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Dosimetric Comparison of 3D-CRT and VMAT in Prostate Cancer Radiotherapy at 72 Gy and 74 Gy

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1.Abstract

1.1. Objective: The aim of this study was to perform a dosimetric comparison between three-dimensional conformal radiotherapy (3D-CRT) and volumetric modulated arc therapy (VMAT) in the treatment of prostate cancer, focusing on planning target volume (PTV) coverage and dose exposure of organs at risk at prescribed doses of 72 Gy and 74 Gy.

1.2. Materials and methods: This retrospective study included 25 patients with localized prostate cancer. For each patient, two treatment plans were generated using identical computed tomography datasets: one using the 3D-CRT technique and one using VMAT. Patients were divided into two groups according to the prescribed dose regimen (72 Gy and 74 Gy). All treatment plans were created in the Monaco treatment planning system. PTV coverage was evaluated using V95% and V90% parameters, while dose–volume parameters for organs at risk, including the rectum, bladder, femoral heads, and small bowel, were analyzed in accordance with international recommendations. Statistical comparison between techniques was performed using paired t-tests, with a significance level set at $p < 0.05$.

1.3. Results: VMAT demonstrated significantly improved PTV coverage compared with 3D-CRT for both dose regimens, with more pronounced differences observed at the 74 Gy prescription. VMAT also reduced intermediate-dose exposure to the rectum and bladder, particularly at the V50Gy and V65Gy levels. High-dose rectal parameters showed variable results at 74 Gy, while doses to the femoral heads and small bowel were generally lower with VMAT.

1.4. Conclusion: VMAT provides superior target volume coverage and more favorable dose distribution compared with 3D-CRT in prostate cancer radiotherapy.

2. Keywords: prostate cancer, radiotherapy, VMAT, 3D-CRT, organs at risk

3. Introduction

Prostate cancer is one of the most common malignancies in men, with incidence increasing significantly with age. Epidemiological and autopsy studies have shown that a substantial proportion of men over the age of 80 harbor histological evidence of prostate cancer, although many cases remain clinically indolent for prolonged periods. The disease is more prevalent in men of African descent and less common in Asian populations, while men of European ancestry exhibit an intermediate risk. Clinical symptoms typically occur late in the course of the disease and often overlap with those of benign prostatic hyperplasia, which may delay diagnosis. Owing to its generally slow progression and favorable radiobiological characteristics, prostate cancer is particularly well suited for radiotherapy, where advances in treatment planning techniques aim to optimize tumor control while minimizing toxicity to surrounding organs at risk. [1]

4. Materials and Methods

4.1. Patients

The study included 25 patients diagnosed with prostate cancer. Patients were divided into two groups according to the prescribed dose regimen:

Group 1: 9 patients treated with a total dose of 72 Gy delivered in 36 fractions

Group 2: 16 patients treated with a total dose of 74 Gy delivered in 37 fractions

For all patients, treatment plans were created using both 3D-CRT and VMAT techniques.

4.2. Treatment Protocols

Contouring of target volumes (CTV and PTV) and organs at risk was performed in accordance with the recommendations of the International Commission on Radiation Units and Measurements [2,3], applying standard anatomical criteria for prostate cancer. Organs at risk included the rectum, bladder, femoral heads, and small bowel. The definition of the PTV volume comprised the CTV with safety margins applied to compensate for daily setup variations on the linear accelerator and internal organ motion [2,3]. All treatment plans were generated in the Monaco treatment

planning system (v6.2.2.0) based on CT simulation data, with the aim of achieving optimal PTV coverage while strictly respecting dose constraints for organs at risk. Three-dimensional conformal radiotherapy (3D-CRT) represents a standard external beam radiotherapy technique in which dose distribution is based on three-dimensional CT patient data, and the shape of the radiation fields is formed by a multileaf collimator (MLC) to conform to the contours of the target volume [4,5].

