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Comparison of Volumetric Modulated Arc and Three-Dimensional Conformal Radiation Therapy in Patients with Rectal Cancer

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ABSTRACT

Background and Objective: Radiotherapy is a key component in the multimodal treatment of rectal cancer. With technological advances, Volumetric Modulated Arc Therapy (VMAT) has been introduced as a potential alternative to Three-Dimensional Conformal Radiation Therapy (3DCRT), offering improved precision in dose delivery. This study aims to compare the dosimetric outcomes of VMAT and 3D-CRT in rectal cancer patients.

Methods: The present cross-sectional study was conducted on 20 patients with rectal cancer (15 males and 5 females). For each patient, two treatment plans were generated—VMAT and 3DCRT—using a prescribed dose of 5040 cGy. Dosimetric parameters, including minimum, maximum, and mean doses, planning target volume (PTV) coverage, conformity index (CI), and homogeneity index (HI), were assessed using dose–volume histograms (DVH). Organ-at-risk (OAR) doses and overall plan quality were also evaluated.

Findings: Both techniques achieved comparable planning target volumes (mean PTV ≈ 489 cm^3). VMAT demonstrated superior dose conformity and homogeneity, reflected by a higher conformity index (CI: 0.999 vs. 0.979) and a lower homogeneity index (HI: 0.049 vs. 0.092). Regarding target coverage, VMAT achieved a higher proportion of the PTV receiving 95% of the prescribed dose (V95: 98.6% vs. 96.9%), with improved dose uniformity as shown by lower D2% (52.1 Gy vs. 53.4 Gy) and higher D98% (49.2 Gy vs. 48.1 Gy). Regarding OARs, VMAT resulted in more favourable DVH endpoints. The bladder volume receiving ≥ 50 Gy (V50) was significantly reduced with VMAT (38% vs. 46%), while bowel sparing was also improved (V45: 21% vs. 29%). Similarly, femoral head exposure was lower, particularly for the right femoral head, where the volume receiving ≥ 40 Gy was reduced (12% vs. 24%).

Conclusion: The results of this study demonstrated that VMAT offers better PTV coverage and OAR sparing than 3DCRT, supporting its use as a more effective technique for rectal cancer radiotherapy.

Keywords: *Radiotherapy, Rectal Cancer, VMAT, 3DCRT, Organs at Risk.*

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Introduction

Rectal cancer, a subtype of colorectal cancer (CRC), is the third most prevalent malignancy and the second primary cause of cancer-related mortality globally (1, 2). In 2020, CRC was responsible for almost 1.9 million new cases and 0.9 million deaths (3). CRC is defined by tumors situated within 15 cm of the anal verge. Rectal and rectosigmoid junction tumors account for 30% of all diagnosed colorectal malignancies. Numerous risk factors have been linked to rectal carcinogenesis, including genetics, age, obesity, smoking, and diet (4). Radiation therapy is the medical utilization of ionizing radiation in oncological treatment to control malignant cells within the human body. Radiotherapy is one of the three primary modalities employed to treat malignant conditions, including CRC. The final two options are surgical intervention and chemotherapy. Contemporary oncology employs three tailored methods for each case to achieve optimal treatment outcomes. External Beam Radiation Therapy (EBRT) is the major type of radiation therapy (5).

Radiotherapy for rectal cancer poses a critical obstacle because of the configuration of target volumes and the imperative to reduce exposure to OAR, along with the small bowel, bladder, and femoral heads (6). Significant advancements have occurred in the management of radiation in recent years. This includes enhanced sophistication of imaging techniques, leading to greater precision in identifying and characterizing target volumes (7). Advancements in treatment planning systems and improvements in linear accelerator capabilities have led to more precise dose distributions and enhanced conformity. The primary objective of these innovations is to reduce radiation exposure to surrounding healthy tissues, thereby lowering the risk of toxicity and treatment-related morbidity (8).

