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Scientific Article

Robust Optimization for Prostate Radiation Therapy: Assessment of Delivered Dose by Incorporating Intrafraction Prostate Position Deviations

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Purpose: To assess the robustness of the dose delivered to the clinical target volume (CTV) between planning target volume (PTV)-based and robust optimization planning approaches in localized prostate cancer radiation therapy.

Methods and Materials: Retrospective data of 20 patients with prostate cancer, including radiation therapy and real-time prostate position, were analyzed. Two sets of volumetric modulated arc therapy plans were generated per patient: PTV-based and robust optimization. PTV-based planning used a 7-mm CTV-PTV margin, whereas robust planning considered same-magnitude position deviations. Differences in CTV dose delivered to 99% volume (D99), PTV dose delivered to 95% volume (D95), and bladder and rectum V40 (volume receiving 40 Gy) and V60 (volume receiving 60 Gy) values were evaluated. The target position, determined by in-house position monitoring system, was incorporated for dose assessment with and without position deviation correction.

Results: In the robust optimization approach, compared with PTV-based planning, the mean (standard deviation) V40 and V60 values of the bladder were reduced by 5.2% (4.1%) and 5.1% (1.9%), respectively. Similarly, for the rectum, the reductions were 0.8% (0.5%) and 0.6% (0.6%). In corrected treatment scenarios, both planning approaches resulted in a mean (standard deviation) CTV D99 difference of 0.1 Gy (0.1 Gy). In the not corrected scenario, PTV-based planning reduced CTV D99 by 0.1 Gy (0.5 Gy), whereas robust planning reduced it by 0.2 Gy (0.6 Gy). There was no statistically significant difference observed in the planned and delivered rectum and bladder dose for both corrected and not corrected scenarios.

Conclusions: Robust optimization resulted in lower V40 and V60 values for the bladder compared with PTV-based planning. However, no difference in CTV dose accuracy was found between the 2 approaches.

Introduction

Prostate cancer is prevalent in men, and more than 60% of patients undergo radiation therapy.[1,2] Geometric safety margins around the clinical target volume (CTV) account for uncertainties in radiation therapy planning.

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Research data are available at [or] Research data are not available at this time. [or] Research data are stored in

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However, adding margins to create the planning target volume (PTV) has limitations. It assumes perfect dose conformity, disregards dose variations resulting from anatomic changes, and compromises dose trade-off with nearby organs at risk (OARs).

To overcome these limitations, treatment planning using robust optimization has been proposed.[3,4] The primary objective of robust optimization is to optimize the beam parameters to deliver a robust dose to the CTV, considering expected uncertainties, while still meeting the dose objectives for OARs. Robust optimization relies on inverse optimization techniques widely used in modern conformal radiation therapy techniques such as intensity modulated radiation therapy and volumetric-modulated arc therapy (VMAT). In intensity modulated radiation therapy and VMAT, the iterative optimization process minimizes the objective function for the target and OARs to achieve an optimal plan. In robust optimization, uncertainties related to the desired robust clinical objectives are also incorporated into the optimization process to generate robust treatment plans.[4-7]

Although robust optimization for photon radiation therapy planning has been available in commercial treatment planning systems for some time, its adoption in clinical treatment planning is not widely undertaken due to the need for a paradigm shift in plan evaluation, consistent and robust dose reporting methods, and, most importantly, the lack of confidence in the dose delivered to the CTV by robust planning due to suboptimal dose coverage in the traditional PTV region.[4,8,9] The majority of current clinical evidence, which is based on the International Commission on Radiation Units and Measurements dose prescription and reporting guidelines, poses challenges for the clinical implementation of robust optimization.[10] The lack of evidence supporting this approach puts its clinical use at risk. In this study, we aimed to compare the reliability of the dose delivered to the CTV in localized prostate radiation therapy using both PTV-based and robust optimization approaches in the RayStation treatment planning system. The assessment of the actual dose delivered to the CTV will be determined by incorporating the actual prostate position obtained from SeedTracker real-time position monitoring system.[11-13]

Methods

Patient data sets

The radiation therapy data set used in this study was obtained from an ethics-approved study (ACTRN12618001421224) that focused on the implementation of an in-house developed real-time position monitoring system called SeedTracker for conventional prostate radiation therapy.[14] This study included a total of 20 patients undergoing radiation therapy for localized prostate cancer. A dose prescription of 60 Gy in 20 fractions was prescribed for the D95 of the PTV. The position tolerance for real-time target position monitoring was gradually reduced from 4 mm to 3 mm in a cohort of 10 patients at each tolerance level.[15] This strategy aimed to prevent an abrupt increase in treatment time caused by the increased occurrence of position deviations resulting from a tighter position tolerance. Such deviations could potentially lead to delays in the treatment machine schedule. The anticipated outcome of this study was to investigate the feasibility of optimizing the CTV-PTV margin in conventional fractionation prostate radiation therapy with real-time position monitoring and tighter position tolerance.[16,17]

Planning techniques

Two treatment plans, PTV-based and robust optimization, were created for each data set. In the PTV-based planning approach, a uniform margin of 7 mm, as per our clinic's protocol, was applied to generate the PTV around the CTV. The CTV included either the prostate alone or the prostate and base of the seminal vesicles depending on the risk of microscopic involvement of the seminal vesicles. For robust planning, the same 7-mm margin was used in the robust optimization process to simulate the systematic position variation of the CTV. The treatment plans were generated using the RayStation v10B (RaySearch Laboratories AB, Stockholm, Sweden) planning system, using either a single or 2 full VMAT arcs based on the complexity of the plan. A 6MV beam model specific to the Elekta linear accelerator with Agility treatment head was employed for plan generation. The dose volume objectives used for plan evaluation can be found in Table 1.

