ORIGINAL ARTICLE

# A Dosimetric Evaluation of VMAT Versus IMRT for Unilateral Lung Cancer Treatment

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## Abstract

**Purpose:** Radiation therapy is a highly effective treatment for lung cancer. The goal of this study was to develop a more effective treatment for lung cancer using radiation, and it achieved this by using two modalities: Intensity-Modulated Radiation Therapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT).

**Materials and Methods:** Thirty patients with a diagnosis of unilateral lung cancer participated in this study. Patients were treated using ELEKTA's linear accelerator with 6 MV or 10 MV energy x-ray photon beams. To plan their therapies, the patients underwent a CT simulation using MONACO version 5.1.

**Results:** In the comparison of VMAT with IMRT, the former demonstrates superiority in several aspects, including enhanced protection of the heart and spinal cord, reduced segments and monitoring units, and more comprehensive coverage of the projected target volume (PTV). VMAT provided superior target coverage (PTV 95%) at 98.52% compared to 97.40% with IMRT ($p = 0.0443$). VMAT also achieved better dose conformity (CI = 0.93 vs. 0.78) and homogeneity (HI = 0.05 vs. 0.11). Additionally, it reduced monitor units (393.5 vs. 457.9, $p < 0.00001$) and the number of segments per plan (44.3 vs. 91.6, $p < 0.00001$), while delivering lower doses to critical organs such as the heart and spinal cord.

**Conclusion:** VMAT demonstrates superior results compared to IMRT in delivering radiation to lung tumors while minimizing damage to the heart and spinal cord.

**Keywords:** Intensity-Modulated Radiation Therapy; Volumetric Modulated Arc Therapy; Monitor Unit; Number of Segments.




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## 1. Introduction

Lung cancer accounts for the highest number of cases and deaths worldwide. In 2000, an estimated 1.2 million new cases, or 12.3% of all malignancies, were diagnosed. The primary reason for lung cancer is tobacco from smoking, which accounts for up to 90% of cases in those who smoke cigarettes [1-5].

Complications in respiratory motion, unequal baseline shifts across initial tumors, and physical changes caused by treatment are some of the complex geometrical uncertainties that come with Radiation Therapy (RT) for those diagnosed with lung carcinoma. The need for substantial safety margins to accommodate these uncertainties renders dosage escalation to enhance treatment results implausible [6-8]. During the early stages of Non-Small Cell Lung Cancer (NSCLC), a technique of Stereotactic Body Radiation Therapy (SBRT) is often used to treat inoperable lung cancer [9, 10].

For small fields with a sharp penumbra and a high dose fraction, more precise treatment planning methods, image-guided localization, and improved immobilization are necessary. SBRT is frequently used for early-stage, medically inoperable lung cancer due to its ability to deliver high-dose radiation precisely. For more advanced or anatomically complex cases, conventional techniques such as three-Dimensional Conformal Radiotherapy (3D-CRT), Intensity-Modulated Radiation Therapy (IMRT), and, more recently, Volumetric Modulated Arc Therapy (VMAT) have become preferred alternatives. The increasing adoption of SBRT has also driven interest in optimizing and comparing these advanced modalities [10, 11].

VMAT and dynamic conformal arc therapy can now be utilized with the latest generation of linear accelerators to deliver high doses of radiation. Variable dosage rates, dynamic Multileaf Collimator (MLC), and gantry speed modulation are some of the features of VMAT [12]. Dynamic Conformal Arc Treatment (DCAT) is similar to VMAT; however, unlike VMAT, the MLCs used in DCAT are only conformed to the target as they rotate around it. These two therapeutic techniques can be administered much more quickly [11]. Recent meta-analyses and clinical planning studies have confirmed the growing role of VMAT in thoracic oncology, due to its superior conformity and delivery efficiency compared to IMRT, particularly in patients with NSCLC [12, 13].

This study aimed to compare the dosimetric performance of volumetric modulated arc therapy (VMAT) and intensity-modulated radiation therapy (IMRT) in the treatment of unilateral lung cancer, with a particular focus on target coverage, plan quality, and dose sparing of critical organs.

