

Article

Prostate–Rectum Spacing from Apex to Base and Its Impact on Organs-At-Risk Dosimetry in Prostate Cancer SBRT

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Simple Summary

Biodegradable balloon spacers provide critical anatomical separation for the management of high-dose gradients during prostate SBRT. This study shows that achieving a prostate–rectum separation threshold of ≥ 14 mm enhances organ-at-risk sparing across all anatomical levels. Specifically, apical separation reduces radiation exposure to the penile bulb and rectum, while base-directed separation lowers the mean bladder dose. By ensuring uniform displacement from base to apex, the balloon spacer facilitates the reduction in dose–volume parameters for various organs. While the current cohort showed low rates of gastrointestinal and genitourinary toxicities, further long-term study is required to confirm these clinical outcomes given the limited follow-up period.

Abstract

Stereotactic body radiation therapy (SBRT) for localized prostate cancer delivers high doses per fraction, making dose constraints for the rectum and other organs at risk critical during treatment planning. This study evaluated the association between prostate–rectum separation, achieved with a biodegradable balloon rectal spacer at different anatomical levels, and corresponding organ-at-risk dose patterns. Thirty-three patients underwent transperineal balloon spacer implantation followed by SBRT to 36.25 Gy in five fractions. Prostate–rectum separation at the apex, mid-gland, and base were measured on CT and/or MRI and categorized as <10 mm, 10–14 mm, or ≥ 14 mm. Rectal dose–volume parameters and mean doses to the rectum, bladder, and penile bulb were assessed using linear regression analyses and group comparisons at 14 mm separation. Mean prostate–rectum separation was 16.6 mm overall, with minimal high-dose rectal exposure observed. Increasing separation was associated with reduced rectal dose–volume parameters at the apex and mid-gland, while greater base separation corresponded primarily to lower bladder mean dose. Increased apical separation was also associated with reduced penile bulb mean dose. No acute gastrointestinal toxicity was observed, and genitourinary toxicity was limited to low-grade events. These findings indicate that prostate–rectum separation varies by anatomical level and is associated with distinct organ-at-risk dose relationships in prostate SBRT.

Keywords: localized prostate cancer; stereotactic body radiation therapy; biodegradable balloon rectal spacer; prostate–rectum separation; organ-at-risk dose



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1. Introduction

Stereotactic body radiation therapy (SBRT) for localized prostate cancer requires strict adherence to dose–volume constraints to minimize the risks of radiation toxicity to adjacent organs at risk (OARs) [1–3]. Rectal spacers are effectively used for temporary physical rectal displacement to reduce radiation-induced toxicity and dose distribution to surrounding tissue [4–6]. Even with variabilities in rectal spacers distribution, they do generally provide significant dose reduction. While previous reports indicate an association between increased apical prostate–rectum spacing and reduced rectal toxicity [7,8], a question remains regarding the effect of space variability on dose distribution to other surrounding tissue at the cranial and caudal boundaries. Hence, non-uniformity in prostate–rectum spacing can limit rectal spacers' benefits, particularly when the apex is close to the penile bulb (PB) and the prostate base is in proximity to the bladder wall, which may lead to higher bladder and PB dose exposure [9]. Additionally, some works showed differences between spacer types and the uniformity of apical separation, whereby balloon spacers tend to produce more uniform apical separation compared to PEG hydrogels [10]. The purpose of this feasibility study is to further explore a hypothesized association between anatomical-level spacing and dose distribution to the bladder, PB, and rectum following a balloon rectal spacer placement.

