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A Comparative Dosimetric Analysis of VMAT and Multi-Beam 3D-CRT in Locally Advanced Lung Cancer Radiotherapy

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ABSTRACT

Background and Objective: Volumetric modulated arc therapy (VMAT) offers excellent dose conformity and organ-at-risk (OAR) sparing but requires advanced equipment, limiting its accessibility in many settings. In contrast, three-dimensional conformal radiation therapy (3D-CRT) remains widely used, especially in resource-limited regions. The objective of the present study was to perform a comparative dosimetric analysis of VMAT and 3D-CRT techniques in the radiotherapy of locally advanced lung cancer, with the aim of evaluating whether a six-beam 3D-CRT approach could represent a viable alternative to VMAT in this clinical setting.

Methods: In this cross-sectional study, fifteen patients with stage III non-small cell lung cancer who had previously received VMAT treatment were selected and replanned using a six-field coplanar 3D-CRT technique on the Monaco planning system. Dosimetric comparisons included target coverage (minimum dose [Dmin], maximum dose [Dmax], D2%, D95%, D98%, mean dose), homogeneity index (HI), and conformity index (CI). The assessed OARs were the lungs, heart, esophagus, and spinal cord.

Findings: VMAT provided significantly better target coverage, homogeneity ($p=0.001$), and conformity ($p=0.001$) compared to 3D-CRT. Dmin to the target was significantly higher in VMAT plans (58.3±2.4 Gy) compared to 3D-CRT (54.1±3.1 Gy), indicating improved coverage of the low-dose regions within the target volume ($p=0.035$). Dmax was comparable between VMAT (68.9±4.5 Gy) and 3D-CRT (69.5±5.0 Gy), with no significant difference was observed. It also achieved superior sparing for heart V30 ($p=0.014$), esophageal V50 ($p=0.016$), and lung V20/V30 ($p<0.05$) compared to 3D-CRT. No significant differences were observed for lung V5/V10, mean heart dose, or maximum esophageal and spinal cord doses.

Conclusion: Based on the findings of the present study, while VMAT demonstrated superior dosimetric performance, optimized six-beam 3D-CRT produced clinically acceptable plans. It remains a practical alternative in settings with limited access to advanced technologies or where VMAT implementation is not feasible.

Keywords: *Advanced Equipment, Lung Cancer, Monaco Planning System, Radiotherapy, Target Coverage.*

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Introduction

Locally advanced lung cancer is one of the most common diseases broadly treated with radiotherapy, both in the postoperative setting and as a sole treatment option when the disease is inoperable (1). Multiple dose and fractionation options range from conventionally fractionated 50-66 Gy to hypofractionated 45 Gy in 15 daily fractions and hyperfractionated twice-daily protocols, with the latter reserved for small cell lung cancer (1, 2). Given the radiosensitivity of lung tissue, the prescribed dose, and the abundance of surrounding radiosensitive organs, there has always been considerable concern regarding the morbidities associated with this treatment (3, 4). The field has undergone continuous refinement and advancement alongside the evolution of radiation therapy techniques. A major turning point came with the introduction of inverse planning methods, such as intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT). These techniques utilize complex computer algorithms and segmentation protocols to achieve highly uniform dose distribution across the target volume while minimizing radiation exposure to surrounding organs at risk. Moreover, they can produce a highly conformal dose line that can prevent dose leaks outside the target volume to a great extent (5). All these are believed to result in better treatment outcomes and improved overall survival, with at least a comparable toxicity profile to 3DCRT, even in very locally advanced disease (6).

