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Integral Dose and Dosimetric Comparison of 3D-CRT, IMRT and VMAT Radiotherapy Techniques for Prostate Cancer

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ABSTRACT

Introduction: This study aimed to compare the treatment planning volumes and the integral doses (ID) during radiotherapy for prostate cancer using three-dimensional conformal radiotherapy (3D-CRT), intensity-modulated radiotherapy (IMRT), and volumetric-modulated arc therapy (VMAT) techniques.
Material and Methods: The study included 10 patients treated in our clinic, diagnosed with intermediate risk prostate cancer at the T2bN0M0 stage, Gleason score ≤ 7 and prostate-specific antigen (PSA) levels between 10-20 ng/mL. For each patient, 6 MV photon energy was used for 3D-CRT, IMRT and VMAT planning.
Results: The rectum, bladder, right and left femur, body IDs, the homogeneity index (HI), and conformity index (CI) values were found to be higher in 3D-CRT planning compared to IMRT and VMAT planning ($p < 0.001$). The body mean, and ID were lower in VMAT planning compared to IMRT and 3D-CRT plans ($p < 0.001$). The monitor unit (MU) value was significantly higher in the IMRT planning compared to VMAT and 3D-CRT plans, and higher in the VMAT plan compared to 3D-CRT plans ($p < 0.001$).
Conclusion: According to our study, for organ protection, body ID doses and HI, as well as CI, the VMAT planning technique is mostly superior to IMRT and 3D-CRT. In terms of MU, the 3D-CRT planning technique is better than the others. Our findings indicate that VMAT could generate plans that deliver lower IDs to healthy tissues while providing relatively uniform doses to the target area; and lower MUs.

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Introduction

Prostate cancer is the second most common malignancy in men and the fifth leading cause of cancer-related deaths worldwide [1]. In radiotherapy, a precise and appropriate dose is delivered to the targeted region; to achieve effective tumor control, while minimizing the dose to surrounding healthy tissues to avoid potential complications [2]. Three-dimensional conformal radiotherapy (3D-CRT) employs multiple fields shaped by multi-leaf collimators to optimize the dose delivered to the target volume while protecting surrounding healthy tissues. Intensity modulated radiotherapy (IMRT) has made it possible to limit the amount of dose that reaches nearby organs while delivering a highly conformal dose distribution to the target. Volumetric arc treatment (VMAT) delivers radiation as the linear accelerator rotates around the patient. The multileaf collimator dynamically adjusts, along with variable dose rates and gantry speeds, to achieve the desired dose distribution in a single optimized arc surrounding the patient [3,4]. In the treatment of patients receiving curative radiotherapy, it is important to keep the dose given to the whole body as low as possible. The integral dose (ID) represents the total absorbed by the body during radiation therapy, and describes the accumulation of energy in the body [5]. The integral radiation dose received by a patient undergoing external beam radiation therapy for prostate cancer is often overlooked. Yet, it carries the possibility of causing damage and should be considered because of the second malignancy risk [6].

This study aimed to compare the treatment planning volumes and the integral doses during radiotherapy of prostate cancer with 3D-CRT, IMRT, and VMAT techniques.

Materials and Methods

The study included 10 patients treated in our clinic, diagnosed with intermediate-risk prostate cancer at the T2bN0M0 stage, with a Gleason score ≤ 7 and PSA levels between 10-20 ng/mL. The patients were scanned on the CT simulator (Siemens Somatom Spirit) with knee support in the supine position. CT images with 3 mm slice thickness were acquired. They were instructed to empty their rectum using an enema the night before the simulation. During the simulation, it was ensured that the anterior-posterior diameter of the rectum was less than 4 cm. Patients emptied their bladder first,

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drank between 500/1000 mL of water, and retained their urine before the simulation. CT scans were acquired from the upper border of the L4 vertebral body to 3 cm below the level of the lesser trochanter. The CT data were transferred to a computerized treatment planning system (TPS).

