Title

Dose impact of rectal gas on prostatic IMRT and VMAT

Authors and Affiliations

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Informed consent was obtained from all individual participants in the study
All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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Original article

Abstract

Purpose: In this study, we compared the dose impact of the heterogeneity caused by rectal gas using two methods of treatment planning for intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc therapy (VMAT).

Materials and Methods: In addition to the structure set used for the standard treatment plan, we created a structure set for evaluation for each patient. The structure sets for evaluation that were created were transferred to the same iso-center as the respective treatment plans for IMRT and VMAT that were to become the standard. The values were then re-calculated.

Results: During the standard prostatic IMRT and VMAT treatment planning, all the subjects met the dose restrictions in place at our hospital. Dose restrictions were fulfilled in the treatment plans for evaluation, excluding those with a clinical target volume (CTV) of $V_{100\%}$ and planning target volume (PTV) of D_{95} when the rectum was excluded. However, in treatment plans for evaluation, IMRT was shown to have a higher concordance rate with standard treatment plans than VMAT.

Conclusion: If rectal gas is present during either IMRT or VMAT, a dose decrease will occur in relation to CTV and PTV, suggesting that a plan does not eliminate adverse effects on organs at risk.

Key words: Intensity-modulated radiotherapy, Volumetric-modulated arc therapy, Gas, Prostate cancer, Dose distribution

1 Introduction

According to the National Comprehensive Cancer Network (NCCN) guidelines for radiotherapy for prostate cancer, patient groups at low risk are those receiving 75.6–79.2 Gy and groups at medium to high risk are those receiving up to 81.0 Gy [1]. Reports suggest that increasing the dose to 70–78 Gy reduces recurrence, particularly in moderate- to high-risk groups, suggesting the usefulness of a dose increase [2]. In the area surrounding the prostate, the organs at risk (OAR) are the rectum and bladder. For this reason, intensity-modulated radiotherapy (IMRT), which is capable of administering a uniform dose to the prostate while simultaneously minimizing radiation exposure of the surrounding OAR, is used at several institutions. Several reports of prostate IMRT have described results ranging from usefulness due to the physical dose distribution to superior clinical outcomes [3-5]. However, the dose gradient becomes steep at the boundary between the prostate and the surrounding OAR. Accordingly, insufficient precision when setting up the patient position has a major effect on the dose administered to both the prostate and the surrounding OAR. For this reason, image-guided radiotherapy (IGRT) is recommended in the NCCN guidelines when exposing patients to a prescribed dose of ≥78 Gy [1].

IGRT uses 2- or 3-dimensional reference images to calculate and correct the change in patient position used in radiotherapy and then reproduces the site of irradiation as close as possible to the side determined during radiotherapy planning. It is based on either a two-dimensional

collated image taken from two or more directions or a three-dimensional collated image. It is used as a verification technique for reproducing the exposure position that was determined in radiotherapy treatment planning as much as possible. When IGRT is used for position collation, there are two kinds: that for bone structure or that for target verification. There are reports of changes in the position of the prostate relative to the bone due to changes in bladder volume or rectal contents such as feces and gas, of which the effects from rectal gas are known to be the greatest [6-8]. Furthermore, as intrafraction organ motion is known to occur during the course of treatment, which changes the position of the prostate, it is desirable to shorten the treatment time by using volumetric-modulated arc therapy (VMAT) [9, 10]. However, in these reports, there was no detailed investigation of the effects of heterogeneity due to rectal gas that was absent during treatment planning.

In this study, we evaluated the effects of rectal gas on dose distribution during prostatic IMRT and VMAT. Although VMAT is better than IMRT in terms of intrafraction organ motion, we compared the influence of rectal gas in both planning methods.

2 Materials and Methods

The subjects were 9 patients with prostate cancer treated with IMRT at our hospital. All patients were treated in the supine position. Patient characteristics are shown in Table 1. Only those who gave informed consent

for the use of their data for research purposes were included in this study. The computed tomography (CT) machine used for treatment planning was a 16-row multislice CT Optima CT580W (General Electric Medical Systems, Waukesha, WI, USA), with a field of view (FOV) of 500 mm, reconstructed slice thickness of 2.5 mm, and matrix size of 512 × 512. The treatment planning system (TPS) used for both IMRT and VMAT treatment planning was the Eclipse version 11.0.3 (Varian Medical Systems, Palo Alto, CA, USA). Contours were defined by a radiologist according to the contour depiction protocol at our hospital, as described later. The clinical target volume (CTV) is the volume of the prostate plus part of the seminal vesicles included in a 2 cm margin from the prostate (Fig. 1). The planning target volume (PTV) is an area established by setting a margin 6 mm posteriorly from the CTV and 8 mm in all other directions from the CTV. With respect to the rectal volume, the radiation therapy oncology group (RTOG) guidelines [11] state that it involves the area from the ischial tuberosity to the area between the descending colon and rectum or an area up to 15 cm in size. However, in this study, in order to minimize differences in the contour measurements between individuals, rectal volume was defined as the CTV plus 6 slices, which corresponds to 1.5 cm, in the craniocaudal direction from the CTV.

2.1 Treatment planning

The IMRT therapeutic images were obtained at 7 gantry angles of 0, 55, 105, 155, 205, 255, and 305 degrees. At the gantry angles of 155 and 205 degrees, we considered dose reduction through X-ray absorption in order to include the beam that passes through the treatment bed. For this reason, we corrected this by couch modeling. The dose prescribed during this study was 76 Gy, which is a dose that covers 95% of the PTV (D_{95}), with the overlapping rectum subtracted from the PTV area [12]. The linear accelerator used for treatment planning was NovalisTx (Varian Medical Systems, Palo Alto, CA) emitting 15MV-X. During the IMRT treatment planning, we applied an inverse planning technique using an optimization calculation algorithm, and created a fluence map in order to obtain the ideal dose distribution. Generally, a gradient method is used in an optimization calculation algorithm, and the level of achievement of the target dose established for each organ is calculated using a cost factor. We used the analytical anisotropic algorithm (AAA) as a dose calculation algorithm, and used a calculation grid size of 2.5 mm × 2.5 mm × 2.5 mm. In addition, there were two arcs for the gantry rotation angles used during VMAT planning: 181–179 degrees in a clockwise (CW) direction and 179–181 in a counterclockwise (CCW) direction. The collimator angles used were 30 degrees and 330 degrees. Couch modeling was used for correction as VMAT involves the passage of a beam through the treatment table. The prescribed dose was the same as that in IMRT. The beam dose restrictions used in this study are shown in Table 2.

The volume of rectal gas in relation to the volume of the rectal contour used in treatment planning was 5% or less in all cases. In order to evaluate the effects exerted by rectal gas on the dose distribution, we created two types of structure set for the evaluation of each subject, in addition to creating a structure set using standard treatment planning. A summary of the two structure sets used for evaluation is as follows. A Hounsfield unit (HU) value of rectal gas is assigned to (1) the entire volume surrounded by the rectal contour, and (2) the area of overlap between the PTV and the rectum (overlap area). The mock values for the HU value of rectal gas were set as −950 based on the mean value of the gas in the rectum in the actual patients. Using the created structure sets that were used for the evaluation, the reference treatment plans for IMRT and VMAT were transferred to the same iso-center and recalculated.

2.2 Plan evaluation

Firstly, we evaluated the dose indicators in Table 3 for the prostatic IMRT and VMAT treatment plans. We used the paired t-test for statistical testing of the two groups in order to determine differences between IMRT and VMAT for all evaluation items. Using a technique similar to the above, we evaluated the difference between the treatment plan that was recalculated using the two structure sets created for the purpose of evaluation and the standard treatment plan. Furthermore, we used three-dimensional dose verification software (3DVH® version 2.2; SunNuclear, Melbourne, FL) and

evaluated CTV, PTV, dose difference (DD) for bladder and rectal volume, distance to agreement (DTA), and gamma analysis (GA). The evaluation targets were DD (1%, 2%, 3%), DTA (1 mm, 2 mm, 3 mm), and GA (1%/1 mm, 2%/2 mm, 3%/3 mm), and were always assessed at 10% of the threshold dose. The TPS measurement results depend on the results of the basic data through beam modeling. Thus, because less than 10% of the beam modeling is considered to be uncertain to a certain extent, in the present study, we selected 10%. The commercially available 3DVH software program can overcome some of the disadvantages of the planar gamma analysis concepts. With the aid of this software, the full 3D dose distribution can be reconstructed based on the measured data, and it can be compared to the TPS planning dose. In addition, a dose-volume histogram (DVH) for each target and each region of interest (ROI) can be drawn. In this study, we used two types of evaluation structure sets for comparison of the recalculated treatment plans, rather than using dose distribution that was reconstructed on the basis of measurement data. Similarly, we used the paired t-test for statistical testing of the two groups in order to determine differences between IMRT and VMAT for all evaluation items.

3 Results

The results of the comparison between the IMRT and VMAT therapeutic images for the 9 subjects are shown in Table 4. All subjects fulfilled the dose

restrictions shown in Table 2. Except for the PTV minimum dose ($p = 0.034$) and V_{65Gy} ($p < 0.01$) in the bladder, no significant differences were observed.

Table 5 shows the differences in the dose indicators between the standard treatment plan and the treatment plan where a mock HU value was assigned for gas in the entire rectum. There were no significant differences between the standard treatment plan for both IMRT and VMAT and the plan with assigned HU value for gas in the entire rectum in the maximum dose for CTV, rectal V_{70Gy}, or bladder V_{40Gy} and V_{65Gy}. In addition, no significant differences were observed between the minimum PTV dose when using IMRT, and the mean PTV dose and rectal V_{60Gy} when using VMAT.

For both IMRT and VMAT, the doses for CTV and PTV were lower in the treatment plan where mock HU values were allocated for gas filling the entire rectum compared with those of the standard treatment plan, and the same decrease was observed in the high-dose regions of ≥75 Gy in the rectum. On the other hand, the values tended to be significantly higher in the moderate-dose areas of ≤ 60 Gy in the rectum. Non-significant changes in rectal V_{40Gy} and V_{60Gy} in IMRT, and PTV D_{95} and rectal $V_{40\,Gy}$ in VMAT, were observed in the overlap gas group compared with the rectal gas group (Table 5a, b). Excluding the CTV of $V_{100\%}$ and the PTV D_{95} (with exclusion of the rectum), the dose distribution was fulfilled in all of the evaluation treatment plans.

Table 6 shows the results of an analysis of the concordance of the dose distributions for the standard treatment plan and the two types of treatment

plan using 3DVH. The results for 1% DD for CTV in treatment plans where mock HU values were allocated for gas filling only in the overlap region were 91.16 ± 5.30% for IMRT and 88.12 ± 4.87% for VMAT, with a significant difference between the two ($p = 0.026$). For this reason, compared with VMAT, IMRT has a high concordance with the standard therapeutic plan. The results for 2% DD, similar to the results for 1% DD, showed significant differences ($p = 0.022$), but there was no significant difference for 3% DD ($p = 0.265$). Similar to CTV, the PTV results at 1% DD and 2% DD showed that the concordance rate for VMAT was significantly lower. Furthermore, in terms of OAR, there were no significant differences in the results for IMRT and VMAT. With respect to DTA, there was no significant difference in any of the organs for DTA of 1 mm; there was no significant difference in any of the organs except the bladder for DTA of 2 mm; and there was a significantly higher concordance rate with IMRT for all volumes for DTA of 3 mm (with exclusion of the rectum). Finally, the results for GA showed that IMRT had a higher concordance with the standard treatment plans at CTV of 1%/1 mm and 2%/2 mm. For treatment plans where mock HU values were allocated for gas filling the entire rectum, in terms of the DD, there was a significantly higher concordance for IMRT when compared with the standard treatment plans for all CTV and PTV evaluation items. In the rectum and the bladder, in terms of DD, there were no significant differences observed in any of the evaluation items. During DTA, we excluded rectal 1 mm DTA and there was no significant difference in any of the results. There was a significant

difference in the GA values for CTV and PTV at 1%/1 mm to 3%/3 mm, and IMRT showed higher concordance with the standard treatment plans. The rectal VMAT only showed significantly higher concordance at 1%/1 mm, but there were no results with significant differences in other evaluation items. Figure 2 shows the sagittal section 2% DD, 2 mm DTA, and 2%/2 mm GA for IMRT and VMAT treatment plans using the structure set for evaluation where mock HU values have been allocated for gas filling the entire rectum and for the treatment plans after substitution and recalculation. Figure 3 also shows the axial dose distribution for the standard treatment plan and the recalculated treatment plan using the two types of structure set for evaluation.