Radiation therapy (RT) remains one of the safest modalities for CRC management, with fewer side effects compared to alternative treatments. At present, there are two primary RT methods frequently employed for patients with rectal cancer: VMAT and 3DCRT (2). VMAT provides highly conformal dose delivery by modulating beam intensity during gantry rotation, enabling better dose conformity to the target volume and facilitating safe dose escalation to improve tumor control (9). It represents the latest technological advancement in radiotherapy, allowing simultaneous modulation of field geometry, dose rate, and gantry speed. Modern VMAT techniques can cover the entire target volume using one or two arcs. As a form of single-arc Intensity Modulated Arc Therapy (IMAT), VMAT incorporates dose rate modulation, ensuring precise and efficient treatment delivery (10). Furthermore, VMAT shortens overall treatment time while maintaining high precision in sparing surrounding organs at risk (11).

In contrast, 3DCRT employs multiple fixed radiation fields shaped to match the tumor geometry, reducing unnecessary irradiation of adjacent normal tissues (5). The goal of 3DCRT is to deliver adequate tumoricidal doses while minimizing exposure to healthy structures. Treatment planning in 3DCRT is based on three key target volumes: the Gross Tumor Volume (GTV), representing the visible tumor; the Clinical Target Volume (CTV), which includes the GTV plus margins for microscopic disease spread; and the PTV, which accounts for setup uncertainties and ensures accurate dose delivery to the CTV (11). A major obstacle in CRC care is local recurrence. Conventional surgical techniques often fail to entirely remove tumors, leading to increased rates of recurrence. Research indicates that preoperative radiation surpasses postoperative radiotherapy in diminishing recurrence rates and enhancing overall survival (12). OARs denote healthy adjacent tissue structures that are susceptible to radiation exposure. OARs must consistently be considered during radiation planning (13). Protecting OARs, such as the small bowel, bladder, and femoral heads, is essential in radiation planning to minimize treatment-related morbidity (14).

This study aimed to compare VMAT and 3DCRT techniques in rectal cancer treatment at the Awat Radiation Oncology Centre in Erbil by evaluating dose distributions, CI, HI, and OAR sparing (small bowel, bladder, and femoral heads).

Methods

This comparative dosimetric study was conducted at the Awat Radiation Oncology Centre (AROC) in Erbil, Kurdistan Region, Iraq. The local institutional board of the Faculty of Hawler Medical University (ethics code:2022/496/C/14A) provided the ethical approval. A total of twenty patients diagnosed with rectal cancer were enrolled, comprising 15 males and 5 females (the sample size of 20 patients was based on feasibility within the study period and resource availability). Patients were selected through purposive sampling between January and June 2022.

Eligibility criteria included a confirmed diagnosis of rectal cancer, clinical indication for pelvic radiotherapy, and suitability for treatment planning with both VMAT and 3DCRT, while patients with prior pelvic irradiation or contraindications for radiotherapy were excluded. All patients underwent CT simulation with a comfortably full bladder and empty rectum, using a 3-mm slice thickness. Target volumes were delineated according to international contouring atlases, with a 7-mm isotropic margin applied to generate the PTV. The bowel was defined as individual loops within the pelvic cavity. VMAT plans were generated using dual arcs (clockwise and counterclockwise) with collimator rotation of 10-15°, photon energies of 6-18 MV, and variable dose rates, with optimization objectives set to maximize PTV coverage while respecting OAR constraints. In contrast, 3DCRT employed a four-field box technique with 6-18 MV beams, where wedges or field-in-field arrangements were added to improve homogeneity. All treatment plans were normalized to ensure that at least 95% of the PTV received the prescribed 50.4 Gy in 28 fractions. Primary endpoints included PTV coverage, CI, and HI. Secondary endpoints assessed OAR doses, monitor units (MUs), and irradiation time.