The innovation of our study lies in providing a head-to-head comparison of VMAT and IMRT specifically for unilateral lung cancer in an Iraqi clinical setting, using consistent treatment parameters and identical simulation techniques. Additionally, we evaluated not only standard dosimetric parameters (PTV coverage, CI, HI) but also efficiency indicators such as monitor units and the number of segments. We correlated these findings with dose sparing to critical organs. The novelty also includes a detailed institutional experience using MONACO TPS with Elekta Agility MLCs, which is less frequently reported in regional studies.

## 2. Materials and Methods

### 2.1. Patients and Methods

This study employed a convenience sampling method with a cohort design, conducted between February 2021 and July 2022 at Al Amal National Hospital for Oncology in Baghdad, Iraq. Al-Nahrain University College of Medicine's Institutional Review Board (IRB) approved this project.

Thirty patients who were sent for radiation treatment after an oncologist diagnosed them with unilateral lung carcinoma were included in this research.

Inclusion criteria were: (1) histologically confirmed unilateral non-small cell lung cancer (NSCLC), (2) age between 30 and 75 years, (3) Karnofsky Performance Status (KPS) ≥ 70, and (4) eligibility for radiotherapy with no prior thoracic RT.

Exclusion criteria included: (1) bilateral lung involvement, (2) distant metastasis, (3) history of prior thoracic radiotherapy, and (4) poor-quality CT images unsuitable for treatment planning.

Patients were staged according to the AJCC 8th edition, ranging from stage II to IIIb. The mean volume of the patient's lung tumors was 196.05 ± 21.37 mm³, ranging from 46.7 to 939.8 mm³. Patients with extensive bilateral disease, prior thoracic radiotherapy, or incomplete imaging were excluded. Comorbidities such as Chronic Obstructive Pulmonary Disease (COPD), cardiovascular disease, and diabetes were documented but did not constitute exclusion unless they contraindicated radical radiotherapy.

The patients had CT scans to organize their treatments using MONACO version 5.1. The oncologist identifies the potential organs and tumors that may be affected. Planned VMAT and IMRT treatments are the work of the medical physicist. The superior strategy is selected and authorized by the oncologist. The patients were exposed to an X-ray photon beam of 6 or 10 MV using the Agility linear accelerator, manufactured by Elekta, Sweden.

Each patient was prescribed a total dose of 60 Gy delivered in 30 fractions (2 Gy per fraction). For VMAT plans, a dual full-arc technique was used, providing treatment with two 360° coplanar arcs. IMRT plans were generated using 5 to 7 coplanar fields with a step-and-shoot technique. All treatments were performed using 6 MV x-ray photon beams on an ELEKTA Agility linear accelerator equipped with a 5 mm Multileaf Collimator (MLC). Treatment planning was conducted using MONACO version 5.1, utilizing inverse planning optimization for both techniques.

A representative plan comparison between IMRT and VMAT is illustrated in Figures 1 and 2, respectively, showing isodose distributions and dose wash patterns for a selected patient.

Dose constraints for the Planning Target Volume (PTV) and Organs-At-Risk (OARs) were adopted following established guidelines. PTV coverage aimed to meet RTOG criteria, requiring ≥95% of the prescribed dose to encompass 95% of the PTV. For the lungs, QUANTEC recommendations were followed, with the mean lung dose (MLD) kept below 20 Gy and V20 < 35%, V5 < 60%. The spinal cord maximum dose was limited to ≤45 Gy, in line with QUANTEC, while the heart maximum dose was restricted to ≤50 Gy and mean dose <26 Gy, consistent with published constraints. These limits were prioritized during optimization to minimize toxicity risk while maintaining target coverage [14].