2. Methods

2.1. Patients and Simulation

In the study population, 33 consecutive patients with low- or intermediate-risk localized prostate cancer (T1–T2N0M0) were enrolled and followed as per the National Comprehensive Cancer Network (NCCN) Clinical Practice Guidelines, version 2.2021 [11]. A patient's eligibility was based on multidisciplinary review for SBRT and spacer suitability and reflects real-world practices. Exclusion criteria included prior pelvic radiotherapy or metastatic disease. All 33 patients completed the implantation procedure successfully. Following IRB approval and consent, a biodegradable balloon spacer (BioProtect Balloon Implantation System) was positioned between the prostate and rectum under local anesthesia using transrectal ultrasound guidance [5]. Computed tomography (CT) simulations (Philips Healthcare, Best, The Netherlands) and Magnetic Resonance Imaging (MRI) simulations (1 mm slice; Siemens Healthcare GmbH, Erlangen, Germany) were done approximately one-week post-implantation with the patient in the supine position, having a full bladder and empty rectum.

2.2. Treatment Planning

Treatment planning was done using Eclipse (Varian Medical Systems, Palo Alto, CA, USA) and Pinnacle (Philips Medical Systems, Fitchburg, WI, USA). The prostate, OAR, and the balloon spacer were delineated on the planning CT. The rectum was contoured as a solid organ (full rectal volume) extending from the anus to the rectosigmoid flexure [12]. The clinical target volume (CTV) comprised the prostate and proximal 2 cm of seminal vesicles (SVs). The planning target volume (PTV) was generated by adding a margin of 3 mm posteriorly and 5 mm in all other directions around the CTV.

2.3. Radiotherapy

SBRT total dose of 36.25 Gy was delivered to the PTV in five fractions of 7.25 Gy each, to 95% of the PTV volume every alternate weekday. Dose constraints for OAR were $V_{36.25\text{ Gy}} < 5\%$, $32.625\text{ Gy} < 11\%$, $V_{29\text{ Gy}} < 20\%$, $V_{27.19\text{ Gy}} < 25\%$, and $V_{18.13\text{ Gy}} < 50\%$ for rectum, $V_{36.25\text{ Gy}} < 8\%$, $V_{18.13\text{ Gy}} < 40\%$, and $V_{37\text{ Gy}} < 5\text{ cc}$ for bladder, and $V_{29.5\text{ Gy}} < 50\%$ for penile bulb (PB). Cone-beam computed tomography

(CBCT) was obtained daily for patient setup verification, and at the completion of the SBRT course to evaluate spacer position stability and anatomical consistency throughout treatment.

2.4. Prostate–Rectum Separation

Prostate–rectum spacing was assessed in the axial plane at mid-gland (center of the CTV), apex, and base. The mid-gland was defined as the central slice of the contoured prostate [7]. To avoid partial-volume effects at the extremes of the gland, the apical plane was defined as 0.5 cm superior to the most caudal prostate slice and the base plane 0.5 cm inferior to the most cranial slice, as previously described [13]. On each axial plane, spacing was measured at the midline as the linear distance between the posterior prostate surface and the anterior rectal wall (Figure 1).

