Feasibility and Benefit of Reduced CTV-to-PTV Margins in Prostate VMAT Using Monte Carlo–Based Geometric Perturbation

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ABSTRACT

Purpose: The MIRAGE trial demonstrated reduced acute toxicity in intact prostate radiotherapy in MRI arm, partially attributed to the use of smaller PTV margins (2 mm versus 4 mm with CT guidance). Motivated by these findings, this study retrospectively evaluates whether CTV-to-PTV margins can be further reduced while maintaining acceptable target coverage.

Methods: Fifty intact prostate cancer patients treated with clinical VMAT plans were retrospectively analyzed. In contrast to conventional margin criteria (3 mm in most directions and 2 mm posteriorly), the PTV was defined using a reduced anisotropic margin of [0, 0, 2] mm in the LR, AP, and SI directions. Geometric uncertainty and robustness were modeled following van Herk et al. (2000). Random setup errors (σ = 1–2 mm) were simulated via dose blurring, and systematic errors (Σ) were evaluated using rigid dose shifts. Robustness was assessed using population-based criteria requiring ≥90% of patients to meet minimum CTV coverage and population TCP loss <1%. TCP and NTCP were evaluated using HyTEC parameters.

Results: VMAT plans exhibited a dosimetric buffer beyond the PTV to the 90% isodose surface. Acceptable coverage (≥90% of patients) was maintained for systematic uncertainties within an ellipsoidal tolerance region with semi-axes of [1.6, 1.3, 2.3] mm in the X, Y, and Z directions. For high-risk disease, acceptable TCP was preserved within a smaller systematic-shift tolerance ellipsoid with semi-axes of [1.3, 1.0, 1.9] mm. Concurrently, OAR doses and NTCP decreased for both rectum and bladder with margin reduction.

Conclusions: For prostate VMAT plans using a [0, 0, 2] mm CTV-to-PTV margin, acceptable target coverage was maintained within a finite tolerance to geometric uncertainty. These results suggest that margin reduction can be dosimetrically feasible in modern inverse-planned prostate radiotherapy, with preserved TCP and improved OAR sparing as reflected by reduced NTCP.

INTRODUCTION

CTV-to-PTV margins compensate for systematic and random geometric uncertainties. The widely used van Herk formula [1] was developed for 3D conformal radiotherapy and may not fully reflect contemporary image-guided VMAT, which can produce anisotropic dose gradients and intrinsic clearance between the minimum-dose isodose and PTV. These features may permit small residual setup errors without compromising target coverage. Because reduced prostate margins may also decrease genitourinary and gastrointestinal toxicity, we used Monte Carlo geometric perturbations of clinical VMAT plans to evaluate whether reduced anisotropic margins could maintain acceptable CTV dose coverage and tumor-control probability.

METHODS AND MATERIALS

Fifty clinically approved prostate VMAT plans were retrospectively analyzed using a reduced anisotropic margin of [0, 0, 2] mm (X/Y/Z). Directional dose falloff and isodose-to-PTV clearance were quantified to characterize intrinsic geometric dose buffers.
Monte Carlo perturbations modeled random uncertainty by Gaussian dose blurring and systematic uncertainty by 3D rigid shifts. Robustness required ≥90% of patients to maintain CTV $Dmin_{0.03cc}$ ≥90% of prescription and population TCP loss <1%. Rectal and bladder dose metrics and NTCP were also evaluated.

RESULTS

The 90% isodose generally extended beyond the reduced-margin PTV, demonstrating a direction-dependent dosimetric buffer with steeper superior–inferior and broader transverse penumbrae (Fig. 1A). Under clinically relevant random uncertainty, the coverage-based acceptable systematic-error region was approximated by an ellipsoid with semi-axes of [1.6, 1.3, 2.3] mm in X, Y, and Z, respectively (Fig. 1B). Low–intermediate-risk disease tolerated relatively large systematic shifts before exceeding 1% TCP loss (Fig. 1C). For high-risk disease, the TCP-based acceptable region had ellipsoid semi-axes of [1.3, 1.0, 1.9] mm (Fig. 1D), and TCP exceeded the 1% loss threshold at smaller shifts (Fig. 1E). Margin reduction also decreased rectal and bladder dose metrics and estimated NTCP (Fig. 1F).