4 Discussion

Increases in the dose of radiotherapy for prostate cancer are known to be useful for improving clinical outcomes [2]. Meanwhile, compared with normal three-dimensional conformal radiotherapy (3D-CRT), set up precision is more important when using irradiation methods that have a steep dose gradient, such as IMRT and VMAT. Zelefsky et al. investigated the outcome of treatment with or without IGRT performed at the same doses among patients with prostate cancer, and came to the conclusion that there was tumor suppression in high-risk cases and a reduction of delayed adverse drug reactions involving the bladder [13]. This suggests that, in IMRT, it is important to ensure the reproducibility of the dose distribution in both the prostate and the surrounding OAR during the period of radiotherapy treatment by performing IGRT. In a previous study focusing on the dose impact due to daily movement of the rectum, bladder, and prostate, after megavoltage CT imaging, the dose distribution in the treatment plan was substituted for recalculation [14]. Although implanted metallic markers were used (as references) to verify the target locations, the study revealed that discrepancies in the prostatic dose due to rectal contents such as feces or gas, or due to changes in the bladder volume, were approximately 10% at most. However, they did not show whether the dose distribution was affected by changes in the position of the prostate due to the presence of gas in the bowel, or by the heterogeneity caused by rectal gas that was not present in the rectum at the time of treatment planning. Therefore, in this study, we

focused on rectal gas, which is said to be the key factor affecting the dose distribution in the prostate. However, we made the assumption that positional changes of the prostate do not occur, and then evaluated the effects of heterogeneity caused by rectal gas on the dose distribution during IMRT and VMAT.

The dose restrictions shown in Table 2 in this study were taken as the standard, and we created the standard prostatic IMRT and VMAT treatment plans. From the results shown in Table 4, during standard prostatic IMRT and VMAT, we believe it is possible to formulate the same level of radiotherapy treatment plan. As shown in Table 5, a significant difference was observed in at least one dose index in all organs other than the bladder in the rectal gas group in both IMRT and VMAT. If there was gas present within the rectum, there was reduced dose scattering in the rectum compared with when there was no gas in the rectum; therefore, we believe that dose reduction occurred from the posterior wall of the CTV to the anterior wall of the rectum. For these reasons, significant differences were observed in the minimum dose for CTV, $V_{100\%}$, and mean dose in the standard treatment plan. The same can be said for the PTV and rectal V_{75Gy}. In contrast, the values tended to be higher in moderate-dose regions of 60 Gy or less, compared with the standard treatment plan, suggesting that the dose that would have been absorbed in the rectum under normal circumstances was transmitted because of rectal gas. Accordingly, the dose was higher in the high-dose regions, and the opposite was shown in the moderate- to

low-dose regions. The fact that no significant difference was noted for the bladder could be because it was separated and at some distance from the rectal gas and therefore exerted no effect. In the overlap group, differences in the dose distribution for the standard IMRT and VMAT treatment plans were small when compared with the rectal gas group, but still significant differences were observed in some dose indicators such as the minimum and mean CTV doses ($p<0.01$). The fact that there was reduced dose scattering when the values for gas in the overlap region were allocated, similar to what was discussed previously, shows that there is an effect on the high-dose-region dose indicators ≥ 75 Gy in the rectum. Meanwhile, we compared the structure set allocated values for when rectal gas was present in the overlap region only with the structure set where mock values were allocated for gas present throughout the rectum and found that the effects were small in the dose regions in the rectum that received ≤70 Gy. On the basis of the concordance results of the standard IMRT and VMAT treatment plans and after substituting the two types of structure set in the standard treatment plan and recalculating, we then discussed performing dose distribution substitution and recalculation in the structure set where there was allocation of values for gas throughout the rectum during IMRT and VMAT. On the basis of the DD and DTA results, if we focus on the rectum, the concordance rate for the DD for both IMRT and VMAT is low compared with that for DTA. However, DD conversely shows higher concordance than DTA for CTV and PTV. On this basis, this would cause differences in the

dose impact on various organs and the characteristics of the dose distribution. Only the organs in the CTV and PTV should be irradiated, but not the rectum as it is an OAR; the advantage of IMRT and VMAT is that these are the only methods capable of providing this exposure. Because the dose distribution has these characteristics, the effects of the CTV and the PTV on the DD were low. With regard to the rectum, we believe that the DD was extremely low because there is a dose distribution that involves dose changes in a fixed range extending from the anterior to the posterior rectal wall. In terms of the DTA, the most important evaluation is whether the compared dose provides the same dose within the shortest distance; therefore, we did not observe an extreme decrease in concordance as with DD. On this basis, we believe that the GA in this evaluation is appropriate when the concordance rate uses either the DD or the DTA only. There was a significant difference in the GA values for CTV and PTV at 1%/1 mm to 3%/3 mm ($p<0.01$), and IMRT showed a higher concordance rate with standard treatment plans. This means that the PTV was irradiated with a greater dose in the direction of the rectum in the VMAT treatment plans than in the IMRT treatment plans. Accordingly, in the case of VMAT, there is scope for investigating a radiation method such as partial restriction of the beam radiation angle from the direction of the rectum. However, because the AAA dose calculation algorithm used in this study does not accurately calculate changes in density in highly heterogeneous regions, it is possible that the value for the rectum is being overestimated and that for the posterior wall of

the CTV is being underestimated [14]. In the future, we plan to use Acuros XB or XVMC, which are dose calculation algorithms that are equivalent to Monte Carlo simulation.

In this study, even when the entire rectal volume was filled with gas, it was possible to meet the dose restrictions for OAR at our hospital. Thus, during exposure prior to position verification, even when there is gas present in the rectum, if there are no changes in the position of the prostate, it is possible to continue irradiation without causing adverse events in OAR even though dose reduction occurs in CTV and OTV. Meanwhile, at many institutions, the concordance rate at 3%/3 mm is used to investigate the dose distribution for IMRT and VMAT, and the GA results in this study suggest that, if the criteria are fulfilled, the therapy can be performed safely. The minimum concordance rate was 95.4% during IMRT and 93.1% during VMAT, and in either case, there was concordance in the CTV, but these results suggest that it is safe to continue treatment.

Next, in the case where there was substitution and recalculation for rectal gas only in the overlap region, compared with when values were allocated for gas filling the entire rectum, the percentage of gas was obviously smaller, but when the 1% and 2% DD in the CTV and PTV were evaluated and compared with the VMAT, the IMRT had significantly better concordance with the standard treatment plans. In the same way as for conventional treatment plans, when trying to support exposure to the dose distribution, we believe that the rectal gas content below the overlap area must be

minimized. However, when gas is in the overlap region, on the basis of the results of GA, even if there is concordance with 2%/2 mm, the minimum concordance is 98.4% for IMRT and 96.1% for VMAT. As previously mentioned, we believe that this concordance rate showed that clinical irradiation can be performed without a problem. In addition, during the present study, although all subjects had rectal gas content that was 5% or less of the rectal volume, the results showed that it is possible to perform irradiation even if gas is present in the overlap region as long as there is no change in prostate position.

5. Conclusions

During this study, in order to evaluate the effects on dose distribution related to the homogeneity created by gas that was not present in the rectum during the treatment planning for prostatic IMRT and VMAT, we assumed no change in the position of the prostate. The results suggested that, compared with VMAT, even when there is gas present in the rectum during IMRT, the effects on dose distribution are low compared with when there is no gas in the rectum. However, even though a dose reduction occurred in the CTV and PTV when rectal gas was present during both IMRT and VMAT, dose restrictions for the OAR at our hospital were met. In addition, a concordance rate of 93.1% was obtained in relation to CTV and PTV for a GA of 3%/3 mm, suggesting that treatment can be concluded successfully if a change in the position of the prostate does not occur.

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Figure Legends

Fig. 1 Delineation of the clinical target volume (CTV). CTV includes the seminal vesicles within 2 cm of the prostate.

Fig. 2 The sagittal section 2% DD, 2 mm DTA, and 2%/2 mm GA for IMRT and VMAT treatment plans using the structure set for evaluation where mock HU values have been allocated for gas filling the entire rectum and for the treatment plans after substitution and recalculation. In the red area, we compared areas that did not match the permitted value for each evaluation item to standard treatment planning, showing that the dose was higher. In the blue area, we compared areas that did not match the permitted value for each evaluation item to standard treatment planning, showing that the dose was lower.

(a) IMRT 2% DD, (b) VMAT 2% DD, (c) IMRT 2 mm DTA, (d) VMAT 2 mm DTA, (e) IMRT 2%/2 mm GA, (f) VMAT 2%/2 mm GA

DD: dose difference

DTA: distance to agreement

GA: gamma analysis

Fig. 3 Dose distribution in the sagittal plane for the standard treatment plan and the treatment plan recalculated using the two types of structure set for evaluation

(a) The dose distribution for the standard prostatic intensity-modulated radiation therapy (IMRT) treatment plan.

(b) The dose distribution for IMRT for the planning target volume (PTV) after substitution and recalculation using the structure set for analysis when the HU value was allocated for gas filling the overlap region.

(c) The dose distribution for IMRT after substitution and recalculation using the structure set for analysis when the HU value was allocated for gas filling the entire rectum.

(d) The dose distribution for the standard prostatic volumetric-modulated radiation therapy (VMAT) treatment plan.

(e) The dose distribution for VMAT treatment planning for the PTV after substitution and recalculation using the structure set for analysis when the HU value was allocated for gas filling the overlap region.

(f) The dose distribution for VMAT treatment planning after substitution and recalculation using the structure set for analysis when the HU value was allocated for gas filling the entire rectum.

Table 1 Patients characteristics.

PSA: preretirement spouse annuity

Table 2 Dose-volume constraints used in the planning.

Table 3 Dose evaluation used in the planning.

Table 4 Dosimetric comparison of organs at risk and target dose of IMRT and VMAT plans.

Table 5 Differences in the dose indicators when using the standard treatment plan and the two types of treatment plan for evaluation.

(a) IMRT, (b) VMAT

Overlap gas: The treatment plan using the structure set that was allocated an HU value for mock gas in the overlap area of the rectum.

Rectum gas: The treatment plan using the structure set that was allocated an HU value for mock gas in the entire rectum.

Table 6 Results of concordance of the dose distributions for the standard treatment plan and the two types of treatment plan under evaluation.

(a) The DD concordance results when using the standard treatment plan and the structure set using an HU value for mock gas filling the overlap region.

