

Impact of Anatomical Changes and PTV Margin Dimensions on Delivered Dose for prostate SBRT patients treated on an MR-Linac

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Introduction

- MR-guided adaptive RT exploits improved target and OAR visualization to adapt to the daily anatomy
- Adaptive RT ↓ interfraction uncertainty, but intrafraction anatomical motion before beam on impacts delivered dose.
- Intrafraction motion may be mitigated via verification adaptation.
- Deformable dose accumulation can estimate delivered dose
- PTV margin design balances target coverage, OAR sparing and frequency of verification adaptation.

Purpose

- To quantify inter- and intrafraction target and OAR motion using the 3D deformation vector field (DVF).
- To quantify motion impact on delivered dose using beam-on anatomy.
- To evaluate impact of reduced PTV margin on target coverage, OAR sparing and verification adaptation frequency.

Methods

- 25 patients treated with 30 Gy/5 prostate SBRT on 1.5 T MR-Linac with uniform 5 mm PTV, followed by 15 Gy HDR boost.
- Adapt-to-shape (ATS, full optimization) for all fractions with adapt-to-position (ATP, isocentre shift) if motion on Verify MR.
- Deformable image registration between Reference, Adapt (adaptive planning), Verify, and BeamOn MR (Figure 1).
- Extracted 3D structure motion using DVF.
- Dose accumulated by deforming each fractional dose to the Reference MR using the DVF and summed across fractions.
- Subset (N=10) compared clinical 5 mm uniform PTV vs 4 mm APSI & 3 mm LR (344) and 3 mm APSI & 2 mm LR (233)
- Simulated verification adaptation: ATP all fractions (ATS-ATP_{fixed}) & ATP if CTV within 1 mm of PTV (ATS-ATP_{selective})
- We estimated delivered dose for each scenario by computing ATS, ATS-ATP_{fixed} or ATS-ATP_{selective} beams on BeamOn MR

