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Fast O-Ring Gantry Halcyon Linac: Enhancing Efficiency and Comfort in Elderly Prostate Cancer Radiotherapy

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ABSTRACT

Introduction: Prostate radiotherapy with pelvic nodal irradiation is challenging, particularly in elderly patients who have difficulty maintainfving bladder filling and immobilization during prolonged treatments. The Varian Halcyon system, with its 6 MV flattening filter-free beam, faster gantry rotation, higher multileaf collimator speed, and rapid imaging, may improve treatment accuracy and patient comfort. This study compares IMRT, single-arc VMAT (SA-VMAT), and dual-arc VMAT (DA-VMAT) on Halcyon.

Material and Methods: Patients with localized prostate cancer and pelvic lymph node involvement were retrospectively analyzed. IMRT, SA-VMAT, and DA-VMAT plans were generated using Eclipse (version 17, Varian Medical Systems, USA) with the Acuros XB algorithm. Target coverage, conformity, homogeneity, OAR sparing, monitor units, beam-on time, total treatment time, modulation factor, and gamma pass rate were evaluated.

Results: All techniques achieved acceptable target coverage and OAR constraints. DA-VMAT demonstrated better conformity, homogeneity, and rectal sparing ($p < 0.05$), with PTV68 D95% = 99.89 ± 0.45, CI = 0.96 ± 0.01, and HI = 0.063 ± 0.03. SA-VMAT had the shortest beam-on time (1.55 min) and lowest monitor units. Both VMAT techniques reduced monitor units and beam-on time compared with IMRT, with DA-VMAT achieving a gamma pass rate of 99.3%.

Conclusion: VMAT improved treatment efficiency. DA-VMAT provided better dosimetric characteristics, while SA-VMAT enabled faster delivery, potentially benefiting elderly patients. Technique selection should consider clinical complexity, patient characteristics, and treatment tolerance.

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Introduction

Prostate cancer remains the most frequently diagnosed malignancy among men worldwide and is a major contributor to cancer-related morbidity and mortality [1, 2]. Radiotherapy plays a pivotal role in the management of localized and locally advanced disease, with advances in conformal techniques significantly improving clinical outcomes while minimizing toxicity [3, 4]. Intensity-modulated radiation therapy (IMRT) has long been recognized as the standard approach for delivering precise dose distributions to the prostate and pelvic lymph nodes, enabling simultaneous dose escalation and enhanced normal tissue sparing [5]. However, conventional Intensity Modulated Radiation Therapy (IMRT) techniques involve prolonged beam-on times and increased monitor unit (MU) requirements, both of which may contribute to patient discomfort, intrafraction motion, and increased machine wear [6, 7].

Volumetric-modulated arc therapy (VMAT) has emerged as a highly efficient alternative to Intensity Modulated Radiation Therapy (IMRT), enabling continuous dose delivery during gantry rotation with dynamic modulation of multileaf collimators and dose rate [1, 8]. Through single-arc (SA-VMAT) or dual-arc (DA-VMAT) approaches, VMAT can achieve comparable or better improved target conformity and homogeneity while markedly reducing treatment duration [9, 10]. Several studies have demonstrated the potential of DA-VMAT to further improve dosimetric quality, particularly for complex target geometries involving seminal vesicle invasion or pelvic nodal irradiation [11–13]. Furthermore, the shorter treatment times achieved with VMAT are especially beneficial for elderly patients or those unable to tolerate prolonged treatment sessions, as they may reduce setup errors and intrafraction motion [14, 15].

The Varian Halcyon linear accelerator, characterized by a 6 MV flattening-filter-free (FFF) beam, coplanar delivery geometry, and an automated image-guided workflow, has expanded access to advanced IMRT and VMAT delivery through streamlined processes and reduced in-room time.

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Although its clinical advantages in pelvic irradiation have been explored, limited evidence exists comparing the relative performance of Intensity Modulated Radiation Therapy (IMRT), SA-VMAT, and DA-VMAT for prostate cancer with pelvic nodal involvement using the Halcyon platform.

This study evaluates Intensity Modulated Radiation Therapy (IMRT), SA-VMAT, and DA-VMAT on the Halcyon platform for prostate cancer with pelvic nodal irradiation by assessing dosimetric quality, treatment efficiency, plan complexity, and quality assurance (QA). Its clinical significance lies in helping clinicians select the most appropriate technique for elderly patients or those unable to tolerate prolonged treatment sessions, without compromising plan quality or safety in a multivendor environment.

Materials and Methods

This study included 23 patients with pathologically confirmed localized prostate cancer and pelvic lymph node involvement who received moderately hypofractionated radiotherapy using a Halcyon linear accelerator (Varian Medical Systems, USA). The cohort comprised elderly patients and those deemed unsuitable for prolonged treatment sessions or unable to tolerate bladder-filling protocols for the duration of treatment. Patients presenting with urinary or rectal symptoms, pain, mobility limitations, anxiety, claustrophobia, or cardiopulmonary conditions that restricted their ability to maintain bladder and rectal preparation during extended treatments were included.

Patient Setup and Simulation

All patients were immobilized in the supine position with lower limb fixation using a leg support device. A standardized bladder and rectal preparation protocol was implemented to achieve a comfortably full bladder and an empty rectum at each fraction. For elderly patients, the preparation protocols were modified to ensure reproducibility and comfort. Computed tomography (CT) simulation was performed from the mid-abdomen to a level inferior to the ischial tuberosities with a 3 mm slice thickness.