On the other hand, the 3D conformal radiation therapy (3DCRT) technique, which was once considered the gold standard in lung cancer radiotherapy and preceded the more advanced methods, is now used less frequently due to its limited capacity to provide a uniform dose to the target and to adequately spare surrounding organs at risk (7). This is due to minimal beam modulation ability, confinement of 3 or 4 treatment fields that each carry a substantial dose passing through the normal lung tissue and at-risk organs. This issue becomes particularly significant when treating larger volumes, such as cases requiring extensive lymphatic coverage. However, 3DCRT remains a practical and viable option in high-volume centers with limited equipment and staffing—common in many developing countries—due to its shorter overall treatment time, reduced need for strict patient immobilization, and lower demand on radiation machines. It is also advantageous in situations where prolonged treatment sessions may compromise accurate positioning, such as with uncooperative patients or those with poor performance status (8, 9). Moreover, clinical data suggest a low real-world toxicity rate associated with 3DCRT, which makes it still a viable treatment option for most locally advanced lung cancer cases (10).

In this study, we aim to determine whether a well-planned multiple coplanar beam 3DCRT can serve as a surrogate for a VMAT plan in terms of target coverage and protection of organs at risk.

Methods

The study was conducted at the Awat Radiation Oncology Center in Erbil, Iraq. The local institutional board of the Faculty of Hawler Medical University provided ethical approval (ethics code: 2022/496/A/12C). Written informed consent was obtained in Arabic or Kurdish, according to the patients' choice. The aim and details of the study were explained to the participants, and they had the freedom to withdraw from the study at any time they wished. In this dosimetric research, fifteen locally advanced lung cancer cases were randomly selected through simple random sampling (all tumors in the same location). The cases had been previously planned and approved for treatment using the VMAT technique. All cases underwent CT simulation in the supine position, with patients fixed on lung boards and their hands raised above their heads, secured by grasping the T-bar (each patient was planned with both techniques).

A retrospective sampling method was employed. The study included patients who had previously received volumetric modulated arc therapy (VMAT) for stage III non-small cell lung cancer (NSCLC). For each patient, a comparative three-dimensional conformal radiotherapy (3DCRT) plan was retrospectively generated using a six-beam multibeam technique applied to the same planning CT scans. This approach enabled a direct dosimetric comparison between the two treatment techniques.

Inclusion and exclusion criteria: Patients were included in the study if they met all of the following criteria: a histologically confirmed diagnosis of stage III non-small cell lung cancer (NSCLC); age of 18 years or older at the time of treatment; receipt of definitive thoracic radiotherapy using volumetric modulated arc therapy (VMAT); successful generation of a valid comparative 3D conformal radiotherapy (3DCRT) plan using a multibeam technique, based on the same CT dataset and identical target and organ-at-risk (OAR) delineations; and availability of complete planning and dosimetric data for both VMAT and 3DCRT plans. Patients were excluded if they presented with a histologic diagnosis other than NSCLC; had stage I, II, or IV disease; had previously undergone thoracic radiotherapy; were under 18 years of age; had incomplete or missing dosimetric data that prevented a valid comparison; or if a valid 3DCRT plan could not be generated using the same target and OAR contours.

Study parameters: The aim of this study was to evaluate and compare dosimetric parameters related to target coverage and organ-at-risk (OAR) sparing between volumetric modulated arc therapy (VMAT) and three-dimensional conformal radiotherapy (3DCRT). Target volume dose parameters analyzed included minimum dose (Dmin), maximum dose (Dmax), near-maximum dose (D2%), near-minimum dose (D95%), median dose (D50%), mean dose, as well as the homogeneity index (HI) and conformity index (CI). For OARs, the following dose metrics were assessed: for the heart, V30 and mean dose; for the esophagus, mean dose, V50, and Dmax; for the ipsilateral, contralateral, and total lungs, V5, V10, V20, V30, and mean dose; and the spinal cord, maximum dose. Dosimetric parameters were extracted from each radiotherapy plan using the treatment planning system, with dose–volume histogram (DVH) analysis conducted in accordance with standard radiotherapy guidelines such as those outlined in ICRU reports.