Robust optimization for systematic errors

The RayStation planning system uses minimax optimization to generate robust optimization plans.[5,8] This approach considers user-defined optimization functions to be robust under worst-case systematic error scenarios. In our study, the minimum dose and dose delivered to 99% volume (D99) to CTV were chosen as the robust optimization objectives. To account for systematic errors, a set of discrete error scenarios is considered during the optimization process. The number of systematic error scenarios depends on certain rules:

1. The nominal error scenario, representing no error, corresponds to one scenario for the considered 7-mm deviation.
2. Systematic error scenarios are created by shifting the patient position a distance 'u' cm in each direction

Table 1 Clinical dose-volume objectives used for plan evaluation

Target volume/OARs	Dose-volume objectives (Dx/Vy)		
	Goal		
	Metric	PTV-based	Robust optimization
PTV	D95	>60 Gy	NA
	D50	60-62.6 Gy	NA
	D2	<63 Gy	NA
CTV	D99	>60 Gy	>60 Gy
	Min	60 Gy	60 Gy
Rectum	V31	<50%	<50%
	V46	<30%	<30%
	V54	<10%	<10%
	V57.5	<5%	<5%
Sigmoid	V31	<50%	<50%
	V38	<40%	<40%
Bladder	V38	<40%	<40%
	V46	<30%	<30%
Femur	V31	<10%	<10%

Abbreviations: CTV = clinical target volume; D2 = dose delivered to 2% volume; D50 = dose delivered to 50% volume; D95 = dose delivered to 95% volume; D99 = dose delivered to 99% volume; Dx = dose received by 'x' % of volume; NA = not applicable; OARs = organs at risk; PTV = planning target volume; V31 = volume receiving 31 Gy; V38 = volume receiving 38 Gy; V46 = volume receiving 46 Gy; V54 = volume receiving 54 Gy; V57.5 = volume receiving 57.5 Gy; Vy = volume receiving 'y' Gy of dose.

(left, right, anterior [ant] posterir[post], superior[sup] and inferior[inf]). This results in 6 scenarios for the considered 7-mm deviation.

3. Intermediate error scenarios between the nominal and 'u' cm positions are determined by the following formula,

$$m = \frac{u}{0.75 + \varepsilon} \quad (1)$$

where $\varepsilon > 0$ and is small enough so that the radial distance equal to u.

These intermediate scenarios represent combined left-right, ant-post, and sup-inf directions with magnitudes of ±4 mm, ±4 mm, and ±4 mm, respectively, equivalent to the radial deviation of 7 mm. This results in 6 additional scenarios.

For the specific 7-mm systematic error magnitude considered in our study, a total of 15 scenarios are generated. In minimax optimization, the worst-case scenario is the one where the robust function achieves the greatest value. If multiple functions are assigned, their values are summed with weights assigned to each function in the optimization. The weights for the optimization functions are manually assigned during the planning process, and their values are adjusted iteratively to achieve clinically acceptable plans. The minimax optimization problem for 'n' robust functions, which need to be robust under all scenarios in the set, is formulated as follows:

$$\min_{x \epsilon X} \max_{s \in S} \sum_{i=1}^{n} w_i f_i(d(x;s)) \quad (2)$$

Where 'X' is the set of feasible variables (MLC position and segment weights for VMAT) and d(x;s) is the dose distribution as a function of variable x and scenario s.

The minimax optimization problem aims to find the optimal combination of feasible variables (x) that maximizes the robustness of the dose distribution under the worst-case scenario. By considering multiple scenarios and their associated dose distributions, the optimization process seeks to identify the set of variables that will result in a robust dose distribution across all scenarios in the set.

PTV-based and robust optimization plan comparison

The PTV-based and robust optimization plans were evaluated quantitatively by comparing various dose-volume histogram (DVH) metrics for the target volumes (CTV and PTV) and OARs (rectum and bladder). The following DVH metrics were used for the assessment: (1) D99 of CTV; (2) D95 (dose delivered to 95% volume) of PTV; (3) dose homogeneity index, calculated using equation 3, which quantifies the dose uniformity within the CTV and PTV volumes[18]; and (4) V40 (volume receiving 40 Gy) and V60 (volume receiving 60 Gy) of rectum and bladder.