Dose Homogeneity reflects how evenly the absorbed dose is distributed within the planning target volume (PTV). An inhomogeneous dose distribution may create regions of over-dosage (“hot spots”) or under-dosage (“cold spots”), potentially affecting tumor control and normal tissue toxicity. A commonly accepted quantitative measure is the Homogeneity Index (HI), defined by the ICRU (83) and other groups as [15] (Equation 1):

$$HI = \frac{D2\% - D98\%}{D50\%} \quad (1)$$

where $D_2\%$ represents the near-maximum dose, $D_{98}\%$ the near-minimum dose, and $D_{50}\%$ the median dose. An HI value close to zero indicates an even dose distribution. For example, with $D_2\%$ = 63 Gy, $D_{50}\%$ = 60 Gy, and $D_{98}\%$ = 57 Gy, the HI equals 0.1, reflecting good homogeneity.

Dose Conformity evaluates the degree to which the high-dose region conforms to the shape and volume of the PTV, minimizing unnecessary irradiation of healthy tissues. According to ICRU Report 83, conformity can be quantified using the Conformity Index (CI) as [15] (Equation 2):

$$CI = \frac{V_{RI}}{TV_{PTV}} \quad (2)$$

Where $V_{RI}$= volume of tissue receiving the reference (prescription) isodose, and $TV_{PTV}$ the portion of the PTV receiving the prescription dose, a CI of 1 represents ideal conformity, with the high-dose region exactly matching the target.

All the doses of PTV and Organs At Risk (OARs) were obtained using the Dose Volume Histogram (DVH) in Monaco TPS.

The Statistical Package for the Social Sciences (SPSS), version 25, was used for data analysis. Simple metrics such as range, standard deviation, mean, and percentage were used to display the data. Data distribution was first assessed with the Shapiro–Wilk test for normality. For normally distributed variables, comparisons between VMAT and IMRT plans were