Native CT images were acquired under free breathing using a slow CT technique to approximate maximum intensity projection (MIP) images. This approach was intended to help compensate for organ motion variability, as breath-hold or four-dimensional CT (4DCT) was not available at the study center (11). All contouring and planning procedures for both VMAT and 3DCRT were performed on the Monaco treatment planning system (Elekta®, France). All 3DCRT plans were generated using forward planning with six fixed beams shaped by multileaf collimators (MLCs). A photon energy of 6 MV was used for both techniques. Identical target coverage objectives and organ-at-risk (OAR) dose constraints were applied to both modalities to ensure a valid dosimetric comparison. The OARs and target volumes contoured for the VMAT plan were used unchanged for the 3DCRT plans and included the PTV60, ipsilateral lung, contralateral lung, total lung minus gross tumor volume (GTV), heart, esophagus, and spinal cord. Additionally, MLC blocks were employed to improve the quality of the 3DCRT plans.

The 3DCRT plan was generated using six coplanar conformal beams with 6-MV photon energy and in-beam segments to control hot spots. At least 95% of the target volume was required to be covered by 98% of the prescribed dose. The organ-specific dose constraint limits used are summarized in Table 1. To better characterize the treatment plan, each lung was analyzed separately across the different dose levels, in addition to the total lung. In addition, other target-related metrics reflecting plan quality, including conformity index (CI), homogeneity index (HI), minimum dose (Dmin), maximum dose (Dmax), dose levels (D2%, D50%, and D98%), and mean target dose (Dmean), were compared between the two techniques (11). All plans were reviewed by a medical physicist.

Table 1. Organ-at-risk (OAR) dose constraint limits

Organ	Constraints
Heart	V30< 45%
	Mean dose< 26Gy
Esophagus	Mean dose< 34Gy
	V50< 40%
	Dmax< 70Gy
Total lung	Mean dose<2 0Gy
	V5< 60%
	V10< 45%
	V20< 35%
	V30< 20%
Spinal cord	Max dose*

Data were analyzed using IBM's Statistical Package for the Social Sciences (SPSS) for Windows, version 27.0. Statistical analyses were performed using both parametric (paired t-tests) and non-parametric (Wilcoxon signed-rank test) methods, depending on the data distribution. A p-value of less than 0.05 was considered statistically significant. Additional metrics, including Z-scores, t-values, and 95% confidence intervals, were reported to quantify differences between the VMAT and 3DCRT techniques.

Results

Dosimetric differences between six-beam 3D conformal radiotherapy (3DCRT) and volumetric modulated arc therapy (VMAT) were demonstrated in the present comparison, encompassing variations in dose distribution and organ-at-risk (OAR) sparing. The statistical results comparing both techniques are listed in Table 2.

Table 2. Comparison of dosimetric results between 3D conformal radiotherapy (3DCRT) and volumetric modulated arc therapy (VMAT) in patients with lung cancer in Erbil

	Parameters	95% Confidence Interval of the Difference (Upper/Lower)		Z	t	Sig. (2-tailed)
Target Volume	Dmin	-524.17	-22.32		-2.321	0.035
	Dmax	-95.91	63.03		-0.441	0.666
	D%2	42.15	191.47		3.335	0.005
	Mean dose*			-.569b		0.569
	D%95*			-3.467c		0.001
	D%50*			-.879b		0.379
	HI*			-3.413b		0.001
	CI*			-3.362c		0.001
Heart	V30	1.96	14.85		2.783	0.014
	Mean dose			-.827b		0.408
Esophagus	Mean dose	-0.06	3.51		2.05	0.058
	V50	1.51	12.7		2.706	0.016
	Dmax*			-1.215c		0.224

	Mean*			-1.551b		0.121
	V5*			-2.741b		0.006
Ipsilateral lung	V10	0.71	5.14		2.82	0.013
	V20	0.8	7.43		2.648	0.018
	V30	1.12	9.92		2.678	0.017
	V5	-10.92	0.64		-1.893	0.078
	V10	-5.19	10.82		0.749	0.466
Contralateral lung	V20	3.89	15.21		3.596	0.003
	V30*			-2.982b		0.003
	Mean*			-1.676b		0.094
	Mean dose	0.79	3.69		3.3	0.005
	V5	-4.29	4.53		0.057	0.955
Total lung	V10	-2.48	7.69		1.092	0.292
	V20	3.42	11.3		3.975	0.001
	V30	1.99	8.8		3.381	0.004
Spinal cord	Max dose*			-1.676b		0.094