The Gross Tumor Volume (GTV) was created without any margin to the prostate. The prostate gland plus the seminal vesicle base (1cm) is contoured as the clinical target volume (CTV). The Planning Target Volume 1 (PTV1) was created by giving the CTV a margin of 0.8 cm from each direction, and 0.5 cm only from the posterior direction to prevent a dose increase in the rectal wall. PTV2 was created by giving the GTV a margin of 0.8 cm expansion around CTV in all directions except a 5 mm posterior margin. The bladder, as the whole organ, and the rectum as the whole organ were contoured to exceed the PTV by 1 cm from the bottom and top. The femurs were contured to the lesser trochanter. A dose of 56 Gy (28 fractions/2Gy) was prescribed for PTV1 and 78 Gy (11 fractions/2Gy) for PTV2. We did not use the simultaneous integrated boost technique. We used sequential plans. First, PTV56 was treated, and then, by 11 fractions, PTV78 was treated. For the dose received by the PTV to be the same in all plans, plan normalization was made according to the fact that 95% of the PTV received 100% of the defined dose. It was determined that the maximum dose limit for PTV was 110% of the total dose. For each patient, 6 MV photon energy was used for 3D-CRT, IMRT, and VMAT planning. All contours were performed by the same radiation oncologist and all plans were performed by the same medical physicist. All patients received the same fractionation schedule and immobilization devices.

3D-CRT planning was performed using seven fields with gantry angles of 0°, 60°, 90°, 135°, 225°, 270°, and 320° in a clockwise (CW) direction. IMRT planning used nine fields with gantry angels 0°, 40°, 80°, 120°, 160°, 200°, 240°, 280°, and 320° in clockwise (CW) direction. VMAT planning used three full arcs (2 CW, 1 counterclockwise (CCW)) for PTV56, and two full arcs (1 CW, 1 CCW) for PTV78 (Figure 1). All plans were designed using the Varian Eclipse TPS version 10.0 (Varian Medical Systems, Palo Alto, USA). The analytical anisotropic algorithm (AAA) was used for volume dose calculation using a 2.5 mm dose grid matrix. Approval for this study was provided by the University of Health Sciences, Istanbul Training and Research Hospital, Turkey, Human Research Ethics Committee (approval number: 2021/2663).

CI (Conformity Index) was used to assess dose homogeneity within PTV and was calculated as [7]:

$$CI = \frac{TV_{PIV} \times TV_{PIV}}{V_{PIV} \times V_{TV}}$$

The CI values of the target volume in the plans made using this equation were calculated. When CI is equal to 1, the ideal conformality is achieved (The ideal value is 1).

PIV (Prescription Isodose Volume) is the treatment volume of the body receiving 95% of the prescribed dose; TV is the tumor volüme and equal to PTV. The TV_{PIV} is the TV covered by the reference isodose.

HI (Homogeneity Index) was evaluated according to ICRU 83 [8].

D2%, D50%, and D98% mean the doses of 2%, 50%, and 98% volume of the PTV.

$$HI = \frac{D_{2\%} - D_{98\%}}{D_{50\%}}$$

The HI values of the target volume in the plans made using this equation were calculated. The fact that HI is equal to or close to 0 indicates that the absorbed dose distribution is homogeneous (The ideal value is 0).

ID (Integral Dose) in the present study, the organ was considered uniform density, and the integral dose was estimated by the equation given below:

ID = The mean dose received by the organ was calculated (Gy) x Volume (L) [5].