To determine the statistical significance of the differences between the PTV-based and robust optimization plans, the Wilcoxon signed rank test was used. The significance level was set at $P < .05$, indicating that a P value < .05 would indicate a statistically significant difference between the 2 planning methods.

$$HI = \frac{Dose\ received\ by\ 5\%\ volume}{Dose\ received\ by\ 95\%\ volume} \quad (3)$$

Delivered dose assessment

The dose delivered to the target volumes (CTV and PTV) and OARs (rectum and bladder) was investigated using the actual target position deviations detected by the SeedTracker system. This was done by employing the voxel-shift method, which accounts for the position deviations in the dose calculation.[19,20] The delivered dose in each treatment fraction was assessed by incorporating the

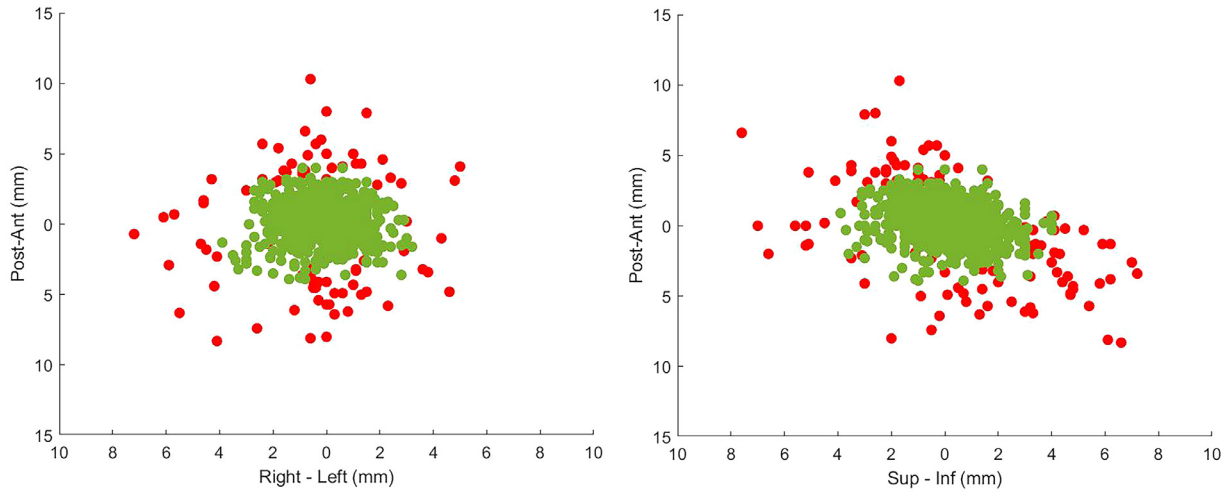

Figure 1 The prostate position during treatment delivery in (a) left−right and posterior−anterior and (b) superior−inferior and posterior−anterior directions with (green data points) and without (red data points) position correction applied. (A color version of this figure is available at 10.1016/j.adro.2024.101455.)

target positions determined by the SeedTracker system. The dose delivered over the entire treatment course was assessed by summing the individual fraction doses through rigid registration. Two treatment scenarios were considered: the "corrected" scenario, where position corrections were applied for observed position deviations, and the "not corrected" scenario, where no position corrections were applied to study the dosimetric effect in the absence of real-time monitoring and corrections.

In the "corrected" scenario, the dose delivered with position corrections applied was assessed. This was done by incorporating the residual position deviations below the action threshold into the 3-dimensional (3D) dose of the VMAT arc in each treatment fraction.

In the "not corrected" scenario, the dose that would have been delivered without monitoring was assessed by considering following scenarios:

- For treatment fractions without position deviations, the residual position errors were incorporated into the VMAT arcs, similar to the corrected scenario.
- For cases in which position deviations occurred at the start of the treatment, the observed position deviation was incorporated into the entire treatment fraction.
- For cases in which position deviations occurred during the delivery of the treatment, the residual error up to the fraction of treatment delivery was incorporated by scaling the 3D dose of the VMAT arc to the delivered monitor units. The position deviation was applied to the 3D dose of the VMAT arc and summed to the delivered dose by scaling it proportionally to the fraction of remaining monitor units of the arc.

The delivered D99 for CTV, D95 for PTV, V40, and V60 for rectum and bladder in the "Corrected" and "Not corrected" treatment scenarios were compared against their respective planned doses in PTV-based and robust planning. To assess the statistical significance of the differences, a one-way analysis of variance and Tukey honestly significant difference test were used with a significance level of $P < .05$.

Results

Position deviations

The prostate position, with and without position corrections, in the right−left, posterior−anterior, and superior−inferior directions for patients treated with 4-mm and 3-mm tolerance criteria are presented in Fig. 1a and 1b. Table 2 displays the mean (standard deviation [SD]) and maximum target position differences in the 3 directions with and without position corrections. The displacements greater than the position tolerance used in this study are mainly observed at the start of the treatment arc after cone-beam computed tomography (CBCT)-based position verification. The reason for this displacement could be the combination of internal organ motion and the patient's involuntary movement during the period between CBCT acquisition and treatment commencement.

