Original Article
Prostate cancer

pISSN: 2287-4208 / eISSN: 2287-4690
World J Mens Health Published online Sep 17, 2025
https://doi.org/10.5534/wjmh.250139

The World Journal of MEN's HEALTH

Systematic Measurement of Membranous Urethral Length Using a Cross-Reference System: A Study on Interrater Variability

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Purpose: To evaluate the effectiveness of a cross-reference system (CRS) in improving the reproducibility of membranous urethral length (MUL) measurements by reducing the interrater variability.
Materials and Methods: A total of 100 patients who underwent robot-assisted radical prostatectomy (RARP) and preoperative MRI were enrolled. MUL measurements were independently performed by two urologists with different levels of experience, both before and after CRS implementation. The radiological reference MUL served as the baseline for comparison. Interrater variability and agreement with the radiological reference were assessed.
Results: Mean MUL values measured by both raters and the radiological reference showed no significant difference after CRS implementation. However, interrater measurement error was substantially reduced after CRS implementation, and Bland–Altman analysis demonstrated markedly narrower limits of agreement. At 6 months, preoperative MUL showed no significant association with continence (area under the curve [AUC] and Brier score unaffected by CRS). By 12 months, MUL remained a significant predictor of continence (unadjusted odds ratio [OR]: 0.79, p=0.003; adjusted OR: 0.76, p=0.001), and CRS modestly improved discrimination (ΔAUC +0.02) and calibration (ΔBrier: -0.01).
Conclusions: A systematic CRS-based measurement approach improved MUL reproducibility by reducing interrater variability. These findings emphasize the need for standardized MUL measurements to enhance the anatomical accuracy and continence prediction after RARP.

Keywords: Interrater variability; Magnetic resonance imaging; Membranous urethral length; Robot-assisted radical prostatectomy

INTRODUCTION

Robot-assisted radical prostatectomy (RARP) has become a cornerstone in prostate cancer treatment. Among postoperative complications, urinary incontinence remains a significant concern, as it not only

Received: Apr 23, 2025 **Revised:** Jul 4, 2025 **Accepted:** Jul 6, 2025 **Published online** Sep 17, 2025
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affects patients' quality of life but also contributes to psychological conditions such as depression and anxiety [1]. Anatomical factors, patient characteristics (*e.g.,* age, preexisting lower urinary tract symptoms, and body mass index), and surgical techniques (*e.g.,* nerve-sparing procedures) can influence the risk of postoperative incontinence [2,3]. Recent studies have highlighted the preoperative membranous urethral length (MUL) as a critical factor in the development of urinary incontinence following RARP [4-8]. Preservation of maximal MUL during RARP is therefore essential not only for maintaining the urethral sphincter mechanism and reducing postoperative incontinence but also for underscoring the need for accurate, patient-specific assessment of this critical anatomical factor.

Preoperative MUL, a unique patient-specific anatomical characteristic, correlates with the risk of postoperative urinary incontinence. Advances in magnetic resonance imaging (MRI) have provided high-resolution imaging, enabling a more accurate assessment of anatomical structures, including MUL. However, despite these advancements, standardized methods for measuring MUL are lacking, and research investigating the reproducibility of MUL measurements is limited. Previous studies have reported considerable variability in MUL measurements among researchers, with some using the sagittal plane and others using the coronal plane or a combination of both; in some cases, the measurement methods were not clearly defined [4,6-12]. The incorporation of a pretreatment incontinence risk assessment, with the MUL as a key parameter, into treatment decision-making is increasingly recognized for its potential impact on urological surgical practices [13].

This study aimed to propose a systematic method for MUL measurements using a cross-reference system (CRS) to establish a more reliable anatomical index, minimize interrater variability, and enhance the accuracy and reproducibility of MUL measurements.

