

Deep Learning-Based Estimation of Minimal Editing Margins for Online Adaptive MR-Linac Prostate SIB

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ABSTRACT

Purpose:

This study investigates the use of a deep learning (DL) dose prediction model to guide the development of a novel contouring strategy that streamlines online adaptive planning while maintaining dosimetric accuracy in prostate simultaneous integrated boost (SIB) treatment on the Unity MR-Linac.

Methods:

A minimal manual editing margin (MMEM)-based contouring strategy was evaluated using six margin sizes (5–30 mm). Twenty adaptive plans with DIR-induced contour limitations involving the bladder, rectum, and bowel bag were analyzed. For each plan, hybrid structure sets were created by combining DIR-propagated contours, MMEM-modified regions, and semi-automatically segmented (SAS) bladder contours. An attention-gated U-Net DL dose prediction model trained on 80 prostate SIB cases was used to assess dose variations associated with different editing margins. Dosimetric accuracy was evaluated by comparison with fully manually edited contours, and planning feasibility was further evaluated in the Monaco treatment planning system.

Results:

SAS bladder contours showed dosimetric differences ≤ 0.8 Gy. Rectal differences were ≤ 2 Gy (or 2%) with the 10-mm MMEM, while bowel bag differences remained ≤ 1.8 Gy without manual editing except for overlap correction. For feasibility evaluation, the hybrid strategy (SAS bladder contours, no bowel bag editing, and 10-mm rectal MMEM) achieved mean differences ≤ 1.0 Gy, except for bowel bag D_{195cc} (~1.5 Gy).

Conclusion:

The proposed MMEM-based hybrid contouring strategy, particularly with a 10-mm rectal MMEM, improved the robustness and efficiency of online adaptive prostate SIB planning and supports streamlined MR-Linac clinical workflows.

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INTRODUCTION

One challenge in prostate simultaneous integrated boost (SIB) treatment on the Unity MR-Linac (Elekta AB, Stockholm, Sweden) is the limited robustness of deformable image registration (DIR)-based contour propagation during online adaptive planning, particularly for the bladder, rectum, and bowel bag.

Because the dosimetric criteria for pelvic OARs primarily concern the medium- to high-dose regions, we proposed an approach to determine the minimal manual editing margin (MMEM) around the target structures that is necessary to restore dosimetric accuracy when DIR performance is insufficient. A DL-based dose prediction model can efficiently quantify the relationship between various contour modifications and the resulting changes in dose distribution. Therefore, this model can be used as a reference for evaluating the appropriate editing margin.

This study aims to develop a novel contour editing strategy, established with the aid of a DL prediction model, to streamline the online adaptive planning workflow for prostate SIB treatment on the Unity MR-Linac without reliance on third-party tools.

METHODS AND MATERIALS

For MMEM determination, six margin sizes were generated by expanding the target structures by 5–30 mm in 5-mm increments (Fig. 1). Twenty adaptive plans with DIR-induced contour limitations involving the bladder, rectum, and bowel bag were analyzed (MMEM group).

For each plan, six hybrid structure sets were created by combining DIR-propagated contours, MMEM-modified regions, and semi-automatically segmented (SAS) bladder contours generated using the Monaco treatment planning system (TPS; Elekta AB, Stockholm, Sweden).

An attention-gated U-Net DL dose prediction model, trained on 80 prostate SIB cases, was used to quantify dose variations associated with different editing margins. Dosimetric accuracy was then evaluated by comparison with fully manually edited (reference) structure sets. This process is illustrated in Figure 2.

Planning feasibility using MMEM-based hybrid structures was further evaluated in the Monaco TPS using ten randomly selected adaptive plans (feasibility group).