Paired Samples Tests for both parametric and non-parametric variables (*denotes non-parametric test). HI: Homogeneity index, CI: Conformity index

Target Dose Parameters: VMAT plans demonstrated improved dose homogeneity for target coverage. The minimum dose (Dmin) to the target was significantly higher with VMAT than with 3DCRT (p=0.035), indicating better coverage of low-dose regions within the target volume. No clinically significant difference in Dmax was observed between the two techniques (p=0.666), suggesting equivalent control of dose hotspots. Furthermore, the near-maximum dose (D2%) was significantly lower with VMAT (p=0.005; Table 2).

Non-parametric analysis further validated the dosimetric benefits of VMAT in terms of dose conformity and homogeneity. VMAT plans yielded significantly higher D95% values (p=0.001), reflecting improved target coverage by the prescription dose. Both the homogeneity index (HI) and conformity index (CI) were also significantly better with VMAT (p=0.001 for both). These findings underscore VMAT's ability to deliver a more homogeneous dose distribution within the target while minimizing unnecessary radiation exposure to surrounding healthy tissues.

Heart Dose Analysis: In terms of cardiac exposure, VMAT was associated with a significant reduction in the heart volume receiving 30 Gy (V30) compared to 3DCRT (p=0.014). However, no significant difference was observed between the two techniques with respect to the mean heart dose (p=0.408).

Esophagus Dose Metrics: With respect to esophageal sparing, VMAT demonstrated superior protection, as reflected by significantly lower V50 values (p=0.016), indicating a reduction in the volume receiving at least 50 Gy. The mean dose to the esophagus was also reduced with VMAT, although this difference did not reach statistical significance (p=0.058). However, no significant difference was observed between the two techniques in terms of the maximum dose to the esophagus (p=0.224).

Lung Dose Sparing: All lung dose parameters favored VMAT over 3DCRT. In the ipsilateral lung, VMAT significantly reduced the volumes receiving 10 Gy (V10; p=0.013), 20 Gy (V20; p=0.018), and 30 Gy (V30; p=0.017), whereas the difference in mean lung dose did not reach statistical significance. For the contralateral lung, similar significant reductions were observed at the V20 and V30 dose cutoffs (p=0.003 for both). However, at lower dose levels (V5; p=0.78 and V10; p=0.466), no significant differences were observed between the two techniques, nor was there a significant difference in the mean dose to the

contralateral lung (p=0.094). Additionally, global lung parameters also showed significant improvement with VMAT, including lower mean lung dose (p=0.005) and reduced volumes receiving 20 Gy (V20; p=0.001) and 30 Gy (V30; p=0.004). However, no significant differences were observed in the low-dose regions (V5; p=0.955 and V10; p=0.292).

Spinal Cord Dose Comparison: Although the maximum spinal cord dose was marginally reduced with VMAT, this difference did not reach statistical significance (p=0.094). Both 3DCRT and VMAT maintained spinal cord doses well within tolerance limits, demonstrating excellent protection of this critical structure.

Discussion

The present study demonstrated that, while VMAT showed superior dosimetric performance for most parameters, an optimized six-beam 3DCRT plan also produced clinically acceptable outcomes. This supports its continued relevance, particularly when modern technologies are inaccessible or impractical due to institutional limitations or patient-specific constraints. Despite the current trend toward precision-based radiotherapy—emphasizing tight dose conformity, reduced irradiation of normal tissues, and improved organ-at-risk (OAR) sparing—there remain clinical contexts in which conventional techniques such as 3DCRT merit reconsideration. This is especially true in resource-limited settings where advanced technologies like VMAT may not be readily available. Historically, 3DCRT was the standard of care for managing locally advanced non-small cell lung cancer (NSCLC), demonstrating both safety and efficacy. It has been used effectively in dose-escalation strategies aimed at increasing tumor control probability without exceeding normal tissue tolerance (12-14). Although modern techniques such as VMAT and IMRT offer enhanced conformity and dose modulation, they also require more sophisticated planning systems, rigorous quality assurance protocols, and strict patient setup reproducibility—requirements that may not be feasible in all clinical environments.