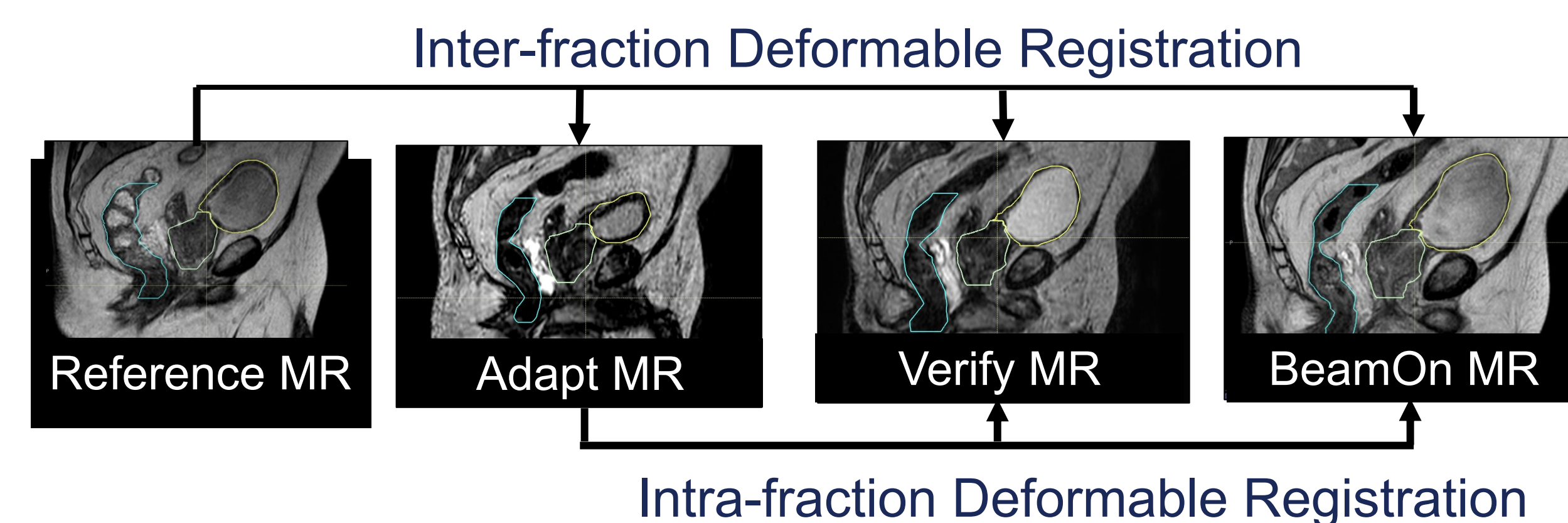


Figure 1: Deformable registrations for motion and dose accumulation

Results

- Mean intrafraction CTV motion: 0.1 ± 1.0 mm right, 1.9 ± 2.7 mm posterior, and 1.2 ± 2.0 mm inferior (Figure 3).
- Bladder & rectum motion larger and more variable than CTV motion, with bladder filling linked to posterior/inferior CTV shift.
- No significant target coverage difference observed between adapted-plan and delivered dose (Figure 4).
- Delivered dose showed lower rectum D1cc ($p < 0.005$) and higher bladder D5cc ($p < 0.001$) than adapted dose.
- ATS-ATP_{selective} frequency ↑ as margins ↓: 8/50 fractions with 555, 14/50 with 344, and 26/50 with 233.
- Reduced margins improved rectal and bladder sparing across adaptive strategies (Figure 5)
- ATS-only target coverage ↓ with smaller margins, but selective ATP restored target coverage without ATP for all fractions

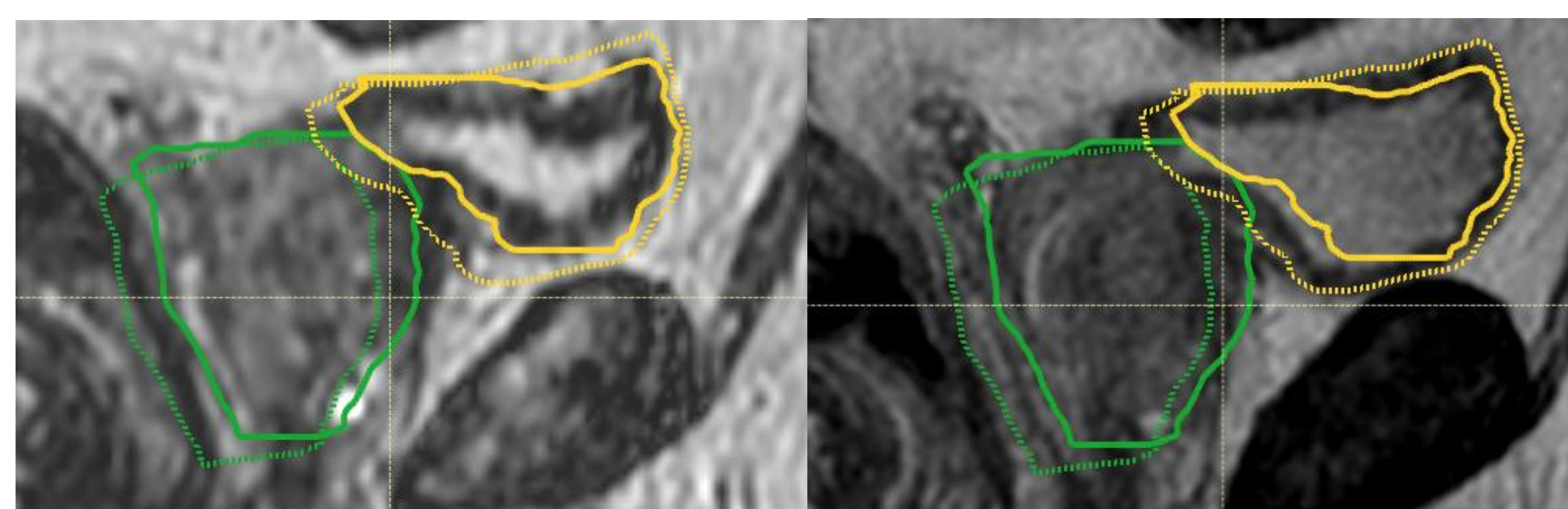


Figure 2: Bladder (yellow) and CTV (green) contours on adapt (left) and beam-on (right) images for the case with the largest CTV deviation. Solid and dashed lines indicate adapt and beam-on contours, respectively.