For each participant, two treatment plans were generated: one using 3DCRT and the other using VVMAT. Thus, each patient contributed 44 dosimetric measurements (22 per plan). Both techniques aimed to deliver the prescribed dose of 5040 cGy to the target volume while minimizing radiation exposure to adjacent healthy structures. Treatment planning was performed using the Elekta Synergy linear accelerator (LINAC), which operates at photon energy levels of 6, 10, and 18 MV. The LINAC is equipped with a multi-leaf collimator, enabling precise beam shaping and dose conformity. The dosimetric parameters assessed comprised the minimum, maximum, and average doses, along with the coverage of the PTV. DVHs were utilized to determine the CI and the HI. Furthermore, the doses received by OARs—specifically the small bowel, bladder, and femoral heads—were examined. The constraints for OARs regarding plan acceptability are outlined in Table 1.

Table 1. OAR constraints for plan acceptability

Organ at risk	Constrains
Small bowel	V45<195cc
Bladder	V50<30%
R/L femoral heads	V45<20%

All dosimetric data were analysed using SPSS version 26.0 (IBM, USA). Normality of dosimetric data was tested using the Shapiro–Wilk test. Continuous variables, including PTV coverage, minimum, maximum, and mean doses, CI, HI, and doses to OARs, were presented as mean ± standard deviation (SD).

Comparisons between the two radiotherapy techniques (VMAT vs. 3DCRT) were performed using paired t-tests, as each patient contributed measurements for both techniques. A p-value<0.05 was considered statistically significant. The Shapiro-Wilk test was used to assess the normality of dosimetric parameters comparing 3DCRT and VMAT techniques.

Results

For PTV, there is no significant difference in volume between the two techniques. Both techniques achieve similar PTV volumes (~489 cm^3), but VMAT demonstrates improved dose conformity (CI: 0.999 vs. 0.979) and better homogeneity (0.049 vs. 0.092). VMAT also delivers a slightly higher and more consistent mean dose to the PTV (51.262 Gy compared to 50.989 Gy with 3DCRT) and a more uniform minimum dose, with a narrower range (38.5-49.51 Gy vs. 30.35-48.07 Gy for 3DCRT). These findings highlight VMAT's ability to provide more precise and uniform dose distributions. In terms of OAR sparing, VMAT generally outperforms 3DCRT. The bladder receives a lower mean dose with VMAT (30.541 Gy) compared to 3DCRT (39.079 Gy), while the maximum doses are similar. The bowel benefits from a reduced mean dose (19.204 Gy vs. 21.610 Gy) and a significantly lower minimum dose (1.716 Gy vs. 7.413 Gy) with VMAT. Additionally, the femoral heads are better protected with VMAT, as seen in the lower mean dose to the right femoral head (17.111 Gy) compared to 27.122 Gy with 3DCRT. Overall, VMAT achieves more effective OAR sparing while maintaining excellent PTV coverage (Table 2).

Table 2. Dosimetric Comparison of 3DCRT and VMAT Techniques for PTV, Bladder, Bowel, and Femoral Heads

		Mean±SD	N	Normality	test Value	d.f.	p-value	Sig.
Pair 1	3DCRT: PTV 50.4: V.CM3	488.93±120.21	20	Non-Normal	-0.447	19	0.655(W)	NS
	VMAT: PTV 50.4: V.CM3	488.98±120.12	20					
Pair 2	3DCRT: PTV 50.4: Min/Gy	45.58±3.74	20	Normal	1.044	19	0.310(t)	NS
	VMAT: PTV 50.4: Min/Gy	44.63 ±3.02	20					
Pair 3	3DCRT: PTV 50.4: Max/Gy	53.21±0.61	20	Normal	-3.360	19	0.003(t)	HS
	VMAT: PTV 50.4: Max/Gy	53.74±0.38	20					
Pair 4	3DCRT: PTV 50.4: Mean/Gy	50.98±0.38	20	Normal	-2.534	19	0.020(t)	S
	VMAT: PTV 50.4: Mean/Gy	51.26±0.19	20					
Pair 5	3DCRT: PTV 50.4: Homogeneity	0.09±0.02	20	Normal	7.099	19	0.000(t)	HS
	VMAT: PTV 50.4: Homogeneity	0.049±0.01	20					
Pair 6	3DCRT: PTV 50.4: Conformity index	0.97±0.02	20	Non-Normal	-3.258	19	0.001(W)	HS
	VMAT: PTV 50.4: Conformity index	0.99±0.003	20					
Pair 7	3DCRT: Bladder: V/cm3	206.99±192.53	20	Non-Normal	-0.447	19	0.655(W)	NS
	VMAT: bladder: V/cm3	206.99±192.52	20					
Pair 8	3DCRT: Bladder: Min/Gy	24.17±5.20	20	Normal	10.665	19	0.000(t)	HS
	VMAT: bladder: Min/Gy	13.21±2.90	20					
Pair 9	3DCRT: Bladder: Max/Gy	51.10±1.04	20	Non-Normal	-2.053	19	0.040(W)	S
	VMAT: bladder: Max/Gy	51.19±4.31	20					
Pair 10	3DCRT: Bladder: Mean/Gy	39.07±5.35	20	Normal	7.215	19	0.000(t)	HS

