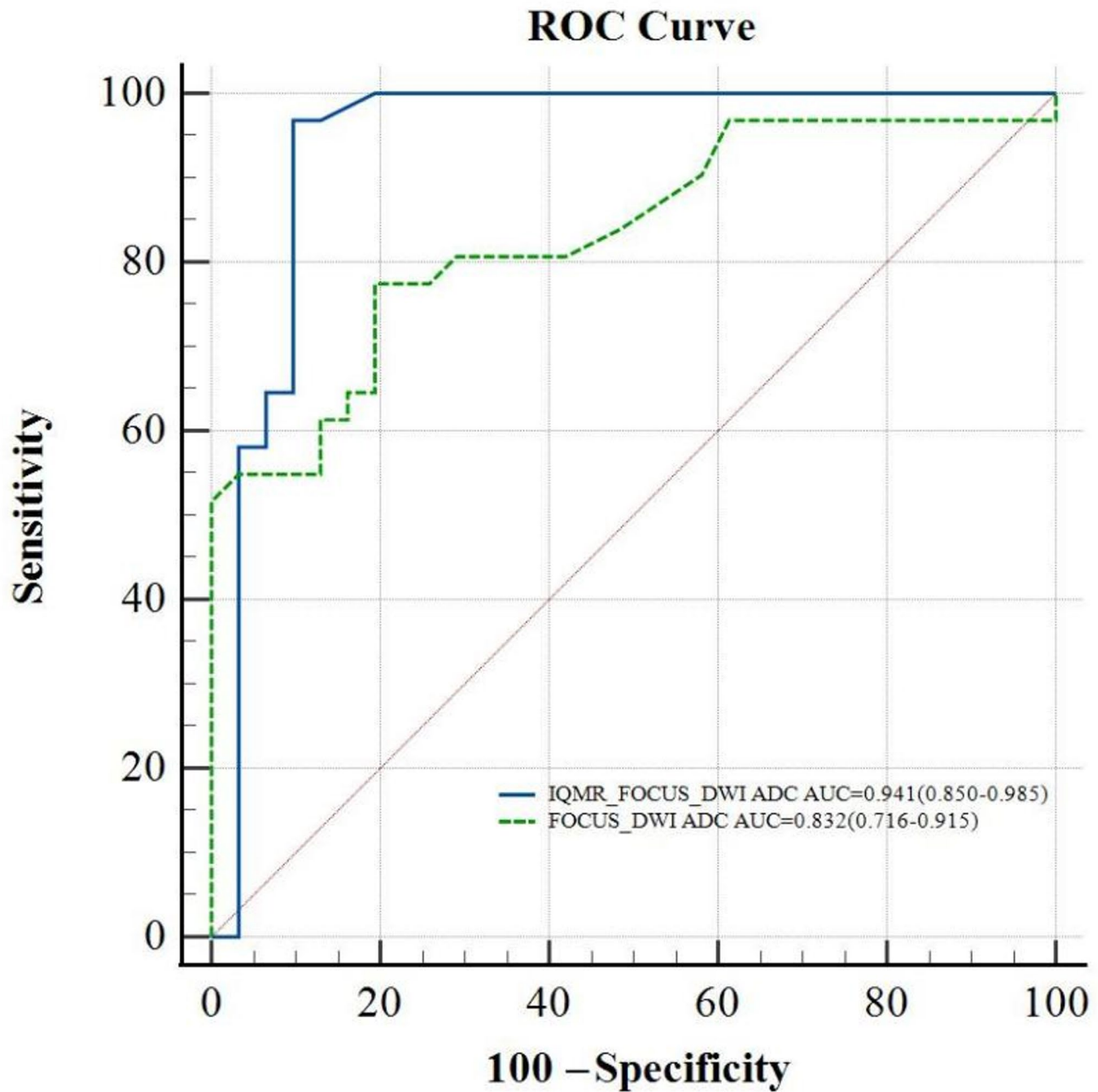


Fig. 8 Receiver operating characteristic curves comparing the effectiveness of ADC values from IQMR-FOCUS-DWI and FOCUS-DWI sequences in differentiating between benign and malignant lesions. *AUC* area under the curve, *ADC* apparent diffusion coefficient

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00261-025-05100-w>.