Target Delineation and Organs at Risk (OARs)

The clinical target volume (CTV) included the prostate and proximal seminal vesicles. The pelvic nodal CTV encompassed the obturator, external and internal iliac, and presacral nodal regions. Margins of 5–7 mm were applied while excluding bone, bowel, bladder, and muscle. A uniform 5 mm margin was used to create the planning target volume (PTV), which was reduced posteriorly to 3–5 mm to limit rectal dose exposure.

Organs at risk (OARs) included the rectum (from the rectosigmoid junction to the anal verge), bladder, penile bulb, femoral heads, bowel, and urethra when delineation was feasible. The prescription dose was 68 Gy in 25 fractions (2.72 Gy per fraction) to the prostate and 45 Gy in 25 fractions (1.8 Gy per fraction) to the pelvic nodes.

Treatment Planning and Dose Calculation

Treatment planning was performed using the Eclipse Treatment Planning System (version 17, Varian Medical Systems, USA) with a 6 MV flattening filter-free (FFF) photon beam on the Halcyon platform. Dose calculation was carried out using the Acuros XB algorithm (version

17) with a 2.5 mm calculation grid, applying heterogeneity correction and employing the default number of control points for VMAT plans in the Varian Eclipse Treatment Planning System (TPS). The optimization priority values represent relative weighting factors used by the Eclipse optimizer and are unitless. Higher values indicate greater optimization importance rather than dose or volume.

Treatment Planning Techniques

The study utilized the Halcyon linear accelerator (Varian Medical Systems) featuring a ring-mounted gantry design delivering a 6 MV flattening-filter-free photon beam at a maximum dose rate of 800 MU/min. It supports a maximum field size of 28 cm × 28 cm per isocenter. The gantry can rotate up to four times per minute, while treatment delivery occurs at up to two rotations per minute. Due to the absence of optical distance indicators and lasers at the isocenter, daily imaging is mandatory before each fraction to ensure accurate patient positioning.

Three radiotherapy planning techniques were compared: seven-field Intensity-Modulated Radiation Therapy (IMRT) with equally spaced gantry angles, single-arc Volumetric Modulated Arc Therapy (SA-VMAT), and dual-arc VMAT (DA-VMAT) involving one and two complete gantry rotations, respectively. The same optimization priorities were used as shown in Table 1. Evaluated dosimetric parameters included target coverage (PTV68 $D_{95\%}$, PTV45 $D_{95\%}$, and Dmax), conformity index (CI), homogeneity index (HI), monitor units (MU), and modulation factor (MF) as a measure of plan complexity. OAR dose indices included bowel V30Gy, bladder V45Gy/V50Gy/V60Gy, rectum V50Gy/V60Gy/V68Gy, and mean dose for the bilateral femoral heads, penile bulb, and external genitalia. All dose constraints were consistent with international guidelines (RTOG, NRG, QUANTEC) (detailed in Table 3). All plans achieved acceptable target coverage and sparing of the OARs. Plan quality and delivery accuracy were validated through gamma analyze.

Table 1. Optimization Parameters

Planning Optimization Parameters		
Structure	Objective	Optimization Priority (Relative Weight in Eclipse Optimizer;
PTV_Prostate	$D_{95\%} \geq 100\%$ (68 Gy)	120
PTV_Prostate	$D_{Max} \leq 105\%$	140
PTV_Nodes	$D_{95\%} \geq 100\%$ (45 Gy)	90
PTV_Nodes	$D_{Max} \leq 105\%$	100
Bowel	$V_{30Gy} < 200$ cc	80
Bowel	$V_{45Gy} < 30\%$	79
Bowel	$V_{50Gy} < 10\%$	90
Rectum	$V_{49Gy} < 30\%$	70
Rectum	$V_{59Gy} < 15\%$	90
Rectum	$V_{68Gy} < 1$ cc	120
Bladder	$V_{45Gy} < 50\%$	60
Bladder	$V_{50Gy} < 25\%$	70
Bladder	$V_{60Gy} < 15\%$	80
Bladder	$V_{68Gy} < 1$	120
Urethra	$D_{Max} \leq 104\%$	120
Femoral Head (LT)	Mean Dose < 23 Gy	50
Femoral Head (RT)	Mean Dose < 23 Gy	50
External Genitalia	Mean Dose < 25 Gy	40
Penile Bulb	Mean Dose < 20 Gy	50

Vxx (%): Volume received by xx (%) dose in Gy; Dxx%: dose to XX % of Volume
Gy=Gray; cc: cubic centimeters; DMax: Maximum Point Dose

Treatment Verification and Delivery

Daily image guidance was conducted using cone-beam computed tomography (CBCT) for patient setup verification before each fraction. The fully integrated Halcyon workflow minimizes in-room time, offering clinical advantages for patients with limited mobility.

Plan Evaluation and Quality Assurance

The plans were evaluated for dosimetric performance, delivery efficiency, and quality assurance (QA). Indices for target coverage, conformity, and homogeneity were assessed (Table 2), while dose–volume histogram (DVH) parameters were extracted to evaluate OAR sparing (Table 3). Efficiency metrics included MU and beam-on time.

Patient-specific QA: Patient-specific QA was performed using the aS1200 EPID mounted on the Halcyon linear accelerator. Each VMAT plan was delivered in QA mode, and measured portal dose distributions were compared with TPS-predicted distributions using portal dosimetry software. Agreement was evaluated using gamma index analysis (3%/2 mm, global normalisation, 10% dose threshold). The gamma passing rate ($\gamma \leq 1$) was recorded, with ≥95% considered acceptable.