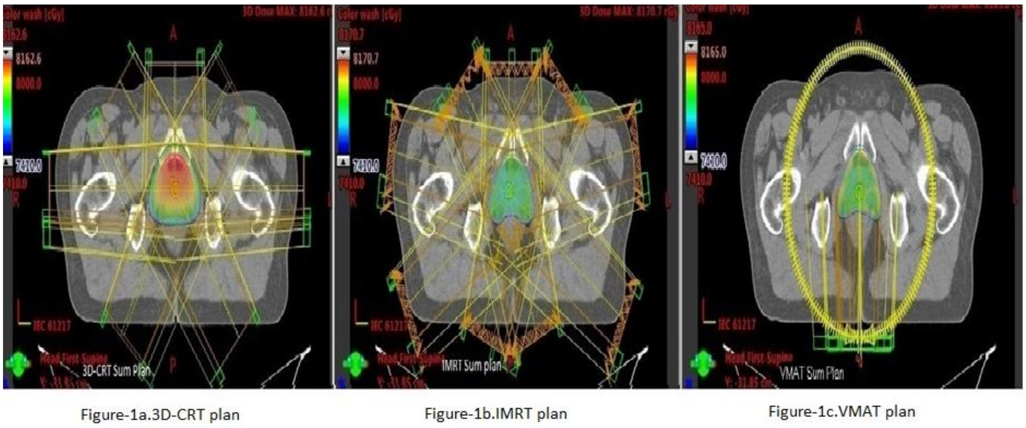

Figure 1. Comparison of 95% isodose distributions on CT slices for 3D-CRT, IMRT, and VMAT treatment plans. 1a-3D-CRT planning used seven fields with ganrty angels of 0º,60º,90º,135º,225º,270º and 320º in clockwise (CW) direction. 1b-IMRT planning used nine fields with ganrty angels of 0º,40º,80º,120º,160º,200º,240º,280º and 320º in CW direction. 1c-VMAT planning using three full arcs (two CW, one counterclockwise (CCW)) for PTV56 and two full arcs (one CW, one CCW) for PTV78.

Statistical analysis

Mean, standard deviation, median, minimum, and maximum values were used for descriptive statistics. The distribution of variables is measured by the Kolmogorov-Smirnov and Shapiro-Wilk tests. The Friedman (Wilcoxon) test was used for the repeated measurement analysis. SPSS 28.0 was used for statistical analyses.

Results

A total of 10 prostate cancer patients with a mean age of 67 years were included in this study. The median rectal volume was found to be 63.5 cc (45 cc-115 cc) and the median bladder volume was 227.5 cc (131 cc-317 cc). The right femoral volume was measured at a median was found to be 186 cc (158 cc-231 cc), while the left femoral volume was 195 cc (148 cc-226 cc).

The rectum mean dose of 54.4 Gy and rectum ID value of 3.5 Gy x L were found to be higher in 3D-CRT planning compared to IMRT and VMAT planning ($p < 0.001$). Additionally, these values were significantly higher in IMRT planning compared to VMAT planning ($p = 0.013$).

The bladder mean dose of 33 Gy and bladder ID value of 7.93 Gy x L were found to be lower in VMAT planning compared to IMRT and 3D-CRT planning ($p < 0.001$). When comparing IMRT and 3D-CRT planning, no statistically significant difference was found ($p > 0.05$).

The mean dose of 27 Gy and ID value of 5.25 Gy x L of the right femur were found to be higher in 3D-CRT planning compared to VMAT and IMRT planning ($p = 0.007$). There was no significant difference between VMAT and IMRT planning ($p > 0.05$). Similarly, the mean dose of 26 Gy and ID value of 5.13 Gy x L of the left femur was found to be higher in 3D-CRT planning than in VMAT and IMRT planning ($p = 0.007$). There was no significant difference between VMAT and IMRT planning ($p >0.05$).

Table 1. Comparison of mean,ID doses, and organs at risk in 3D-CRT, IMRT, and VMAT planning

	3D-CRT (Mean ± SD) (Median)	IMRT (Mean ± SD) (Median)	VMAT (Mean ± SD) (Median)	p value
Rectum (Gy)	54.4 ± 10.0 54.0	39.0 ± 7.0 40.0	36.0 ± 7.0 37.0	<0.001
Rectum ID (Gy x L)	3.50 ± 0.8 3.50	2.52 ± 0.6 2.53	2.29 ± 0.4 2.37	<0.001
Bladder (Gy)	36.3 ± 9.8 36.3	38.0 ± 10.0 37.0	34.0 ± 8.0 33.0	<0.001
Bladder ID (Gy x L)	7.99 ± 2.35 8.75	8.14 ± 1.7 8.50	7.40 ± 1.6 7.93	<0.001
Right femur (Gy)	27.07 ± 4.5 27.2	18.6 ± 4.6 17.5	18.05 ± 2.6 18.3	0.007
Right femur ID (Gy x L)	5.1 ± 0.6 5.2	3.5 ± 0.5 3.4	3.4 ± 0.2 3.3	0.002
Left femur (Gy)	26.49 ± 4.2 26.0	18.7 ± 4.0 18.9	19.5 ± 3.1 20.0	0.007
Left femur ID (Gy x L)	5.1 ± 0.6 5.1	3.5 ± 0.4 3.5	3.7 ± 0.4 3.8	0.002
Rectum V50 < 50 %	69.5 ± 18.7 71.5	32.3 ± 12.9 38.0	24.9 ± 10.6 29.5	<0.001
Rectum V60 < 35 %	50.6 ± 21,2 48.5	23.2 ± 9.9 26.0	18.0 ± 9.1 19.5	<0.001
Rectum V65 < 25 %	36.8 ± 17.1 33.5	19.4 ± 8.9 20.5	14.7 ± 7.9 14.0	<0.001
Rectum V70 < 20 %	29.6 ± 14.7 28.5	15.1 ± 7.4 15.0	11.4 ± 6.8 10.5	<0.001
Rectum V75 < 15 %	19.5 ± 10.9 19.5	9.4 ± 5.6 9.0	7.7 ± 5.2 7.5	<0.001
Bladder V40 < 50 %	44.7 ± 15.9 44.5	41.5 ± 15.7 39.5	36.7 ± 13.0 33.0	0.003
Bladder V65 < 50 %	22.6 ± 12.1 21	19.0 ± 9.6 18.5	16.6 ± 7.8 16.0	<0.001
Bladder V70 < 35 %	19.9 ± 10.9 18.0	16.0 ± 8.2 15.5	14.1 ± 6.7 13.5	<0.001
Bladder V75 < 25 %	16.3 ± 9.5 13.5	13.1 ± 6.7 13.0	11.5 ± 5.6 11.0	<0.001
Bladder V80 < 15 %	5.9 ± 7.4 3.5	1.9 ± 1.3 1.5	1.9 ± 2.2 1.0	0.091
Right femur V50<10%	5.5 ± 9.3 1.5	0.2 ± 0.42 0.0	0.0 ± 0.0 0.0	0.006
Left femur V50<10%	5.1 ± 9.2 1.5	0.2 ± 0.42 0.0	0.0 ± 0.0 0.0	0.002