Plans for all patients were created using a protocol that included multiple fixed radiation beams—six partially opposed fields: APOL–PAOD, LLAT–DLAT, APOD–PAOL, and one direct AP field. Field shaping to the PTV was performed using the MLC, with an additional margin of 0.7 cm applied around each PTV. This field geometry allows the distribution of entrance and exit beams from multiple directions, thereby reducing the relative dose burden to the rectum and bladder compared with traditional box techniques [4]. For all fields, a photon beam energy of 10 MV was used. The field isocenter was positioned at the center of the treatment volume, and the dose normalization point coincided with the isocenter. The dose calculation algorithm used was the collapsed cone photon (Figure 1).

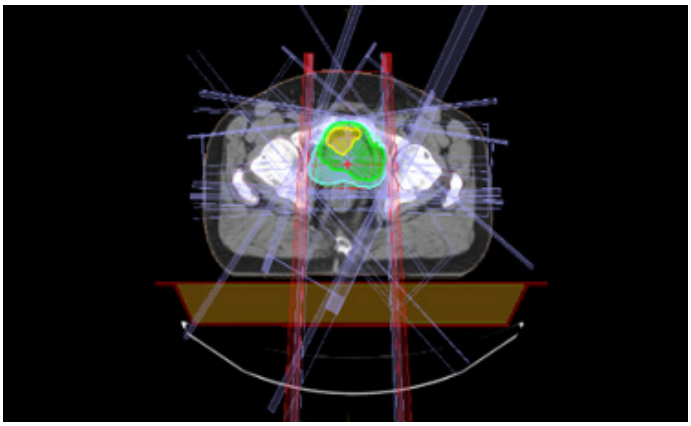

Figure 1. Geometric arrangement of beams in a 3D-CRT plan for prostate cancer

Volumetric Modulated Arc Therapy (VMAT) is an advanced radiotherapy technique that enables dose delivery during continuous gantry rotation with simultaneous modulation of multiple parameters, namely: gantry rotation speed, the position and dynamics of the multileaf collimator (MLC) leaves, and the dose rate. This allows for high dose conformity and homogeneity of the dose distribution [7]. In all VMAT plans, a 6 MV photon beam energy was used. A margin of 0.3 cm was added to the PTV, enabling improved control of geometric uncertainties compared with the 3D-CRT technique. The field isocenter was positioned at the center of the treatment volume, and the Monte Carlo algorithm was used for dose calculation. The application of the Monte Carlo algorithm is particularly important in regions with steep dose gradients, complex anatomical contours, and close proximity of organs at risk. In all plans, two arcs with full gantry rotation were used (Figure 2).

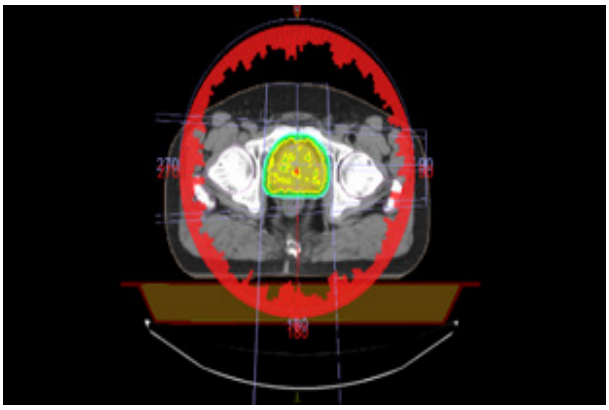

Figure 2: Geometry of rotation and arc trajectories in a VMAT plan for prostate cancer

5. Results

5.1. Plan Evaluation and Statistical Analysis

The evaluation of the generated radiotherapy plans was performed through a detailed analysis of target volumes (PTV) and organs at risk (OAR), applying internationally accepted recommendations outlined in the ICRU 50 and ICRU 62 documents, which define standards for dose prescription, recording, and reporting in photon radiotherapy [2,3]. Volumes receiving at least 95% (V95%) and 90% (V90%) of the prescribed dose were analyzed [2]. For organs at risk, high-dose volumes were evaluated, including V75Gy, V70Gy, V65Gy, V60Gy, and V50Gy for the rectum and bladder, as well as V50Gy for the femoral heads, in accordance with QUANTEC publications [8] and relevant NCCN guidelines [9].