(b) The DTA concordance results when using the standard treatment plan and the structure set using an HU value for mock gas filling the overlap region.

(c) The GA concordance results when using the standard treatment plan and the structure set using an HU value for mock gas filling the overlap region.

(d) The DD concordance results when using the standard treatment plan and the structure set using an HU value for mock gas filling the entire rectum.

(e) The DTA concordance results when using the standard treatment plan and the structure set using an HU value for mock gas filling the entire rectum.

(f) The GA concordance results when using the standard treatment plan and the structure set using an HU value for mock gas filling the entire rectum.

DD: dose difference

DTA: distance to agreement

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Figures

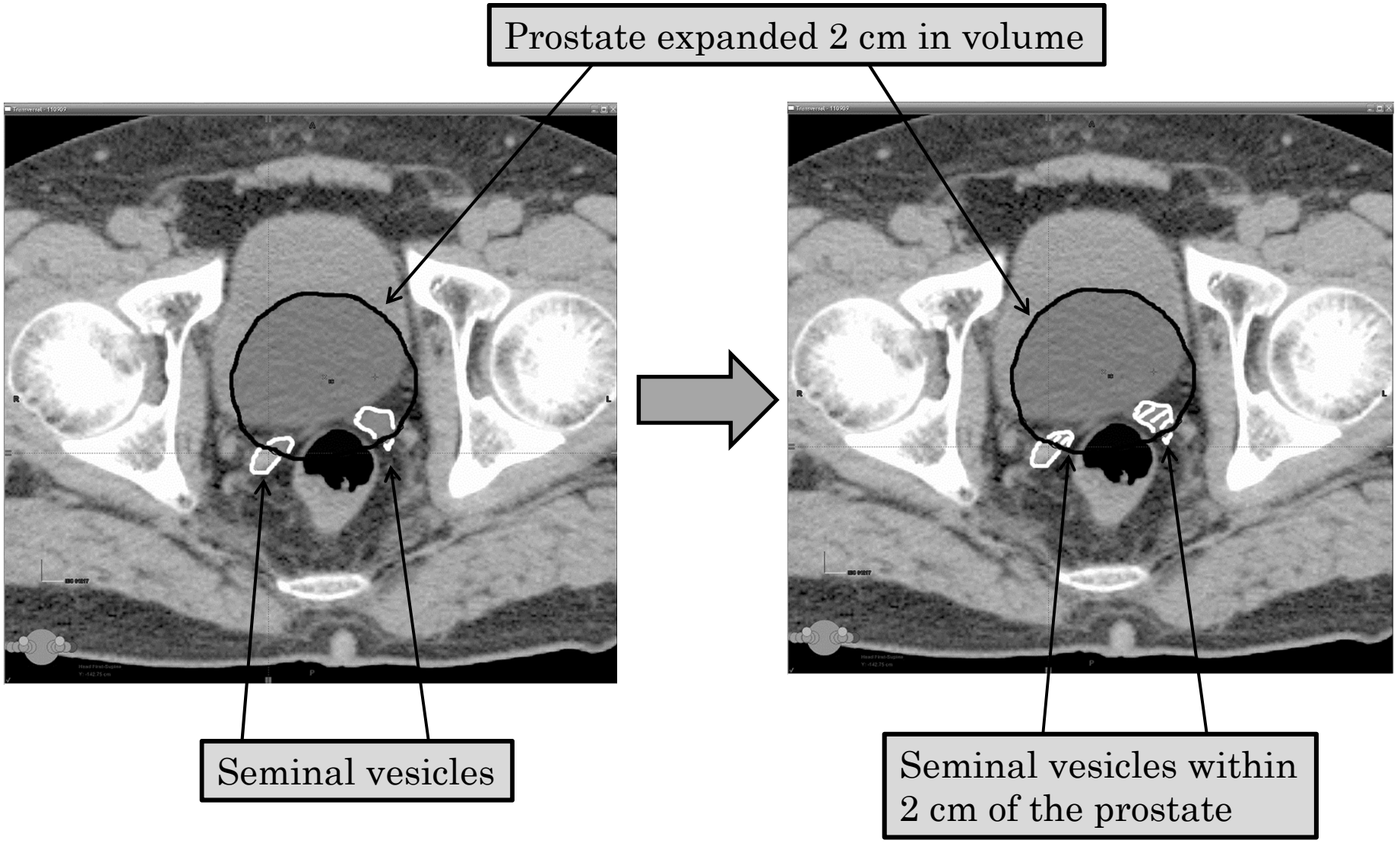
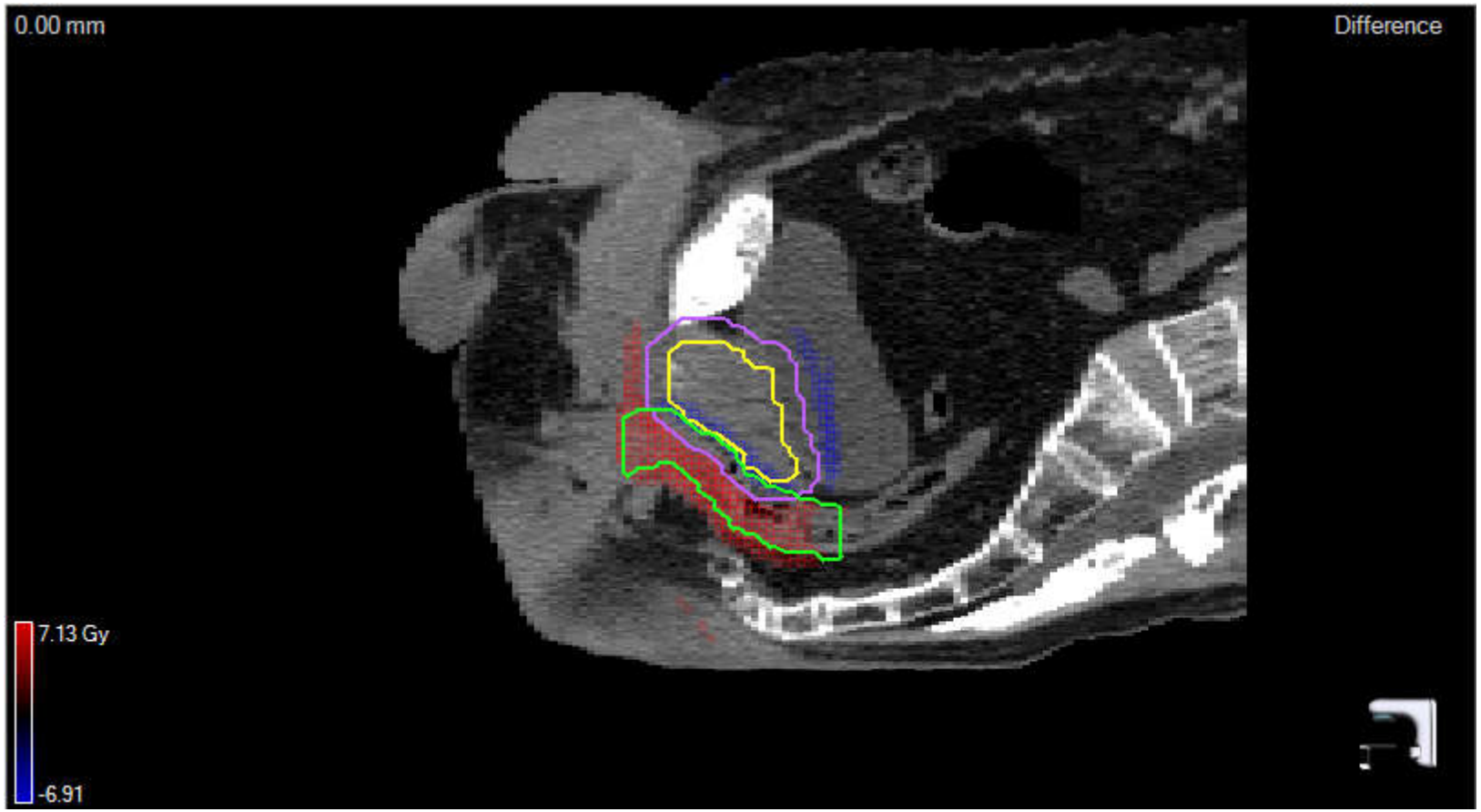


Fig 1 Delineation of the clinical target volume (CTV).
CTV includes the seminal vesicles within 2 cm of the prostate.

Fig 2(a)



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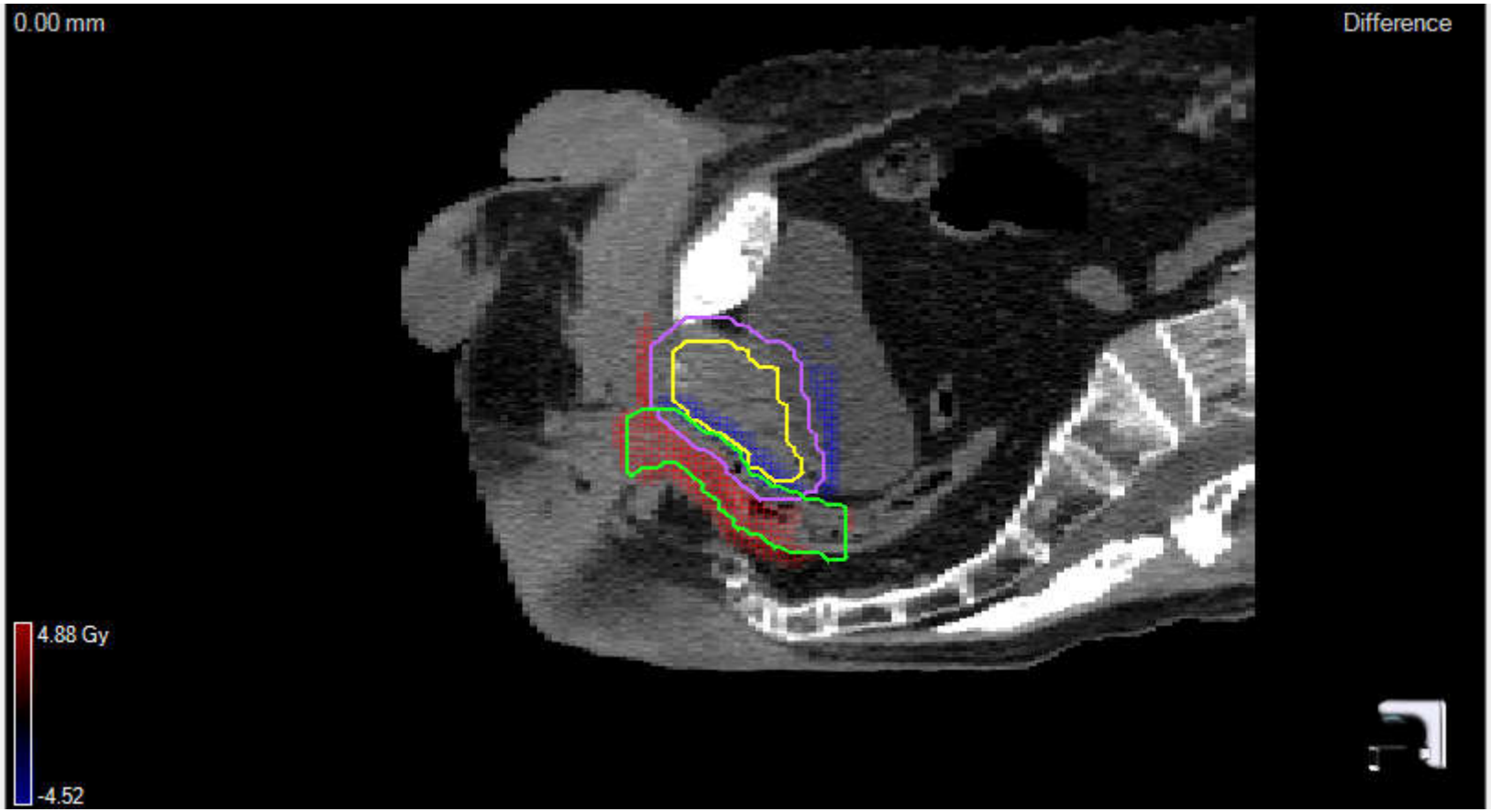