Plan comparison

Target volumes dose

Table 3 shows the mean (SD) and range of CTV D99 and PTV D95 of plans generated using PTV-based and robust planning methods. The difference in CTV D99 and PTV D95 between the 2 planning methods is depicted

Table 2 The mean (SD) and maximum position deviations of prostate compared with planned position in patients treated with 4-mm and 3-mm position tolerance cohort

Tolerance cohort		Prostate position during treatment, mm					
		With corrections			Without corrections		
		L-R	A-P	S-I	L-R	A-P	S-I
4 mm	Mean	0.0	−0.1	−0.1	0.0	0.0	−0.3
	SD	1.1	1.5	1.5	1.5	2.3	2.3
	max	3.9	4.0	4.0	7.2	10.3	7.6
3 mm	Mean	−0.2	−0.4	0.2	−0.4	−0.3	0.5
	SD	1.1	1.3	1.3	1.6	2.8	1.9
	max	3.0	3.0	3.0	5.0	8.3	7.0

Abbreviations: P-A = posterior−anterior; L-R = left−right; SD = standard deviation; S-I = superior−inferior.

in Fig. 2. The study found a mean (SD) difference of 0.0 (0.1) Gy and −2.9 (1.4) Gy in CTV D99 and PTV D95, respectively, between PTV-based and robust planning methods. There was no statistically significant difference in CTV D99 between the 2 techniques ($P > .05$). However, a statistically significant difference in PTV D95 was observed between the 2 techniques (Table 3). Figure 3 illustrates the dose distribution of PTV-based and robust optimization plans for a representative case in axial and sagittal planes.

Rectum and bladder dose

Table 3 presents the mean (SD) and range of V40, and V60 for the rectum and bladder in PTV-based and robust planning methods. The results of the difference between the 2 methods are illustrated in Fig. 2. The robust

Table 3 The mean (SD) and range of difference in target volumes and OARs DVH metrics between PTV-based and robust planning methods

Structure	DVH metric		Dose (Gy) or volume (%)		Difference Gy/% volume	*P*
			PTV	Robust		
CTV	D99	Mean (SD)	60.1 (0.0)	60.1 (0.1)	0.0 (0.1)	.64
		Range	60.1-60.2	59.8-60.3	−0.2 to 0.2	
	HI	Mean (SD) Range	1.02 (0.01) 1.01-1.03	1.03 (0.01) 1.01-1.06	0.01 (0.01) −0.01-0.02	.00*
PTV	D95	Mean (SD)	58.4 (0.9)	54.6 (2.9)	−2.9 (1.4)	.00*
		Range	57.0-60.0	47.1-58.0	−8.4 to 0.2	
	HI	Mean (SD) Range	1.07 (0.04) 1.02-1.15	1.14 (0.07) 1.07-1.32	0.08 (0.04) 0.03-0.2	.00*
Rectum	V40	Mean (SD)	11.0 (3.6)	10.1 (3.1)	−0.8 (0.5)	.00*
		Range	5.5-20.1	4.9-17.9	−2.2 to −0.1	
	V60	Mean (SD)	2.8 (1.5)	2.2 (1.2)	−0.6 (0.6)	.00*
		Range	0.3-7.0	0.1-5.0	−2.4 to 0.3	
Bladder	V40	Mean (SD)	41.4 (9.4)	35.8 (9.9)	−5.2 (4.1)	.00*
		Range	27.0-63.0	24.3-60.3	−11.8 to 3.0	
	V60	Mean (SD)	12.2 (5.0)	7.0 (4.5)	−5.1 (1.9)	.00*
		Range	6.3-24.8	2.2-18.6	−8.7 to −2.3	

Abbreviations: CTV = clinical target volume; D95 = dose delivered to 95% volume; D99 = dose delivered to 99% volume; DVH = dose-volume histogram; HI = homogeneity index; OARs = organs at risk; PTV = planning target volume; SD = standard deviation; V40 = volume receiving 40 Gy; V60 = volume receiving 60 Gy.
*Statistically significant differences.

planning method shows a reduction in rectum V40 and V60 of 0.8 (0.5)% and 0.6 (0.6)%, respectively, compared with PTV based planning. Additionally, the bladder V40 and V60 were reduced by a mean (SD) of 5.2 (4.1)% and 5.1 (1.9)%, respectively, in robust planning. The reduction of V40 and V60 in the bladder and rectum was statistically significant ($P < .05$).

Optimization time

To generate clinically acceptable plans, the PTV-based and robust optimization approaches in our clinical RaySTation treatment planning system required a mean (SD) optimization time of 8.7 (2.6) minutes and 69.6 (29.6) minutes, respectively.

Delivered dose analysis

Figures 4 and 5 show the differences between the planned and delivered DVH metrics for the target volume and OARs in plans generated using PTV based and Robust planning techniques. Table 4 presents the results of the analysis of variance Tukey honestly significant difference test for plan and delivered dose with and without corrections for both planning methods.

Target volumes dose

In both PTV-based and robust planning methods, a mean (SD) difference of 0.1 (0.1) was observed between planned and delivered CTV D99 for treatment with corrections applied. For treatment without corrections, the mean (SD) difference in CTV D99 was −0.1 (0.5) Gy and −0.2 (0.6) Gy for PTV-based and robust planning methods, respectively. The delivered CTV D99 did not differ statistically from the planned dose in both planning methods (Table 4). However, a large difference was observed between planned and delivered PTV D95 in both planning methods. In PTV-based planning, treatment without position correction resulted in a statistically significant difference of D95 to PTV.