Statistical analysis of the plans was conducted with the aim of identifying true differences in dosimetric characteristics between the 3D-CRT and VMAT techniques for the same patients. For all variables, descriptive statistical parameters were first calculated, including the mean value and standard deviation (Mean ± SD). Since two plans were generated for each patient—one 3D-CRT and one VMAT—a paired t-test was used, which represent

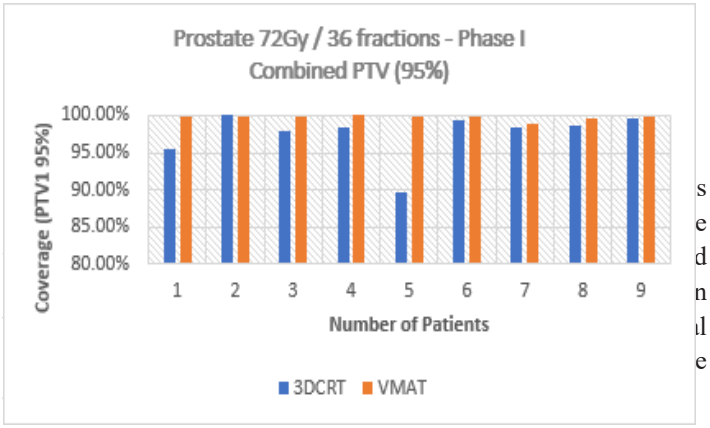

Figure 3: PTV volume coverage (V95%) for 3D-CRT and VMAT

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plans at a dose of 72 Gy – Phase I.

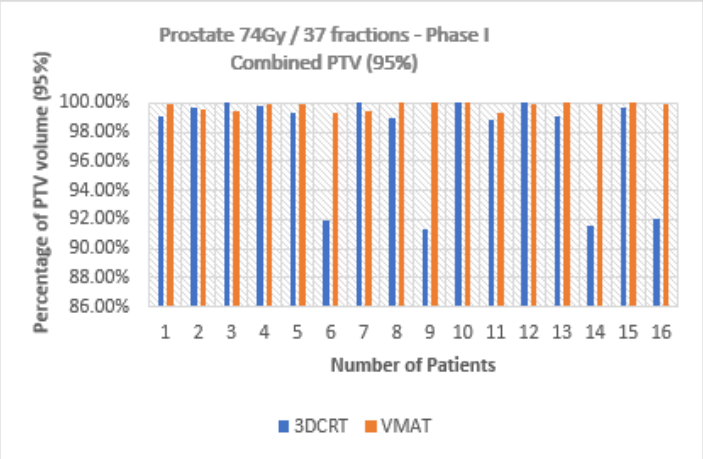

Figure 4: PTV volume coverage (V95%) for 3D-CRT and VMAT plans at a dose of 74 Gy – Phase I.

Table 1. Comparative analysis of target volume coverage and dose constraints of organs at risk for 3D-CRT and VMAT techniques (72 Gy dose).

72Gy			
	Parameter	**3DCRT (Mean ± SD) (%)**	**VMAT (Mean ± SD) (%)**
PTV1	V95%	89.91 ± 9.31	99.14 ± 1.07
	V90%	97.47 ± 3.14	99.99 ± 0.02
PTV2	V95%	92.20 ± 9.02	99.78 ± 0.43
	V90%	98.58 ± 2.61	99.99 ± 0.04
PTV3	V95%	/	/
	V90%	/	/
Combined PTV1	V95%	96.18 ± 4.49	99.81 ± 0.33
	V90%	99.38± 0.33	100 ± 0.00
Combined PTV2	V95%	95.96 ± 4.25	99.74 ± 0.38
	V90%	99.60 ± 0.47	99.97 ± 0.08
Combined PTV3	V95%	/	/
	V90%	/	/
Rectum V75Gy<15%		0.00 ± 0.00	0.00 ± 0.00
V70Gy<20%		4.79 ± 4.62	4.39 ± 1.41
V65Gy<25%		16.01 ± 7.00	13.47 ± 3.50
V60Gy<35%		25.46 ± 9.43	21.54 ± 5.53
V50Gy<50%		43.74 ± 6.74	39.25 ± 8.55
BladderV75Gy<25%		1.14 ± 3.21	0.14 ± 0.42
V70Gy<35%		16.79 ± 10.24	14.69 ± 6.66
V65Gy<50%		37.30 ± 13.09	27.36 ± 8.94
Femoral head left V50Gy<5%		0.51 ± 0.93	0.00 ± 0.00
Femoral head right V50Gy<5%		0.68 ± 1.17	0.00 ± 0.00
Small bowel		5632.87±983.92	5066.33±834.72