Statistical Analysis

Normality was assessed using the Shapiro–Wilk test. Normally distributed variables were analyzed using repeated-measures ANOVA with Greenhouse–Geisser correction when required; non-normal variables were analyzed using the Friedman test with Wilcoxon post hoc tests.

Results

Figure 1,2 and 3 demonstrate Comparison of dose distributions in a representative patient using different techniques: (1) Intensity Modulated Radiation Therapy (IMRT); (2) (SA-VMAT); (3) (DA-VMAT).

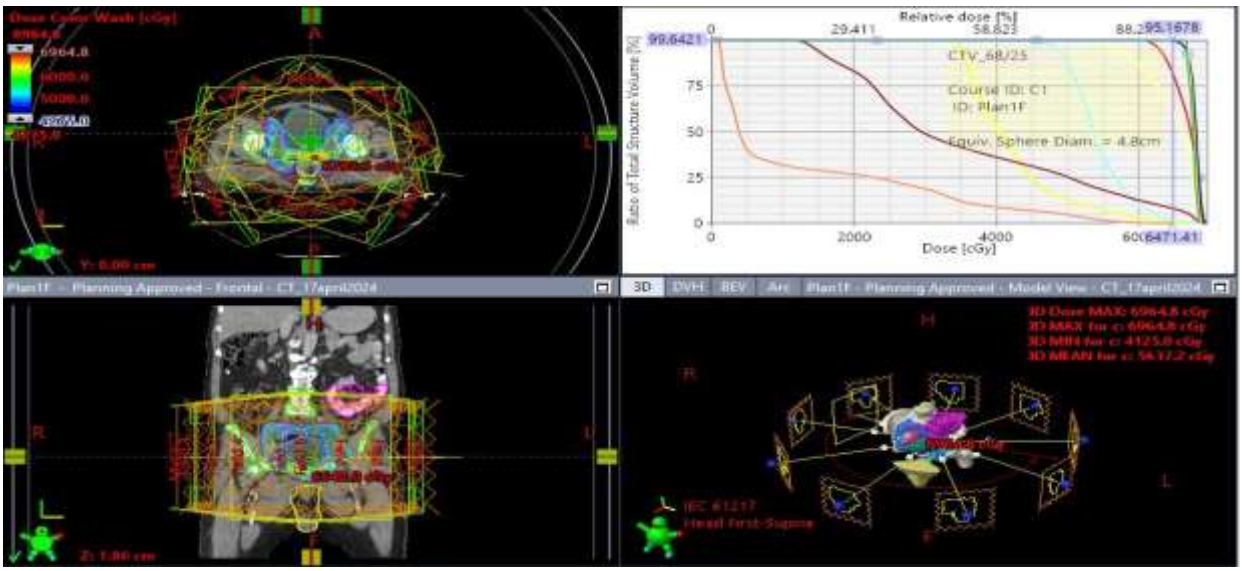


Figure 1. Illustrating 95% prescribed isodose distribution in transverse, coronal, with dose–volume histograms (DVHs) for the planning target volume (PTV) and organs at risk (OARs) in the Intensity Modulated Radiation Therapy (IMRT) plan.