Rectum and bladder dose

Treatment delivery with position corrections applied resulted in less difference between planned and delivered DVH metrics of rectum and bladder in both PTV-based and robust planning methods (Fig. 5a and 5b). There was no statistically significant difference between the planned

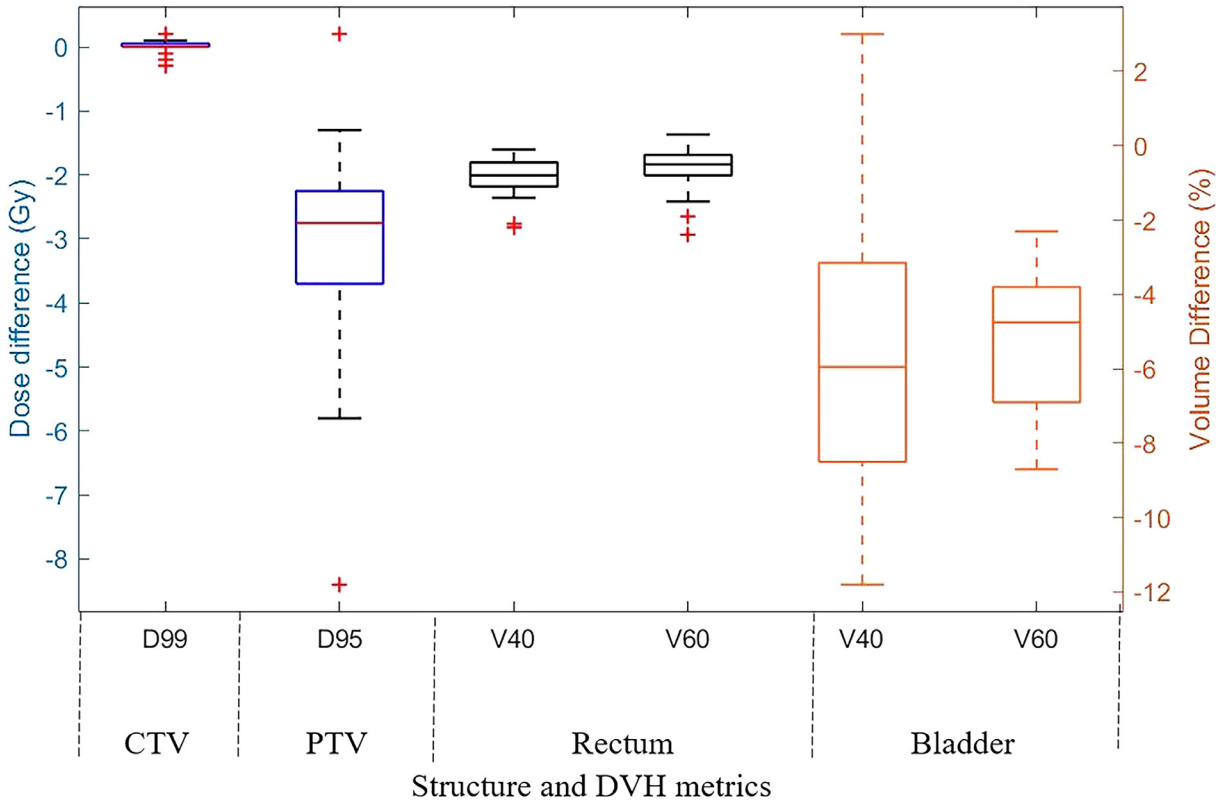

Figure 2 The difference in CTV, PTV, rectum and bladder DVH metrics between PTV-based and robust planning methods. *Abbreviations:* CTV = clinical target volume; DVH = dose-volume histogram; PTV = planning target volume. (A color version of this figure is available at 10.1016/j.adro.2024.101455.)