Table 1 presents a detailed comparative analysis of target volume coverage and dose exposure of organs at risk at a total dose of 72 Gy for 3D-CRT and VMAT plans. The results clearly indicate that VMAT achieves superior PTV coverage. Statistically significant differences were observed for PTV1 (V95%: $p = 0.021$; V90%: $p = 0.043$) and PTV2 (V95%: $p = 0.036$), while the difference for PTV2 V90% was not statistically significant ($p = 0.144$), although a trend in favor of VMAT was maintained.

Rectal analysis reveals a more complex pattern. At very high dose levels (V75Gy and V70Gy), no significant differences between the techniques were observed, whereas for V65Gy and V60Gy, a slightly lower mean volume was noted in VMAT plans, albeit without statistical significance. Importantly, the most pronounced difference was observed at the V50Gy level, where VMAT significantly reduced the volume receiving intermediate-to-high doses. For the bladder, a more favorable trend was observed in VMAT plans, with the difference at the V65Gy < 50% level being borderline statistically significant ($p = 0.05$). For the femoral heads, VMAT consistently achieved lower V50Gy values, although the differences were not statistically significant. The small bowel demonstrated a trend toward reduced mean dose in VMAT plans, but without statistical significance. Overall, the results for the 72 Gy dose regimen confirm the advantage of the VMAT technique primarily through improved PTV coverage and a reduction in intermediate-dose volumes to the rectum and bladder.

Table 2. Comparative analysis of target volume coverage and dose constraints of organs at risk for 3D-CRT and VMAT techniques (74 Gy dose).

74Gy			
	Parameter	**3DCRT (Mean ± SD) (%)**	**VMAT (Mean ± SD) (%)**
PTV1	V95%	85.16 ± 8.65	98.15 ± 2.25
	V90%	95.23 ± 3.72	99.84 ± 0.46
PTV2	V95%	84.80 ± 12.52	98.97 ± 1.57
	V90%	95.77 ± 4.56	99.87 ± 0.26
PTV3	V95%	97.27 ± 2.15	99.92 ± 0.10
	V90%	99.52 ± 0.78	99.99 ± 0.00
Combined PTV1	V95%	97.57 ± 3.51	99.78 ± 0.25
	V90%	99.20 ± 1.42	99.99 ± 0.04
Combined PTV2	V95%	84.89 ± 14.93	99.31 ± 1.97
	V90%	96.31 ± 4.12	99.82 ± 0.68
Combined PTV3	V95%	91.14 ± 5.19	99.61 ± 0.77
	V90%	97.97 ± 3.69	99.93 ± 0.09
Rectum V75Gy<15%		0.0 ± 0.0	0.5 ± 0.68
V70Gy<20%		1.81 ± 2.95	8.48 ± 4.47
V65Gy<25%		9.06 ± 5.19	15.25 ± 6.02
V60Gy<35%		22.12 ± 5.63	21.83 ± 7.04
V50Gy<50%		49.13 ± 4.29	37.01 ± 10.08
Bladder V75Gy<25%		5.63 ± 6.44	1.51 ± 1.41
V70Gy<35%		23.83 ± 8.15	17.08 ± 6.05
V65Gy<50%		37.58 ± 11.09	27.98 ± 9.55

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Femoral head left V50Gy<5%		2.15 ± 1.42	0.07 ± 0.19
Femoral head right V50Gy<5%		1.12 ± 1.48	0.13 ± 0.32
Small bowel		5019.18 ± 1429.52	4706.15 ± 984.9