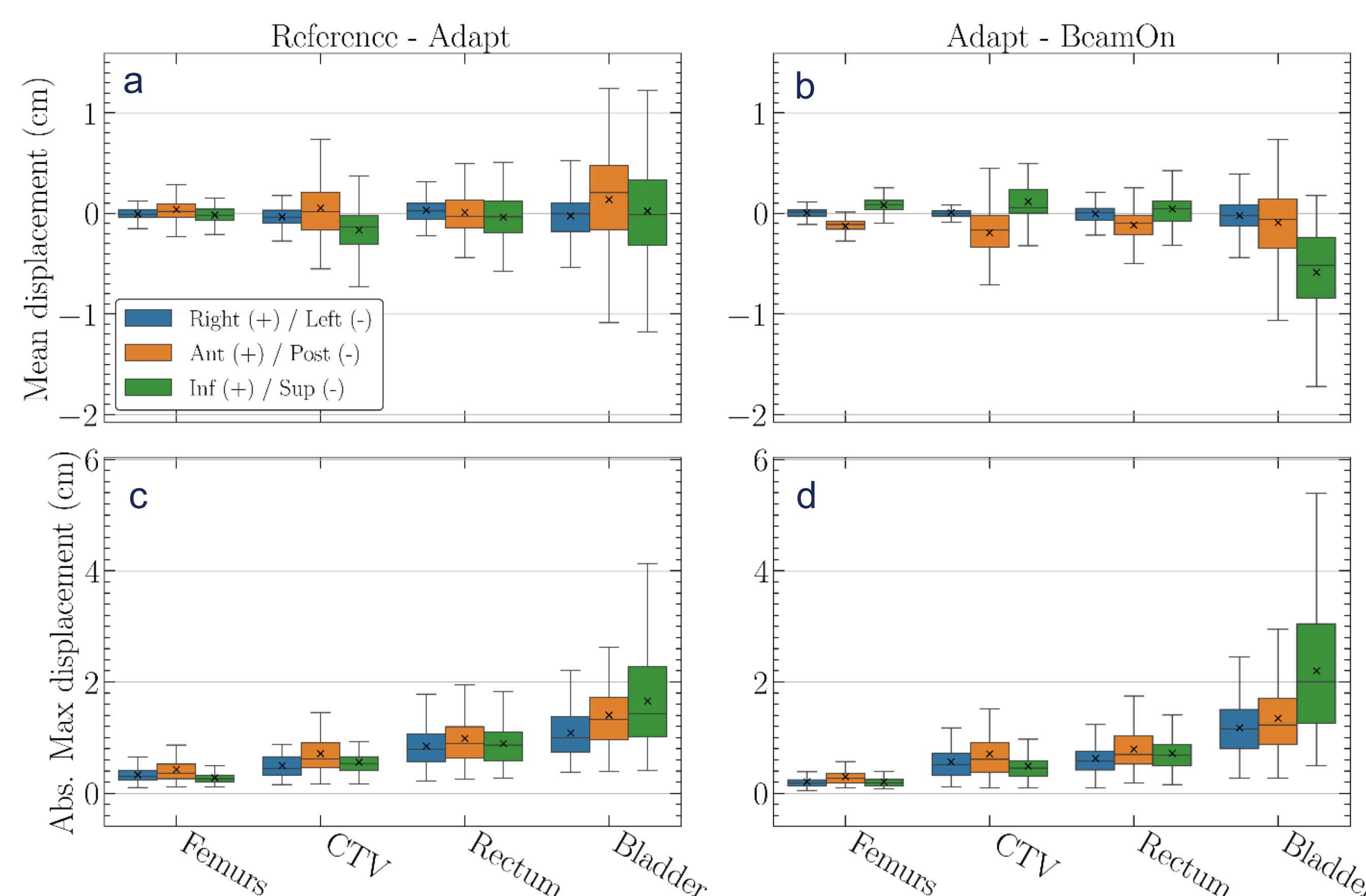


Figure 3: Geometric deviations for inter (a,c) and intra (b,d) fraction motion quantified using the mean (a,b) and absolute maximum distance (c,d).