Notably, there is a paucity of randomized clinical trials directly comparing 3DCRT and VMAT. The NRG Oncology-RTOG 0617 trial remains the most significant study in this area, in which 47% of patients received IMRT (including VMAT) and 53% were treated with 3DCRT. While no significant difference in overall survival was observed between the two approaches, the trial did reveal a substantial reduction in cardiac radiation exposure with IMRT, which subsequently led to the adoption of stricter heart dose constraints in clinical practice (15, 16).

In our study, beam arrangements for 3DCRT were carefully designed to avoid direct exposure to OARs whenever possible, particularly the contralateral lung. No beam was permitted to pass through the contralateral lung unless strictly necessary. This strategic planning played a crucial role in achieving clinically acceptable OAR sparing. As expected, both the homogeneity index (HI) and conformity index (CI) were significantly improved with VMAT, owing to its advanced segment modulation and high-resolution delivery. HI reflects dose uniformity within the target, whereas CI quantifies how well the prescribed dose conforms to the target volume while sparing adjacent tissues (17, 18). These indices are commonly derived from near-minimum (D98%) and near-maximum (D2%) doses, where D2% represents the dose received by the hottest 2% of the target and D98% the dose covering 98% of the target volume (19).

The minimum dose (Dmin) was significantly higher with VMAT than with 3DCRT (mean difference: 0.22-5.24 Gy; p=0.035), indicating improved low-dose coverage within the target volume. In contrast, the maximum dose (Dmax) showed no statistically significant difference between the two techniques (p=0.666), suggesting comparable control over dose hotspots. Overall, these findings indicate that VMAT offers more effective control of both target coverage and hotspot management within the target and surrounding healthy

tissues. Cardiac exposure remains a major concern in thoracic radiotherapy, as it is a leading cause of radiation-associated mortality, and growing evidence indicates that the risk of cardiac events increases with radiation dose (20, 21). Although universally accepted heart dose constraints have not been established, the QUANTEC guidelines are commonly referenced, recommending a V30 of <50% and a mean heart dose of <26 Gy. In our analysis, VMAT plans achieved better heart V30 values, whereas the difference in mean heart dose did not reach statistical significance, suggesting that, with meticulous planning, 3DCRT can also provide adequate cardiac protection. Recent literature has further underscored the prognostic significance of dose to specific heart substructures—such as the left atrium—in relation to survival outcomes. Although contouring these substructures adds complexity and time, it may be particularly valuable in patients with preexisting cardiovascular disease (22). Figure 1 illustrates how 3DCRT beam arrangements can be adjusted to avoid sensitive subregions, such as the sinoatrial node, especially when specific toxicity concerns arise.