Table 2 presents the dosimetric results for the prescribed dose of 74 Gy (Figure 5, Figure 6) and confirms a markedly more pronounced advantage of the VMAT technique compared with 3D-CRT. Statistically significant differences were observed for all analyzed PTV parameters, with extremely low p-values for PTV1 (V95%: p = 0.00004; V90%: p = 0.00012) and PTV2 (V95%: p = 0.0003; V90%: p = 0.002), confirming superior homogeneity and conformity of the VMAT dose distribution at higher therapeutic doses. VMAT also achieved more favorable values for PTV3, although the difference was smaller due to already high baseline values in both planning techniques.With respect to organs at risk, the results demonstrate a more complex pattern. (Figure 7, Figure 8, Figure 9, Figure 10)

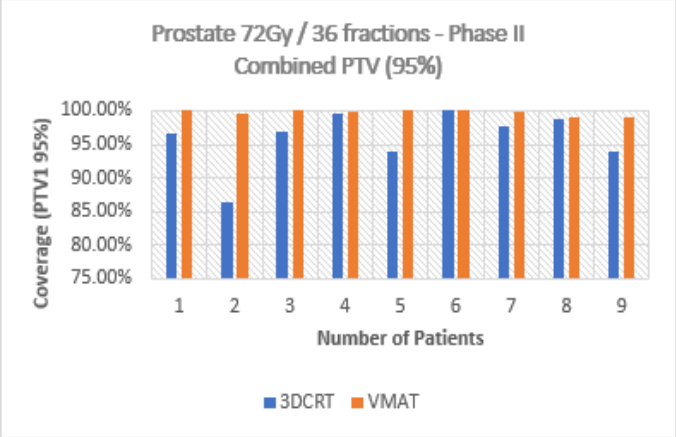

Figure 5: PTV volume coverage (V95%) for 3D-CRT and VMAT plans at a dose of 72 Gy – Phase II.

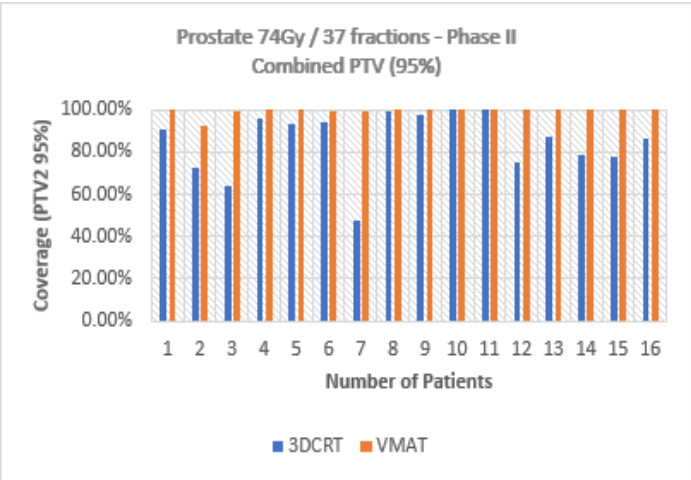

Figure 6: PTV volume coverage (V95%) for 3D-CRT and VMAT plans at a dose of 74 Gy – Phase II.

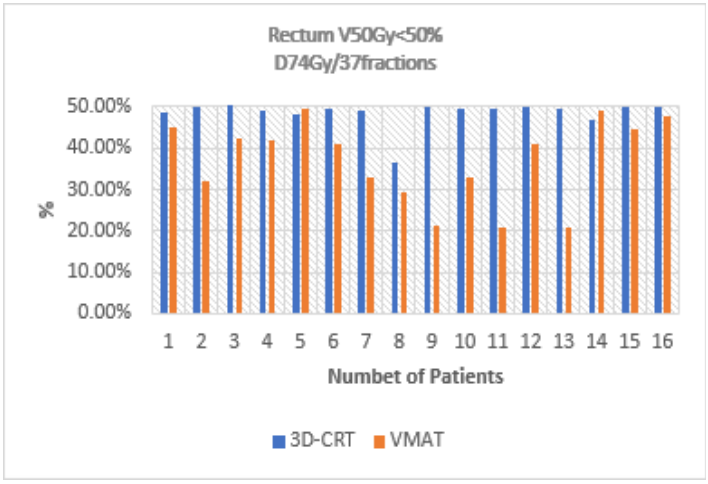

Figure 7: Rectal dose distribution (V50Gy) for 3D-CRT and VMAT plans at a dose of 74 Gy.