Results

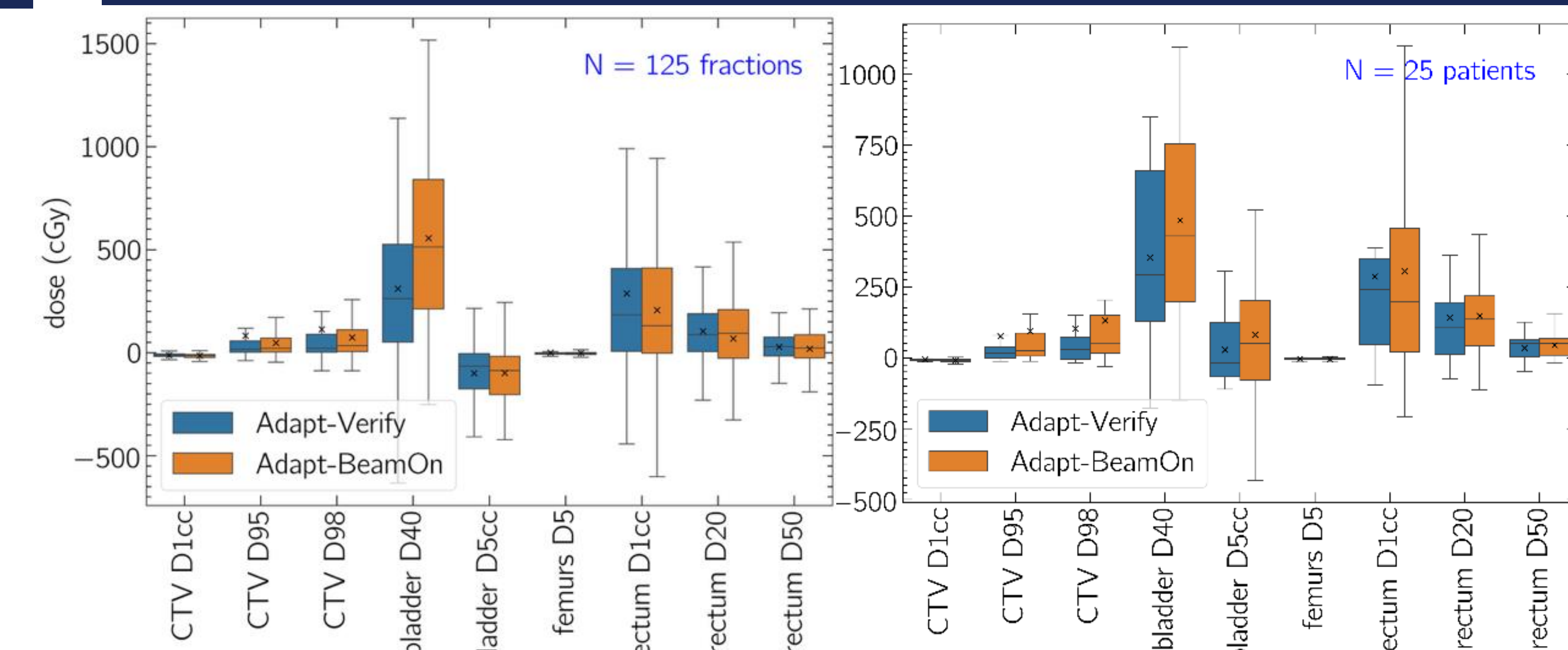


Figure 4: DVH differences at multiple time points for the clinical cohort (left) fractional (right) accumulated dose.