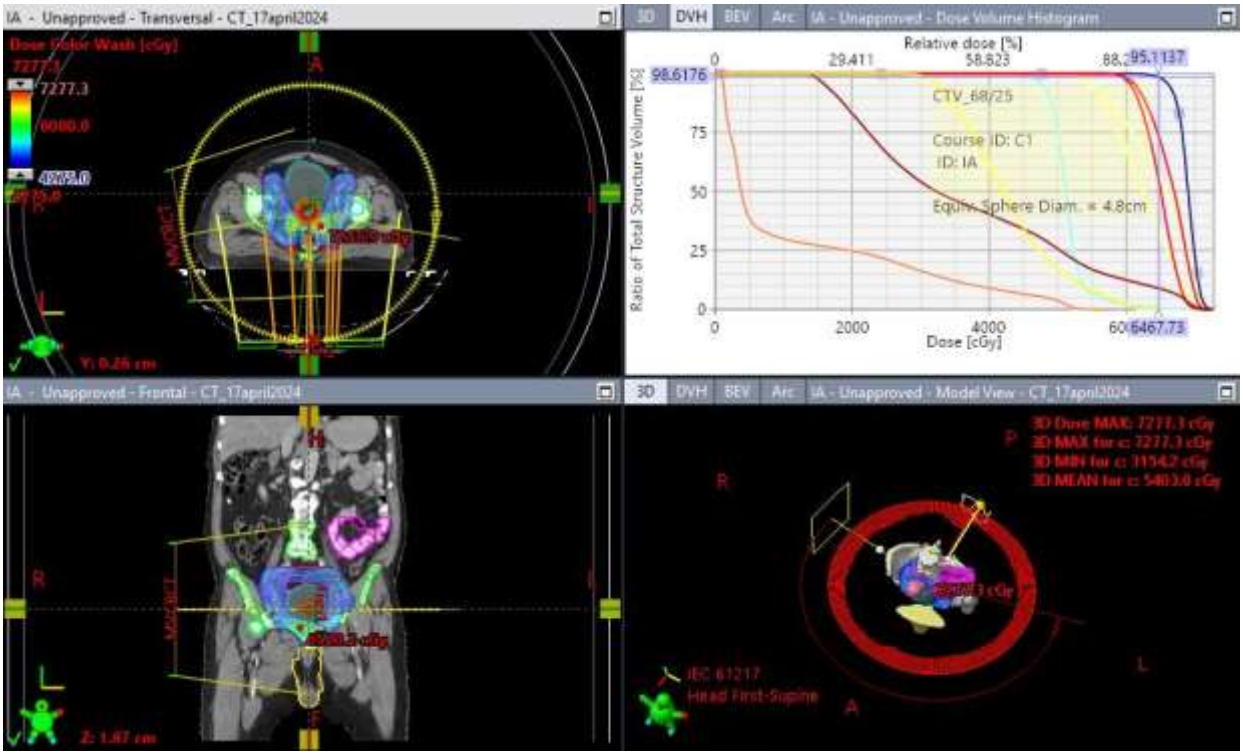


Figure 2. Illustrating 95% prescribed isodose distribution in transverse and coronal views, with dose–volume histograms (DVHs) for the planning target volume (PTV) and organs at risk (OARs) in the Single Arc VMAT (SA-VMAT) plan.

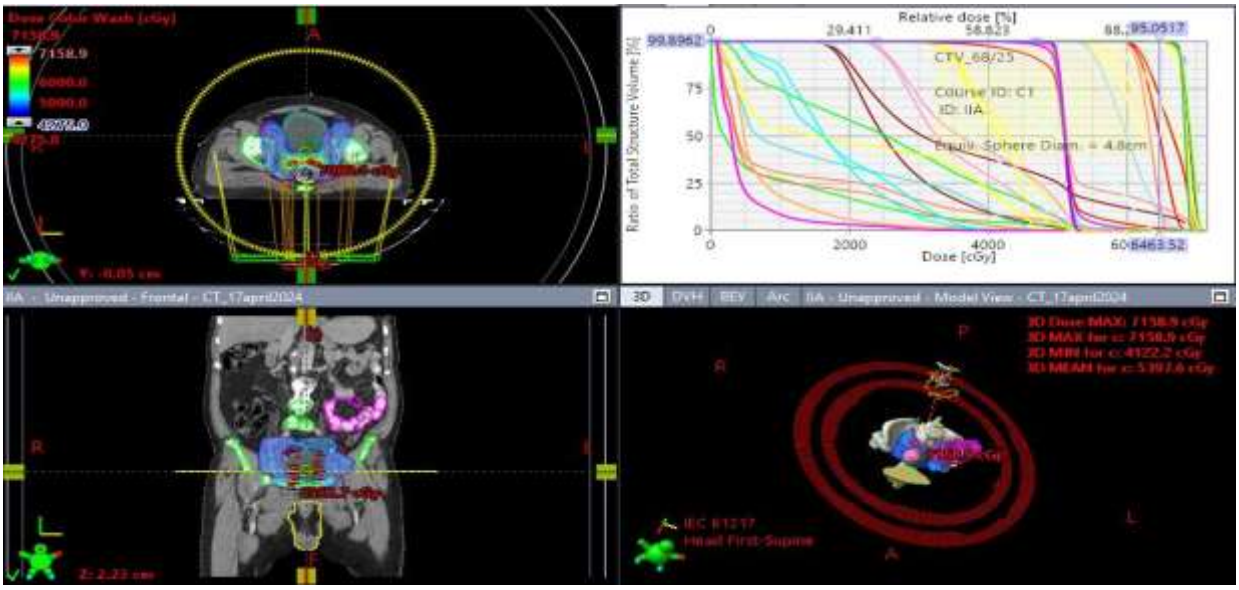
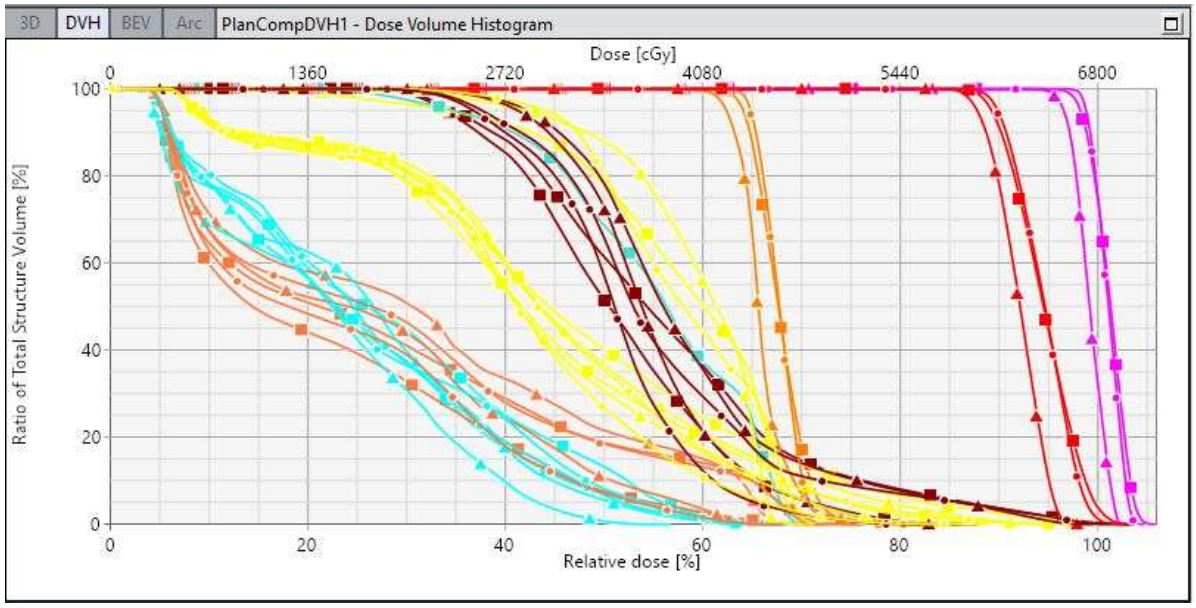


Figure 3. Illustrating 95% prescribed isodose distribution in transverse, coronal, and sagittal planes, with dose–volume histograms (DVHs) for the planning target volume (PTV) and organs at risk (OARs) in the Dual Arc VMAT (DA-VMAT) plan.