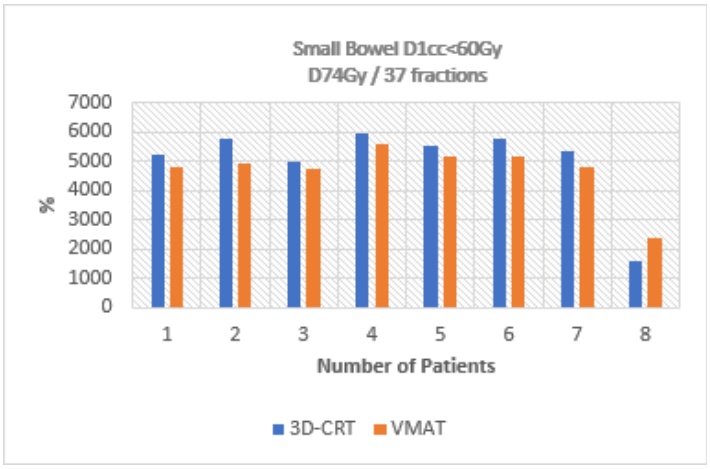

Figure 8: Bladder dose distribution (V65Gy) for 3D-CRT and VMAT plans at a dose of 74 Gy.

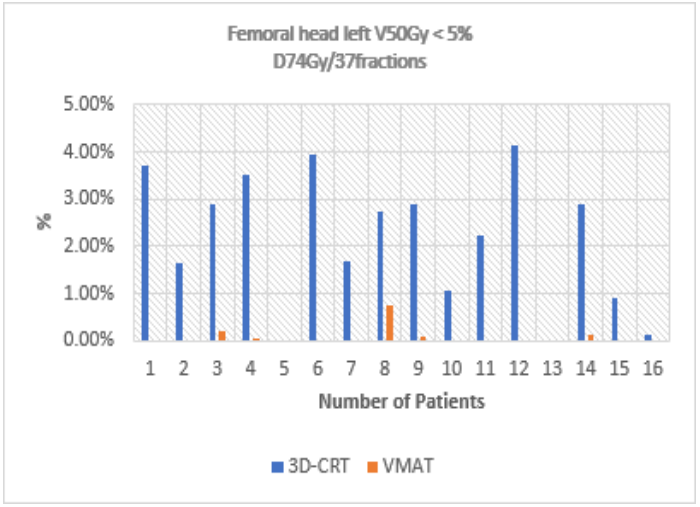

Figure 9: Dose distribution to the left femoral head (V50Gy) for 3D-CRT and VMAT plans at a dose of 74 Gy.

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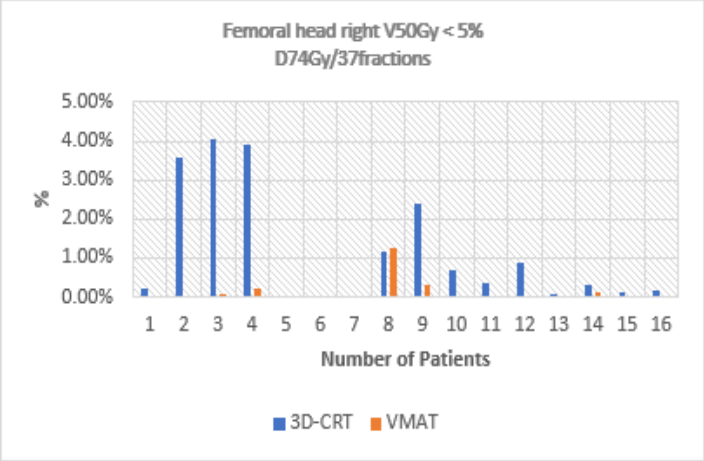

Figure 10: Dose distribution to the right femoral head (V50Gy) for 3D-CRT and VMAT plans at a dose of 74 Gy.