Acknowledgements The authors would like to thank all the reviewers who participated in the review and MJEdition (www.mjeditor.com) for its linguistic assistance during the preparation of this manuscript.

Author contributions Yi Zhao: Conceptualization, Writing- Original draft preparation. Xiao-Liang Xie: Data curation, Writing- Original draft preparation. Xi Zhu: Methodology, Writing- Original draft preparation. Wen-Nuo Huang: Software, Validation. Chang-Wu Zhou: Supervision, Validation. Kai-Xuan Ren: Supervision, Investigation.

Run-Ya Zhai: Supervision, Investigation. Wei Wang: Writing- Reviewing and Editing. Jian-Wei Wang: Writing- Reviewing and Editing. Yi Zhao, Xiao-Liang Xie and Xi Zhu contributed equally to this work and were listed as co-first authors; Wei Wang and Jian-Wei Wang are co-corresponding authors.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

References

- Mirzaei S, Paskeh MDA, Okina E, et al. Molecular Landscape of LncRNAs in Prostate Cancer: A focus on pathways and therapeutic targets for intervention[J]. *J Exp Clin Cancer Res*, 2022,41(1):214.
- Rosellini M, Santoni M, Mollica V, et al. Treating Prostate Cancer by Antibody-Drug Conjugates[J]. *Int J Mol Sci*, 2021, 22(4):1551.
- Sherafatmandjoo H, Safaei AA, Ghaderi F, et al. Prostate cancer diagnosis based on multi-parametric MRI, clinical and pathological factors using deep learning[J]. *Sci Rep*, 2024, 14(1):14951.
- Lee CY, Mani M. 2D CAIPI accelerated 3D multi-slab diffusion weighted EPI combined with qModel reconstruction for fast high resolution microstructure imaging[J]. *Magn Reson Imaging*, 2024,111:57–66.
- Lee PK, Zhou X, Hargreaves BA. Robust multishot diffusion-weighted imaging of the abdomen with region-based shot rejection[J]. *Magn Reson Med*, 2024, 92(2):519–531.
- Chatterjee A, Harmath C, Oto A. New prostate MRI techniques and sequences[J]. *Abdom Radiol (NY)*, 2020, 45(12):4052–4062.
- Tsuruta C, Hirata K, Kudo K, et al. DWI-related texture analysis for prostate cancer: differences in correlation with histological aggressiveness and data repeatability between peripheral and transition zones[J]. *Eur Radiol Exp*, 2022, 6(1):1.
- Gong XQ, Tao YY, Wang R, et al. Application of Diffusion Weighted Imaging in Prostate Cancer Bone Metastasis: Detection and Therapy Evaluation[J]. *Anticancer Agents Med Chem*, 2021, 21(15):1950–1956.
- Bai Y, Pei Y, Liu WV, et al. MRI: Evaluating the Application of FOCUS-MUSE Diffusion-Weighted Imaging in the Pancreas in Comparison With FOCUS, MUSE, and Single-Shot DWIs[J]. *J Magn Reson Imaging*, 2023,57(4):1156–1171.
- Fang S, Zhu J, Wang Y, et al. The value of whole-lesion histogram analysis based on fieldofview optimized and constrained undistorted single shot (FOCUS) DWI for predicting axillary lymph node status in early-stage breast cancer[J]. *BMC Med Imaging*, 2022, 22(1):163.
- Feng Z, Min X, Sah VK, et al. Comparison of field-of-view (FOV) optimized and constrained undistorted single shot (FOCUS) with conventional DWI for the evaluation of prostate cancer[J]. *Clin Imaging*, 2015,39(5):851–5.
- Wicaksono KP, Fujimoto K, Fushimi Y, et al. Super-resolution application of generative adversarial network on brain time-of-flight MR angiography: image quality and diagnostic utility evaluation[J]. *Eur Radiol*, 2023, 33(2):936–946.
- DO W J, SEO S, HAN Y, et al. Reconstruction of multicontrast MR images through deep learning[J]. *Med Phys*, 2020, 47(3):983–997.