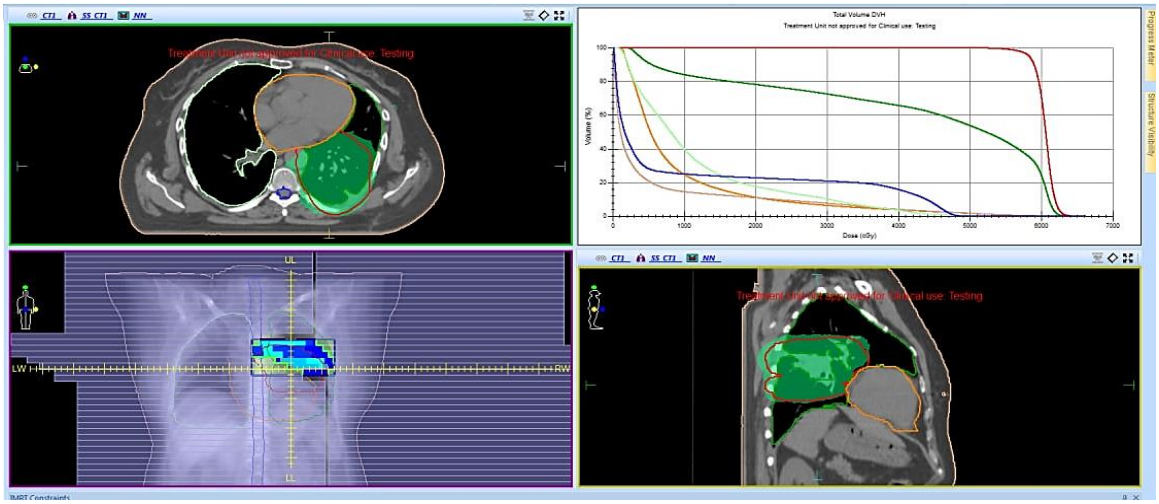

**Figure 1.** Dose distribution of lung cancer with IMRT treatment planning technique

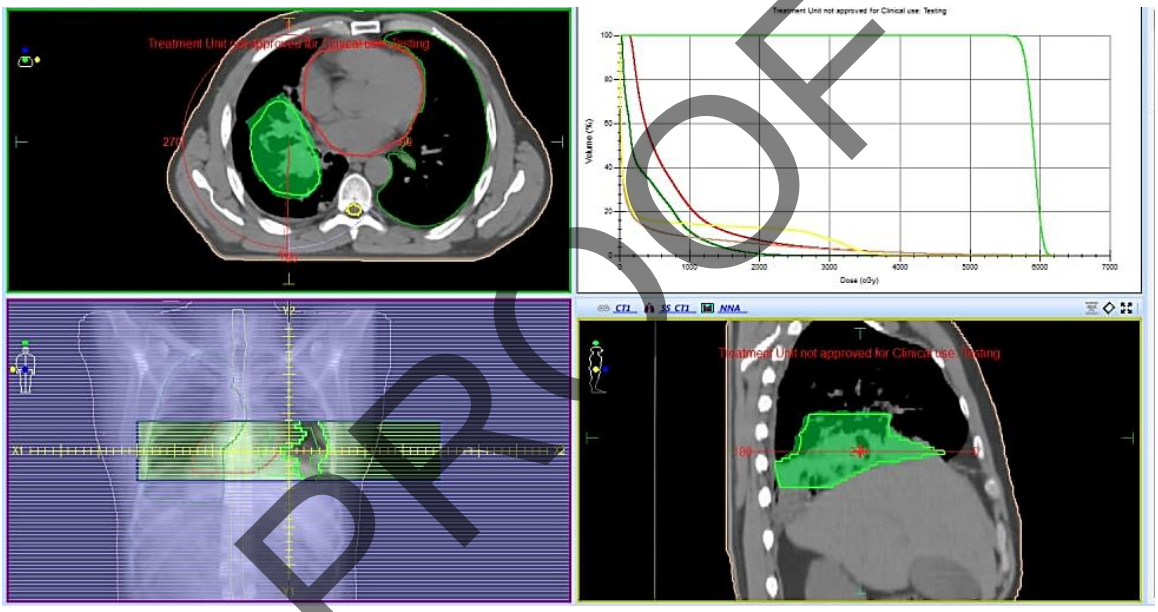

**Figure 2.** Dose distribution of lung cancer with VMAT treatment planning technique



carried out using a paired-samples *t*-test. For non-normally distributed data, the Wilcoxon signed-rank test was applied. In addition, mean differences with 95% Confidence Intervals (CIs) were calculated. Statistical significance is attained when the p-value is ≤0.05.

## 3. Results

In this representative case, the PTV 95% coverage was 98.9% with VMAT, compared to 96.7% with IMRT. The conformity index was 0.94 with VMAT and 0.77 with IMRT. For organ-at-risk sparing, the mean heart dose was 610 cGy with VMAT compared to 685 cGy with IMRT, while the spinal cord received a mean dose of 580 cGy with VMAT versus 655 cGy with IMRT. These findings provide both visual and numerical support for the improved dosimetric outcomes of VMAT over IMRT.

The dose that covered the lung was recorded and analyzed. The mean volume of the patient's lung tumors was 196.05 ± 21.37 mm³, ranging from 46.7 to 939.8 mm³. The results show a significant difference between the IMRT and VMAT concerning 95% of the PTV (planning target volume). The results indicate that VMAT (98.52 ± 1.85) provided higher PTV 95% coverage compared to IMRT (97.40 ± 2.55), with a statistically significant difference ($p = 0.0443$), as shown in Figure 3.