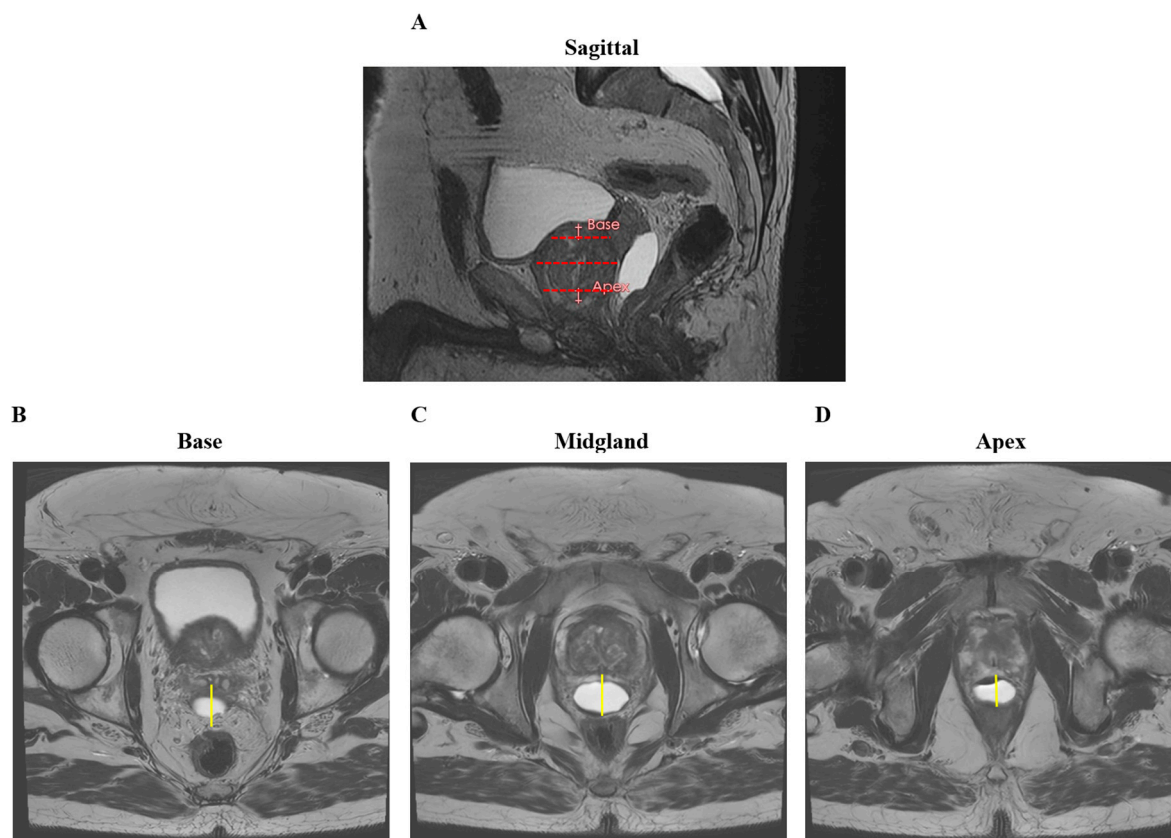


Figure 1. Sagittal MRI (A) and axial (B–D) MRI views showing prostate–rectum distance measurements at the base, mid-gland, and apex. Measurements were obtained at the rectal midline on axial MRI. Red dashed lines in (A) mark the base and apex reference levels; yellow lines in (B–D) indicate midline anteroposterior prostate–rectum separation.

All measurements were subsequently reviewed by a senior radiation oncologist, and standard anatomical definitions were strictly applied independently of dosimetric results.

2.5. Follow-Up Protocol

Patients were seen every 3–6 months after SBRT completion. Acute genitourinary (GU) and GI radiation toxicities occurring within 90 days after SBRT completion were confirmed based on the Common Terminology Criteria for Adverse Events (CTCAE) version 4.0, and included urinary frequency, retention, urgency, urinary tract pain, and incontinence occurring within 90 days after SBRT. Acute GI toxicity was defined as intestinal-related symptoms occurring within 90 days.

2.6. Statistical Analysis

Patients were stratified into three categories based on clinical benchmarks identifying 10–14 mm as the target separation for optimal rectal sparing [5,14,15]. The “medium” group was defined as within this range, while the “small” and “large” groups were <10 mm and ≥ 14 mm, respectively. These literature-based thresholds are used for illustrative purposes rather than being derived from current dataset optimization. Descriptive statistics summarized characteristics using mean and standard deviation (SD) or median and interquartile range (IQR). Linear regression was employed to evaluate dose–volume relationships (V18.25–V36.25 Gy) for the rectum, bladder, and penile bulb, with the coefficient of determination (R^2) used to quantify the proportion of dosimetric variance explained by anatomical spacing. To mitigate Type I error from multiple comparisons, a Holm–Bonferroni adjustment was applied to the 29.0 Gy analysis (ordered p -value cut-offs: 0.0133, 0.025, 0.05), while a strict $p < 0.01$ was maintained for other parameters to identify robust associations. The sample size ($n = 33$) provided 80% power to detect a large effect size of 1.24 at the $\alpha = 0.0133$ level. Secondary analyses utilized two-sided t -tests and 95% CIs for groups dichotomized at 14 mm.