* ●_PTV 68Gy ▲_PTV 45Gy ■_(IMRT) ●_(DA-VMAT) ▲_(SA-VMAT)

Figure 4. Illustrating Dose–volume histogram (DVH) comparison of Intensity Modulated Radiation Therapy (IMRT), Single Arc VMAT (SA-VMAT), and Dual Arc VMAT (DA-VMAT) plans for target volumes (PTV 68 Gy and PTV 45 Gy) and key organs at risk (OARs).

Target Coverage and Treatment Efficiency

Table 2 summarizes the dosimetric and efficiency parameters for Intensity Modulated Radiation Therapy (IMRT), single-arc VMAT (SA-VMAT), and dual-arc VMAT (DA-VMAT). DA-VMAT achieved the highest numerical PTV coverage values, with significantly higher $D_{95\%}$ for both PTV68 Gy and PTV45 Gy compared with SA-VMAT ($p < 0.05$), while differences compared with Intensity Modulated Radiation Therapy (IMRT) were not statistically significant. Conformity and homogeneity indices demonstrated numerically improved dose conformity and dose uniformity with DA-VMAT. Statistically significant improvements were observed primarily in comparison with SA-VMAT, whereas target coverage remained comparable with Intensity Modulated Radiation Therapy (IMRT).

Regarding treatment efficiency, both VMAT techniques required significantly fewer monitor units (MU) and shorter beam-on times (BOT) than Intensity Modulated Radiation Therapy (IMRT) ($p < 0.05$). SA-VMAT exhibited the lowest MU and BOT overall, whereas DA-VMAT required higher MU and BOT than SA-VMAT but provided improved dosimetric characteristics. The modulation factor (MF) was lower for VMAT plans, consistent with reduced plan complexity. Both VMAT techniques achieved excellent gamma pass rates (>98%),

with DA-VMAT demonstrating the highest numerical value (99.3%); however, the difference between SA-VMAT and DA-VMAT was not statistically significant.

Pairwise comparisons of target metrics revealed that DA-VMAT provided better target coverage and conformity than SA-VMAT for both PTV68 Gy and PTV45 Gy. Intensity Modulated Radiation Therapy (IMRT) was significantly better than SA-VMAT for these endpoints, whereas differences between Intensity Modulated Radiation Therapy (IMRT) and DA-VMAT were not statistically significant. For the homogeneity index, DA-VMAT demonstrated numerically improved values compared with both techniques, although statistically significant improvements were observed primarily relative to SA-VMAT. The observed numerical improvements in the conformity index (CI) and homogeneity index (HI) suggest that DA-VMAT may provide more conformal and homogeneous dose distributions, particularly when compared with SA-VMAT.

Maximum dose (DMax, %) differed significantly across all pairwise comparisons ($p < 0.05$). DA-VMAT produced the lowest hotspot value (DMax = 103.99%), followed by Intensity Modulated Radiation Therapy (IMRT) (104.55%) and SA-VMAT (105.55%). Efficiency comparisons (MU and BOT) were significant between all technique pairs: Intensity Modulated Radiation Therapy (IMRT) required the highest MU and BOT, SA-VMAT the lowest, and DA-VMAT intermediate values.

Table 2. Target coverage and treatment efficiency metrics for the planning target volume (PTV) among different plan modalities

Parameter	(IMRT)(Mean ± SD)	(SA-VMAT) (Mean ± SD)	(DA-VMAT) (Mean ± SD)	IMRT vs. SA-VMAT vs. DA-VMAT (p)	IMRT vs. SA-VMAT (p)	IMRT vs. DA-VMAT (p)	SA-VMAT vs. DA-VMAT (p)
($D_{95\%}$) PTV68 Gy	99.64 ± 0.61	98.61 ± 1.14	99.89 ± 0.45	< 0.05	< 0.05	> 0.05	< 0.05
($D_{95\%}$) PTV45 Gy	98.79 ± 0.58	98.10 ± 1.16	99.19 ± 0.43	< 0.05	< 0.05	> 0.05	< 0.05
CI (PTV68 Gy)	0.95 ± 0.03	0.92 ± 0.04	0.96 ± 0.01	< 0.05	< 0.05	> 0.05	< 0.05
CI (PTV45 Gy)	0.92 ± 0.05	0.91 ± 0.04	0.95 ± 0.03	> 0.05	> 0.05	< 0.05	< 0.05
HI (PTV68 Gy)	0.075 ± 0.01	0.080 ± 0.02	0.063± 0.03	< 0.05	> 0.05	> 0.05	< 0.05
HI (PTV45 Gy)	0.081 ± 0.01	0.089 ± 0.03	0.071 ± 0.01	< 0.05	> 0.05	> 0.05	< 0.05
D_{Max} (%)	104.55 ± 0.91	105.55 ± 0.51	103.99 ± 0.61	< 0.05	< 0.05	< 0.05	< 0.05
MU	2165.4 ± 222.7	815.9 ± 69.4	1021.6 ± 154.9	< 0.05	< 0.05	< 0.05	< 0.05
BOT (min)	3.99 ± 0.28	1.55 ± 0.11	2.69 ± 0.19	< 0.05	< 0.05	< 0.05	< 0.05
Modulation Factor	7.96 ± 0.15	3.00 ± 0.19	3.76 ± 0.11	< 0.05	< 0.05	< 0.05	< 0.05
Gamma Pass Rate (3 %/2 mm)	97.8 ± 0.9 %	98.9 ± 0.7 %	99.3 ± 0.5 %	< 0.05	< 0.05	< 0.05	> 0.05