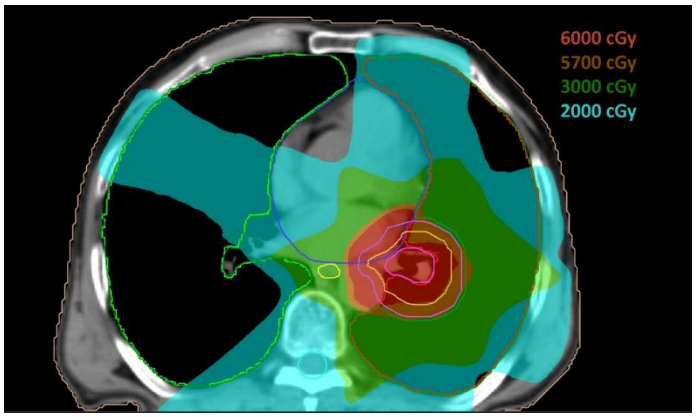


Figure 1. Cardiac subregion protection in 3DCRT

Regarding pulmonary dose parameters, mean lung dose and V20 are established predictors of radiation pneumonitis. VMAT demonstrated superiority in sparing high-dose lung volumes (V20 and V30), which correlates with a reduced risk of higher-grade pneumonitis, whereas no significant differences were observed for low-dose volumes (V5 and V10), which are associated with milder forms of pneumonitis (23-25). Sparing the contralateral lung from even low-dose radiation can improve the overall toxicity profile, and Figure 2 illustrates how beam orientation in 3DCRT can be effectively optimized to minimize low-dose spillage into the contralateral lung.

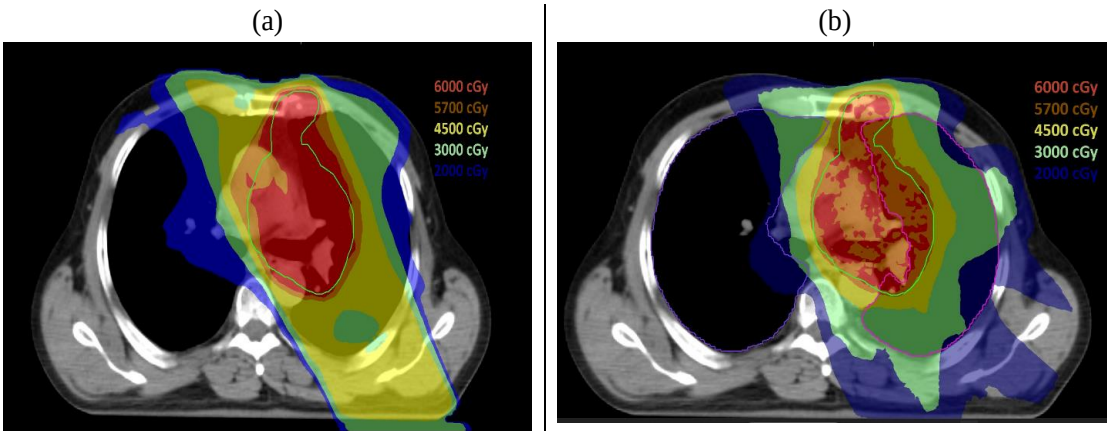


Figure 2. Low and high dose isolines in the contralateral lung, (a) 3DCRT, (b) VMAT

Regarding the esophagus and spinal cord, our study found that both structures were well spared in the 3DCRT plans. This can be attributed in part to patient selection—none of the cases involved tumors directly abutting the spine or requiring vertebral irradiation—and in part to beam arrangements that deliberately avoided passing through the spinal cord unless absolutely necessary. Furthermore, current trends in lymphatic irradiation favor involved-field radiotherapy, while elective nodal irradiation is seldom practiced (26, 27). As a result, mediastinal targets are more limited, which in turn reduces unnecessary esophageal dose exposure. Although VMAT still provided superior sparing, 3DCRT demonstrated an acceptable safety profile for both organs.

In conclusion, VMAT demonstrated statistically superior dosimetric outcomes in several key areas, including improved target coverage (higher D95%, better homogeneity and conformity indices) and enhanced sparing of critical organs—namely, the heart (lower mean dose), spinal cord (lower maximum dose), and esophagus (reduced Dmax and mean dose). It also achieved significant reductions in high-dose lung volumes (V20 and V30), which are important for minimizing pulmonary toxicity. Nevertheless, 3DCRT consistently met clinically acceptable thresholds for all key parameters, including Dmax, mean lung dose, and mean heart dose. Although no significant differences were observed in low-dose lung volumes (V5 and V10), these metrics should be interpreted cautiously, particularly in patients at higher risk for radiation pneumonitis.

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