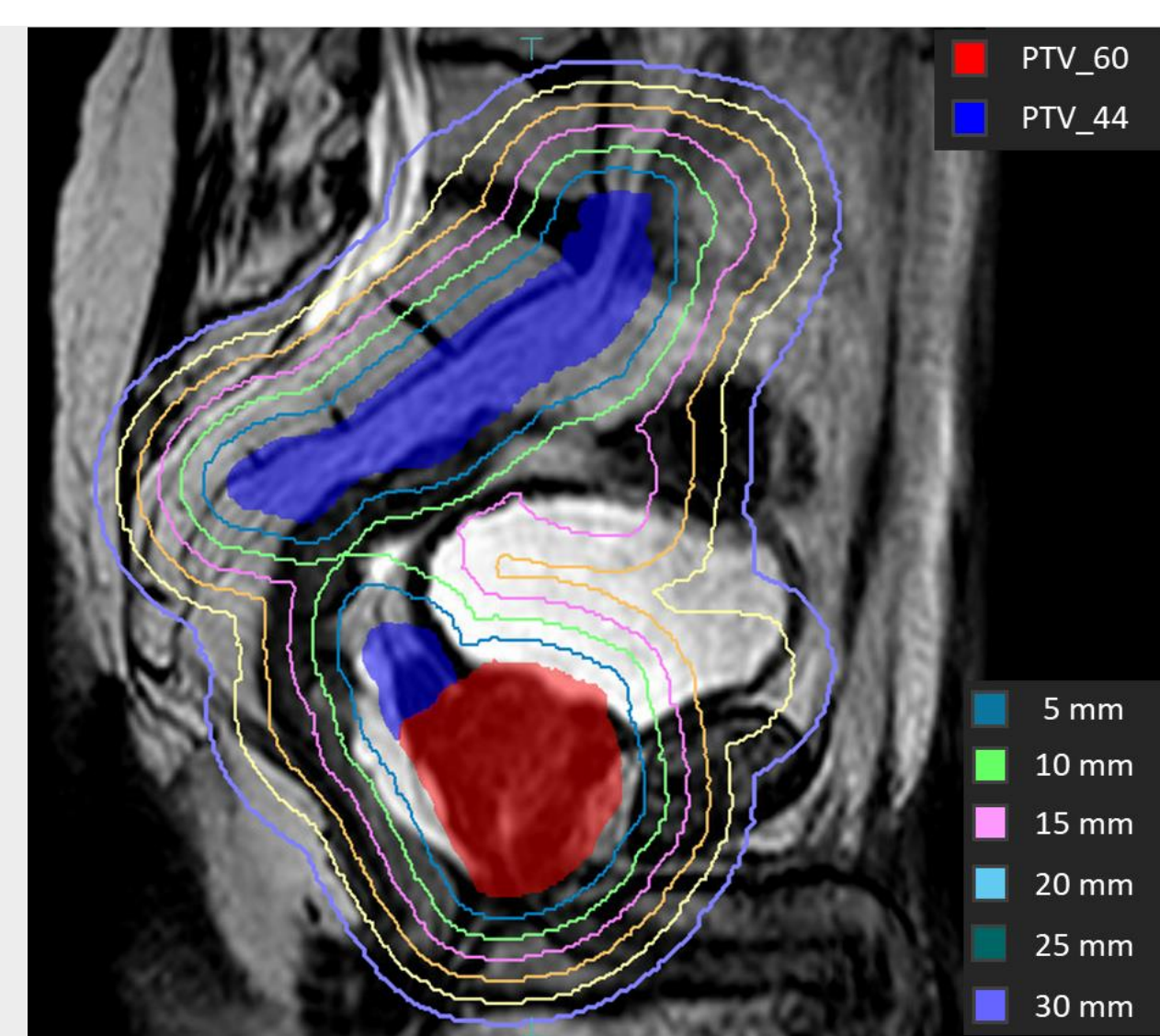


Figure 1. A representative case showing the six margin sizes.

RESULTS

Figure 3 shows the average dosimetric differences (mean absolute error) between the hybrid and reference structure sets for the bladder, rectum, and bowel bag in the MMEM group across different dosimetric criteria. SAS bladder contours showed dosimetric differences ≤ 0.8 Gy. Rectal dosimetric differences were ≤ 2 Gy (or 2%) when using 5-mm and 10-mm MMEMs. Bowel bag dosimetric differences remained ≤ 1.8 Gy without manual editing, aside from correcting contour overlaps.

Based on these findings, feasibility evaluation was performed using hybrid structure sets incorporating SAS bladder contours, no manual bowel bag editing, and 5-mm or 10-mm rectal MMEMs. Average dosimetric differences for the bladder, rectum, and bowel bag were ≤ 1.0 Gy with the 10-mm MMEM and ≤ 1.5 Gy with the 5-mm MMEM, except for bowel bag D_{195cc} , which was approximately 1.5 Gy for both MMEMs (Fig. 4).