3. Results

Thirty-three patients were included in the study. Table 1 shows the clinical characteristics, target and organ-at-risk volumes, prostate–rectum separation, and dosimetry parameters.

Table 1. Clinical characteristics and post-implant dosimetric parameters. Abbreviations: SD, standard deviation; IQR, interquartile range; PSA, prostate-specific antigen; IPSS, International Prostate Symptom Score; AUA, American Urological Association; DVH, dose–volume histogram; OAR, organ at risk.

Characteristics	Mean (SD)	Median (IQR)
Age (y)	72.12 (6.65)	73 (6.0)
PSA (ng/mL)	8.40 (3.78)	6.8 (5.3)
Gleason Score, n (%)		
6	10 (30.30%)	
7	18 (54.55%)	
≥ 8	5 (15.15%)	
Clinical T-Stage, n (%)		
T1c	18 (54.55%)	
T2a	9 (27.27%)	
T2b	6 (18.18%)	
IPSS Score	13.85 (7.14)	14.0 (11.0)
AUA symptom score, n (%)		
0	1 (3.03%)	
1–7 (mild)	13 (39.39%)	
8–19 (moderate)	16 (48.48%)	
20–35 (severe)	3 (9.09%)	
Target Volume (cc)		
Prostate	56.70 (15.46)	51.60 (17.27)
Bladder	293.29 (275.12)	160.8 (339.3)
Rectal	68.03 (20.96)	68.7 (23.66)
Post-Implant Rectal DVH (%)		
rV18.25 Gy	8.02 (3.68)	7.97 (4.04)
rV21.75 Gy	5.27 (3.11)	5.46 (4.04)
rV25.38 Gy	2.93 (2.59)	2.62 (2.72)
rV29 Gy	1.18 (1.30)	0.88 (1.88)
rV32.63 Gy	0.46 (0.78)	0.09 (0.61)
rV36.25 Gy	0.08 (0.22)	0.00 (0.04)

Table 1. Cont.

Characteristics	Mean (SD)	Median (IQR)
Post-Implant OAR Mean Dose Volume (%)		
Bladder	8.04 (3.77)	8.72 (5.29)
Penile Bulb	3.92 (3.09)	2.47 (3.36)
Rectal	6.71 (4.15)	5.91 (5.10)
Post-Implant Prostate–Rectum Separation (mm)		
Apical Distance	15.93 (4.30)	16.33 (5.22)
Mid-gland Distance	17.12 (4.69)	17.21 (6.10)
Base Distance	17.25 (8.05)	15.29 (7.55)
Average Distance	16.63 (3.55)	16.02 (3.82)

3.1. Prostate–Rectum Distance

Prostate–rectum distance varied across anatomical levels. At the apex, two-thirds of patients (67%) achieved ≥ 14 mm spacing, while 15% each had <10 mm and 10–14 mm separation. At the mid-gland, most patients (70%) had ≥ 14 mm spacing, with fewer showing 10–14 mm (21%) or <10 mm (6%). At the base, ≥ 14 mm spacing was observed in 61% of patients, whereas <10 mm and 10–14 mm separation was each present in 18%. Overall, ≥ 14 mm spacing predominated across all planes.

3.2. Penile Bulb and Bladder Dose Sparing

The penile bulb mean dose was significantly associated with separation at the prostate apex ($p < 0.001$). Patients with apical spacing ≥ 14 mm had a lower mean PB dose compared with those with <14 mm spacing, with an absolute difference of 4.36 Gy (95% CI: 2.40–6.32; $p < 0.001$). No significant differences were found for the penile bulb at the mid-gland or base.

For the bladder, an absolute mean bladder dose difference of 3.07 Gy (95% CI: 0.41–5.73; $p = 0.025$) was observed between base separation of ≥ 14 mm compared to <14 mm separation. No differences were observed at the apical or mid-gland levels (Figure 2, Table 2).