D_{Max}: Maximum Point dose D_{Mean}: Mean dose $D_{xx\,(\%)}$: Volume of xx (%) of dose in percentage
$D_{95\,(\%)}$: Percentage of the prescription dose received by 95% of the planning target volume (PTV)
CI: conformity index; HI: Homogeneity index. NS = Not significant ($p > 0.05$); Significant = $p < 0.05$

Table 3. Dose–volume metrics for organs at risk (OARs) according to plan modality

Parameter	(IMRT) (Mean ± SD)	(SA-VMAT) (Mean ± SD)	(DA-VMAT) (Mean ± SD)	p-value	IMRT vs. SA-VMAT (p)	IMRT vs. DA-VMAT (p)	SA-VMAT vs. DA-VMAT (p)
Bowel V_{30gy}(%)	22.20 ± 7.23	22.76 ± 7.89	20.33 ± 6.58	> 0.05	> 0.05	> 0.05	> 0.05
Bladder V_{45gy}(%)	25.18 ± 7.20	24.08 ± 8.91	27.52 ± 8.80	> 0.05	> 0.05	> 0.05	> 0.05
Bladder V_{50gy}(%)	17.27 ± 6.88	16.23 ± 8.25	19.09 ± 8.07	> 0.05	> 0.05	> 0.05	> 0.05
Bladder V_{60gy}(%)	7.93 ± 4.68	6.69 ± 5.42	9.54 ± 5.26	> 0.05	> 0.05	> 0.05	> 0.05
Rectum V_{50gy}(%)	15.84 ± 3.37	16.95 ± 2.76	14.67 ± 1.78	> 0.05	> 0.05	> 0.05	< 0.05
Rectum V_{60gy}(%)	9.67 ± 3.68	13.64 ± 1.45	8.1 ± 4.17	< 0.05	< 0.05	> 0.05	< 0.05
Rectum V_{68gy}(%)	5.71 ±2.61	7.95 ± 1.31	4.99 ±0.35	< 0.05	< 0.05	> 0.05	< 0.05
Femoral Head (LT): Mean Dose (Gy)	17.63 ± 2.75	19.06 ± 2.81	18.71 ± 2.23	>0.05	> 0.05	> 0.05	> 0.05
Femoral Head (RT): Mean Dose (Gy)	17.15 ± 1.61	19.74 ± 3.30	18.27 ± 3.64	< 0.05	< 0.05	> 0.05	> 0.05
External Genitalia: Mean Dose (Gy)	8.62 ± 9.01	9.25 ± 10.04	7.85 ± 7.45	> 0.05	> 0.05	> 0.05	> 0.05
Penile Bulb :Mean Dose (Gy)	37.26 ± 13.24	32.96 ± 14.12	33.23 ± 14.07	> 0.05	> 0.05	> 0.05	> 0.05
Urethra : Dmax (%)	103.03 ± 1.10	104.05 ± 2.64	103.55 ± 0.95	> 0.05	> 0.05	> 0.05	> 0.05

NS = Not significant ($p > 0.05$); Significant = $p < 0.05$.
$V_{xx\,(\%)}$: Volume of xx (%) of dose in percentage
Vx = percentage (%) of organ volume receiving ≥ x (%); Mean dose = average dose in Gy; Dmax = maximum dose, expressed as a percentage (%) of the prescription dose; LT = left; RT = right; SD = standard deviation.

Dose–Volume Parameters for Organs at Risk

Table 3 summarises the dose–volume metrics for the organs at risk (OARs). No significant differences were observed among the techniques for bowel or bladder dose metrics ($p > 0.05$). Rectum V68 was significantly lower with DA-VMAT than with SA-VMAT ($p < 0.05$), indicating improved rectal sparing with dual-arc planning. Mean doses to both femoral heads were slightly higher with VMAT plans than with Intensity Modulated Radiation Therapy (IMRT). No significant differences were observed in the doses to the external genitalia, penile bulb, or urethra ($p > 0.05$).

Specifically, for rectal dose–volume parameters, SA-VMAT resulted in higher V60Gy and V68Gy values than both Intensity Modulated Radiation Therapy (IMRT) and DA-VMAT. Overall, bowel and bladder dose metrics were comparable across all techniques, while Intensity Modulated Radiation Therapy (IMRT) and DA-VMAT demonstrated marginally better sparing of the right femoral head than SA-VMAT.