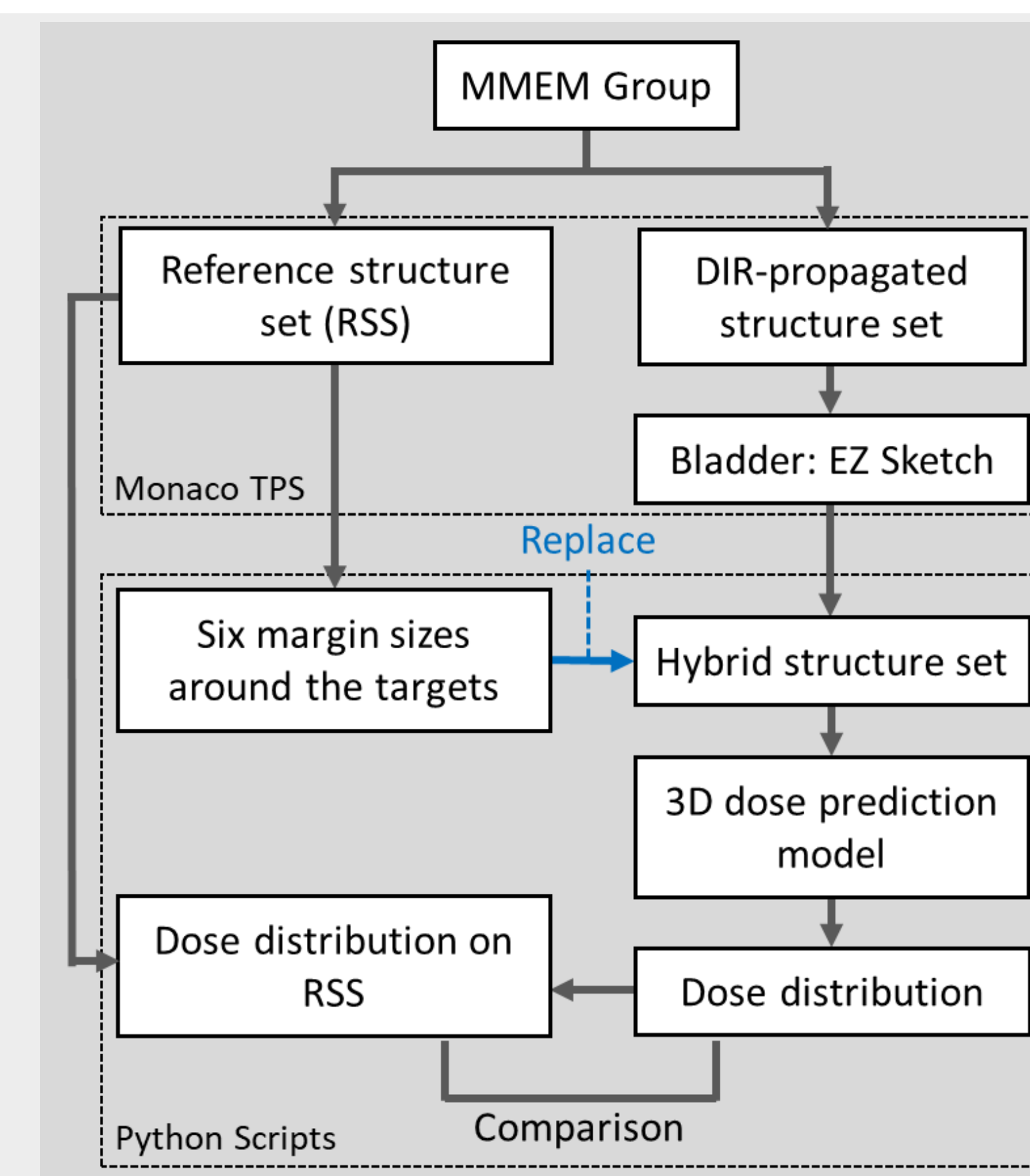


Figure 2. Flowchart of hybrid structure set generation and dose comparison for the MMEM determination.