MATERIALS AND METHODS

After Institutional Review Board (IRB) approval, a retrospective review of 123 patients who underwent RARP with preoperative prostate MRI between 2023 and 2024 was conducted. Among them, MRIs performed using individual protocols from external institutions were excluded. The MRIs included in the study was performed using a 3.0 Tesla system (Intera Achieva 3.0 T, Philips Medical System) equipped with a six-channel phased-array coil (Supplement Material 1). The MRI protocol included both diffusion- and T2-weighted imaging. T2-weighted turbo spin-echo sequences were obtained in the axial, sagittal, and coronal planes. All datasets were acquired at identical slice locations, with a slice thickness of 3 mm and no gaps between slices. Two b-values (0–1,400) were applied, and the diffusion restriction was assessed using apparent diffusion coefficient mapping. Additionally, dynamic contrast-enhanced MRI was performed. All prostate MRI images were reviewed by an experienced urologic radiologist and graded using the Prostate Imaging Reporting and Data System, version 2.1 (PI-RADS v2.1) criteria [14].

The preoperative MUL, defined as the distance from the superior border of the penile bulb to the inferior aspect of the prostate apex, was measured using the CRS on prostate MRI, based on a predetermined standardized protocol. The CRS is a method for measuring MUL on MRI using the coronal and serial sagittal planes, including the midsagittal plane configured perpendicular to the prostate as a reference point. Corresponding sagittal- and coronal-plane coordinates are identified at the same anatomical location. Four to ten planes, including mid-sagittal and para-sagittal, were analyzed depending on the curvature of the prostate apex and penile bulb. This approach facilitates the precise identification of anatomical landmarks required for MUL measurements while allowing for easier recognition of curvature changes in the prostate apex and penile bulb (Fig. 1). Additional details on the measurement methods are provided in Supplement Fig. 1–3 (Supplement Material 2).

The reference MUL was initially measured during a radiology consultation. Subsequently, two urologists, one with 14 years of experience (JKK as rater A) and one with 2 years of experience (SEB as rater B), independently measured the MUL in a randomized order to minimize potential bias. Initial measurements were performed using a preoperative prostate MRI in the sagittal plane. After a washout period of approximately 3 months, the MUL was remeasured using the CRS. The measurements were then compared and analyzed.

All statistical analyses, including the Bland–Altman analysis [15,16], were conducted using R (version 4.3.2; R Foundation for Statistical Computing) and Python (version 3.11, Python Software Foundation). Numeri-

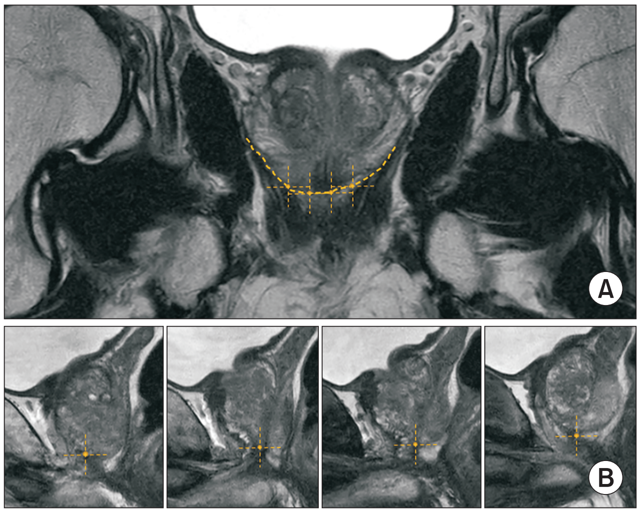

Fig. 1. Cross-reference system (CRS) for identifying anatomical landmarks of membranous urethral length (MUL) in mid- and serial parasagittal planes. The CRS aids in the precise identification of anatomical landmarks necessary for MUL measurement by providing spatial coordinates across serial mid-/para-sagittal and coronal planes. (A) The coronal plane allows for the recognition of the continuous curvature of the prostate apex, helping to identify the MUL landmark. (B) By correlating these findings with corresponding coordinates in serial sagittal planes, the anatomical boundaries essential for accurate MUL measurement can be confirmed. The same approach can also be applied to identify and measure the penile bulb landmark, ensuring a comprehensive assessment of MUL.

