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Are two intrafraction CBCT-based corrections adequate for online adaptive prostate SBRT to ensure accurate target coverage?

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ABSTRACT

Purpose: To evaluate whether two intrafraction Cone Beam Computed Tomography (CBCT)-based motion corrections are sufficient and necessary to ensure accurate target coverage in online adaptive stereotactic body radiotherapy (SBRT) of prostate cancer.
Methods: This retrospective study includes fourteen prostate patients who received online adaptive SBRT on the Ethos platform. After adaptation, patients underwent verification CBCT (CBCT0) with final shifts, and immediately treated with nine IMRT beams. Intrafraction CBCTs acquired after beam 3 (CBCT1) and beam 6 (CBCT2) served as intrafractional surveillance. Prostate displacement was determined by rigidly registering the implanted fiducials on the CBCTs to the adaptive planning CBCT, and corresponding shifts were applied. For a retrospective dose reconstruction, the prostate, bladder, and rectum were automatically segmented using an in-house AI algorithm, and contours were reviewed by expert clinicians. Bladder/rectum contour-based deformable image registration (C-DIR) was performed between the CBCTs and the adaptive planning CBCT. Subsequently, the delivered dose was reconstructed, accounting for anatomical changes and registration uncertainties. Dose indices for the prostate, bladder, and rectum were extracted and evaluated with and without motion corrections.
Results: Mean 3D displacement of prostate was 1.7±1.4mm (range: 0.2-8.9 mm) between CBCT0 and CBCT1, and 1.1±0.7mm (range: 0-3.4 mm) between CBCT1 and CBCT2. Significant (≥2mm) prostate movement occurred in 19% of the surveillances, with the majority (85%) along the bladder-rectum axis. C-DIR had sub-millimeter accuracy for the prostate, measured by fiducial positions. Correcting twice during delivery, as in the actual treatment, brought the tumor coverage (CTV-D95) within 3% of the planned values for all evaluated cases. In contrast, either correcting once or not correcting at all would cause frequent violations exceeding 3%.
Conclusion: Two intrafraction corrections during online adaptive prostate SBRT treatments provide a balance between treatment accuracy and efficiency. Converting post-treatment to automated online dose reconstruction for real-time, dosimetrics-oriented guidance is underway to further improve treatment efficacy.

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INTRODUCTION

Online adaptive radiotherapy (ART) accounts for interfraction anatomy, but intrafraction prostate motion from rectal/bladder filling can compromise SBRT target coverage (1). The Ethos platform enables intrafraction CBCT surveillance with corrective shifts - currently two verifications (after beams 3 and 6 of 9) (2). However, the necessity of two corrections has not been systematically evaluated. This study assesses whether two intrafraction CBCT-based corrections maintain accurate target coverage and quantifies the dosimetric impact of fewer corrections.

METHODS AND MATERIALS

- Patients: 14 prostate SBRT patients (fiducial markers).
- Imaging: Adaptive CBCT → verification CBCT → 9 IMRT beams delivered. Intrafraction CBCTs after beams 3 (CBCT1) & 6 (CBCT2).
- Motion Correction: Fiducial rigid-registration from intrafraction CBCTs to planning CBCT; 3D shifts applied to the following beams, as illustrated in Fig. 1.
- Dose Reconstruction: AI-based segmentation (CTV, bladder, rectum) reviewed by clinicians. Contour-based DIR (rigid + deformable) validated via fiducial/OAR comparison, as shown in Fig. 2.
- Dose Accumulation: RADAR algorithm: Total = D0 + D1(Δv1) + D2(Δv2).
- Scenarios: None, 1 correction (CBCT1 but not CBCT2), 1 correction (CBCT2 but not CBCT1), or 2 corrections (CBCT1+CBCT2).
- Endpoints: CTV-D95, CTV-V100%, OAR Dmax. Violation = CTV-D95 drop >3%.

