Original Article

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Anatomy Section

Impact of Urinary Bladder Filling on Prostate Volume Prediction using Fractal Dimension Analysis of Ultrasound Images: A Cross-sectional Study

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ABSTRACT

Introduction: Fractal Dimension (FD) analysis has emerged as a powerful tool for quantifying the morphological complexity of structures in medical images, including the analysis of cancerous tissue. Because the prostate is located inferior to the neck of the urinary bladder, accurate measurement is essential for the reliable diagnosis and treatment of clinical conditions such as Benign Prostatic Hyperplasia (BPH) and prostate cancer.

Aim: To evaluate whether urinary bladder filling status affects prostate FD and the accuracy of FD-based volume prediction models.

Materials and Methods: A cross-sectional study using a matched-pairs (within-subject) design was conducted at the Department of Radiology, Chalmeda Anand Rao Institute of Medical Sciences, Telangana, India, from September 2025 to December 2025. The study was carried out on 42 male ultrasonographic images of the prostate gland acquired with a filled and an empty urinary bladder (filled=21, empty=21). Prostate FD and volume prediction accuracy were measured using fractal analysis software and compared between the two bladder states using a paired t-test.

Results: The study population had a mean age of 52.58±5.43 years. The RMSE for volume prediction was 0.4071 mL (filled bladder) and 0.4106 mL (empty bladder). The mean FD value of the prostate gland was 1.52 in both filled and empty bladder conditions. No statistically significant association was observed between bladder filling status and prostate volume prediction accuracy or FD.

Conclusion: The findings of the present study indicated that urinary bladder filling status had minimal impact on prostate morphology.

Keywords: Angiogenesis, Prostate gland, Prostrate translocation

INTRODUCTION

The prostate gland is a cornerstone of male urological health, and its pathologies, primarily BPH and prostate cancer, represent significant sources of global morbidity and mortality [1]. Timely and precise diagnosis of these conditions is critical for guiding treatment decisions and improving patient outcomes. Traditional diagnostic imaging relies heavily on accurate measurements of prostate size, shape, and volume, which are essential for assessing BPH progression and for estimating tumour stage, extent, and growth in prostate cancer, thereby supporting treatment planning and guiding clinical decision-making [2]. Prostate volume is a key quantitative metric for diagnosing BPH and determining appropriate management and treatment strategies [1].

The anatomical relationship between the urinary bladder and the prostate gland is closely interdependent. Variations in bladder volume have been shown to cause prostate translocation and distortion, altering its position and glandular shape during imaging. Such dynamic changes may influence morphometric assessment, affecting both its position and apparent morphology during imaging [3].

Fractal analysis has emerged as a potent computational tool to address the limitations of traditional morphometric metrics [4]. In essence, fractal geometry provides a framework for quantifying the complexity and irregularity of natural structures that exhibit self-similarity across different scales. In general, FD values for 2D structures range from one to two, while for 3D volumetric objects they range from two to three [4]. In ultrasonography, FD quantifies textural roughness and structural complexity from grayscale intensity variations. Malignant tissues, which are often characterised by disorganised growth patterns, irregular cellular arrangements, and increased angiogenesis, typically exhibit greater architectural complexity and therefore higher FD values compared with normal or benign tissues, which tend to be more homogeneous and organised [5,6]. Despite its promise, a critical question remains unexplored: to what extent does the physiological state of the bladder, whether full or empty, affect the fractal properties of the prostate and the accuracy of FD-based predictive models? Current clinical guidelines regarding bladder filling during prostate ultrasonography are inconsistent; some recommend a moderately filled bladder to improve the acoustic window, while others provide limited guidance [7]. This inconsistency largely reflects a lack of empirical evidence, with recommendations often based on qualitative assessments of image quality rather than quantitative measures of accuracy [8].