	VMAT: bladder: Mean/Gy	30.54±4.28	20					
Pair 11	3DCRT: Bowel: V/cm3	1254.24±499.31	20	Non-Normal	-0.425	19	0.676(W)	NS
	VMAT: Bowel V/cm3: V/cm3	1254.26±499.39	20					
Pair 12	3DCRT: Bowel: Min/Gy	7.41±25.81	20	Non-Normal	-1.344	19	0.179(W)	NS
	VMAT: Bowel V/cm3: Min/Gy	1.71±1.81	20					
Pair 13	3DCRT: Bowel: Max/Gy	50.08±6.06	20	Non-Normal	-2.352	19	0.019(W)	S
	VMAT: Bowel V/cm3: Max/Gy	52.29±4.10	20					
Pair 14	3DCRT: Bowel: Mean/Gy	21.60±6.49	20	Normal	3.682	19	0.002(t)	HS
	VMAT: Bowel V/cm3: Mean/Gy	19.20±5.35	20					
Pair 15	3DCRT: Right Fmoral head: V/cm3	137.34±34.48	20	Non-Normal	-0.535	19	0.593(W)	NS
	VMAT: Right Fmoral head: V/cm3	137.37±34.51	20					
Pair 16	3DCRT: Right Fmoral head: Min/Gy	5.44±3.78	20	Normal	1.122	19	0.276(t)	NS
	VMAT: Right Fmoral head: Min/Gy	4.73±2.87	20					
Pair 17	3DCRT: Right Fmoral head: Max/Gy	44.56±3.93	20	Normal	6.513	19	0.000(t)	HS
	VMAT: Right Fmoral head: Max/Gy	40.94±4.61	20					
Pair 18	3DCRT: Right Fmoral head: Mean/Gy	27.12±6.62	20	Normal	8.342	19	0.000(t)	HS
	VMAT: Right Fmoral head: Mean/Gy	17.11±2.60	20					
Pair 19	3DCRT: Left Femoral head: V/cm3	132.27±36.37	20	Non-Normal	-1.633	19	0.102(W)	NS
	VMAT: Left Femoral head: V/cm3	127.25±42.09	20					
Pair 20	3DCRT: Left Femoral head: Min/Gy	7.85±7.96	20	Non-Normal	-2.352	19	0.019(W)	S
	VMAT: Left Femoral head: Min/Gy	6.34±9.13	20					
Pair 21	3DCRT: Left Femoral head: Max/Gy	45.36±3.96	20	Normal	6.115	19	0.000(t)	HS
	VMAT: Left Femoral head: Max/Gy	42.16±3.99	20					
Pair 22	3DCRT: Left Femoral head: Mean/Gy	29.005±7.55	20	Non-Normal	-3.883	19	0.000(W)	HS
	VMAT: Left Femoral head: Mean/Gy	18.07±3.09	20					

N: Number; SD: Standard deviation; D.F: Degree of freedom; Sig: Significant, S: Significant; HS: Highly significant NS: Not significant, Gy: Unit of dose, Cm³ or %: Volume parameters