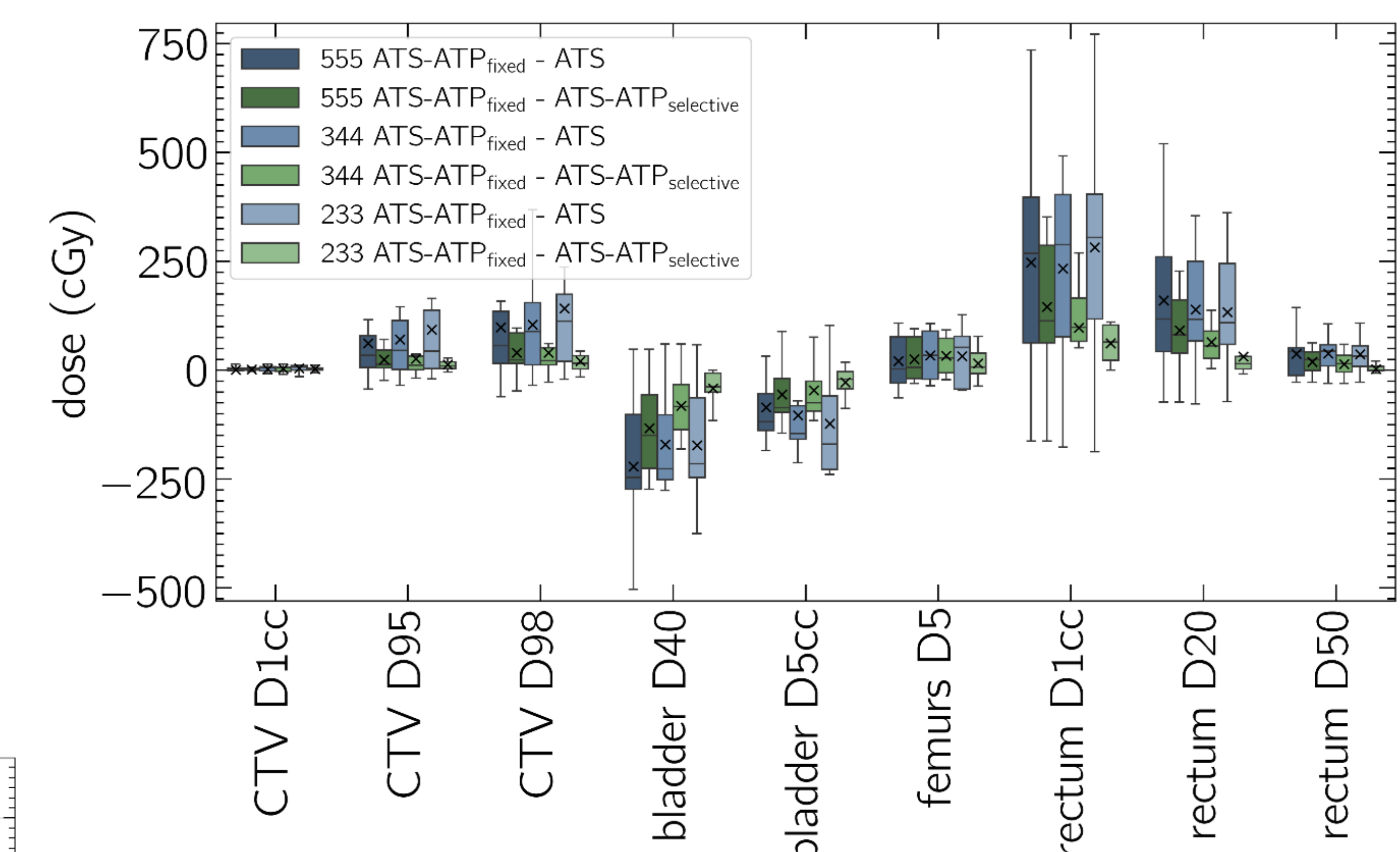


Figure 5: BeamOn DVH metric difference between adaptive strategies ATS, ATS-ATP_{fixed}, and ATS-ATP_{selective} with three PTV margins: 555; uniform 5 mm, 344; 3 mm LR and 4 mm APSI, 233; 2 mm LR and 3 mm APSI.

Discussion

- DVF motion analysis revealed structure-specific inter- and intrafractional motion patterns.
- Limited CTV motion supports LR PTV reduction down to 2 mm.
- Motion had minimal target dose impact for clinical 5 mm PTV margin.
- Selective ATP-of-ATS restored coverage for reduced margins of 3 mm (2 mm lateral), at the cost of increased session time.
- Our framework links motion and delivered dose to support evidence-based PTV margin and workflow optimization.