OAR Dose

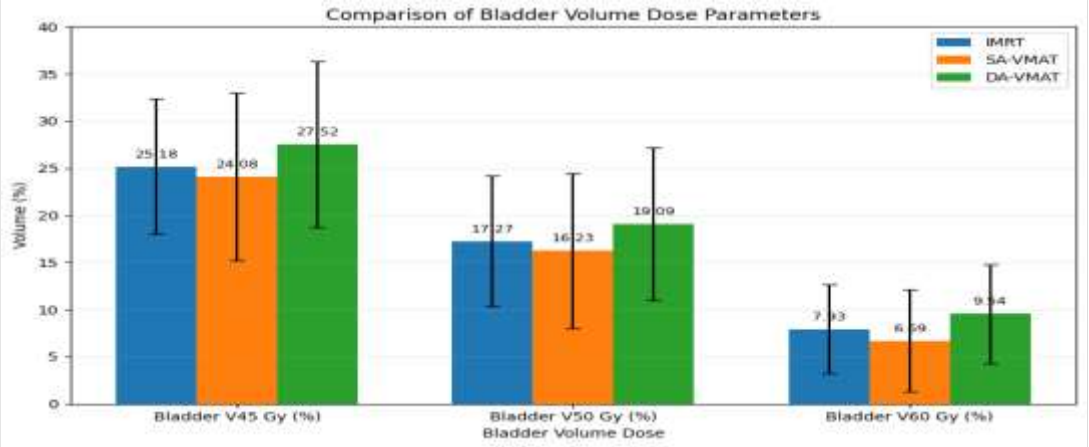


Chart 1. Comparison of bladder dose-volume parameters

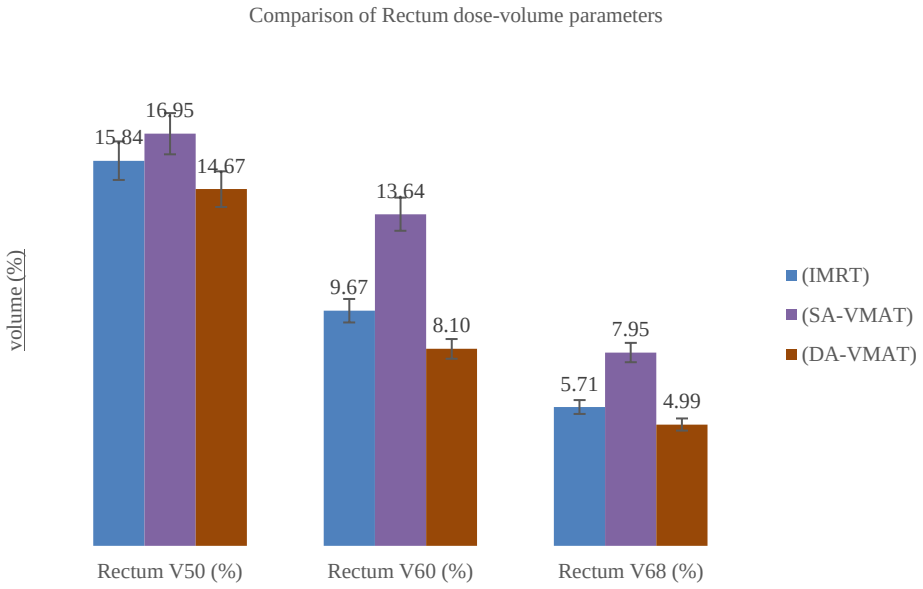


Chart 2. Comparison of Rectum dose-volume parameters

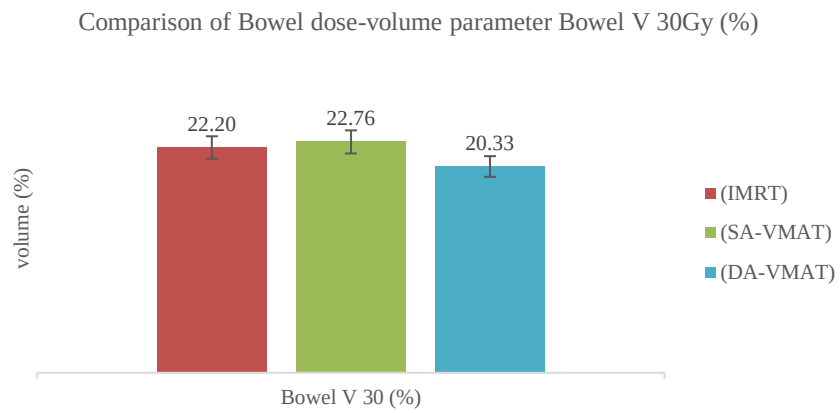


Chart 3 Comparison of Bowel dose-volume parameter

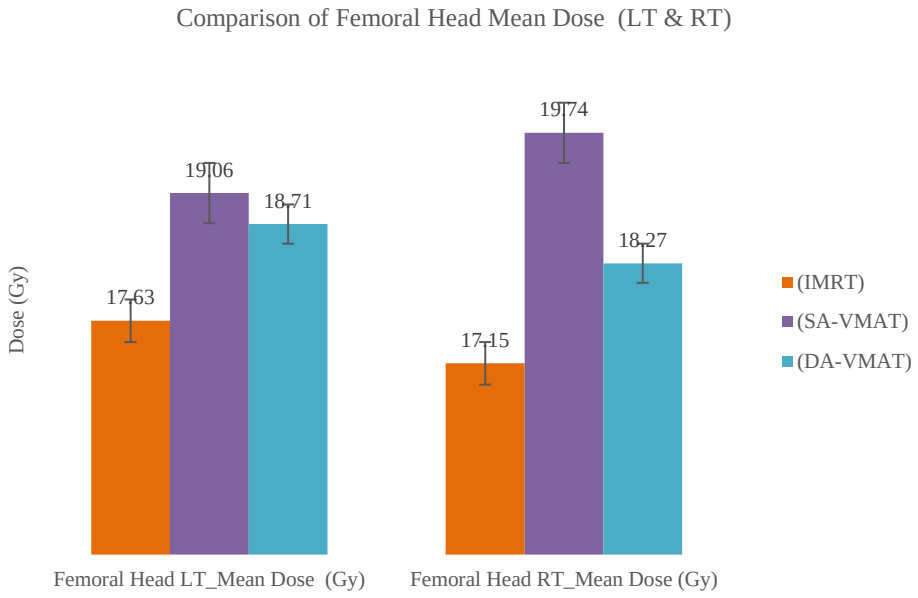


Chart 4 Comparison of Femoral Heads Mean Dose (LT & RT)