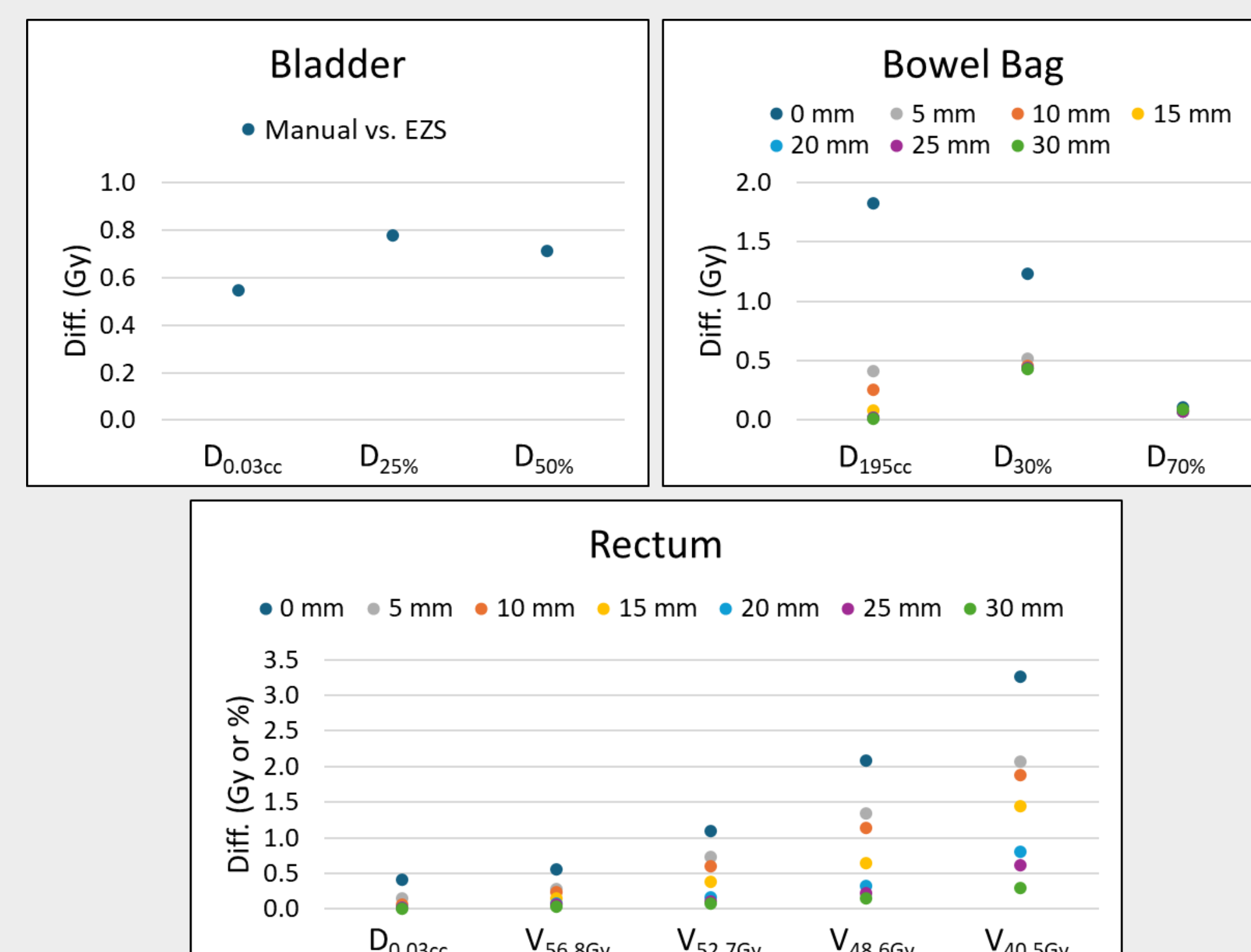


Figure 3. Average dosimetric differences between the hybrid and reference structure sets in the MMEM group across different dosimetric criteria.