Several studies have successfully employed FD analysis to differentiate between benign and malignant tissues in organs such as the thyroid, breast, and prostate by quantifying the underlying architectural disorganisation associated with malignancy [5,6]. Previous studies reported that bladder filling protocols are applied inconsistently in prostate imaging and radiotherapy [9], with most evidence focusing on qualitative image quality rather than quantitative measurement accuracy. However, to date no study has systematically investigated how bladder filling status affects FD-based analysis in prostate imaging. Evidence from related imaging domains further highlights the importance of this issue. For instance, studies have demonstrated that rectal filling can affect prostate measurements on magnetic resonance imaging, underscoring the broader impact of physiological variability on quantitative assessments [10]. Studies have explored FD-based

models for prostate imaging and volume prediction [11]. Quantitative imaging studies have also employed matched-pairs designs and robust statistical frameworks to ensure reliability and reproducibility of results [12,13]. Hence, the present study aimed to evaluate whether bladder filling status significantly affects the accuracy of an exponential regression model used to predict prostate volume from FD values. Second, the null hypothesis was tested to understand statistically significant differences in the FD of the prostate gland before and after voiding.

MATERIALS AND METHODS

A cross-sectional study using a matched-pairs (within-subject) design was conducted at the Department of Radiology, Chalmeda Anand Rao Institute of Medical Sciences, Telangana, India, from September 2025 to December 2025. This design was selected to eliminate inter-subject variability; as each participant served as his own control, we could isolate the specific impact of urinary bladder filling on prostate FD, volume prediction and morphological complexity. The study was conducted in accordance with the National Ethical Guidelines, and formal prior clearance was obtained from the Institutional Ethical Committee (IEC Certificate No: CAIMS/IEC/PhD/003/2025).

Inclusion criteria: Patients (age above 40) referred for prostate ultrasonography due to Lower Urinary Tract Symptoms (LUTS) or elevated Prostate-Specific Antigen (PSA) levels were included.

Exclusion criteria: Patients with a history of prior prostate surgery, active urinary tract infections, or significant pelvic structural abnormalities that could distort the prostate's baseline morphology.

Sample size: A total of 21 male participants were recruited from the Chalmeda Anand Rao Institute of Medical Sciences, Telangana, India, using purposive sampling. As this was a pilot study, all eligible patients who fulfilled the predefined inclusion and exclusion criteria and were available during the study period were consecutively recruited. A matched-pairs (within-subject) design was employed, wherein each participant served as his own control, thereby reducing inter-individual variability.

Study Procedure

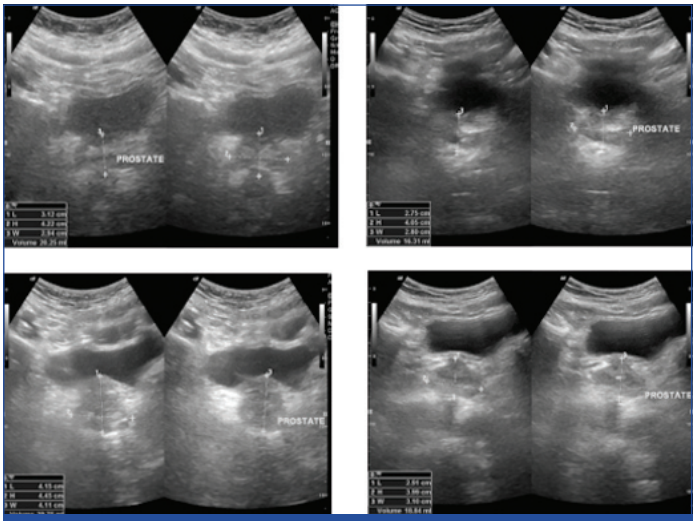
Image acquisition protocol: Each participant underwent two transabdominal ultrasound sessions during a single visit using the GE VOLUSON S8T BT18 (US8809649) ultrasound system with a convex array transducer operating at 3.5 MHz. For the full bladder scan, participants were instructed to drink one litre of water approximately one hour before the examination and to refrain from voiding. Immediately after completing the first scan, participants were asked to empty their bladders, and an empty-bladder scan was performed within five minutes. The patient's posture during scanning was maintained in the supine position. A curvilinear (convex) probe was placed on the lower abdomen, just above the pubic bone in the suprapubic region, to obtain optimal visualisation. Imaging was performed in the axial plane. The Region of Interest (ROI) included the entire prostate gland, located inferior to the neck of the urinary bladder. All images were acquired and stored in Digital Imaging and Communications in Medicine (DICOM) format. Equipment consistency was ensured through proper calibration prior to imaging. All ultrasound examinations were performed by the same experienced sonographer to minimise operator-dependent variability. The ellipsoid formula (ϖ/6×width×height×length) was used to compute the standard prostate volume [14].