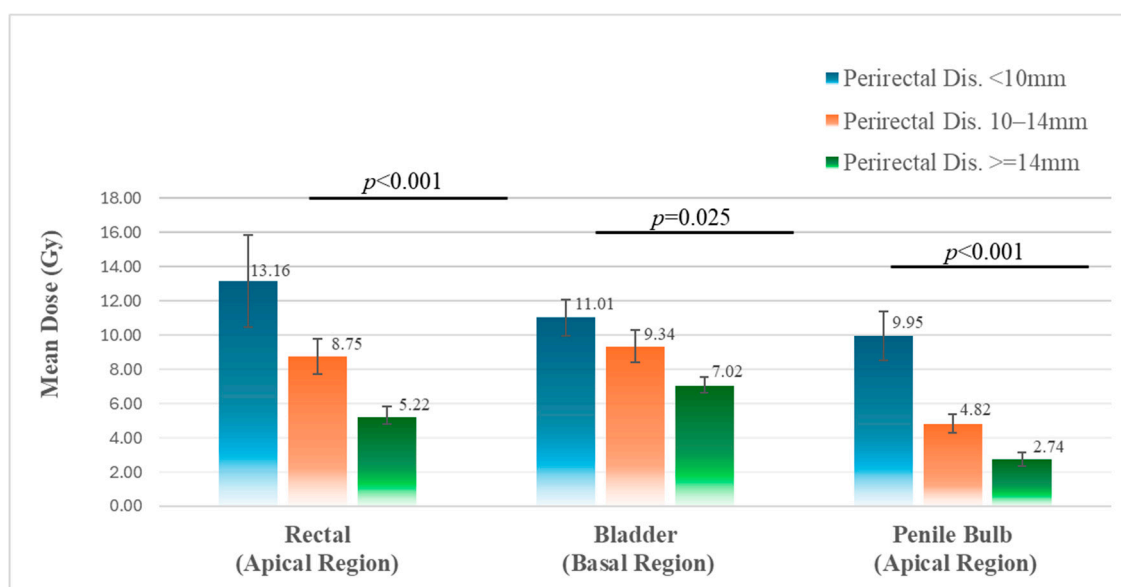


Figure 2. Mean dose (Gy) to the rectum (apical region), bladder (basal region), and penile bulb (apical region) stratified by perirectal separation (<10 mm, 10–14 mm, ≥ 14 mm). Error bars denote standard deviation; p -values indicate between-group comparisons.

Table 2. OAR dosimetry stratified by prostate–rectum separation (<14, ≥14 mm) at the apex, mid-gland, and base. Values are mean ± SE; blue shading indicates statistically significant differences between spacing groups. ¹ Two-sided 0.05 *t*-test for difference in means; R² indicates coefficient of determination for linear regression.

Organ at Risk	Parameter	Anatomical Level	Distance < 14 mm Mean (SD)	Distance ≥ 14 mm Mean (SD)	Difference 95% CI	<i>p</i> -Value ¹	R ²
Penile Bulb	Mean Dose (Gy)	Apical	7.09 (3.33)	2.74 (2.01)	2.42, 6.29	<0.001	0.51
		Mid-gland	4.27 (3.23)	3.79 (3.08)	−2.02, 2.9	0.700	
		Base	4.11 (3.42)	3.83 (2.99)	−2.09, 2.645	0.813	
Bladder	Mean Dose (Gy)	Apical	7.97 (3.86)	8.07 (3.81)	−3.15, 2.95	0.946	0.57
		Mid-gland	9.95 (2.11)	7.33 (4.03)	−0.27, 5.52	0.075	
		Base	10.09 (2.40)	7.02 (3.95)	0.48, 5.73	0.025	
Rectum	Mean Dose (Gy)	Apical	10.71 (4.33)	5.22 (2.97)	2.80, 8.18	<0.001	0.46
		Mid-gland	8.08 (5.58)	6.20 (3.48)	−1.40, 5.17	0.252	
		Base	7.59 (5.00)	6.27 (3.70)	−1.81, 4.46	0.397	
	36.25 Gy (%)		0.22 (0.39)	0.02 (0.05)	0.03, 0.36	0.022	
	32.63 Gy (%)		0.96 (1.24)	0.26 (0.40)	0.11, 1.29	0.021	
	29 Gy (%)		2.19 (1.70)	0.78 (0.86)	0.49, 2.33	0.004	

3.3. Rectal Dosimetry

Lower rectal dose was mostly associated with an increase in apical spacing ($p < 0.001$), where patients with apical spacing ≥14 mm had a lower mean rectal dose (difference: 5.49 Gy; [95% CI: 3.41–7.56]). These differences were seen particularly for higher doses > 29.0 Gy (Figure 3, Table 2).