Fig 2(c)

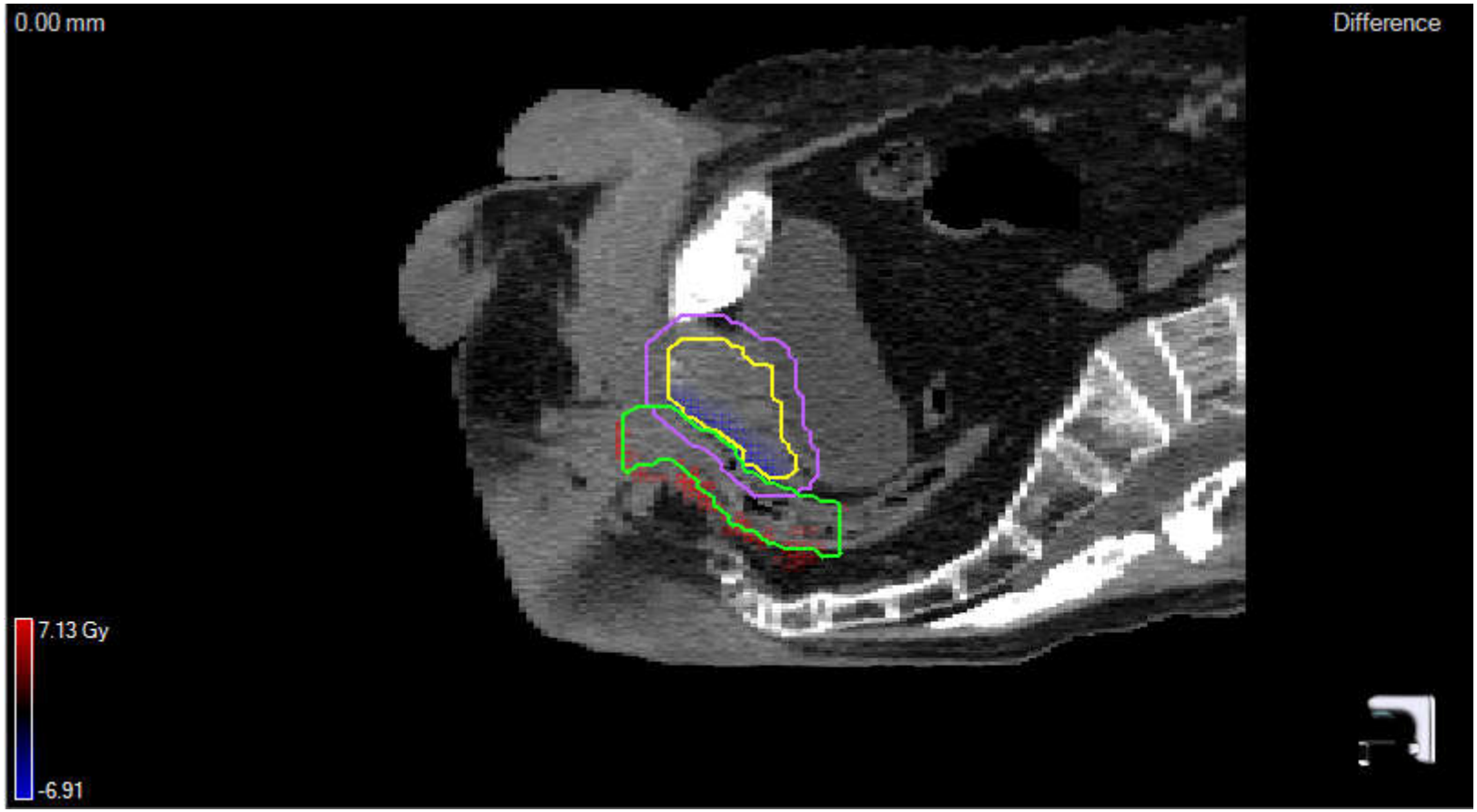


Fig 2(d)

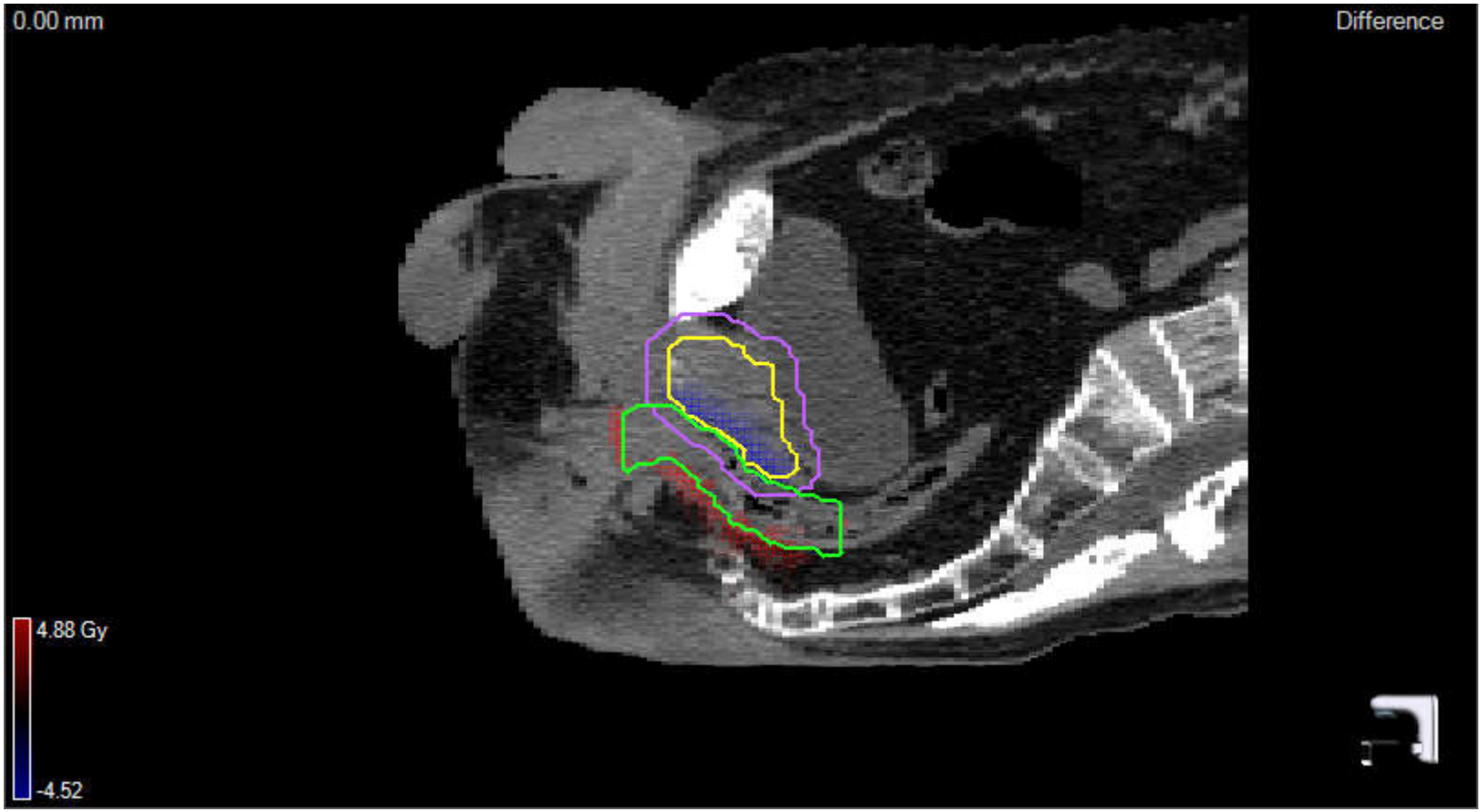


Fig 2(e)

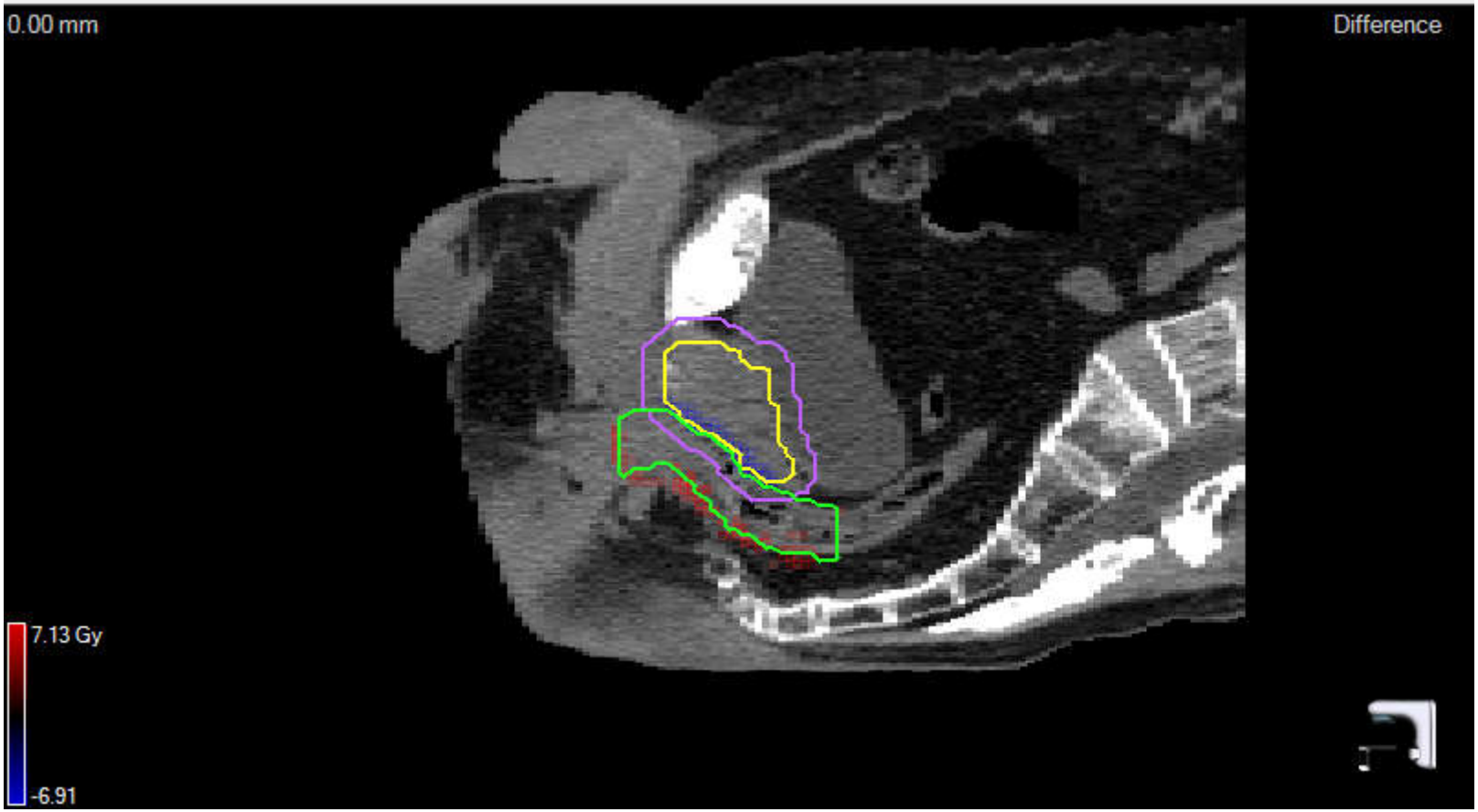


Fig 2(f)