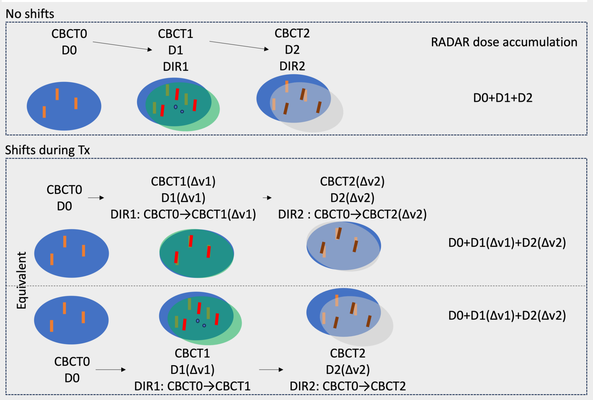

Figure 2. Schematic diagram illustrating three distinct dose accumulation workflows for online adaptive prostate SBRT. The top panel ("No shifts") shows dose accumulation using DIR without intrafraction corrections. The middle panel demonstrates the clinical workflow where 3D isocenter shifts are applied during treatment. The bottom panel represents an equivalent evaluation scenario where delivered beams are shifted prior to rigid and DIR back to the planning CBCT.

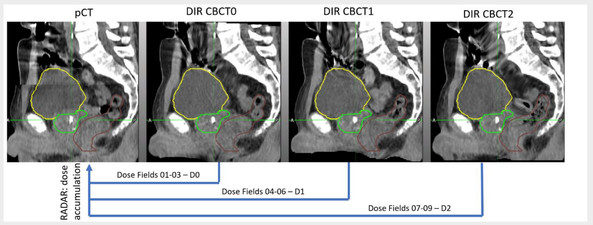

Figure 1. C-DIR was performed to register in CBCT to planning CBCT, as basis for dose accumulation. Contours outline the target volume - CTV prostate (green) and adjacent organs at risk, including the bladder (yellow) and rectum (brown).

RESULTS

- Prostate Displacement:
  - CBCT0 → CBCT1: 1.7 ± 1.4 mm (range: 0.2–8.9 mm)
  - CBCT1 → CBCT2: 1.1 ± 0.7 mm (range: 0–3.4 mm)
- Significant motion (≥2 mm): Observed in 19% of surveillances; 85% along AP (bladder-rectum) axis.
- DIR Accuracy: Evaluation of C-DIR performance on an example intrafraction CBCT to planning CBCT are shown in Table 1-3. Sub-millimeter OAR (via COM), and prostate (via fiducials) registration validated.
- Target Coverage (CTV-D95 within 3%): No correction < 1 correction < 2 corrections, as shown in Fig. 3 and 4.
- OAR Doses (Reconstructed vs. Adapted): Bladder ↑ (higher); Rectum ↓ (lower).

Contour 1 on deformed CBCT	Contour 2 on planning CBCT	HD (mm)	MDA (mm)	Dice	Jaccard
Bladder	Bladder	4.01	0.43	0.98	0.96
Rectum	Rectum	6.00	0.87	0.91	0.83
CTV prostate	CTV prostate	14.62	1.05	0.90	0.81

Table 1. Evaluation of C-DIR performance on an example intrafraction CBCT to planning CBCT. This comparison between the deformed intrafraction CBCT contours (Contour 1) and planning CBCT contours (Contour 2) demonstrates high geometric fidelity, with Dice coefficients >0.90 across all structures.

Structure	Image	Volume (cc)	Center of mass (COM) (mm)			
			x	y	z	Magnitude
Bladder	pCT	271.79	-36.13	-1.76	-28.08	
	iCBCT	327.71	-39.12	-4.22	-9.05	
	diCBCT	274.77	-36.17	-1.73	-28.2	
	diff i-p	55.92	-2.99	-2.46	19.03	19.42
	diff di-p	2.98	-0.04	0.03	-0.12	0.13
Rectum	pCT	60.86	-61.82	4.33	41.97	
	iCBCT	46.62	-68.5	0.19	38.61	
	diCBCT	67.16	-62.15	4.32	41.7	
	diff i-p	-14.24	-6.68	-4.14	-3.36	8.55
	diff di-p	6.3	-0.33	-0.01	-0.27	0.43
CTV prostate	pCT	46.81	-69.92	-0.68	4.58	
	iCBCT	48.46	-69.79	-0.38	4.53	
	diCBCT	48.84	-69.78	-2.84	4.59	
	diff i-p	1.65	0.13	0.3	-0.05	0.33
	diff di-p	2.03	0.14	-2.16	0.01	2.16
Intrafraction - planning CBCT	Average volume Differences	3.77	Average magnitude of COM differences			0.91

Table 2. Volume and COM Analysis for OARs and target. Abbreviations: pCT: Planning CBCT; iCBCT: Intrafraction CBCT; diCBCT: Deformed Intrafraction CBCT; diff i-p: differences between Intrafraction CBCT-planning CBCT; diff di-p: differences between deformed Intrafraction CBCT-planning CBCT.