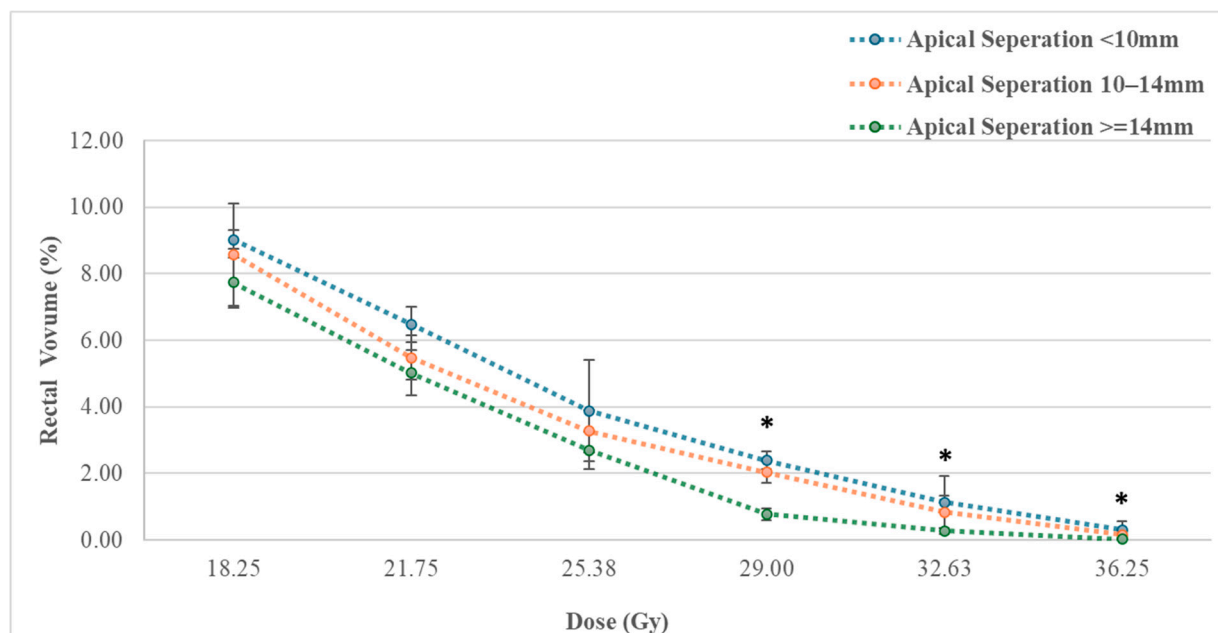


Figure 3. Rectal dose volumes (%) stratified by apical separation thresholds. Asterisks (*) denote significant sparing ($p < 0.05$) at high-dose levels.

3.4. Spacer Stability

The mean spacer balloon volume was 15.3 ± 0.37 cc at simulation and 14.7 ± 0.37 cc at the end of treatment (3.9% decrease; [95%CI: 2.4–5.6%]; $p = 0.1$). The mean prostate–rectum dis-

tance, measured at a consistent central axial level through the prostate, was 1.67 ± 0.04 cm at simulation and 1.63 ± 0.04 cm at the end of treatment (3.3% decrease; [95%CI: 1.9–8.4%]; $p = 0.3$). None of the images indicated any balloon migration.