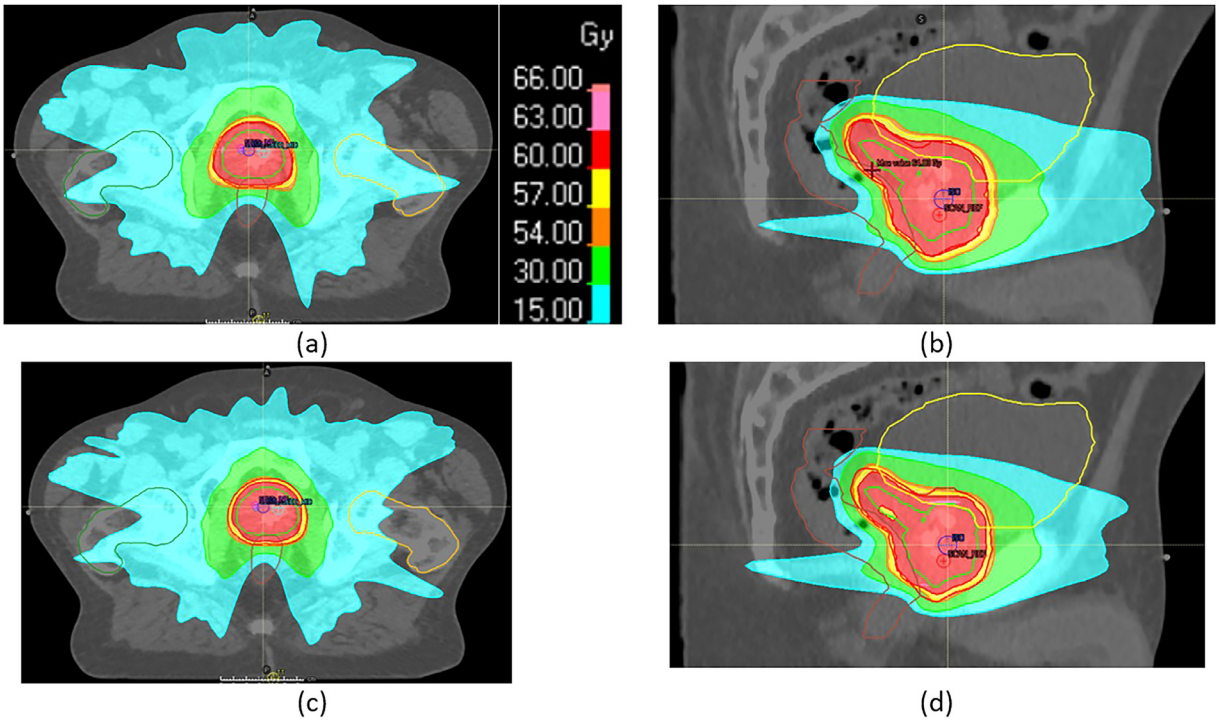

Figure 3 Dose distribution in (a) axial and (b) sagittal planes of the PTV-based plan for a representative case. Corresponding dose distribution in (c) axial and (d) sagittal planes of the robust optimization plan generated for the same representative case. *Abbreviations:* PTV = planning target volume. (A color version of this figure is available at 10.1016/j.adro.2024.101455.)

and delivered DVH metrics in both planning methods (Table 4).

Discussion

In the conventional planning approach, a fixed CTV-PTV margin is used, and a uniform dose is planned for the PTV to ensure adequate coverage of the planned dose to the CTV, considering a range of target position variations within the magnitude of the PTV margin. Robust optimization, in contrast, optimizes beam parameters for specific systematic position error scenarios. When we compared DVH metrics for CTV of PTV-based and robust optimization plans, both planning approaches resulted in equivalent D99 to the CTV ($P > .05$) in the nominal treatment scenario where no shifts were applied (Table 3). The goal of both PTV-based and robust optimization methods is to ensure an adequate dose to the CTV in the presence of uncertainties. Although the dose delivered to the CTV is clinically crucial, the comparison of dose to the PTV is presented in this study to discern the dose differences in the classical CTV-PTV region between PTV-based and robust optimization planning approaches, In terms of the OARs, there was a statistically significant reduction in V40 and V60 of the rectum in robust plans compared with PTV-based plans in the nominal treatment scenario. However, the mean reduction in dose magnitude was small (0.8 [0.5]% and 0.6 [0.6]%), which is not considered clinically significant. Similarly, there was a statistically significant reduction in V40 and V60 of the bladder in robust plans compared with PTV-based plans, with a mean reduction of 5.2 [4.1]% and 5.1 [2.1]% observed, respectively (Table 3).

In this study, the CTV-PTV margin used in our clinic was defined as the systematic patient position uncertainty to generate robust optimization plans. In addition to the systematic uncertainties, the interfraction random uncertainties in patient position and the position uncertainties arising from intrafraction organ motion can also be included in robust optimization to account for errors from these sources. At the time of conducting this study, the RayStation system available in our clinic was not licensed to include the random uncertainties in the optimization process. Future studies are warranted to include random uncertainties in the robust optimization process and assess the delivered dose. The inclusion of intrafraction motion in robust optimization requires time-resolved 3D image sets to account for intrafraction motion, and as such, it is applicable for treatment sites such as the lung and abdomen where the tumor position is influenced by periodic breath motion. However, it is not applicable for prostate treatment, where intrafraction motion is random in nature.

Wada et al[9] compared robust and PTV-based plans in prostate cancer patients. They used a prescription dose of 78 Gy in 39 fractions with an asymmetrical PTV margin