Fractal Dimension (FD) calculation: The ROI encompassing the entire prostate gland was manually segmented on a mid-gland transverse image by two experienced radiologists who were blinded to the bladder filling status. For each ROI, the FD was calculated using the widely established box-counting method [15] implemented in Python [16]. The procedure involved first converting the grayscale image to a binary image using Otsu's thresholding [17]. A grid of boxes of size *s* was then applied, and the number of boxes, N(s), containing part of the prostate outline was counted. This process was repeated for progressively smaller box sizes, and the FD was estimated as the negative slope of the linear regression line on the log-log plot of N(s) versus 1/s [15].

Mathematical modelling for volume prediction: An exponential decay model was chosen for its ability to capture non linear relationships between complexity (FD) and volume (BV):

$$f(x)=a\times\exp(-b\times x)+c$$

where a, b, and c are the model parameters, and x is the FD value. The curve-fitting function in the Python SciPy library was used for parameter optimisation, employing a least-squares minimisation approach to fit the model to the data for each bladder condition separately [18]. Representative examples of prostate ultrasonography before and after voiding of the bladder [Table/Fig-1]. These images are provided for illustrative purposes only and do not represent study outcomes.



[Table/Fig-1]: Figure of prostate ultrasonography before and after voiding of the urinary bladder.

Pseudocode for computational methods: The computational workflow for FD calculation, volume prediction, and statistical analysis is implemented in Python [18]. The key steps are presented below as pseudocode to ensure reproducibility [19]. The workflow encompasses three main components. First, the box-counting FD algorithm quantifies the complexity of prostate tissue from segmented ultrasound images [15,16]. Second, an exponential regression model is fitted to predict prostate volume from FD values using non linear least squares optimisation [11,18]. Third, statistical analyses, including paired and unpaired tests as well as bootstrap resampling [12], are performed to evaluate differences in FD and model accuracy across full and empty bladder conditions. The detailed pseudocode for each step is available in the supplementary material [Supplementary data].

Error metric and statistical analysis: The primary outcome for prostate volume prediction was assessed using the Root Mean Squared Error (RMSE), calculated as:

$$RMSE=\sqrt{(\Sigma\ (y\_actual-y\_predicted)^2/n)}$$

For the FD comparison, the primary outcome was the direct comparison of FD values between full and empty bladder states.

STATISTICAL ANALYSIS

For unpaired comparisons of RMSE, independent samples t-tests with Welch's correction were used, while paired t-tests were applied to matched FD values. Non parametric tests, including the Mann-Whitney U test (unpaired) and Wilcoxon signed-rank test (paired), were performed to confirm results without assuming normality. Additionally, bootstrap resampling with 10,000 iterations was conducted to generate confidence intervals for the mean

differences in RMSE and FD [12]. Effect sizes were quantified using Cohen's d to evaluate the magnitude of differences independent of sample size. All statistical analyses were performed in Python 3.8 using SciPy (version 1.10.1), NumPy (version 1.24.3), and statsmodels (version 0.14.0) libraries [18], with a significance threshold (α) established at 0.05.

RESULTS

The study population consisted of 21 male participants with a mean age of 52.58±5.43 years. The mean FD was identical across both conditions, at 1.52 with a standard deviation of 0.03 [Table/Fig-2].

Condition	N	Mean FD	Std. Dev.	Range
Full	21	1.5204	0.035	1.43-1.58
Empty	21	1.5157	0.037	1.41-1.57

[Table/Fig-2]: Fractal Dimension (FD) characteristic statistics.

Volume prediction model performance: The exponential model was successfully fitted to both the full- and empty-bladder datasets. Optimal model parameters differed substantially, reflecting the model's adaptability to different data distributions:

- Full Bladder: $a=1.7705\times10^{3}$, $b=2.1163\times10^{-3}$, $c=-1.7596\times10^{3}$
- Empty Bladder: $a=3.1325\times10^{-61}$, $b=-8.8173\times10^{1}$, $c=5.0951$

Despite these parameter differences, prediction accuracy was nearly identical, with Root Mean Square Error (RMSE) values of 0.4071 for the full bladder and 0.4106 for the empty bladder. The absolute difference in RMSE was 0.0035, corresponding to a negligible relative difference of 0.86%. These results indicate that the model is robust to bladder filling status.