Table 2. Comparison of PTV56, PTV78, body mean, ID doses, HI, CI, and MU values for 3D-CRT, IMRT, and VMAT planning techniques.

	3D-CRT (Mean ± SD) (Median)	IMRT (Mean ± SD) (Median)	VMAT (Mean ± SD) (Median)	p value
PTV56 mean dose (Gy)	76.8 ± 1.2 77.0	75.8 ± 1.3 75.6	75.8 ± 1.1 75.6	0.001
PTV56 ID (Gy x L)	17.62 ± 58.3 18.14	174.0 ± 56.9 17.94	173.9 ± 56.7 17.93	0.006
PTV78 mean dose (Gy)	80.1 ± 0.5 80.1	79.0 ± 0.3 79.0	79.0 ± 0.3 79.0	0.005
PTV78 ID (Gy x L)	13.34 ± 48.3 13.42	13.13 ± 47.7 13.22	13.17 ± 47.7 13.27	<0.001
Body mean dose (Gy)	5.7 ± 1.0 5.6	5.3 ± 0.9 5.3	5.07 ± 0.8 5.1	0.005
Body ID (Gy x L)	199.1 ± 36.8 199.3	186.0 ± 32.0 190.0	177.0 ± 30.0 179.0	<0.001
HI	0.06 ± 0.02 0.06	0.04 ± 0.01 0.04	0.04 ± 0.01 0.04	0.006
CI	0.56 ± 0.04 0.56	0.69 ± 0.03 0.69	0.76 ± 0.04 0.76	<0.001
MU (monitor unit)	689.2 ± 30.07 689.2	2646.3±246.7 2646.3	1492.7±135.6 1492.7	<0.001

Rectum V50, V60, V65, V70, and V75 values were found to be statistically significantly higher in 3D-CRT planning compared to VMAT and IMRT planning ($p < 0.001$). These rectum values were found to be statistically significantly higher in IMRT planning than in VMAT planning ($p < 0.001$).

Bladder V40, V65, V70, and V75 values were found to be statistically significantly higher in the 3D-CRT planning than in the VMAT and IMRT plans ($p < 0.001$). There was no statistically significant difference between bladder V80 values among VMAT, IMRT, and 3D-CRT plans ($p = 0.091$).

The right femur V50 < 10% value was found to be statistically significantly higher in the 3D-CRT planning than in the VMAT and IMRT plans ($p = 0.006$). There was no significant difference between VMAT and IMRT planning ($p > 0.05$).

The left femur V50 < 10% value was found to be statistically significantly higher in the 3D-CRT planning than in the VMAT and IMRT plans ($p = 0.002$). There was no significant difference between VMAT and IMRT planning ($p > 0.05$).

The comparison of mean, ID doses, and organs at risk in 3D-CRT, IMRT, VMAT planning techniques is shown in Table 1.