Table 1. Baseline patient characteristics

	Value
No. of patients	100
Age (y)	69.5±6.2
BMI (kg/m^2)	24.7±2.7
PSA (ng/mL)	10.9±9.7
Prostate volume (mL)	39.7±11.5
Gleason score	
6	20
7	55
≥8	25
Lymph node dissection	
Not performed	75
Unilateral	8
Bilateral	17
Nerve sparing	
Not performed	8
Unilateral	7
Bilateral	85
Console time (min)	164±41.3
Intraoperative bleeding (mL)	232±165
Extracapsular extension	36
Seminal vesicle invasion	19
Positive resection margin	34

Values are presented as mean±standard deviation.
BMI: body mass index, PSA: prostate-specific antigen.

cal analyses, including multivariate logistic regression for 6- and 12-month incontinence prediction, were performed in R using the base stats package, broom for tidying model outputs, pROC for receiver operating characteristic (ROC)/area under the curve (AUC) calculations, and DescTools for Brier scores. Intraclass correlation coefficient (ICC) and ΔICC computations were conducted in R with readxl for data import and irr for reliability analysis. Visualizations were generated in Python using NumPy for data manipulation, Matplotlib for plotting, and Seaborn for enhanced graphics. Two-sided p-values <0.05 were considered statistically significant.

This study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki (2013). Ethical Approval: This study was approved by the IRB under approval number 3-2024-0257. The requirement to obtain informed consent was waived.

RESULTS

One hundred patients with measurable MUL on prostate MRI were enrolled. The mean age of the participants was 69.5±6.2 years, and the mean prostate-specific antigen level and prostate volume were 10.9±9.7 ng/mL and 39.7±11.5 mL, respectively (Table 1). In the MUL measurements obtained before and after applying the CRS, together with variability analysis based on the radiological reference, no statistically significant differences were observed between the mean MUL values obtained initially without CRS and those obtained after CRS implementation (p=0.52 and p=0.27, respectively) (Supplement Table 1).

To examine the MUL measurements distribution from the radiological reference and individual raters, MUL values for all patients were sorted in ascending order and visualized graphically. A comparison of the measurements before and after using the CRS is shown in Fig. 2. MUL measurements obtained using the CRS aligned more closely with the radiological reference than the initial measurements. Additionally, the variability between the two raters decreased after CRS implementation.

The application of CRS markedly enhanced inter-rater agreement across all comparisons (Table 2). All

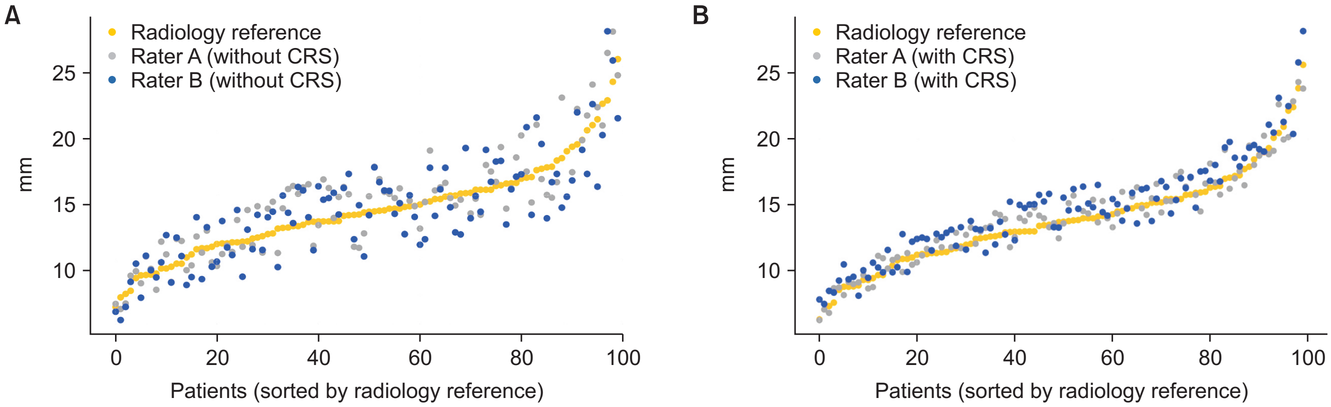

Fig. 2. Distribution of membranous urethral length (MUL) measurements by raters before and after using the cross-reference system (CRS). Effect of CRS on MUL measurement reproducibility. (A) MUL measurements without CRS: Scatter plot showing initial MUL measurements by two raters A and B compared to the radiology reference. The measurements show high interrater variability, particularly for rater B. (B) MUL measurements with CRS: after CRS application, measurements align more closely with the radiology reference, indicating reduced variability and improved reproducibility.