3.5. Safety

Among 33 treated patients, no acute GI or rectal toxicities were observed, and no spacer or procedure-related adverse events were reported. Acute grade 1 GU toxicities occurred in 3 patients (9%), consisting of mild, transient urinary symptoms such as dysuria or nocturia, all resolving to baseline by the three-month follow-up.

Late GU toxicities were observed in 2 patients (6%). One patient with a history of transurethral resection of a bladder tumor (TURBT) experienced grade 1 dysuria at eight months post radiation therapy (RT), and one patient experienced urinary leakage at four months post RT and was diagnosed with grade 2 radiation cystitis at six months.

4. Discussion

While preliminary, this pilot study evaluated the use of balloon rectal spacers in prostate cancer patients treated with SBRT, and the relationship between prostate–rectum spacing across the gland and dose distribution to near organs at risk. Since the anterior rectum frequently abuts the treatment target, separated only by the thin Denonvilliers' fascia [16], the apex remains a critical region for rectal protection. Nevertheless, while previous reports primarily looked at apical spacing as a key element for rectal sparing, we thought to further explore this anatomical-level dependency of apical and base separation as a potential determinant for penile bulb and bladder dose sparing, respectively [17,18]. As illustrated in Figure 4, the impact of the spacer was less pronounced at the prostate base, where the seminal vesicles naturally increase the baseline recto-prostatic distance in the superior region [19].

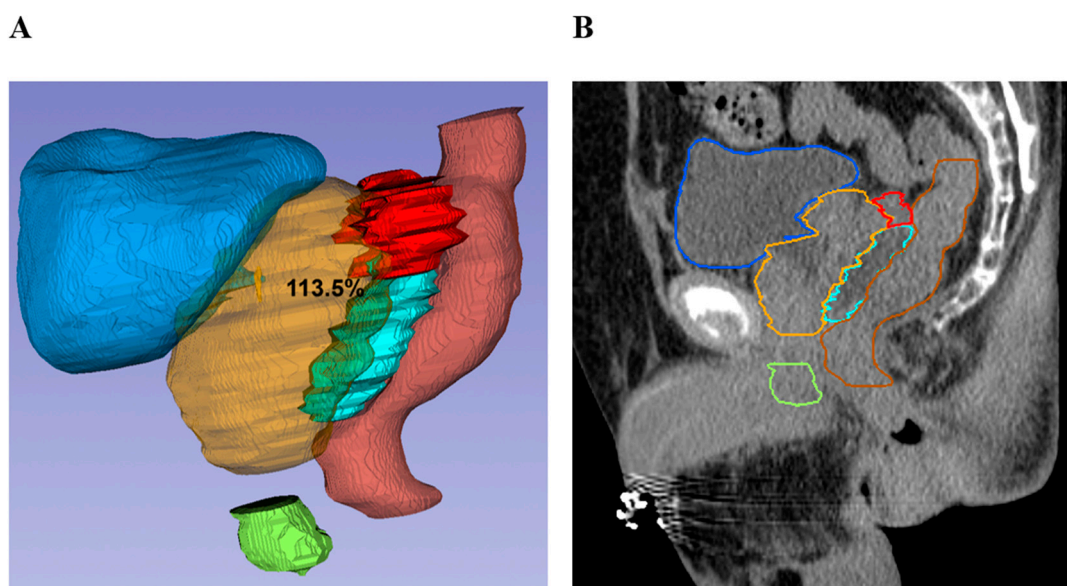


Figure 4. Representative SBRT plan (A): 3D; (B): sagittal illustrating the prostate (orange), rectum (red-brown), balloon spacer (light blue), and penile bulb (green). The 3D view shows the high-dose region (113.5%), highlighting increased apical separation compared to the base (seminal vesicles, red).

As an initial pilot study and when considering the primary objective, we further characterized the anatomical variations, including pacing distances and stability across the three gland levels, and cited previous reports for comparison (Table 3).

Table 3. Comparative analysis of spacer geometry and stability.