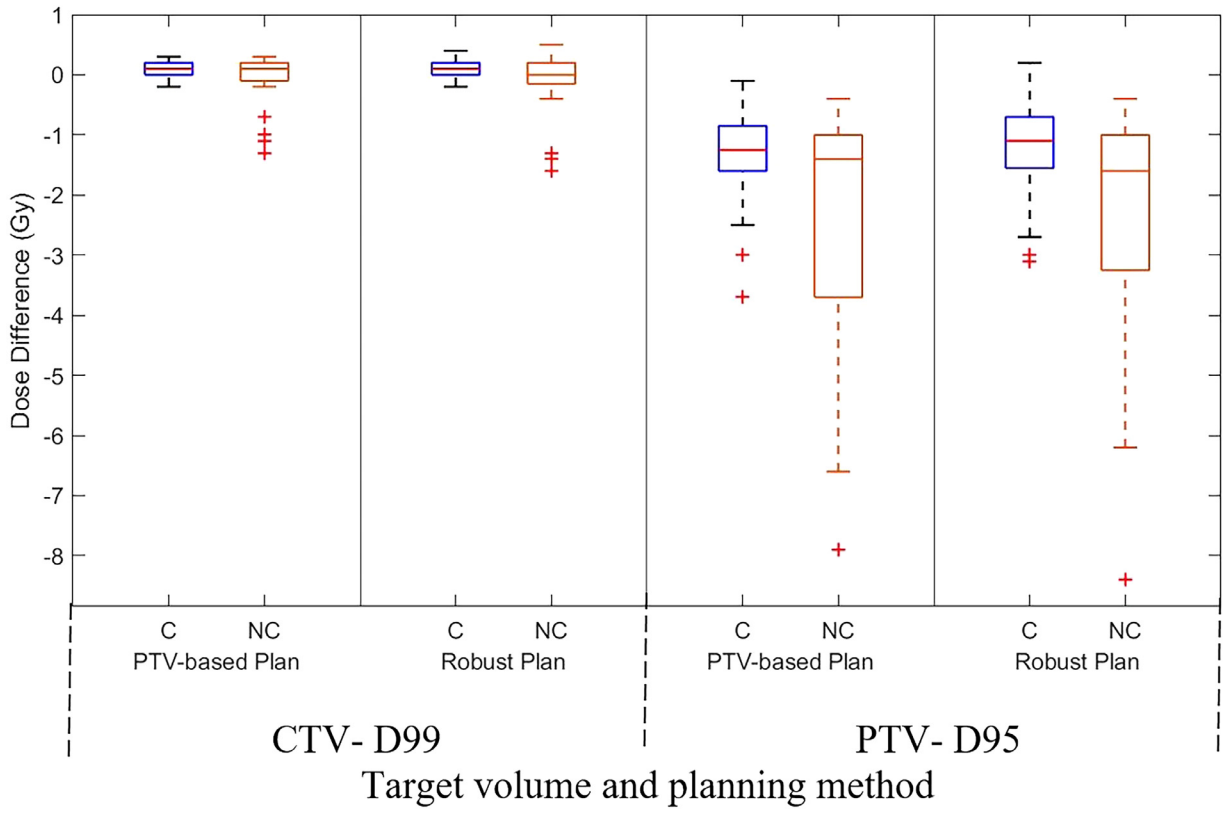

Figure 4 The difference between planned and delivered target volumes DVH metrics of plans generated using PTV-based and robust planning methods, with and without position corrections applied. The letters 'C' and 'NC' represent corrected and not corrected scenarios for position deviations, respectively. *Abbreviations:* DVH = dose-volume histogram; PTV = planning target volume. (A color version of this figure is available at 10.1016/j.adro.2024.101455.)

(superior−inferior: 10 mm, left−right: 8 mm, posterior −anterior: 6 mm). Their study demonstrated similar CTV and PTV doses between the 2 planning approaches. Wada et al observed slightly lower V70, V65, and V40 values for the rectum in robust plans compared with PTV-based plans. They also found significant differences in V70, V65, and V40 of the bladder between the 2 approaches, consistent with the current study's findings.

No difference was found in the delivered dose to the CTV between corrected and not corrected scenarios in

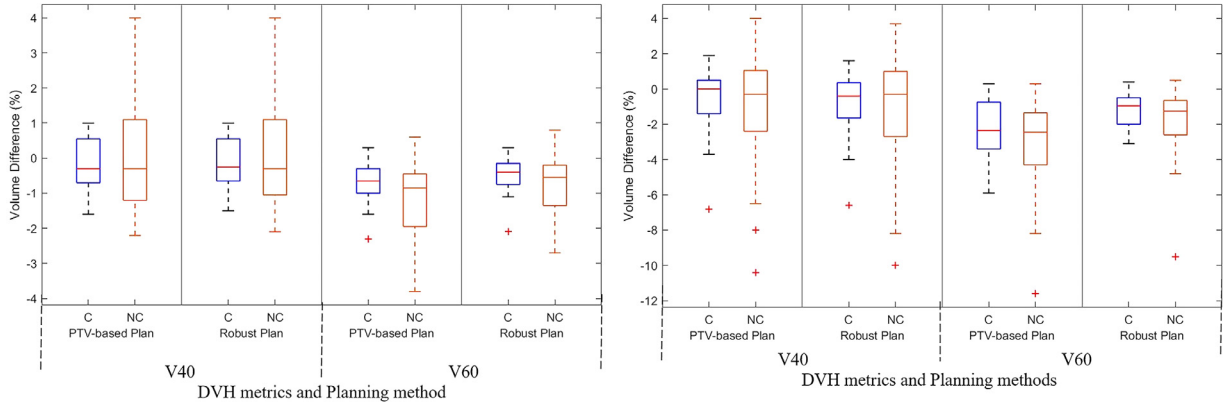

Figure 5 The difference between planned and delivered (a) rectum and (b) bladder DVH metrics of plans generated using PTV-based and robust planning methods, with and without position corrections applied. The letters 'C' and 'NC' represent corrected and not corrected scenarios for position deviations, respectively. *Abbreviations:* DVH = dose-volume histogram; PTV = planning target volume. (A color version of this figure is available at 10.1016/j.adro.2024.101455.)