Table 2. Intraclass correlation coefficients (ICCs) for interrater agreement with and without CRS

ICC pair	Without CRS	With CRS	ΔICC	Interpretation
Radiology *vs.* rater A	0.875 (0.812–0.917)	0.964 (0.942–0.977)	+0.089	Good → Excellent
Radiology *vs.* rater B	0.828 (0.755–0.881)	0.939 (0.746–0.975)	+0.111	Moderate → Excellent
Rater A *vs.* rater B	0.902 (0.850–0.936)	0.920 (0.870–0.950)	+0.018	Good → Good

ICC (2, 1): two-way random-effects, absolute-agreement, single measure, all p<0.001.
CRS: cross-reference system.

ICCs were calculated using a two-way random-effects, absolute-agreement, single-measure model (ICC [2,1]) and were statistically significant (p<0.001). Without CRS, the ICC between radiology and rater A was 0.875 (95% CI, 0.812–0.917), which increased to 0.964 (95% CI, 0.942–0.977) after CRS (ΔICC, +0.089), shifting agreement from "good" to "excellent." Similarly, radiology *versus* rater B showed an ICC of 0.828 (95% CI, 0.755–0.881) without CRS and 0.939 (95% CI, 0.746–0.975) with CRS (ΔICC, +0.111), improving from "moderate" to "excellent." Agreement between rater A and rater B was already "good" at baseline (ICC, 0.902; 95% CI, 0.850–0.936) and further increased to 0.920 (95% CI, 0.870–0.950; ΔICC, +0.018), remaining within the "good" range.

As shown in Table 3, preoperative MUL demonstrated only a modest, non–statistically significant association with 6-month incontinence when measured by the radiology reference (unadjusted odds ratio [OR], 0.90; 95% CI, 0.79–1.01; p=0.078; adjusted OR, 0.89; 95% CI, 0.79–1.01; p=0.076). Among the rater-based measurements without CRS, only rater A reached significance (unadjusted OR, 0.89; 95% CI, 0.80–0.99; p=0.037; adjusted OR, 0.89; 95% CI, 0.80–0.99; p=0.038), whereas all other assessments at 6 months fell short of p<0.05. Model discrimination at 6 months was modest (AUC range, 0.62–0.69) and calibration acceptable (Brier scores, 0.186–0.192), with CRS yielding negligible changes in ORs, AUCs, or Brier scores.

In contrast, MUL was a consistent and significant predictor of 12-month incontinence across all measurement methods. The radiology reference showed unadjusted OR, 0.79 (95% CI, 0.68–0.92; p=0.003) and adjusted OR, 0.76 (95% CI, 0.64–0.89; p=0.001), with discrimination improving from AUC 0.70 to 0.77 and calibration from Brier 0.187 to 0.167. Both rater A and rater B—whether with or without CRS—also yielded unadjusted ORs between 0.82 and 0.87 (all p≤0.05) and adjusted ORs between 0.78 and 0.84 (all p≤0.010). After introducing CRS, unadjusted AUC increased from 0.64 to 0.68 for rater A and from 0.64 to 0.69 for rater B, while Brier scores fell from 0.198 to 0.191 and from 0.200 to 0.190, respectively. In the adjusted models, AUC increased from 0.73 to 0.75 for rater A and from 0.73 to 0.76 for rater B, with Brier scores decreasing from 0.178 to 0.169 and from 0.179 to 0.170. These shifts reflect im-

Table 3. Membranous urethral length as a predictor of 6- and 12-month incontinence: unadjusted and adjusted ORs, AUC, and Brier scores