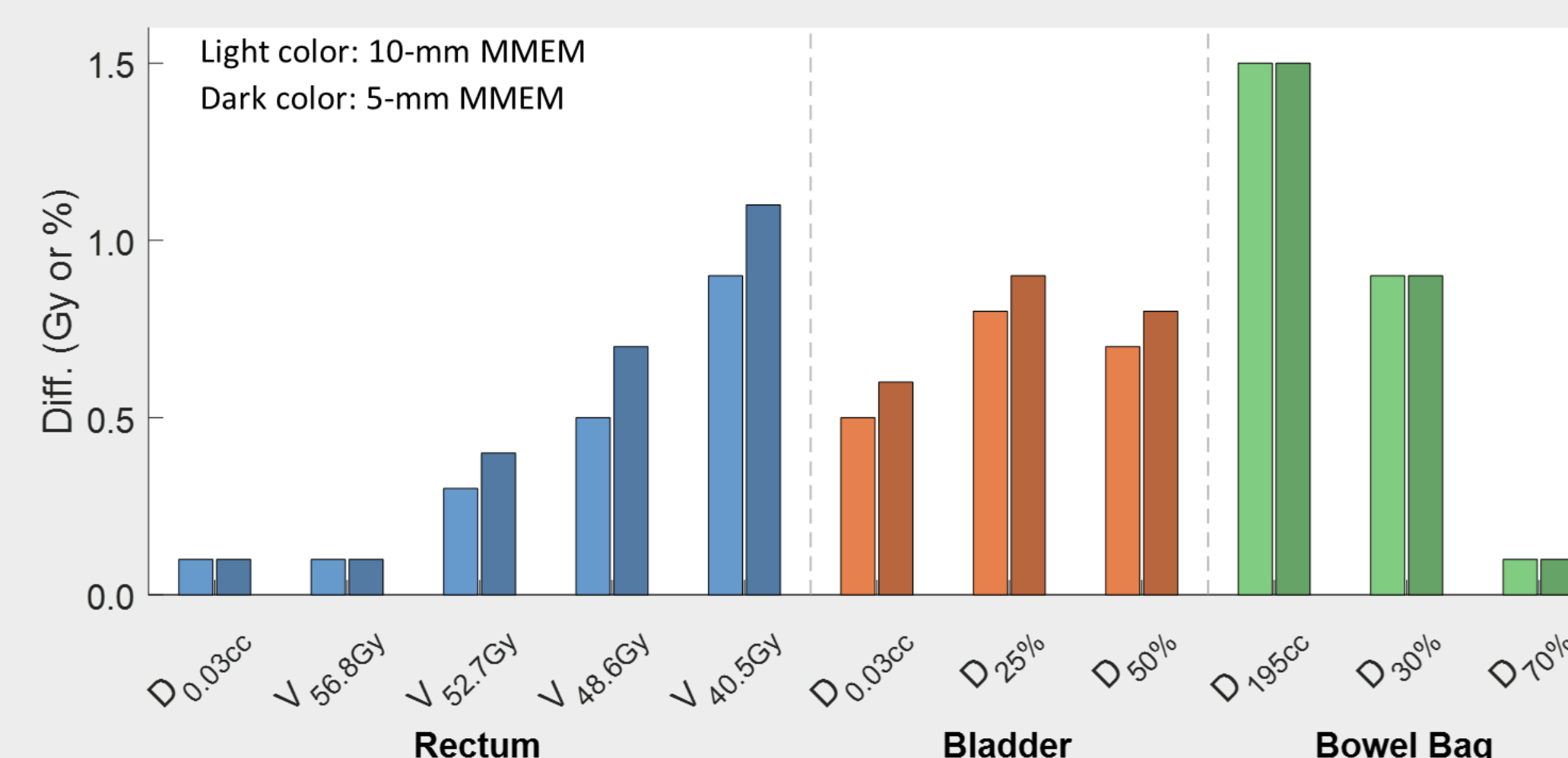


Figure 4. Average dosimetric differences between the MMEM-based hybrid and the reference contours in the feasibility group across different dosimetric criteria.

DISCUSSION

Online adaptive planning relies critically on the efficient generation of daily contours. We observed that the DIR-based contour propagation is less effective in the Monaco TPS when structure boundaries are ill-defined or when there are large volume changes, often requiring contour adjustments.

For a fully automated adaptive workflow that relies on auto-segmentation tools to correct DIR-propagated contours, objective indicators are needed to ensure contour robustness. Thus, it is important to quantify the relationship between automatically generated contours and their corresponding dosimetric accuracy using evaluation metrics. However, standardized indicators are currently lacking, which underscores the need for a practical strategy.

This work leverages DL-predicted dose distributions to systematically and efficiently assess the dosimetric impact of contour variations, enabling the identification of the MMEM for online adaptive prostate SIB treatment on the Unity MR-Linac. The proposed framework is directly compatible with the Monaco TPS and does not rely on third-party tools, supporting seamless clinical implementation in the Unity MR-Linac workflow.

Based on this framework, we developed an MMEM-based contouring strategy that limits editing to only the necessary regions, thereby minimizing editing time while maintaining dosimetric accuracy.

The average time required for the MMEM-based contouring strategy was less than six minutes, demonstrating that this method can reduce the need for extensive manual editing or third-party tools while maintaining clinically acceptable dosimetric accuracy and supporting a more streamlined adaptive treatment workflow on the Unity MR-Linac.

CONCLUSIONS

The proposed MMEM-based hybrid contouring strategy, particularly with a 10-mm rectal MMEM, improved the robustness and efficiency of online adaptive prostate SIB planning and supports streamlined MR-Linac clinical workflows.

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