- Ren J, Eriksen JG, Nijkamp J, et al. Comparing different CT, PET and MRI multi-modality image combinations for deep learning-based head and neck tumor segmentation[J]. *Acta Oncol*, 2021,60(11):1399–1406.
- Bielak L, Wiedenmann N, Berlin A, et al. Convolutional neural networks for head and neck tumor segmentation on 7-channel multiparametric MRI: a leave-one-out analysis[J]. *Radiat Oncol*, 2020,15(1):181.
- Herrmann J, Afat S, Gassenmaier S et al (2023) Image Quality and Diagnostic Performance of Accelerated 2D Hip MRI with Deep Learning Reconstruction Based on a Deep Iterative Hierarchical Network[J]. *Diagnostics (Basel)* 13(20):3241
- Kanemaru N, Takao H, Amemiya S, et al. The effect of a post-scan processing denoising system on image quality and morphometric analysis[J]. *J Neuroradiol*, 2022, 49(2):205–212.
- Yao H, Jia B, Pan X, et al. Validation and Feasibility of Ultrafast Cervical Spine MRI Using a Deep Learning-Assisted 3D Iterative Image Enhancement System[J]. *J Multidiscip Healthc*, 2024, 17:2499–2509.
- Lee SM, Kim M, Park C, et al. Deep Learning-reconstructed Parallel Accelerated Imaging for Knee MRI. *Curr Med Imaging*[J]. 2024, 20:e240523217293.
- Muckley MJ, Ades-Aron B, Papaioannou A, et al. Training a neural network for Gibbs and noise removal in diffusion MRI[J]. *Magn Reson Med*, 2021, 85(1):413–428.
- Li J, Xia Y, Dai J, et al. Comparison of single-shot, FOCUS single-shot, MUSE, and FOCUS MUSE diffusion weighted imaging for pulmonary lesions: A pilot study[J]. *Heliyon*, 2024, 10(15):e35203.
- Ravi KS, Nandakumar G, Thomas N, et al. Accelerated MRI using intelligent protocolling and subject-specific denoising applied to Alzheimer's disease imaging[J]. *Front Neuroimaging*, 2023, 2:1072759.
- Xiao Y, Chen C, Wang L, et al. A novel hybrid generative adversarial network for CT and MRI super-resolution reconstruction[J]. *Phys Med Biol*, 2023, 68(13).
- Sabouri S, Chang SD, Goldenberg SL, et al. Comparing diagnostic accuracy of luminal water imaging with diffusion-weighted and dynamic contrast-enhanced MRI in prostate cancer: A quantitative MRI study[J]. *NMR Biomed*, 2019, 32(2):e4048.
- Iima M, Partridge SC, Le Bihan D. Six DWI questions you always wanted to know but were afraid to ask: clinical relevance for breast diffusion MRI[J]. *Eur Radiol*, 2020, 30(5):2561–2570.
- Lee KL, Kessler DA, Dezonie S, et al. Assessment of deep learning-based reconstruction on T2-weighted and diffusion-weighted prostate MRI image quality[J]. *Eur J Radiol*, 2023, 166:111017.
- Li X, Zhang H, Yang H, Li TQ. CS-MRI Reconstruction Using an Improved GAN with Dilated Residual Networks and Channel Attention Mechanism[J]. *Sensors (Basel)*, 2023, 23(18):7685.
- Hales PW, Pfeuffer J, A Clark C. Combined Denoising and Suppression of Transient Artifacts in Arterial Spin Labeling MRI Using Deep Learning[J]. *J Magn Reson Imaging*, 2020, 52(5):1413–1426.
- Kim E, Cho HH, Cho SH, et al. Accelerated Synthetic MRI with Deep Learning-Based Reconstruction for Pediatric Neuroimaging[J]. *AJNR Am J Neuroradiol*, 2022,43(11):1653–1659.
- Zeng G, Guo Y, Zhan J, et al. A review on deep learning MRI reconstruction without fully sampled k-space[J]. *BMC Med Imaging*, 2021,21(1):195.
- Ming Y, Yang F, Xiao Y, et al. Exploring the feasibility of FOCUS DWI with deep learning reconstruction for breast cancer diagnosis: A comparative study with conventional DWI[J]. *PLoS One*, 2024, 19(10):e0313011.
- Yasaka K, Akai H, Kato S, et al. Iterative Motion Correction Technique with Deep Learning Reconstruction for Brain MRI:

- A Volunteer and Patient Study[J]. *J Imaging Inform Med*, 2024, 37(6):3070–3076.
33. Takahashi Y, Ishikawa H, Nemoto H, et al. [Evaluation of the Latest Motion Correction Techniques in Periodically Rotated Overlapping Parallel Lines with Enhanced Reconstruction (PROPELLER) Imaging across Different Vendors][J]. *Nihon Hoshasen Gijutsu Gakkai Zasshi*, 2024, 80(11):1155–1164. Japanese.
 34. Afat S, Herrmann J, Almansour H, et al. Acquisition time reduction of diffusion-weighted liver imaging using deep learning image reconstruction[J]. *Diagn Interv Imaging*, 2023, 104(4):178–184.
 35. Ozyoruk KB, Harmon SA, Lay NS, et al. AI-ADC: Channel and Spatial Attention-Based Contrastive Learning to Generate ADC Maps from T2W MRI for Prostate Cancer Detection[J]. *J Pers Med*, 2024, 14(10):1047.
 36. Agrotis G, Pooch E, Abdelatty M, et al. Diagnostic performance of ADC and ADCratio in MRI-based prostate cancer assessment: A systematic review and meta-analysis[J]. *Eur Radiol*, 2025, 35(1):404–416.
 37. Ajami T, Han S, Porto JG et al (2024) Molecular and diffusion features for identification of clinically significant prostate cancer in PI-RADS 3 lesions[J]. *Urol Oncol* 42(11):e9-370-370.e14
 38. Morelli L, Paganelli C, Marvaso G, et al. Addressing intra- and inter-institution variability of a radiomic framework based on Apparent Diffusion Coefficient in prostate cancer[J]. *Med Phys*, 2024, 51(11):8096–8107.
 39. Buss A, Radzina M, Liepa M, et al. Role of Apparent Diffusion Coefficient Value and Apparent Diffusion Coefficient Ratio as Prognostic Factors for Prostate Cancer Aggressiveness[J]. *Diagnostics (Basel)*, 2024, 14(21):2438.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Yi Zhao¹ · Xiao-Liang Xie¹ · Xi Zhu² · Wen-Nuo Huang² · Chang-Wu Zhou¹ · Kai-Xuan Ren¹ · Run-Ya Zhai¹ · Wei Wang¹ · Jian-wei Wang³

✉ Wei Wang
waywang@126.com

✉ Jian-wei Wang
wangjianwei@jshp.org.cn

Yi Zhao
zhaoyi8706@163.com

Xiao-Liang Xie
YDFY_Xiexiaoliang@163.com

Xi Zhu
sbrmyradiol@foxmail.com

Wen-Nuo Huang
huangwennuo@sina.com

Chang-Wu Zhou
changwu83@163.com

Kai-Xuan Ren
rkaix97@163.com

Run-Ya Zhai
466587205@qq.com

¹ The Affiliated Hospital of Yangzhou University, Yangzhou, China

² Northern Jiangsu People's Hospital, Yangzhou, China

³ The First Affiliated Hospital of Nanjing Medical University, Nanjing, China