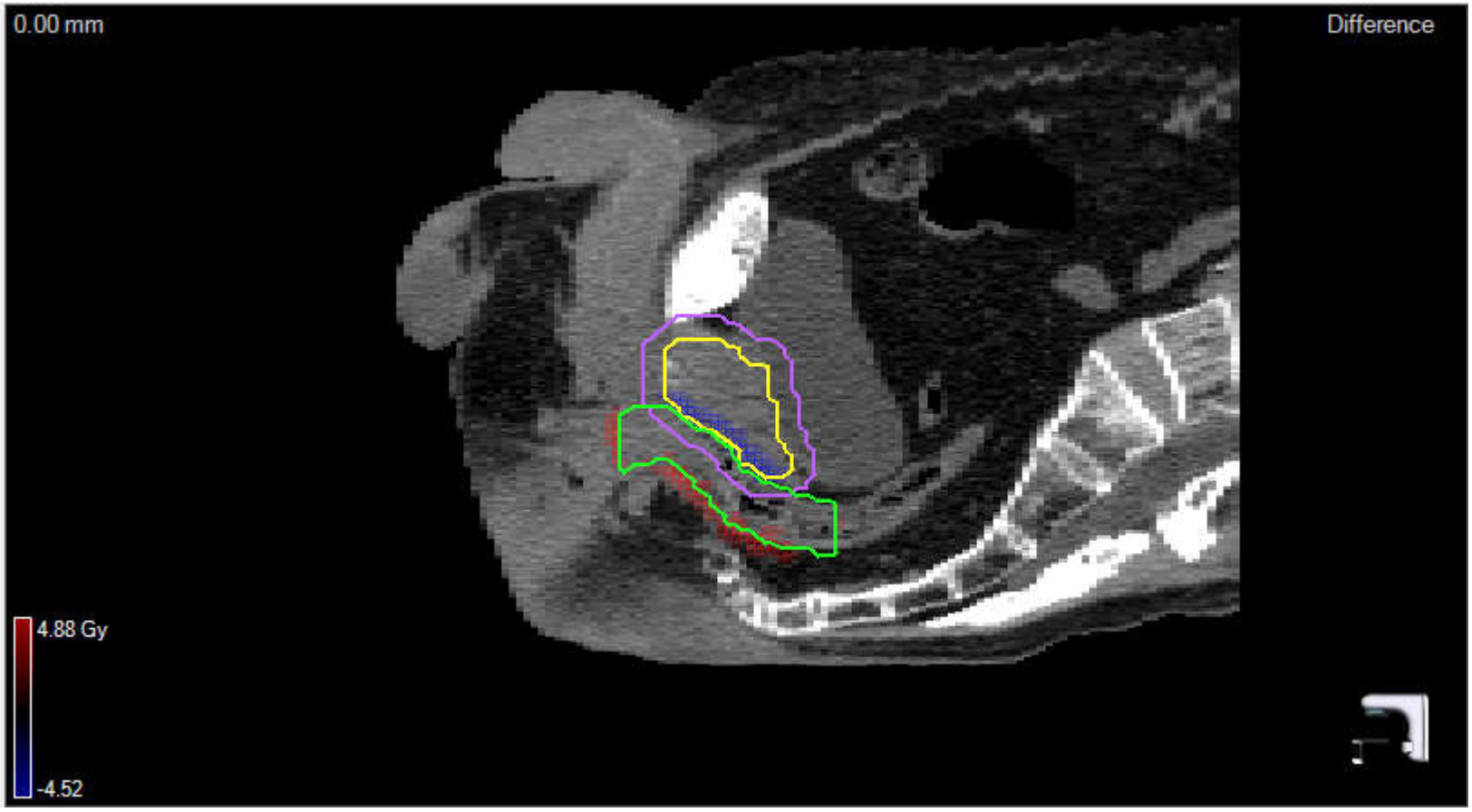


Fig 3(a)

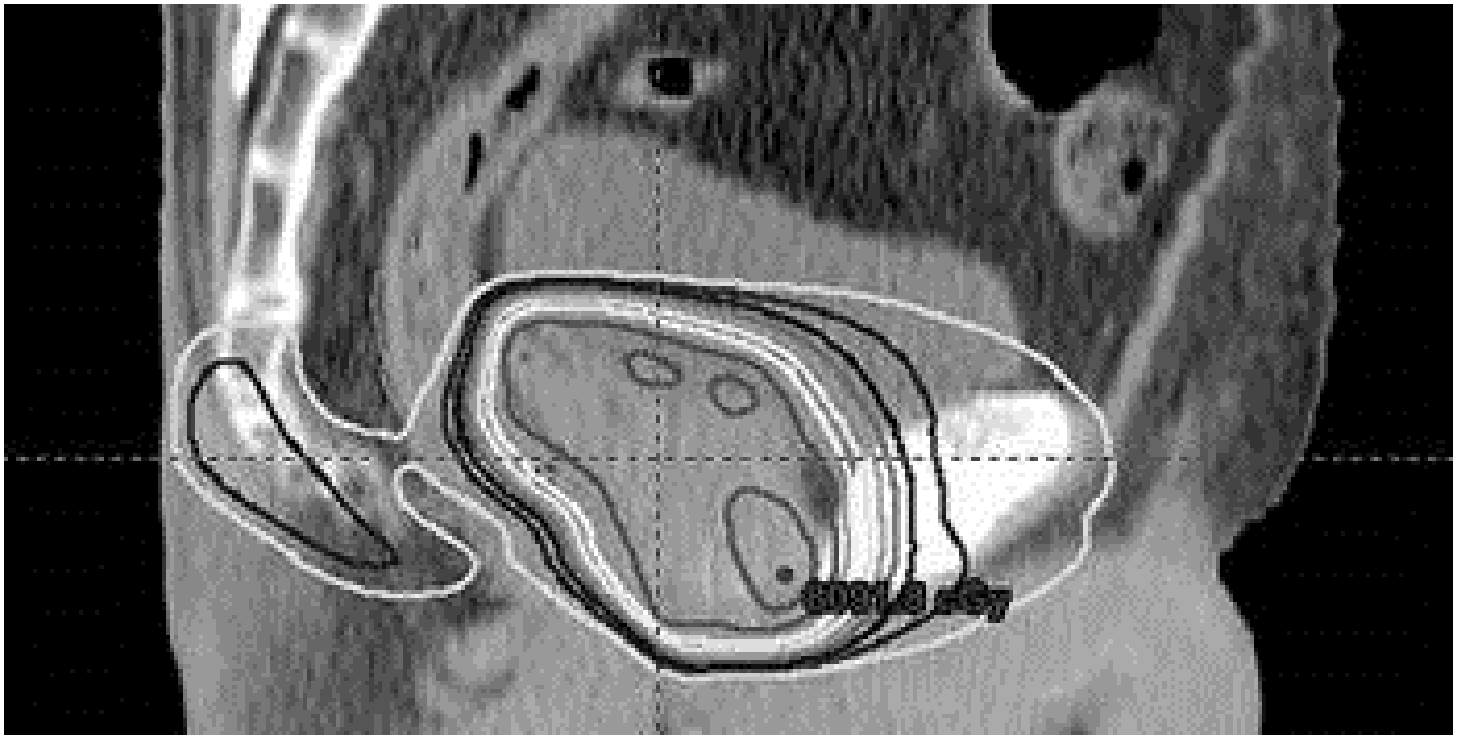


Fig 3(b)

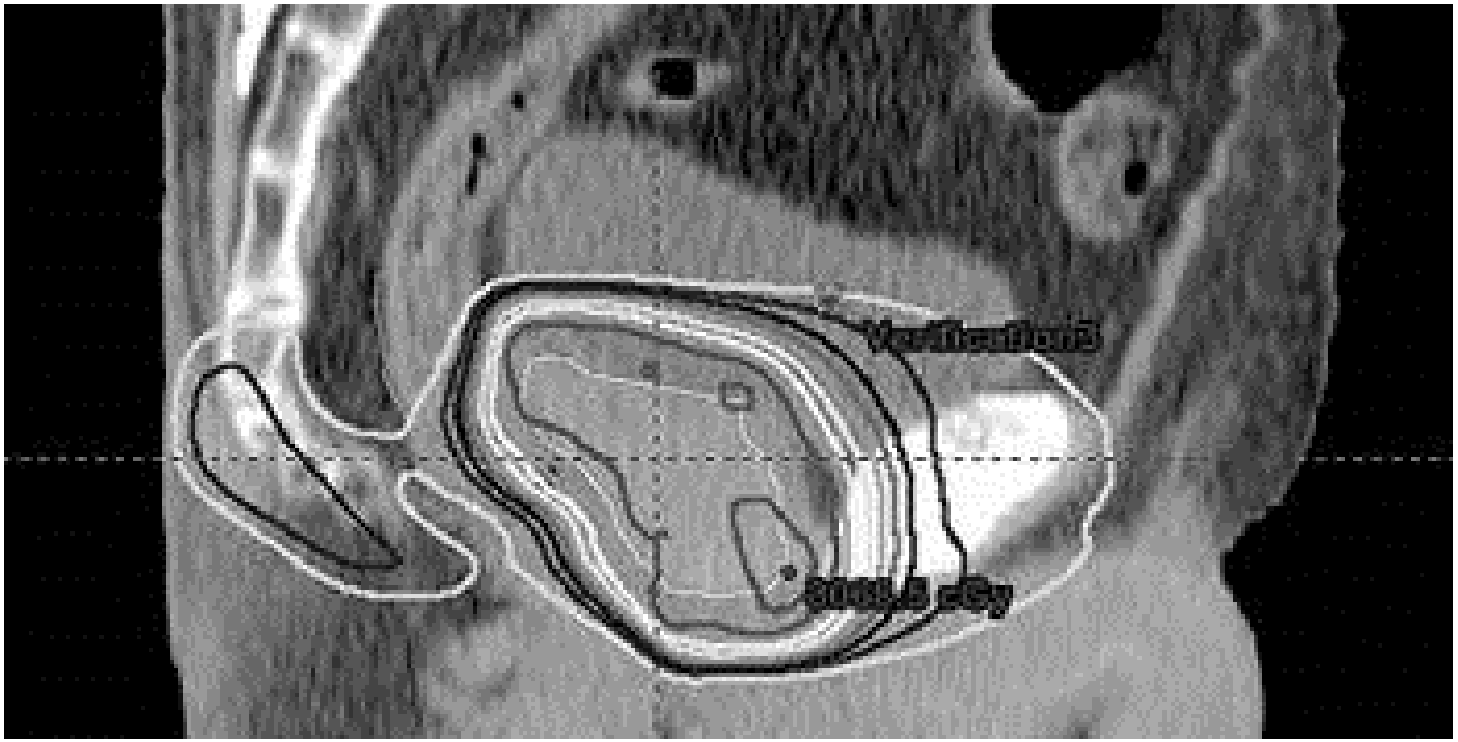


Fig 3(c)