		Unadjusted				Adjusted[a]			
		OR (95% CI)	p-value	AUC	Brier score	OR (95% CI)	p-value	AUC	Brier score
Measure (6 mo)									
Radiology reference		0.90 (0.79–1.01)	0.078	0.62	0.191	0.89 (0.79–1.01)	0.076	0.66	0.187
Without CRS	Rater A	0.89 (0.80–0.99)	0.037	0.65	0.189	0.89 (0.80–0.99)	0.038	0.69	0.186
	Rater B	0.89 (0.80–1.00)	0.055	0.62	0.190	0.89 (0.80–1.00)	0.059	0.68	0.187
With CRS	Rater A	0.89 (0.78–1.01)	0.066	0.62	0.191	0.89 (0.78–1.00)	0.059	0.67	0.187
	Rater B	0.91 (0.81–1.02)	0.097	0.62	0.192	0.90 (0.80–1.02)	0.088	0.66	0.188
Measure (12 mo)									
Radiology reference		0.79 (0.68–0.92)	0.003	0.70	0.187	0.76 (0.64–0.89)	0.001	0.77	0.167
Without CRS	Rater A	0.87 (0.77–0.98)	0.021	0.64	0.198	0.84 (0.73–0.96)	0.009	0.73	0.178
	Rater B	0.87 (0.77–0.99)	0.029	0.64	0.200	0.84 (0.73–0.96)	0.010	0.73	0.179
With CRS	Rater A	0.82 (0.71–0.94)	0.005	0.68	0.191	0.78 (0.67–0.91)	0.002	0.75	0.169
	Rater B	0.82 (0.71–0.94)	0.005	0.69	0.190	0.79 (0.68–0.92)	0.002	0.76	0.170

OR: odds ratio, CI: confidence interval, AUC: area under the curve.
[a]Adjusted models include age, LND, operation time (min), and NS as covariates.

proved predictive accuracy—both better separation of incontinent *versus* continent patients and tighter probability calibration—at 12 months after CRS implementation. Taken together, preoperative MUL is a robust independent predictor of long-term continence, showing its strongest performance at 12 months in models adjusted for age, lymph node dissection, operation time, and nerve-sparing status, and the introduction of CRS further enhances its predictive precision.

To further analyze these findings, a Bland–Altman analysis was performed to calculate the 95% limits of agreement (LOA) and mean difference (bias) for each comparison. Before using the CRS, rater A and B had an LOA upper limit of 3.9 mm, LOA lower limit of -2.8 mm, and bias of 0.54 mm. For the radiological reference and rater A, the LOA upper and lower limits were 3.1 and -4.2 mm, respectively, and the bias was -0.57 mm. For the radiological reference and rater B, the LOA upper and lower limits were 4.3 and -4.4 mm, respectively, and the bias was -0.03 mm (Fig. 3).

Following CRS implementation, LOA and bias improved significantly. For rater A and B, the LOA and bias were reduced to an LOA upper limit of 2.2 mm, LOA lower limit of -3.3 mm, and bias of -0.52 mm. For the radiological reference and rater A, the LOA upper and lower limits were 1.5 and -2.1 mm, respectively, and the bias was -0.32 mm. For the radiological reference and rater B, the LOA upper and lower limits were 1.2 and -2.8 mm, respectively, and the bias was -0.84 mm (Fig. 4).

DISCUSSION

Accurate MUL measurement has several limitations. Significant challenges include difficulties defining the superior limit (*e.g.*, abnormal peripheral zone intensity or signal intensity in the retroprostatic rectovesical space resembling the peripheral zone) and the inferior limit (*e.g.*, difficulty delineating the correct penile bulb contour on the midsagittal slice, continuity of rhabdosphincter fibers into the prostate, angulated membranous urethra, and cross-linking errors between sagittal and coronal images) [17,18]. Therefore, a thorough understanding of the membranous urethra and surrounding anatomy is essential. Accurate identification of the midsagittal plane and precise recognition of anatomical landmarks are critical for reliable MUL measurements. However, consistently setting the correct midsagittal plane and including all necessary landmarks within the plane on MRI is challenging [19]. This limitation increases the potential for interrater variability during intuitive measurements and even intrarater variability, depending on the timing of the assessment. These challenges underscore the need for a systematic and standardized MUL measurement approach.