The PTV56 mean dose value 77 Gy and ID dose value 3.50 Gy x L were higher in 3D-CRT planning than in the VMAT and IMRT plans ($p = 0.001$ and $p = 0.006$, respectively), with no significant difference between VMAT and IMRT planning ($p > 0.05$).

The PTV78 mean dose value 80.1 Gy and ID dose value 13.42 Gy x L were higher in 3D-CRT planning than in VMAT and IMRT plans (for both, $p = 0.005$), with no significant difference between VMAT and IMRT planning ($p > 0.05$).

The body mean dose value 5.6 Gy and ID dose 199.3 Gy x L were higher in 3D-CRT planning compared to VMAT and IMRT plans ($p < 0.001$). Additionally, these values were significantly higher in IMRT planning compared to VMAT planning ($p < 0.001$).

The HI value (0.06) was statistically significantly higher in 3D-CRT plans than in VMAT and IMRT plans ($p = 0.006$), with no difference between the VMAT and IMRT plans ($p > 0.05$).

The CI value (0.76) was statistically significantly higher in VMAT plans than in IMRT and 3D-CRT plans ($p < 0.001$), while the CI value was significantly lower in 3D-CRT plans compared to IMRT plans ($p < 0.001$).

The MU value (2646.4) was significantly higher in the IMRT planning compared to VMAT and 3D-CRT plans, and higher in the VMAT plan compared to 3D-CRT plans ($p < 0.001$) (Table 2).

Discussion

The purpose of radiotherapy is to provide a high radiation dose to the targeted volume and, at the same time, avoid healthy organs at risk. For prostate cancer, radiotherapy is a useful substitute treatment. The rectum and bladder are important organs that should be protected in prostate cancer radiotherapy [9,10]. In all three treatment techniques, dosimetric parameters for organs at risk were within the tolerance limits; in the present study.

In various studies, IMRT has been reliably linked to a reduced incidence of late rectal toxicity in comparison to 3D-CRT among patients undergoing radiotherapy for localized prostate cancer [11-14]. In our study, the best rectum protection was observed in VMAT planning, followed by IMRT and 3D-CRT planning, respectively.

Although no significant difference was observed in terms of late genitourinary side effects in the study of Viani et al., statistical significance was not detected in our study for bladder protection V80 dose (15). For other bladder volumes, VMAT planning was found to be the best, followed by IMRT; and 3D-CRT.

Among the organs at risk, the femurs were better protected in IMRT and VMAT planning than in the 3D-CRT plan, as in our study [4,11].

ID is the total energy absorbed by the body and is computed according to the mean organ density [5,15]. ID is taken up by all tissues in the CT scan region and includes the PTV, organs at risk and nontarget body tissues. In our study, the body ID was found to be lower in VMAT planning. This is due to a more homogeneous dose achieved by VMAT planning. The total body ID was higher in IMRT because the treated area causes an unwanted dose at the edges of the target volume. IMRT planning leads to extended treatment durations and a higher number of monitor units, which contributes to a greater integral body dose due to leakage and scattered radiation. In the study by Slorasek et al., it was shown that the highest integral dose in the patient's body was during treatment with TomoTherapy and CyberKnife, and VMAT treatment was characterized by the lowest ID given to the patient's body [16]. In Samir et al.'s study, VMAT techniques delivered lower IDs than IMRT, as in our study [17].

Some studies, similar to our investigation, show that radiation dose distribution in prostate cancer treatment can be provided with high quality and safety with VMAT planning [2,4,17]. Compared to IMRT, it was found that VMAT significantly reduced the number of MUs, treatment duration, and doses for the bladder and rectum, consistent with our study. [4,17].

In some studies, VMAT plans showed better CI and HI values, and along with lower MUs than IMRT, while 3D-CRT had the lowest MUs, CI, and HI, similar to our findings [18-20]. In Ekici et al., the number of MUs in 3D-CRT was found to be less than in the other planning techniques, while in VMAT, the number of MUs was lower compared to IMRT, aligning with our results [21].

The limitation of the current study includes the small number of patients. Additional studies with larger sample sizes are needed to confirm these results.

Conclusion

According to our study, for organ protection, body ID doses and HI as well as CI, the VMAT planning technique is mostly superior to IMRT and 3D-CRT. In terms of MU, the 3D-CRT planning technique is better than the others. Our findings indicate that VMAT could generate plans that deliver lower IDs to healthy tissues while providing relatively uniform doses to the target area; and lower MUs.

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