Statistical comparison of RMSE and FD: The statistical comparisons of RMSE and FD showed consistent and unequivocal findings across parametric, non parametric, and bootstrap analyses. All methods demonstrated no significant differences between the compared conditions, confirming the robustness of the results. These findings indicate that the observed RMSE and FD values are stable across statistical approaches, as summarised in [Table/Fig-3,4], respectively.

Test	Statistic value	p-value
Independent t-test	t=0.1584	0.8743
Mann-Whitney U test	U=1098.5	0.8865
Bootstrap analysis (mean difference 95% Confidence Interval)	(-0.0421, 0.0488)	p=0.8914

[Table/Fig-3]: Results of statistical tests for RMSE difference.

Test	Statistic value	p-value
Paired t-test	t=0.1612	0.8721
Wilcoxon signed-rank test	W=110.5	0.8872

[Table/Fig-4]: Results of statistical tests for FD difference (Paired).

All p-values were far above the significance threshold of 0.05, providing overwhelming support for the null hypothesis that there is no difference between the two bladder conditions.

Effect size and power analysis: The calculated Cohen's d for RMSE differences was 0.0086, which is orders of magnitude below the threshold for a 'small' effect (d=0.2), indicating that the observed difference is negligible in practical terms. A post-hoc power analysis showed that, with 21 matched samples, the investigation has adequate power (>0.8) to detect a medium effect size (d=0.5). The study was therefore adequately powered to detect a medium or larger effect but, by design, would not be expected to detect the trivial difference observed (d=0.0086). Overall, these findings suggest that prostate FD and volume predictions are robust to variations in bladder filling, supporting flexible imaging protocols in clinical practice.

DISCUSSION

The present study provides compelling evidence that urinary bladder filling status is not a confounding factor in FD-based analysis of the prostate gland, either for direct quantification of tissue complexity or for volume prediction modelling. The most plausible explanation for these results is that FD captures an intrinsic property of the prostate tissue's architecture- its textural complexity [4,15]. While gross mechanical compression from a full bladder may alter the gland's shape and size, it does not fundamentally change its underlying textural pattern as visualised by ultrasound [8,20]. The present study results align with studies that differentiate tissue types using FD [1,7] by confirming that FD is a robust marker of tissue architecture.

Furthermore, FD should not be viewed as a standalone metric but as a feature within a broader diagnostic framework; future studies should integrate FD with clinical and imaging biomarkers, including PSA levels, patient age, and other radiomic features, to develop machine learning-based classifiers. From a clinical workflow perspective, these findings suggest refining the bladder-filling protocol for quantitative analyses. Finally, extending this investigation to other quantitative imaging biomarkers across modalities would help determine broader applicability.

Limitation(s)

While the sample size was adequate to detect clinically significant differences, larger multicentre trials might improve generalisability. The use of transabdominal ultrasound, while standard for volume estimation, introduces greater variability in segmentation than Transrectal Ultrasound (TRUS). Future investigations should assess whether similar robustness is observed with TRUS for more precise segmentation and explore correlations between FD stability and specific pathological states, such as BPH and prostate cancer. Additionally, the impact of bladder filling on other quantitative imaging biomarkers warrants further investigation. Explore the use of machine learning models on top of FD features for classification tasks.

CONCLUSION(S)

The present study conducted a rigorous investigation to determine whether bladder filling status influences FD measurements and FD-based prostate volume prediction. The findings demonstrate that bladder volume has a minimal and statistically insignificant effect on both the FD of the prostate gland and the accuracy of an exponential regression model for volume estimation. Although the exponential models were parameterised differently under each condition, their nearly identical RMSE values confirm that predictive performance is preserved regardless of bladder status. These results provide strong quantitative evidence that strict bladder preparation is unnecessary for FD-based prostate analysis, paving the way for more flexible, efficient, and patient-friendly imaging protocols without sacrificing analytical rigour.

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