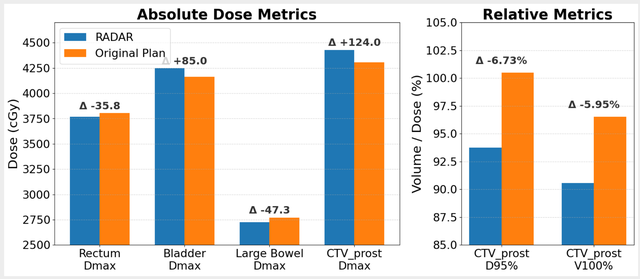

Figure 3. Dosimetric comparison between the RADAR and Original treatment plans. The left panel displays absolute maximum dose (Dmax, cGy) for organs at risk (rectum, bladder, large bowel) and the clinical target volume in prostate (CTV_prost). The right panel illustrates relative target coverage metrics (D95% and V100%, %). Bold text above the bars indicates the absolute difference (Δ) between the RADAR and Original plans. Note: Y-axes are truncated to emphasize dosimetric variations.

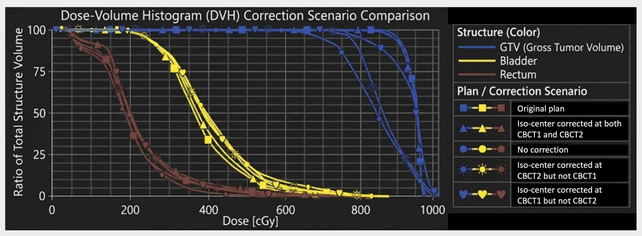

Figure 4. DVH comparison between the original plan (triangles) and the RADAR-reconstructed plan with isocenter shifts and DIR (squares). Light blue curves represent bladder (higher dose) and rectum (lower dose); light green curves represent CTV.

DISCUSSION

- Key Finding: Two intrafraction CBCT corrections maintain CTV-D95 within 3% of planned values for all cases; ≤1 correction → frequent violations.
- Motion Drivers: AP (bladder-rectum) axis predominates → confirms physiological origin. Even with daily adaptation, residual intrafraction motion requires active management.
- Interval Difference: First interval displacement (1.7 mm) > second (1.1 mm) → likely reflects initial patient settling post-setup.
- Clinical Balance: Two corrections = pragmatic trade-off between dosimetric accuracy and efficiency (~2–3 min per CBCT added).
- Limitations: Small sample size; DIR uncertainties in high-deformation regions; no PTV or toxicity endpoint analysis.
- Future Work: Automating pipeline for real-time, dosimetry-guided adaptation.

Object		Center of mass (COM) (mm)			
	Image	x	y	z	Magnitude
Fiducial 1	pCT	-73.6	15.06	-0.76	
	iCBCT	-75.77	19.25	1.87	
	diCBCT	-73.6	15.54	-0.76	
	diff i-p	-2.17	4.19	2.63	5.4
	diff di-p:	0	0.48	0	0.48
Fiducial 2		x	y	z	
	pCT	-75.51	-6.92	-4.91	
	iCBCT	-78.87	-3.48	-1.9	
	diCBCT	-75.83	-6.92	-5.08	
	diff i-p	-3.36	3.44	3.01	5.67
	diff di-p:	-0.32	0	-0.17	0.36
Fiducial 3		x	y	z	
	pCT	-75.9	-2.39	0.39	
	iCBCT	-78.93	0.95	3.02	
	diCBCT	-76.07	-2.36	-0.39	
	diff i-p	-3.03	3.34	2.63	5.22
	diff di-p:	-0.17	0.03	-0.78	0.8
Average magnitude of COM differences: Intrafraction CBCT - planning CT					0.55

Table 3. Prostate Fiducial Marker Tracking and Center of Mass. Differences. Abbreviations the same with those in Table 2.

CONCLUSIONS

Two intrafraction CBCT-based motion corrections during online adaptive prostate SBRT provide a sufficient and necessary balance between treatment accuracy and clinical efficiency. This workflow maintained CTV-D95 within 3% of planned values for all evaluated cases, whereas one or zero corrections led to frequent dosimetric violations. Future efforts to automate online dose accumulation for real-time guidance may further enhance treatment precision and patient outcomes.

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