Spacer Type	Reference	Mean Spacing Distance (mm)	Stability (mm)
Balloon	Current Study	Base 17.2 ± 8.0 , Mid-gland 17.1 ± 4.7 , Apex 15.9 ± 4.3 Mean distance 16.6 ± 3.5	Mean distance 16.3 ± 0.4 (end of RT)
	[10]	Base 20 ± 4.0 , Mid-gland 20.0 ± 4.4 , Apex 18.0 ± 3.8	NA
	[5]	Mean distance 19.0 ± 3.7	18.0 ± 3.9 (end of RT)
	[20]	Mean distance 18.6 ± 0.24	16.7 ± 2.2 (end of RT)
	[14]	Mean distance 12.6 ± 3.9	10.9 ± 5.8 (end of RT)
SpaceOAR	[21]	Base 8.0 ± 6.9 , Mid-gland 10.0 ± 4.4 , Apex 6.7 ± 5.6	NA
Hyaluronic Acid	[7]	Base 15.6 ± 6.0 , Mid-gland 12.7 ± 3.7 , Apex 9.4 ± 4.0	NA
	[15]	12.9 ± 3.5	12.6 ± 3.5 (end of RT)

Our observations are in line with data from the literature where Narukawa et al. [22] suggested that ≥ 7.5 mm of apical spacing was required for stepwise reductions in GI toxicity. Another report [7] implied that an apical threshold of ≥ 10 mm was identified as a primary predictor of lower rectal V30 and preserved bowel quality of life (QOL), whereas an apical separation < 10 mm (mean 9.4 mm) was associated with higher rectal V30 and significantly increased risk of a minimal clinically important decline in bowel QOL. While the current study is constrained by a modest sample size, despite the limited scope of the study, our analysis used a 14 mm threshold, which although used as an illustrative benchmark, further highlights the association between increased separation and dosimetric gain. In our present work, we found a mean apical separation of 15.9 mm, which was associated with relatively low dose to the PB and the anterior. As the space created by liquid spacers may vary [7,13,23], the balloons design provides consistent and high volume separation that accommodates the steep dose gradients inherent to SBRT, and consequently, may overcome the “critical failure” of uneven distribution at the apex [8,24,25] by providing a uniform expansion where it is most required. Confirming other data in the literature [5,26,27], we found that the balloon geometric stability was maintained throughout the treatment course, with minimal changes observed in perirectal distance and space volume between simulation and treatment completion. This stability is essential to a greater extent in SBRT, where the total biological effect is determined by only a few high-dose fractions.

Balloon utilization was not associated with procedural complications and treatment was generally well tolerated, which is in line with previous study reports [6,28]. Observed GU events were infrequent, mild, and self-limiting. While these safety data are consistent with reported late grade ≥ 2 GI toxicity rates in spacer-based SBRT [29,30], the low event rates should be weighed within the scope of the retrospective assessment and limited follow-up rather than as definitive evidence of long-term clinical benefit.

Limitations of this study include the retrospective design, single-institution cohort, and modest sample size. However, despite the exploratory nature of this study, we believe that data derived from this limited cohort on the associations observed across multiple

anatomical levels and dosimetry outcomes, may help shape future, larger, robust studies. To strengthen the hypothesis that spatial separation at the apex and mid-gland can be a dominant determinant of rectal and PB dose sparing in prostate SBRT, functional and long-term QOL assessments are needed for further evaluation of rectal protection at the apex of the prostate level.

5. Conclusions

In conclusion, this pilot study provides initial, encouraging evidence on anatomical-level dose relationships. Our findings imply that increased apical spacing is associated with lower PB and rectal dose, and base-directed separation may have a greater impact on lowering bladder dose.

Although the sample size was limited, these preliminary results justify the need for a fully comprehensive longitudinal study to confirm patient outcome and clinical significance, specifically on GI, GU, and sexual QOL.

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Informed Consent Statement: The requirement for informed consent was waived due to the retrospective nature of the study and the use of de-identified patient data.

Data Availability Statement: The data presented in this study are available from the corresponding author upon reasonable request. The data is not publicly available due to patient privacy and institutional restrictions.

Conflicts of Interest: The authors declare no conflicts of interest.

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