At high rectal dose levels, VMAT showed larger volumes compared with 3D-CRT for the parameters V70Gy < 20% (8.48% vs 1.81%) and V65Gy < 25% (15.25% vs 9.06%), which deviates from classical expectations and indicates that VMAT, despite its overall superior conformity, may generate localized increases in high-dose regions. This outcome arises from the fact that the 3D-CRT technique, owing to its characteristic tangential beam arrangement, often inherently reduces dose in the central rectal region, whereas VMAT, due to its highly modulated nature, may allow the formation of narrow high-dose segments in order to achieve optimal PTV conformity and coverage [6].However, despite the increase in the highest dose fractions, VMAT achieved a significant reduction in intermediate and lower high-dose rectal volumes, as confirmed by statistically significant differences in the V50Gy < 50% parameter (37.01% vs 49.13%, p = 0.0003). According to QUANTEC recommendations and available clinical data, intermediate dose–volume parameters show a stronger correlation with the occurrence of late gastrointestinal toxicity than small volumes exposed to extremely high doses [6]. These findings suggest that VMAT, despite localized high-dose regions, provides a more favorable overall rectal sparing profile.For the bladder, VMAT achieved significantly better results in the parameters V70Gy < 35% (p = 0.010) and V65Gy < 50% (p = 0.007), indicating more effective preservation of urogenital structures despite the high prescribed dose. For the small bowel, a trend toward reduced overall dose burden was observed with VMAT, although the difference was not statistically significant (p = 0.112). Doses to the femoral heads were consistently lower in VMAT plans, but the differences did not reach statistical significance (left: $p \approx 0.09$; right: $p \approx 0.12$).Overall, despite localized increases in high-dose rectal volumes for certain parameters (V70, V65), attributable to the nature of optimization at high doses and the anatomical relationship between the PTV and rectum, VMAT as a whole provides a superior combination of dose conformity, homogeneity, and reduced integral dose burden. These results fully support VMAT as a clinically more favorable and dosimetrically more advanced technique compared with 3D-CRT at high doses of 74 Gy.

6. Study Limitations

The limitations of this study include a relatively small patient sample size, the use of a single treatment planning system (Monaco), and a single type of linear accelerator, as well as the absence of parameters related to treatment delivery time. These limitations indicate the need for larger, multicenter studies to confirm the observed trends.

7. Ethical Considerations

This research was conducted as a retrospective analysis of anonymized clinical radiotherapy treatment plans without the use of any patient-identifying information. All analyzed data were fully anonymized prior to processing, and the study did not involve any interventions, additional radiation exposure, or deviations from standard therapeutic procedures.

8. Conclusion

The results of this study clearly confirm the dosimetric superiority of the VMAT technique compared with 3D-CRT for both analyzed dose regimens, 72 Gy and 74 Gy. In terms of target volume coverage, VMAT consistently achieves higher PTV coverage percentages for the V95% and V90% parameters, with a significantly more homogeneous and conformal dose distribution. This advantage is particularly pronounced in the 74 Gy plans, where the differences were highly statistically significant, indicating the stability and robustness of VMAT optimization in treatments requiring higher total therapeutic doses. With regard to the sparing of organs at risk, VMAT generally achieves lower dose values in the intermediate and moderately high dose ranges, particularly for the bladder and femoral heads. However, it is important to emphasize that high-dose rectal volumes (V70Gy and V65Gy) in the 74 Gy regimen were, in certain cases, higher in VMAT plans compared with 3D-CRT, as a consequence of the intensely modulated nature of VMAT optimization. Nevertheless, the overall dose distribution profile demonstrates that VMAT significantly reduces broader high-dose regions (e.g., V50Gy), which is clinically more relevant for reducing late gastrointestinal toxicity. In other words, although VMAT may generate localized high-dose segments within the rectum, it simultaneously substantially reduces the volume of tissue exposed to moderate and high doses, ultimately resulting in a more favorable therapeutic profile.When combining the analysis of PTV coverage with detailed exposure profiles of organs at risk, it can be concluded that VMAT achieves a more optimal balance between tumor dose escalation and normal tissue sparing. This advantage is particularly evident in more complex treatment plans and at higher prescribed doses, where 3D-CRT demonstrates limited conformity and poorer control of dose gradients.

Overall, VMAT has proven to be a more efficient, precise, and clinically favorable technique compared with 3D-CRT, and

therefore represents the recommended method of choice in contemporary radiotherapy planning for prostate cancer.

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