RESULTS

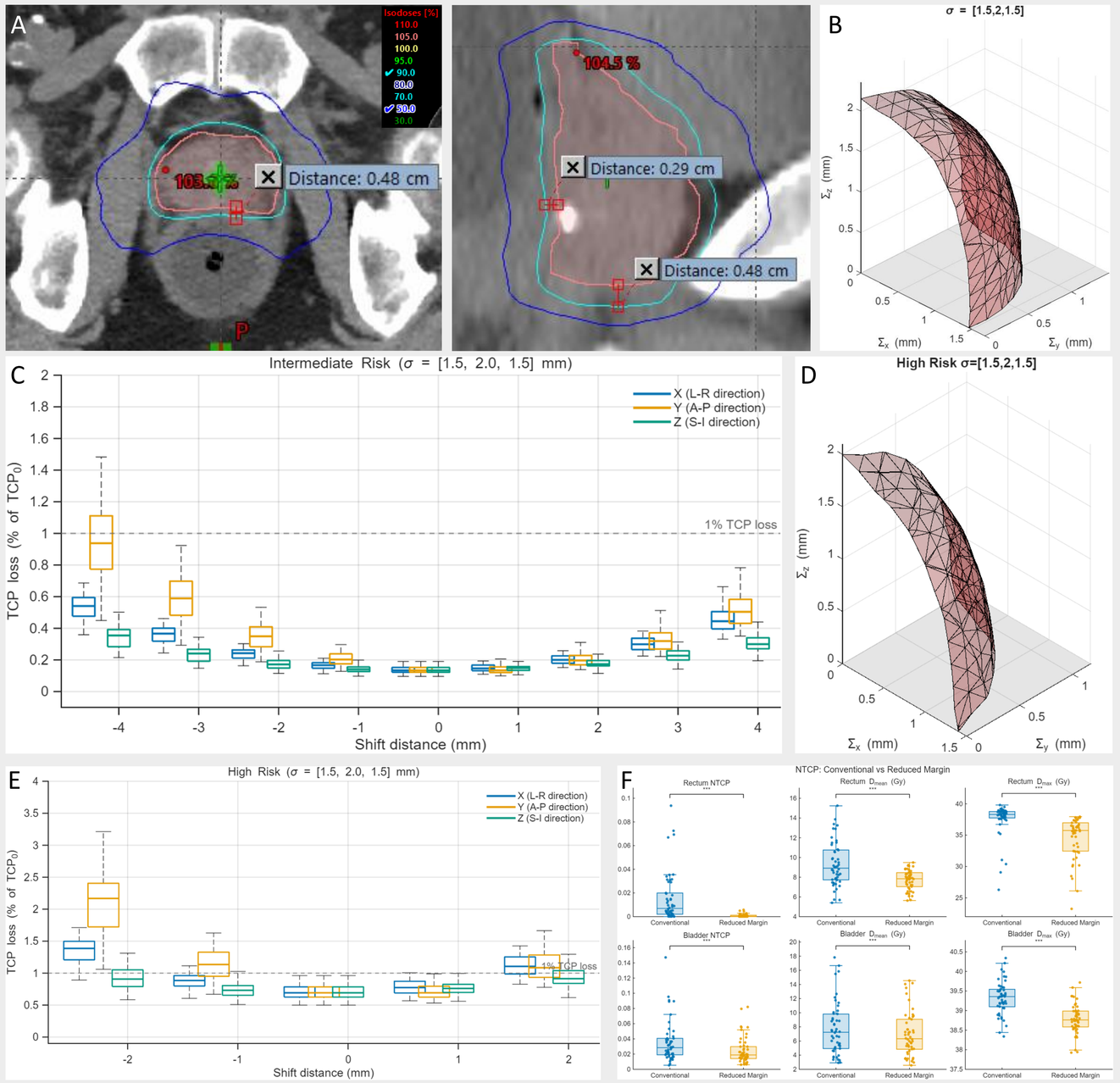

Figure 1. Dosimetric robustness, TCP, and NTCP with reduced prostate VMAT margins. (A) Representative dose distributions for a [0,0,2] mm margin, showing extension of the 90% isodose beyond the PTV. (B) Coverage-based acceptable Σ-space region for σ = [1.5,2.0,1.5] mm, fitted by an ellipsoid with semi-axes [1.6,1.3,2.3] mm. (C) TCP loss versus systematic shift for low-risk disease. (D) High-risk TCP-based acceptable region (TCP loss <1%), with semi-axes [1.3,1.0,1.9] mm. (E) TCP loss versus systematic shift for high-risk disease. (F) Changes in rectal and bladder dose metrics and NTCP with margin reduction and geometric uncertainty.

DISCUSSION

Reduced CTV-to-PTV margins may be feasible for image-guided prostate VMAT when residual uncertainties are well controlled. Robustness likely reflects the anisotropic dose falloff and intrinsic isodose-to-PTV clearance characteristic of coplanar VMAT, consistent with prior findings [2].
TCP analysis showed risk-dependent sensitivity to systematic shifts, while reduced-margin planning maintained acceptable biological robustness under the evaluated conditions. Lower rectal and bladder NTCP further suggests a potential normal-tissue sparing benefit.

CONCLUSIONS

A reduced anisotropic [0, 0, 2] mm margin maintained target coverage and TCP within the evaluated geometric uncertainty range. These findings support the dosimetric feasibility of data-driven margin reduction in image-guided prostate VMAT, with potential rectal and bladder sparing.

REFERENCES

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