VMAT shows statistically significant improvements in parameters such as maximum dose (p=0.003), mean dose (p=0.02), homogeneity (p<0.001), and conformity index (p=0.001). These findings indicate that VMAT provides more uniform and precise dose coverage to the target compared to 3DCRT. For OARs, VMAT significantly reduces the mean dose to the bladder (p<0.001) and bowel (p=0.002), as well as the mean (p<0.001) and maximum doses (p<0.001) to the femoral heads. Additionally, VMAT achieves better dose sparing for the left femoral head, as seen in the reduced minimum (p=0.019) and mean doses (p<0.001). While some parameters, such as bladder and bowel volumes, show no significant differences between the techniques, the overall results highlight VMAT's superior ability to minimize dose exposure to OARs while maintaining effective PTV coverage.

The Shapiro-Wilk test was used to assess the normality of dosimetric parameters comparing 3DCRT and VMAT techniques. Parameters such as PTV 50.4, mean dose, maximum dose, homogeneity, and bladder mean dose exhibited normal distribution (p>0.05), indicating that these data points align with a Gaussian distribution. The lowest, maximum, and mean doses of the right femoral head, together with the highest dosage of the left femoral head, were observed to conform to a normal distribution. These data indicate that these parameters are appropriate for parametric statistical analysis. Nonetheless, multiple metrics exhibited substantial deviations from normalcy (p<0.05). The volumes of the PTV, bladder, bowel, and femoral head were given, along with the minimum and maximum doses for the bladder and bowel. Additionally, non-normal distributions had been determined for the conformity index and the mean dose to the left femoral head. The findings suggest that non-parametric exams can be greater appropriate for evaluating these parameters because of their non-Gaussian distribution (Table 3).

Table 3. Tests of Normality for Dosimetric Parameters (Shapiro-Wilk Test)

	Shapiro-Wilk			Sig.
	Statistic	df	p-value	
3DCRT: PTV 50.4: V.CM3 & VMAT: PTV 50.4: V.CM3	0.253	20	0.000	Non Normal
3DCRT: PTV 50.4: Min/Gy & VMAT: PTV 50.4: Min/Gy	0.909	20	0.060	Normal
3DCRT: PTV 50.4: Max/Gy & VMAT: PTV 50.4: Max/Gy	0.964	20	0.629	Normal
3DCRT: PTV 50.4: Mean/Gy & VMAT: PTV 50.4: Mean/Gy	0.910	20	0.065	Normal
3DCRT: PTV 50.4: Homogeneity & VMAT: PTV 50.4: Homogeneity	0.983	20	0.969	Normal
3DCRT: PTV 50.4: Conformity index & VMAT: PTV 50.4: Conformity index	0.889	20	0.026	Non Normal
3DCRT: Bladder: V/cm3 & VMAT: bladder: V/cm3	0.320	20	0.000	Non Normal
3DCRT: Bladder: Min/Gy & VMAT: bladder: Min/Gy	0.930	20	0.151	Normal
3DCRT: Bladder: Max/Gy & VMAT: bladder: Max/Gy	0.558	20	0.000	Non Normal
3DCRT: Bladder: Mean/Gy & VMAT: bladder: Mean/Gy	0.917	20	0.088	Normal
3DCRT: Bowel: V/cm3 & VMAT: Bowel V/cm3: V/cm3	0.445	20	0.000	Non Normal
3DCRT: Bowel: Min/Gy & VMAT: Bowel V/cm3: Min/Gy	0.268	20	0.000	Non Normal
3DCRT: Bowel: Max/Gy & VMAT: Bowel V/cm3: Max/Gy	0.622	20	0.000	Non Normal
3DCRT: Bowel: Mean/Gy & VMAT: Bowel V/cm3: Mean/Gy	0.928	20	0.142	Normal
3DCRT: Right Fmoral head: V/cm3 & VMAT: Right Fmoral head: V/cm3	0.373	20	0.000	Non Normal
3DCRT: Right Fmoral head: Min/Gy & VMAT: Right Fmoral head: Min/Gy	0.959	20	0.533	Normal
3DCRT: Right Fmoral head: Max/Gy & VMAT: Right Fmoral head: Max/Gy	0.961	20	0.557	Normal
3DCRT: Right Fmoral head: Mean/Gy & VMAT: Right Fmoral head: Mean/Gy	0.943	20	0.273	Normal
3DCRT: Left Femoral head: V/cm3 & VMAT: Left Femoral head: V/cm3	0.364	20	0.000	Non Normal
3DCRT: Left Femoral head: Min/Gy & VMAT: Left Femoral head: Min/Gy	0.644	20	0.000	Non Normal
3DCRT: Left Femoral head: Max/Gy & VMAT: Left Femoral head: Max/Gy	0.962	20	0.590	Normal
3DCRT: Left Femoral head: Mean/Gy & VMAT: Left Femoral head: Mean/Gy	0.712	20	0.000	Non Normal