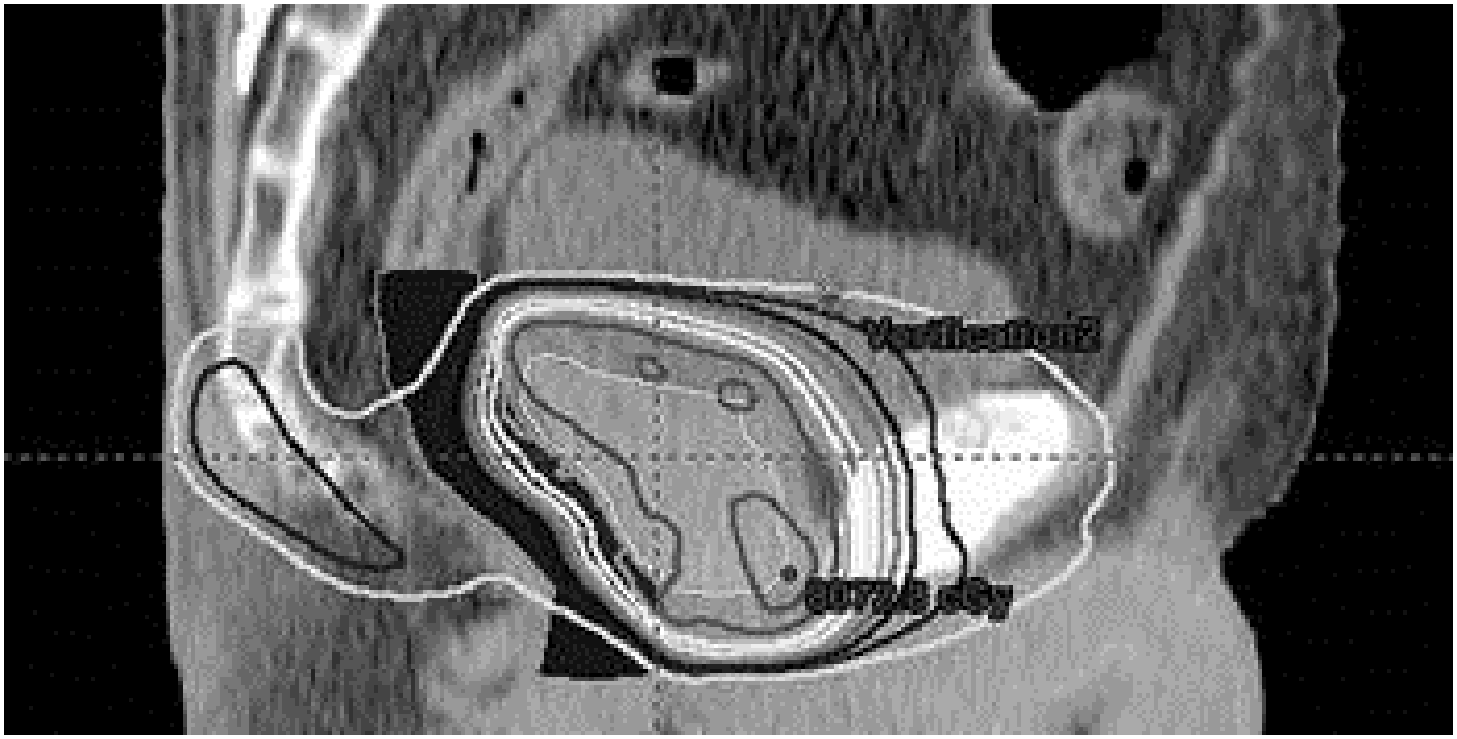
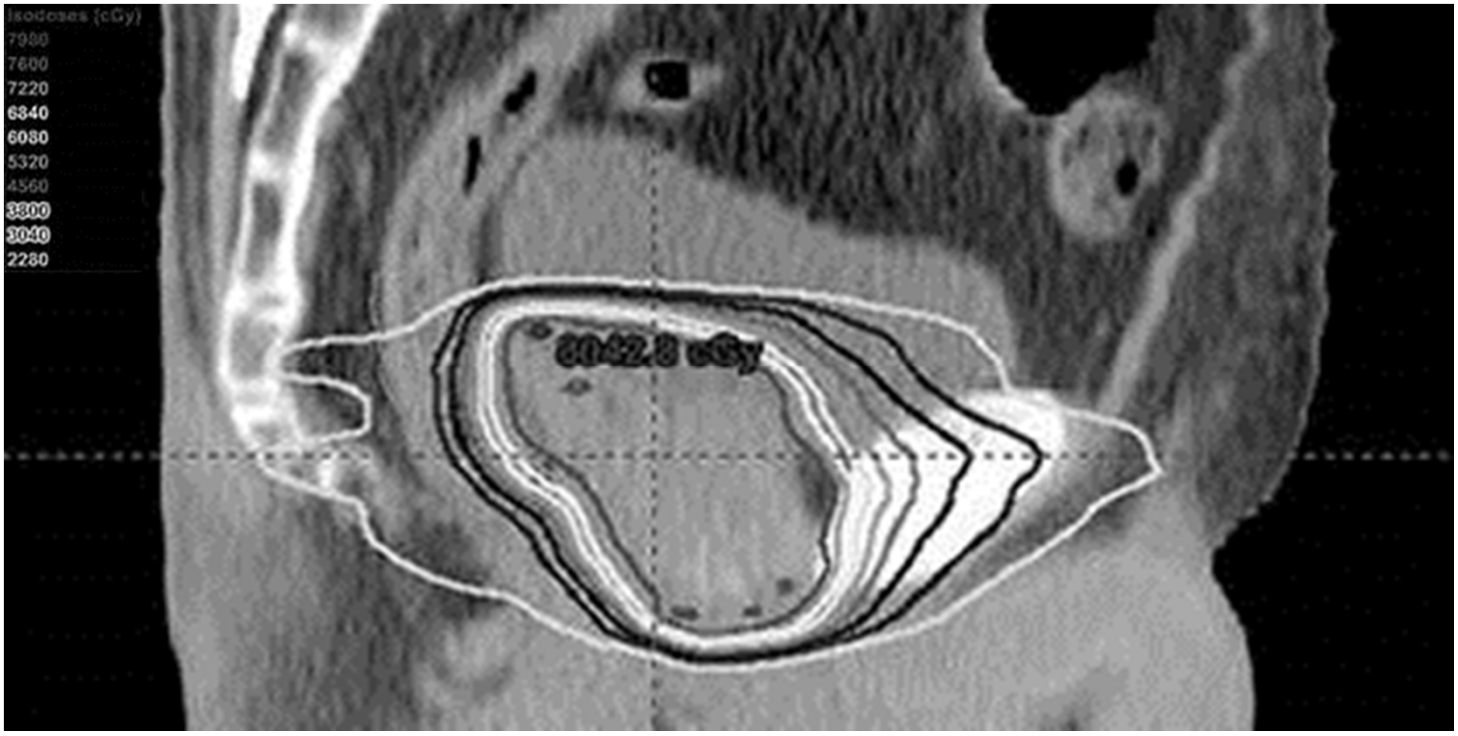


Fig 3(d)


Isodoses (cGy)
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7220
6840
6080
5320
4560
3800
3040
2280

Fig 3(e)

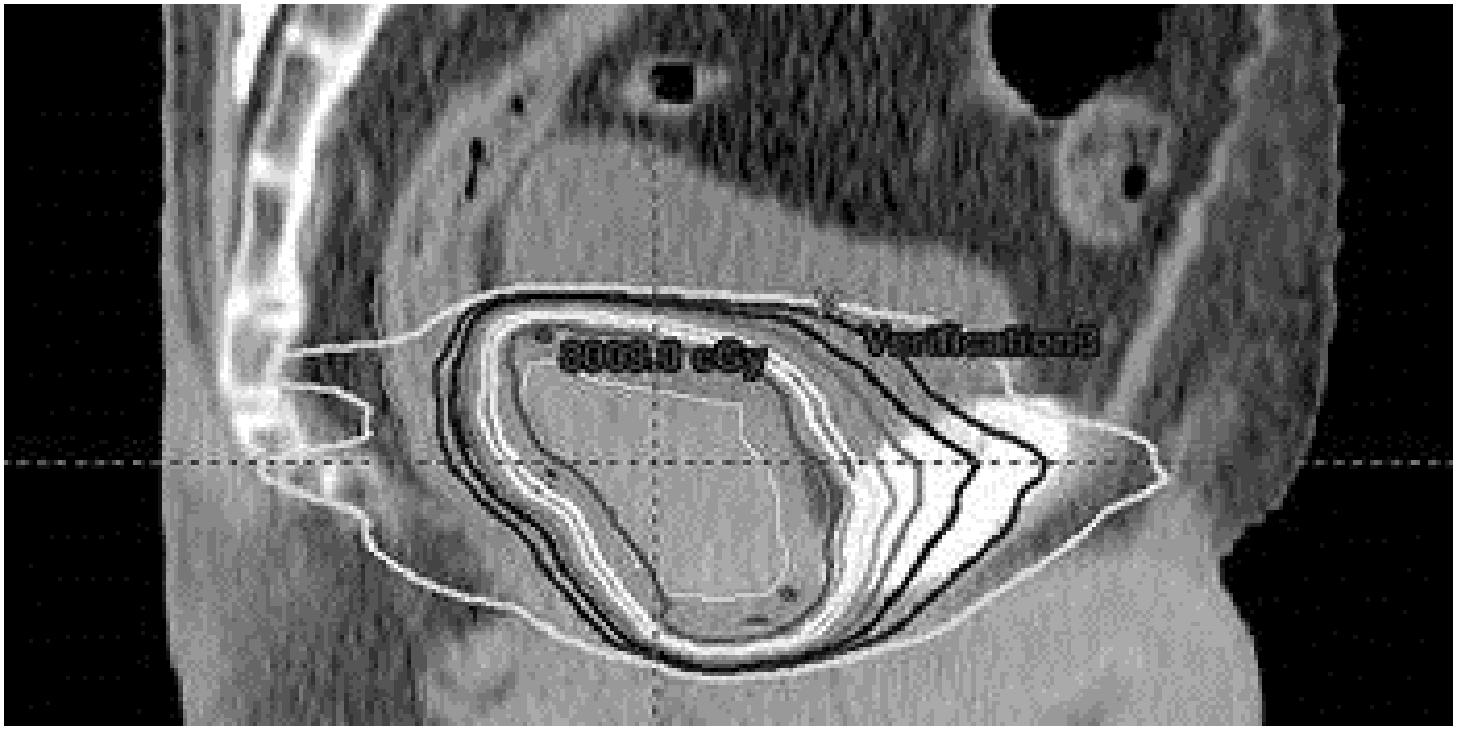
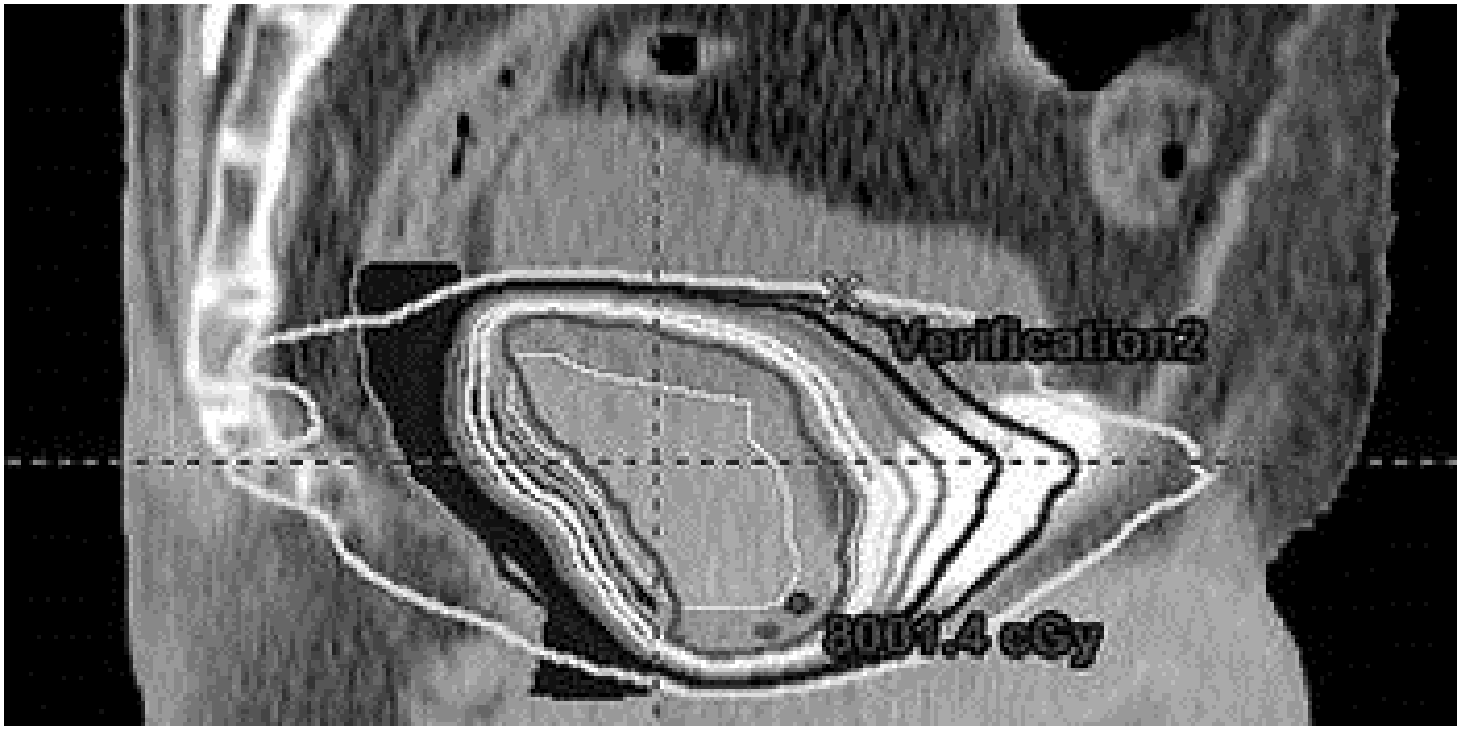