This study demonstrates that a systematic measurement system for anatomical indices can effectively reduce the interrater variability. While a simple comparison of mean MUL values before and after CRS implementation showed slight reductions in p-values, no statistically significant differences were observed

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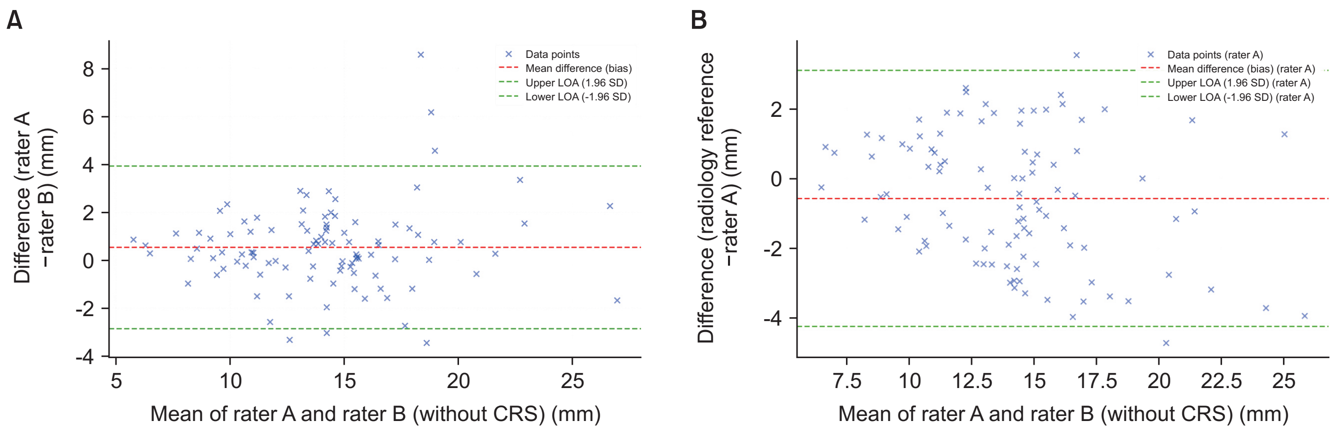


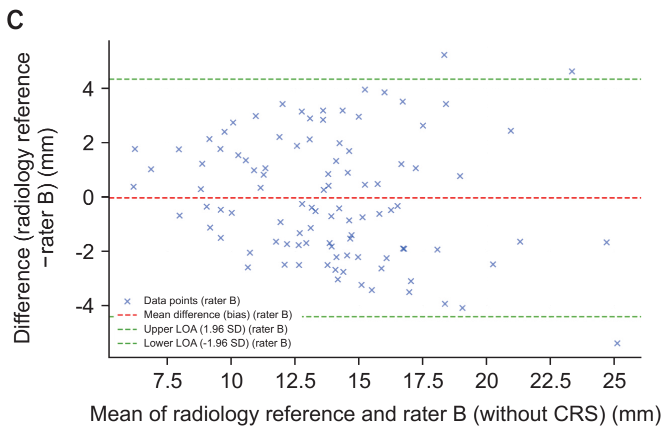
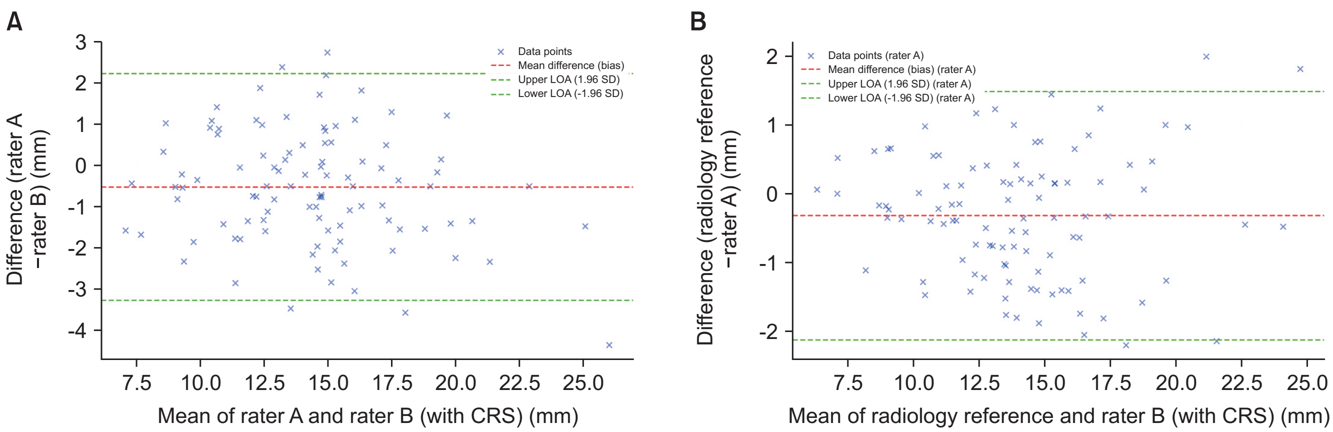