Table 4 The ANOVA and Tukey honestly significant difference test results of delivered DVH metrics compared with planned dose in PTV-based and robust planning methods, with and without position corrections applied

		PTV-based planning		Robust optimization	
Structures	DVH metric	Corrected	Not corrected	Corrected	Not corrected
CTV	D99	*F* = *2.15*		*F* = *2.15*	
		P = .64	*P* = .48	*P* = .70	*P* = .43
PTV	D95	*F* = 4.54		*F* = 2.60	
		P = .22	*P* = .01*	*P* = .44	*P* = .07
Rectum	V40	*F* = 0.02		*F* = 0.02	
		P = .98	*P* = 1.00	*P* = .99	*P* = 1.00
	V60	*F* = 3.03		*F* = 2.77	
		P = .27	*P* = .05	*P* = .32	*P* = .06
Bladder	V40	*F* = 0.09		*F* = 0.12	
		P = .97	*P* = .90	*P* = .96	*P* = .88
	V60	*F* = 2.66		*F* = 1.20	
		P = .29	*P* = .74	*P* = .63	*P* = .28

Abbreviations: ANOVA = analysis of variance; CTV = clinical target volume; D95 = dose delivered to 95% volume; D99 = dose delivered to 99% volume; DVH = dose-volume histogram; PTV = planning target volume; V40 = volume receiving 40 Gy; V60 = volume receiving 60 Gy.
*Statistically significant difference.

both PTV-based and robust planning approaches. The planned and delivered D99 showed no statistically significant difference. For the bladder and rectum, there was no significant difference in the planned and delivered V40 and V60 in both scenarios and planning methods ($P > .05$). However, robust planning resulted in lower V40 and V60 to the bladder compared with PTV-based planning, indicating potential OAR dose reduction without compromising CTV dose delivery.

Most of the current clinical evidence in radiation therapy is based on the PTV-based planning approach. The unconventional dose distribution in the PTV-CTV region requires new approaches in the clinical plan evaluation compared with plans generated using the PTV-based planning approach. The use of robust plan evaluation tools, which calculate the dose distribution for isocenter offset scenarios of desired magnitude, allows for the evaluation of the CTV's dose in extreme systematic position deviation scenarios. This information helps determine whether further optimization of robust plans is necessary to achieve the desired robust dose delivery to the CTV.

In the study by Wada et al,[9] the robustly optimized prostate plans were evaluated using the robust plan evaluation tool available in RayStation. They simulated systematic error scenarios with a position deviation range equal to the magnitude of the asymmetrical PTV margin used in PTV-based plans. The study found that the robustness of D99 to the CTV was suboptimal in robust plans compared with PTV-based plans when only the CTV was considered in the robust optimization. However, the robustness of CTV coverage was improved in the hybrid robust optimization, where the overlapping region between the PTV and rectum was included as the target optimization structure in VMAT optimization.

The main contribution of this study is the assessment of the delivered dose during treatment by incorporating the actual position deviations detected. This allows for a realistic comparison of the robustness of dose delivery to the CTV in both corrected and uncorrected treatment scenarios for PTV-based and robust optimization planning methods. However, one limitation of the study is that the delivered dose assessment was based on the planning CT data sets, which do not account for daily internal organ position variations due to changes in rectum and bladder contents. Although this approach provides a good estimate of the dose delivered to the CTV, the dose estimation to the rectum and bladder may not be representative. Performing dose assessment based on internal structures defined on daily CBCT pretreatment verification images may provide a more clinically representative dose. However, accurate contouring of these structures on verification CBCT images can introduce additional uncertainties.[21]

The PTV-based planning approach has established clinical outcomes data and a standardized dose prescription reporting mechanism in radiation therapy. However, the lack of clinical outcomes data and guidelines on dose prescription and reporting methods limits the adaptation of robust optimization for routine clinical planning.[4] Conceptually, the dose prescription method in the currently practiced PTV-based approach also has an inherent

limitation, as it does not contain the magnitude of the PTV margin used, which ultimately decides the robustness of the dose to the CTV. One of the limitations of PTV-based planning, particularly in cases involving multilevel dose prescriptions, such as prostate treatment with pelvic nodes and boosting the dominant intraprostatic lesion, is that expanding the margin for individual dose levels becomes cumbersome. This makes it challenging to achieve an optimal dose distribution for individual target volumes. Robust optimization, on the other hand, has the potential to generate an optimal dose distribution in these complex scenarios. Future studies are warranted to investigate the efficacy and dose delivery accuracy of the robust planning approach for these treatment sites.

In the dose prescription for robust optimization method, the robustness level of the CTV, as assessed by the dose evaluation, could be a possible practical approach for dose prescription and reporting in robust optimization.[6] In the clinical implementation of the robust optimization process, the utilization of real-time position monitoring and the assessment of delivered dose by incorporating the actual target position during treatment will provide the necessary confidence in achieving uncompromised dose delivery to the CTV.

Conclusions

Our study evaluated the robustness of dose delivery to the prostate CTV using PTV-based and robust optimization planning methods in prostate cancer radiation therapy. By incorporating the actual prostate position, we found that both planning methods resulted in equivalent robustness of D99 to the CTV. However, the robust optimization planning approach offered additional benefit of reduction of rectum and bladder dose compared with PTV-based planning.

Disclosures

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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