Fig 3(f)



Tables

Table 1 Patients characteristics

	n	%
Tumor stage		
T1c	2	22.2
T2c	2	22.2
T3a	5	55.6
PSA		
≤ 10	2	22.2
10< - <20	3	33.3
20 ≤	4	44.4
Gleason score		
≤ 6	1	11.1
7	4	44.4
≥ 8	4	44.4
Risk		
Low risk	1	11.1
Intermediate risk	0	0.0
High risk	8	88.9

Table 2 Dose-volume constraints used in the planning

Structure	Constraint
PTV excluding the rectum	D_{95} = 100% Max dose < 110%
CTV	$V_{100\%} \geq 99.5\%$
Rectum volume	$V_{40Gy} \leq 50\%$ $V_{60Gy} \leq 25\%$ $V_{70Gy} \leq 15\%$ $V_{75Gy} \leq 5\%$
Bladder volume	$V_{40Gy} \leq 50\%$ $V_{65Gy} \leq 25\%$

Table 3 Dose evaluation used in planning

Structure	
CTV	minimum dose (Gy) $V_{100\%}$ (%) mean dose (Gy) maximum dose (Gy)
PTV excluding the rectum	D_{95} (Gy)
PTV	D_{95} (Gy) minimum dose (Gy) mean dose(Gy)
Rectum	V_{40Gy} (%) V_{60Gy} (%) V_{70Gy} (%) V_{75Gy} (%)
Bladder	V_{40Gy} (%) V_{65Gy} (%)

Table 4 Dosimetric comparison of organs at risk and target doses of IMRT and VMAT plans

Structure		IMRT		VMAT		*P*-value
CTV	minimum dose (Gy)	75.87 ± 0.62	(75.18 - 77.14)	75.95 ± 0.39	(75.29 - 76.69)	0.772
	$V_{100\%}$ (%)	99.97 ± 0.06	(99.81 - 100.00)	99.99 ± 0.01	(99.96 - 100.00)	0.271
	mean dose(Gy)	79.29 ± 0.50	(78.43 - 79.91)	79.29 ± 0.37	(78.81 - 79.88)	0.963
	maximum dose (Gy)	81.56 ± 0.95	(80.06 - 83.05)	81.08 ± 0.44	(80.45 - 81.63)	0.106
PTV excluding the rectum	D_{95} (Gy)	76.00		76.00		-
PTV	D_{95} (Gy)	74.02 ± 0.73	(72.38 - 74.85)	73.96 ± 0.97	(71.19 - 75.00)	0.725
	minimum dose (Gy)	57.40 ± 4.31	(49.81 - 63.68)	60.80 ± 3.68	(56.59 - 67.69)	0.034
	mean dose (Gy)	78.55 ± 0.34	(78.09 - 79.16)	78.43 ± 0.25	(78.14 - 78.82)	0.328
Rectum	V_{40Gy} (%)	41.46 ± 3.38	(36.39 - 47.47)	42.17 ± 3.26	(36.71 - 47.92)	0.063
	V_{60Gy} (%)	21.57 ± 1.58	(19.71 - 23.98)	21.39 ± 1.33	(19.77 - 23.93)	0.569
	V_{70Gy} (%)	11.66 ± 1.40	(9.88 - 14.18)	11.22 ± 0.73	(9.63 - 12.30)	0.297
	V_{75Gy} (%)	3.41 ± 1.18	(1.58 - 4.98)	3.59 ± 1.01	(1.89 - 4.97)	0.737
Bladder	V_{40Gy} (%)	33.97 ± 9.26	(19.69 - 46.41)	31.85 ± 8.96	(19.82 - 43.99)	0.109
	V_{65Gy} (%)	16.67 ± 4.74	(8.95 - 22.48)	14.82 ± 4.28	(8.62 - 19.65)	< 0.01

Table 5 Differences in the dose indicators when using the standard treatment plan and the two types of treatment plan for evaluation.
(a) IMRT

Structure		Overlap gas		*P*-value	Rectum gas		*P*-value
CTV	minimum dose (Gy)	74.86 ± 0.76	(73.85 - 75.92)	< 0.01	73.05 ± 0.91	(71.82 - 74.28)	< 0.01
	$V_{100\%}$ (%)	99.18 ± 1.06	(96.72 - 99.99)	0.046	95.86 ± 1.92	(93.24 - 98.76)	< 0.01
	mean dose (Gy)	79.04 ± 0.48	(78.20 - 79.79)	< 0.01	78.87 ± 0.44	(78.09 - 79.41)	< 0.01
	maximum dose (Gy)	81.41 ± 0.81	(80.01 - 82.72)	0.235	80.47 ± 2.97	(80.05 - 82.84)	0.300
PTV excluding the rectum	D_{95} (Gy)	75.63 ± 0.23	(75.22 - 75.98)	< 0.01	75.19 ± 0.25	(74.88 - 75.68)	< 0.01
PTV	minimum dose (Gy)	57.83 ± 3.77	(50.79 - 63.20)	0.600	58.50 ± 4.61	(50.60 - 65.44)	0.424
	D_{95} (Gy)	73.67 ± 0.67	(72.37 - 74.58)	0.018	73.05 ± 0.59	(71.99 - 73.93)	< 0.01
	mean dose (Gy)	78.36 ± 0.36	(77.95 - 79.14)	< 0.01	78.29 ± 0.29	(77.92 - 78.89)	< 0.01
Rectum	V_{40Gy} (%)	42.32 ± 3.51	(38.90 - 48.97)	0.061	44.74 ± 3.19	(40.69 - 49.87)	< 0.01
	V_{60Gy} (%)	22.25 ± 2.16	(20.07 - 24.45)	0.144	22.62 ± 1.65	(20.73 - 24.22)	0.030
	V_{70Gy} (%)	11.63 ± 1.49	(10.25 - 15.05)	0.950	11.61 ± 1.48	(10.11 - 15.01)	0.866
	V_{75Gy} (%)	2.33 ± 0.93	(0.61 - 3.64)	< 0.01	0.44 ± 0.52	(0.01 - 1.56)	< 0.01
Bladder	V_{40Gy} (%)	35.83 ± 10.29	(19.69 - 49.85)	0.422	35.93 ± 10.34	(19.74 - 49.89)	0.400
	V_{65Gy} (%)	17.44 ± 5.00	(8.96 - 23.04)	0.486	17.51 ± 5.02	(9.00 - 23.11)	0.450

(b) VMAT

Structure		Overlap gas		*P*-value	Rectum gas		*P*-value
CTV	minimum dose (Gy)	74.70 ± 0.32	(74.26 - 75.22)	< 0.01	72.87 ± 0.40	(72.25 - 73.42)	< 0.01
	$V_{100\%}$ (%)	99.58 ± 0.54	(98.63 - 99.99)	0.048	96.11 ± 1.96	(93.33 - 99.43)	< 0.01
	mean dose (Gy)	78.99 ± 0.35	(78.48 - 79.61)	< 0.01	78.69 ± 0.37	(78.19 - 79.30)	< 0.01
	maximum dose (Gy)	81.00 ± 0.44	(80.54 - 81.90)	0.252	80.06 ± 0.85	(78.78 - 81.92)	0.284
PTV excluding the rectum	D_{95} (Gy)	75.76 ± 0.18	(75.46 - 75.97)	< 0.01	75.11 ± 0.26	(74.62 - 75.34)	< 0.01
PTV	minimum dose (Gy)	60.69 ± 2.77	(57.20 - 65.18)	< 0.01	60.31 ± 1.88	(58.07 - 62.85)	< 0.01
	D_{95} (Gy)	73.72 ± 0.93	(71.97 - 74.91)	0.154	72.80 ± 0.86	(71.18 - 73.88)	< 0.01
	mean dose (Gy)	78.23 ± 0.25	(77.92 - 78.73)	0.897	78.00 ± 0.25	(77.67 - 78.50)	0.580
Rectum	V_{40Gy} (%)	43.01 ± 3.65	(37.44 - 49.66)	0.079	44.94 ± 3.45	(39.61 - 49.88)	< 0.01
	V_{60Gy} (%)	22.02 ± 2.06	(18.34 - 24.66)	0.143	22.23 ± 1.83	(18.57 - 24.66)	0.051
	V_{70Gy} (%)	11.42 ± 1.36	(9.36 - 13.63)	0.556	10.72 ± 1.48	(8.50 - 12.87)	0.190
	V_{75Gy} (%)	2.46 ± 1.66	(0.19 - 4.85)	< 0.01	0.48 ± 0.68	(0.01 - 2.19)	< 0.01
Bladder	V_{40Gy} (%)	33.38 ± 9.21	(19.48 - 44.25)	0.475	33.44 ± 9.24	(19.51 - 44.34)	0.460
	V_{65Gy} (%)	15.51 ± 4.18	(8.37 -19.73)	0.468	15.54 ± 4.19	(8.39 - 19.79)	0.450

Table6 Results of concordance of the dose distributions for the standard treatment plan and the two types of treatment plan under evaluation.