Fig. 3. Bland-Altman plot before using the cross-reference system (CRS). Bland-Altman plot comparing initial membranous urethral length (MUL) measurements between two raters and the radiology reference before applying the CRS. The red dashed line represents the mean difference (bias), while the green dashed lines indicate the 95% limits of agreement (LOA). Wide dispersion suggests significant interobserver variability. Comparison with the radiology reference shows measurement discrepancies and high variability before CRS implementation, particularly in measurements of rater B. The larger data dispersion in rater B highlights the inconsistency in MUL assessment without CRS. (A) Comparison between rater A *vs.* B. (B, C) Radiology reference *vs.* rater A and B (before using CRS).



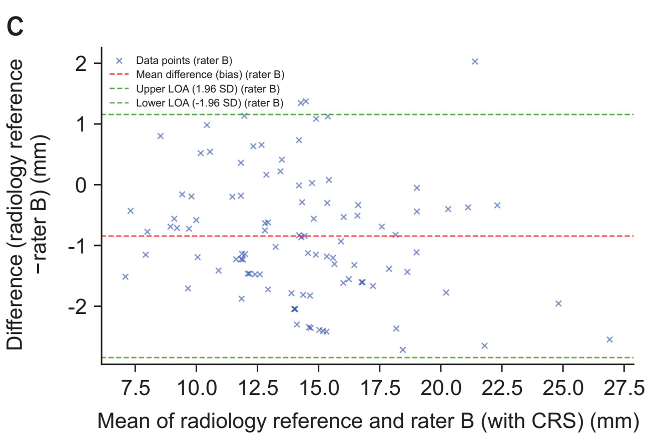


Fig. 4. Bland-Altman plot using the cross-reference system (CRS). Bland-Altman plots comparing membranous urethral length (MUL) measurements after applying the CRS. The red dashed line represents the mean difference (bias), while the green dashed lines indicate the 95% limits of agreement (LOA). After CRS implementation, bias is reduced, and the limits of agreement are narrower, indicating improved measurement consistency. Interrater variability is significantly lower, and measurements align more closely with the radiology reference, showing reduced bias and improved agreement compared to initial measurements without using CRS. (A) Comparison between rater A *vs.* B. (B, C) Radiology reference *vs.* rater A and B (using CRS).

among the three groups (Supplement Table 1). This suggests that even without the reference system, average MUL measurements may appear similar across groups. However, an analysis of the interrater variability revealed that the initial measurements could differ by up to approximately ±4 mm, with discrepancies between observers of nearly 8 mm (Fig. 3). After CRS implementation, interrater measurement error (defined as 1-ICC) was reduced by approximately 71% between the radiology reference and rater A (from 12.5% to 3.6%), by 65% between the radiology reference and rater B (from 17.2% to 6.1%), and by 18% between raters A and B (from 9.8% to 8.0%). In parallel, Bland–Altman LOA narrowed by roughly 51% to 54% across comparisons, for example from a 7.3 mm width to 3.6 mm between the radiology reference and rater A and from 8.7 mm to 4.0 mm between the radiology reference and rater B (Table 2, Fig. 4). These findings indicate that the use of the CRS not only enhanced the agreement between observer measurements and the radiological reference but also reduced the variability between the two observers. Such differences are substantial, as previous studies have shown that MUL variations of this magnitude can significantly affect urinary-related statistical outcomes. For example, Song et al [5] reported that preoperative MUL differences of approximately 2.5 mm and postoperative differences of approximately 1 mm are associated with urinary incontinence outcomes in patients undergoing RARP. Similarly, other studies have suggested that a significant preoperative MUL difference among patients with incontinence is approximately 2 mm [20], with most studies reporting differences of <4 mm [6-12]. Given the inherent limitations of manual MUL measurements, such variability has the potential to significantly influence the overall research findings. We also demonstrated that introducing the CRS for MUL measurement led to improvements in interrater reliability (ΔICC), model discrimination (ΔAUC), and calibration (ΔBrier score). Although these gains were modest, they nevertheless represent meaningful improvements in predictive performance that can aid in individualized patient counseling and risk stratification for long-term continence (Table 2). Moreover, the observed narrowing of LOA after CRS implementation, together with the simultaneous migration of ICC categorizations from moderate or good to excellent, vividly illustrates that systematic use of CRS in MUL measurement significantly curtails interrater variability and bolsters both the precision and reproducibility of these assessments in routine clinical practice. This underscores the importance of adopting systematic, standardized approaches for MUL assessment.