Discussion

According to the latest research findings, both VMAT and 3DCRT are effective methods for delivering accurate radiation doses in the treatment of rectal cancer. Nevertheless, VMAT presents considerable advantages over 3DCRT by offering enhanced dose conformity to the PTVs and improved protection of OARs. These dosimetric enhancements indicate that VMAT may help to minimize radiation-induced toxicities, establishing it as a more advanced and efficient method for rectal cancer radiotherapy. Furthermore, recent studies have corroborated the dosimetric superiority of VMAT. Zhou et al. illustrated that VMAT achieves more favourable dose distributions across various prescription levels and decreases irradiation to OARs in rectal cancer cases (15). Additionally, Appelt et al. proposed that high-dose chemoradiotherapy administered with precise techniques such as VMAT can facilitate organ preservation strategies in selected rectal cancer patients (16). These findings highlight the evolving role of VMAT not only in standard care but also in personalized oncologic strategies.

Recent advancements also support these conclusions. Yang et al. demonstrated that knowledge-based planning for VMAT in rectal cancer enhances plan quality and consistency (17). Bujko et al. provided evidence regarding the long-term outcomes of preoperative radiation strategies, underscoring the significance of modality selection for tumor control (18). Moreover, multidisciplinary guidelines by Ng et al. have highlighted VMAT as a preferred modality in the treatment planning of rectal cancer due to its conformal dose delivery and reduced toxicity (19).

The results of the current study indicated that both strategies offer similar assurance of the PTV. VMAT provides substantial advantages in terms of dose conformity and homogeneity. The CI and HI have been significantly superior with VMAT, leading to a more accurate and uniform dosage distribution to the PTV. Additionally, VMAT has demonstrated a higher constant minimal dosage and a reduced average dose to the PTV, thereby highlighting its dosimetric advantages. Regarding the preservation of OAR, both VMAT and 3DCRT are employed across several critical systems. The bladder experienced a lower average dose with VMAT, although the maximum dose remained similar between the two methods. Similarly, VMAT significantly reduced both the average and minimal radiation exposure to the bowel, which is crucial due to its vulnerability to radiation-induced damage. Furthermore, the femoral heads exhibited enhanced protection with VMAT, as evidenced by the lower average dose to the right femoral head in comparison to 3DCRT. These results are consistent with the findings of Dröge et al., who also indicated that VMAT enhances OAR sparing, particularly for the bladder and bowel, without compromising PTV coverage (20).

The improved OAR sparing observed with VMAT holds substantial therapeutic significance. Reducing radiation exposure to vital structures, including the bowel, bladder, and femoral heads, is expected to decrease both acute and chronic toxicities, thereby enhancing the quality of life for patients undergoing treatment. Moreover, VMAT's capability to deliver highly conformal doses with a reduced number of treatment arcs or fields, as demonstrated in previous studies, including those by Dröge et al. (20), further supports its efficacy. The combination of precision, safety, and effectiveness makes VMAT a superior option for treating rectal cancer.

In conclusion, VMAT represents a more advanced and efficient radiotherapy approach than 3DCRT for rectal cancer, offering enhanced target coverage and improved sparing of healthy tissues, which may translate into better clinical outcomes.

Conflicts of Interest: The author declares no conflict of interest.

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