Discussion

Target Coverage, Dose Conformity, and OAR Sparing

This study compared the dosimetric performance and treatment efficiency of Intensity Modulated Radiation Therapy (IMRT), SA-VMAT, and DA-VMAT for prostate radiotherapy. DA-VMAT achieved higher numerical target coverage values, with significantly higher $D_{95\%}$ for both PTV68 Gy and PTV45 Gy compared with SA-VMAT, while differences compared with Intensity Modulated Radiation Therapy (IMRT) were not statistically significant. DA-VMAT also demonstrated improved conformity and homogeneity, particularly relative to SA-VMAT. These findings are consistent with previous reports demonstrating the potential advantages of VMAT in optimizing prostate dose distributions [1, 2, 4, 15].

The better conformity index (CI) and homogeneity index (HI) observed with DA-VMAT indicate improved dose conformity and homogeneity, which may contribute to reducing dose heterogeneity within the target volume. [5, 9, 10]. DA-VMAT may be particularly advantageous for patients with complex anatomy, such as those with seminal vesicle involvement or pelvic nodal disease [6, 11].

Treatment Efficiency

Both VMAT techniques substantially reduced monitor units (MUs) and beam-on time (BOT) compared with Intensity Modulated Radiation Therapy (IMRT) ($p < 0.05$), consistent with previous findings that VMAT improves delivery efficiency and may reduce machine wear [4, 13, 15]. Although DA-VMAT required higher MUs and longer BOT than SA-VMAT, reflecting the increased modulation associated with dual-arc delivery, it demonstrated improved dosimetric characteristics, illustrating the trade-off between plan complexity and delivery time [5, 12].

The lower modulation factor (MF) observed in VMAT plans suggests reduced plan complexity and may improve treatment robustness and reproducibility [9, 14]. Both VMAT techniques achieved better gamma pass rates, with DA-VMAT demonstrating the highest numerical value, although the difference between SA-

VMAT and DA-VMAT was not statistically significant [7, 12].

OAR Sparing

Overall, OAR sparing was comparable among the techniques for several dose metrics. Bowel V30, bladder V45–V60, and urethral Dmax showed no significant differences ($p > 0.05$), indicating similar protection across the three modalities [2, 3, 10, 11]. However, differences were observed in the high-dose rectal parameters: SA-VMAT produced significantly higher rectal V60 and V68 values than Intensity Modulated Radiation Therapy (IMRT) and DA-VMAT ($p < 0.05$).

DA-VMAT suggest better rectal high-dose volumes comparable to Intensity Modulated Radiation Therapy (IMRT), likely owing to the enhanced modulation provided by the second arc, consistent with previous reports on dual-arc techniques [5, 12]. Given the established association between high-dose rectal volumes and late rectal toxicity, these differences may be clinically relevant [8]. Both VMAT techniques resulted in slightly higher mean doses to the femoral heads than Intensity Modulated Radiation Therapy (IMRT) ($p < 0.05$); however, all doses remained within commonly accepted tolerance limits [2, 4, 10].

Overall, DA-VMAT demonstrated favorable dosimetric characteristics across several evaluated parameters and provided a balanced combination of plan quality and treatment efficiency in this cohort. It achieved organ-at-risk (OAR) sparing comparable to Intensity Modulated Radiation Therapy (IMRT) while reducing high-dose rectal volumes more effectively than SA-VMAT. However, Intensity Modulated Radiation Therapy (IMRT) may remain preferable when minimizing femoral head dose is the primary consideration, whereas SA-VMAT may be advantageous when shorter treatment times are prioritized, particularly for elderly patients or those unable to tolerate prolonged treatment sessions, despite its comparatively lower rectal sparing.

Study Limitations

The small sample size and single-institution dataset may limit the generalizability of these findings. In addition, all plans were generated using a single treatment planning system and linear accelerator model with institution-specific Optimization objectives.

Recommendations for Future Research

Future studies should include larger, multi-institutional cohorts and evaluate different treatment planning systems and delivery platforms. Prospective clinical studies correlating dosimetric outcomes with toxicity and tumor control are warranted. Further investigation of hybrid or partial-arc techniques and Optimization parameter tuning may help improve the balance between plan quality and delivery efficiency.

Conclusion

This comparative planning study demonstrated that all three planning techniques met the clinical objectives. DA-VMAT achieved improved target coverage, conformity, homogeneity, and organ-at-risk sparing compared with SA-VMAT, while remaining comparable with Intensity Modulated Radiation Therapy (IMRT) for several target coverage parameters. In contrast, SA-VMAT provided shorter beam-on times and simpler delivery, which may be advantageous for elderly patients or those unsuitable for prolonged treatment sessions, as it minimizes treatment duration. Therefore, the choice of technique should consider both clinical complexity and patient tolerance to optimize treatment outcomes.

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