(a) The DD concordance results when using the standard treatment plan and the structure set using an HU value for mock gas filling the overlap region.

Structure	DD	IMRT (%)	VMAT (%)	*P*-value
CTV	1%	91.16 ± 5.30 (82.40 - 99.10)	88.12 ± 4.87 (78.80 - 94.60)	0.026
	2%	99.56 ± 0.69 (98.00 - 100.00)	98.03 ± 1.88 (93.90 - 99.90)	0.022
	3%	100.00 ± 0.00 (100.00 - 100.00)	99.93 ± 0.17 (99.50 - 100.00)	0.265
PTV	1%	91.61 ± 3.93 (85.80 - 98.30)	88.92 ± 3.84 (80.70 - 94.20)	0.043
	2%	99.10 ± 0.95 (97.90 - 100.00)	97.79 ± 1.70 (94.30 - 99.50)	< 0.01
	3%	99.91 ± 0.15 (99.60 - 100.00)	99.71 ± 0.42 (99.00 - 100.00)	0.093
Rectum	1%	72.26 ± 22.75 (34.30 - 98.80)	64.37 ± 20.62 (35.80 - 96.60)	0.222
	2%	90.03 ± 13.94 (58.40 - 100.00)	87.11 ± 13.55 (57.80 - 100.00)	0.109
	3%	95.74 ± 8.68 (73.30 - 100.00)	95.23 ± 7.93 (75.10 - 100.00)	0.195
Bladder	1%	75.87 ± 29.14 (25.60 -100.00)	68.21 ± 24.61 (30.90 - 100.00)	0.282
	2%	91.02 ± 14.25 (59.00 - 100.00)	88.30 ± 12.04 (65.80 - 100.00)	0.363
	3%	97.32 ± 4.55 (87.20 - 100.00)	95.40 ± 5.00 (86.90 - 100.00)	0.139

(b) The DTA concordance results when using the standard treatment plan and the structure set usingan HU value for mock gas filling the overlap region.

Structure	DTA	IMRT (%)	VMAT (%)	*P*-value
CTV	1 mm	57.07 ± 4.95 (49.20 - 63.30)	52.47 ± 7.60 (41.20 - 62.60)	0.116
	2 mm	82.31 ± 2.87 (77.70 - 86.60)	77.00 ± 6.42 (67.90 - 84.80)	0.102
	3 mm	93.19 ± 2.40 (90.70 - 97.80)	88.01 ± 4.44 (81.70 - 94.00)	0.032
PTV	1 mm	76.01 ± 3.56 (70.30 - 80.70)	73.09 ± 4.06 (67.20 - 80.20)	0.166
	2 mm	91.76 ± 1.71 (89.30 - 94.90)	89.20 ± 2.03 (86.30 - 91.70)	0.072
	3 mm	96.67 ± 1.13 (95.60 - 98.80)	94.69 ± 1.33 (93.20 - 96.70)	0.038
Rectum	1 mm	97.89 ± 2.77 (90.80 - 99.80)	97.89 ± 1.95 (93.80 - 99.80)	0.367
	2 mm	99.93 ± 0.09 (99.80 - 100.00)	99.91 ± 0.08 (99.80 - 100.00)	0.815
	3 mm	99.99 ± 0.03 (99.90 - 100.00)	99.99 ± 0.03 (99.90 - 100.00)	-
Bladder	1 mm	96.52 ± 6.61 (79.10 - 99.60)	94.14 ± 8.67 (71.70 - 99.20)	0.772
	2 mm	99.76 ± 0.23 (99.20 - 99.90)	99.27 ± 0.31 (98.70 - 99.70)	< 0.01
	3 mm	99.89 ± 0.12 (99.70 - 100.00)	99.70 ± 0.15 (99.40 - 99.90)	< 0.01

(c) The GA concordance results when using the standard treatment plan and the structure set using an HU value for mock gas filling the overlap region.

Structure	GA	IMRT (%)	VMAT (%)	*P*-value
CTV	1%/1 mm	91.88 ± 4.99 (84.50 - 99.70)	88.98 ± 4.66 (80.20 - 95.40)	0.027
	2%/2 mm	99.68 ± 0.54 (98.40 - 100.00)	98.78 ± 1.39 (96.10 - 100.00)	0.048
	3%/3 mm	100.00 ± 0.00 (100.00 - 100.00)	100.00 ± 0.00 (100.00 - 100.00)	-
PTV	1%/1 mm	95.84 ± 1.97 (93.10 - 99.00)	94.50 ± 1.70 (90.50 - 95.80)	0.054
	2%/2 mm	99.84 ± 0.22 (99.40 - 100.00)	99.51 ± 0.54 (98.60 - 100.00)	0.058
	3%/3 mm	100.00 ± 0.00 (100.00 - 100.00)	100.00 ± 0.00 (100.00 - 100.00)	-
Rectum	1%/1 mm	98.21 ± 2.82 (90.80 - 99.80)	98.69 ± 1.07 (96.60 - 99.80)	0.476
	2%/2 mm	100.00 ± 0.00 (100.00 - 100.00)	99.99 ± 0.03 (99.90 - 100.00)	0.351
	3%/3 mm	100.00 ± 0.00 (100.00 - 100.00)	100.00 ± 0.00 (100.00 - 100.00)	-
Bladder	1%/1 mm	99.13 ± 1.73 (95.00 - 100.00)	99.11 ± 1.41 (95.80 - 100.00)	0.803
	2%/2 mm	100.00 ± 0.00 (100.00 - 100.00)	100.00 ± 0.00 (100.00 - 100.00)	-
	3%/3 mm	100.00 ± 0.00 (100.00 - 100.00)	100.00 ± 0.00 (100.00 - 100.00)	-

(d) The DD concordance results when using the standard treatment plan and the structure set using an HU value for mock gas filling the entire rectum.

Structure	DD	IMRT (%)	VMAT (%)	*P*-value
CTV	1%	77.81 ± 5.59 (70.00 - 83.90)	73.29 ± 6.11 (63.90 - 81.40)	< 0.01
	2%	90.18 ± 2.91 (85.60 - 93.90)	87.17 ± 3.47 (8180 - 92.60)	< 0.01
	3%	97.00 ± 1.52 (94.60 - 98.90)	94.22 ± 2.14 (90.80 - 96.90)	< 0.01
PTV	1%	82.44 ± 4.54 (75.60 - 88.90)	78.17 ± 4.18 (71.30 - 82.40)	< 0.01
	2%	92.73 ± 1.98 (89.70 - 95.50)	89.66 ± 2.46 (85.80 - 92.00)	< 0.01
	3%	97.73 ± 1.00 (96.50 - 99.10)	95.47 ± 1.30 (93.00 - 96.70)	< 0.01
Rectum	1%	20.49 ± 9.55 (7.80 - 35.90)	22.03 ± 10.54 (10.00 - 41.70)	0.184
	2%	46.30 ± 17.83 (20.40 - 71.00)	48.59 ± 14.67 (22.10 - 70.50)	0.497
	3%	71.19 ± 19.88 (33.00 - 91.80)	71.42 ± 17.23 (34.30 - 90.80)	0.941
Bladder	1%	76.02 ± 26.74 (27.90 - 100.00)	68.91 ± 23.27 (33.50 - 99.80)	0.313
	2%	91.88 ± 12.85 (62.90 - 100.00)	89.09 ± 11.27 (68.30 - 100.00)	0.236
	3%	97.54 ± 4.20 (88.10 - 100.00)	95.68 ± 4.65 (88.30 - 100.00)	0.148

(e) The DTA concordance results when using the standard treatment plan and the structure set using an HU value for mock gas filling the entire rectum.

Structure	DTA	IMRT (%)	VMAT (%)	*P*-value
CTV	1 mm	40.27 ± 8.15 (30.30 - 55.80)	38.12 ± 7.15 (29.20 - 49.40)	0.812
	2 mm	64.01 ± 7.07 (55.50 - 74.30)	59.87 ± 6.97 (51.10 - 69.90)	0.346
	3 mm	75.97 ± 5.73 (67.60 - 84.60)	73.33 ± 6.73 (64.80 - 83.80)	0.464
PTV	1 mm	56.84 ± 9.01 (42.40 - 67.20)	60.46 ± 5.16 (55.70 - 69.90)	0.373
	2 mm	79.39 ± 5.16 (71.10 - 85.20)	79.76 ± 3.17 (76.30 - 84.90)	0.808
	3 mm	87.74 ± 3.64 (82.00 - 92.30)	88.30 ± 2.53 (85.00 - 92.30)	0.835
Rectum	1 mm	61.07 ± 11.27 (36.80 - 75.70)	65.02 ± 9.79 (43.30 - 76.20)	< 0.01
	2 mm	89.49 ± 3.17 (83.40 - 93.40)	89.71 ± 3.43 (83.00 - 92.30)	0.264
	3 mm	97.09 ± 1.04 (95.30 - 98.60)	96.94 ± 1.46 (93.90 - 98.20)	0.973
Bladder	1 mm	93.78 ± 6.87 (77.90 - 99.20)	93.77 ± 8.38 (71.70 - 98.90)	0.301
	2 mm	99.00 ± 0.91 (96.90 - 99.80)	98.80 ± 0.67 (97.30 - 99.60)	0.918
	3 mm	99.51 ± 0.47 (98.40 - 99.90)	99.51 ± 0.30 (99.10 - 100.00)	0.943

(f) The GA concordance results when using the standard treatment plan and the structure set using an HU value for mock gas filling the entire rectum.

Structure	GA	IMRT (%)	VMAT (%)	*P*-value
CTV	1%/1 mm	78.21 ± 5.40 (70.03 - 84.10)	73.80 ± 5.96 (64.50 - 81.90)	< 0.01
	2%/2 mm	91.31 ± 2.77 (86.60 - 94.10)	88.64 ± 3.58 (83.10 - 95.00)	< 0.01
	3%/3 mm	97.66 ± 1.45 (95.40 - 99.60)	96.02 ± 2.14 (93.10 - 99.50)	< 0.01
PTV	1%/1 mm	87.91 ± 2.49 (84.30 - 91.40)	85.02 ± 2.76 (81.20 - 88.50)	< 0.01
	2%/2 mm	95.92 ± 1.28 (93.80 - 97.50)	94.73 ± 1.22 (92.90 -96.70)	0.014
	3%/3 mm	98.96 ± 0.61 (97.90 - 99.80)	98.39 ± 0.72 (97.60 - 99.50)	0.030
Rectum	1%/1 mm	61.40 ± 11.65 (36.80 - 75.90)	65.46 ± 9.99 (43.30 - 77.80)	0.012
	2%/2 mm	90.00 ± 3.30 (83.50 - 94.00)	90.67 ± 2.99 (85.70 - 93.90)	0.100
	3%/3 mm	97.86 ± 1.17 (96.10 - 99.00)	97.84 ± 1.33 (95.00 - 99.10)	0.726
Bladder	1%/1 mm	99.03 ± 1.76 (94.60 - 100.00)	99.12 ± 0.91 (97.90 - 100.00)	0.622
	2%/2 mm	100.00 ± 0.00 (100.00 - 100.00)	100.00 ± 0.00 (100.00 - 100.00)	-
	3%/3 mm	100.00 ± 0.00 (100.00 - 100.00)	100.00 ± 0.00 (100.00 - 100.00)	-