Our analysis of CRS-guided MUL measurements (Table 3) revealed that in the early postoperative period (6 months after surgery), implementation of CRS did not materially improve discrimination or calibration; neither AUC nor Brier scores shifted meaningfully. This finding is consistent with previous reports suggesting that early continence recovery depends more on factors such as surgical technique, nerve-sparing quality, and individual healing trajectories than on measurement precision alone [21]. Barakat et al [21] further emphasized that restoration of continence early after prostatectomy is driven primarily by modifiable surgical factors, including nerve-sparing dissection, posterior urethral reconstruction, and bladder-neck or Retzius-sparing approaches, while anatomical measurements may play a secondary role. In contrast, at 12 months, both discrimination and calibration exhibited modest yet consistent enhancements with CRS. Brier scores declined, indicating tighter probability calibration, and AUC increased, reflecting improved separation of continent *versus* incontinent outcomes. Consequently, while CRS-driven refinement of MUL measurement may have limited influence on early continence prediction, it provides a measurable benefit for longer-term outcome forecasting.

This study has several limitations. First, the sample size of the patient population was relatively small, which may have limited statistical power. We explicitly acknowledge that interrater reproducibility was assessed using only two urologists at a single center, thereby restricting the generalizability of our findings across different institutions and levels of experience. Moreover, although the systematic CRS demonstrated clear potential to reduce variability in MUL measurements, the CRS methodology itself has not yet been fully optimized. Further research is needed to refine and standardize CRS-guided MUL measurement protocols before broad implementation. External validation is therefore required: future studies should enroll a larger, more diverse patient cohort from multiple centers with varying MRI protocols, include a broader panel of raters spanning different expertise levels, and incorporate standardized training in CRS methodology. We suggest that a prospective multicenter study with an expanded rater pool and harmonized measurement procedures be undertaken to confirm the reproducibility and clinical utility of CRS-guided MUL assessment and to establish its role in improving postoperative continence prediction. Second, only two observers participated. Future studies should include more observers for robust validation. Additionally, the inclusion of more experienced urologists specializing in prostate cancer may further enhance reliability. Finally, although efforts were made to minimize bias in the MUL measurements through random selection and a washout period, measurements were still performed in a small, identical patient cohort, and completely eliminating potential bias was challenging.

Despite these limitations, this study is valuable as a collaborative effort with the radiology department to establish a systematic measurement methodology. Using a reference-based approach, this study effectively addressed the interrater variability in MUL measurements and proposed a structured method for improving the accuracy and reliability of such measurements. This methodological approach highlights the importance of advancing research in this field.

CONCLUSIONS

Implementing a systematic MUL measurement method using CRS, an anatomical factor associated with predicting urinary incontinence after RARP, is expected to improve reproducibility by reducing the interrater variability. Further studies are required to standardize MUL measurement methods and enhance their clinical applicability.

Conflict of Interest

The authors have nothing to disclose.

Funding

None.

Acknowledgements

None.

Author Contribution

Conceptualization: JK, JJ, DK, HSL, ESC, KSC. Data curation: JK, DK, HSL, ESC, KSC. Formal analysis: JK, KSC. Funding acquisition: JK, KSC. Investigation: JK, SB, KSC. Methodology: JK, SB, KSC. Project administration: JK, KSC. Resources: JK, Software: JK, JJ, DK KSC. Supervision: SS, DK, HSL. Validation: JK, SB, DK, HSL, ESC, KSC. Visualization: JK, KSC. Writing – original draft: JK, KSC. Writing – review & editing: JK, KSC.

Supplementary Materials

Supplementary materials can be found via https://doi.org/10.5534/wjmh.250139.

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