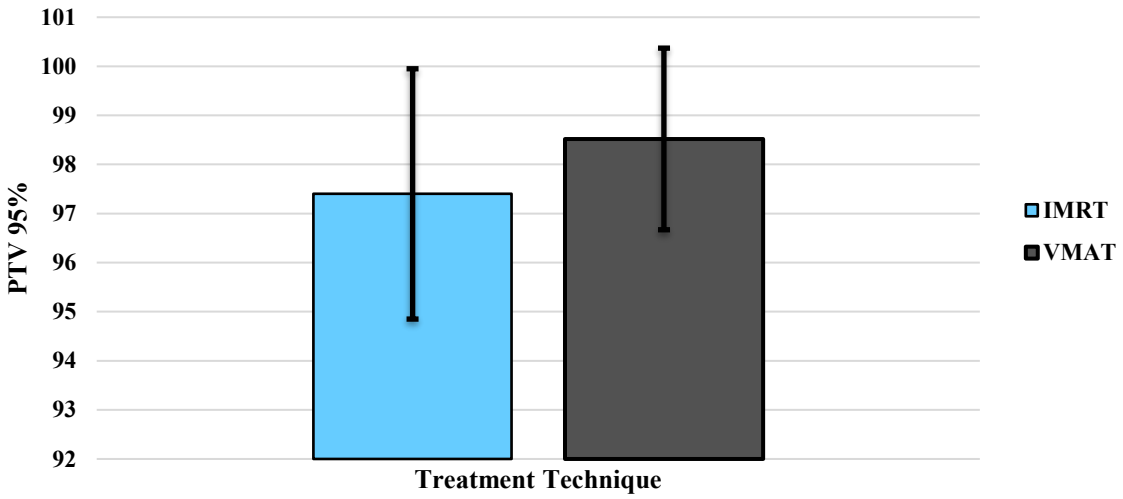


**Figure 3.** Comparison of the PTV 95% of the Target Volume Between the IMRT and VMAT

The plan quality is measured by many parameters, including the Homogeneity (HI) and Conformity (CI) indices. Table 1 shows the HI and CI results. The VMAT shows a significantly better homogeneity and conformity to the PTV 95% than the IMRT.

Dosimetric parameters that could be acquired from the planning and included in this study were the number of segments used in the plan and the monitor units (MU) per fraction of each plan. The results of the number of segments and MUs are shown in Table 2. The IMRT had more segments and monitor units than the VMAT.

The organs at risk are near the heart and spinal cord. The minimum, maximum, and mean dose reached by these organs are listed in Table 3. The VMAT treatment planning technique results in a lower overall dose to all organs compared to IMRT. The maximum dose shows a significantly higher difference between IMRT and VMAT for the heart. In contrast, the minimum and mean doses reaching the spinal cord were highly significant in IMRT compared to VMAT.

Figure 4 illustrates a schematic isodose distribution for IMRT versus VMAT in a single patient, demonstrating the superior target coverage and organ-at-risk sparing achieved with VMAT compared to IMRT. The red line indicates the 95% isodose level. In this representative case, PTV 95% coverage was 98.9% with VMAT, compared to 96.7% with IMRT. The conformity index was 0.94 with VMAT and 0.77 with IMRT. For organ-at-risk sparing, the mean heart dose was 610 cGy with VMAT compared to 685 cGy with IMRT, while the spinal cord received a mean dose of 580 cGy with VMAT versus 655 cGy with IMRT.

**Table 1.** Comparison of the Dose Homogeneity and Conformity Between the IMRT and VMAT

| Quality Index | VMAT (mean ± SD) | IMRT (mean ± SD) | *P*-Value |
|---|---|---|---|
| **CI** | 0.93 ± 0.05 | 0.78 ± 0.09 | 0.04291* |
| **HI** | 0.05 ± 0.01 | 0.11 ± 0.06 | 0.03567* |

**Table 2.** The Number of Segments and Monitor Units Between the IMRT and VMAT

| Dosimetric Values | VMAT (mean ± SD) | IMRT (mean ± SD) | *P*-Value |
|---|---|---|---|
| **No. of Segments** | 44.31 ± 21.19 | 91.65 ± 23.10 | <0.00001* |
| **No. of MUs** | 393.51 ± 87.87 | 457.89 ± 85.89 | <0.00001* |

Figure 5 presents the Dose–Volume Histogram (DVH) curves for a representative patient, comparing the VMAT and IMRT treatment plans. The DVH curves demonstrate that VMAT achieved superior dose coverage of the Planning Target Volume (PTV), with a higher proportion of the volume receiving ≥95% of the prescribed dose compared to IMRT. Additionally, the heart and spinal cord DVHs show that VMAT plans resulted in lower high-dose volumes to these Organs-At-Risk (OARs). Specifically, the

**Table 3.** Comparison of OAR Doses Between IMRT and VMAT

| Dose Metric | Heart (VMAT) (mean ± SD) | Heart (IMRT) (mean ± SD) | Spinal Cord (VMAT) (mean ± SD) | Spinal Cord (IMRT) (mean ± SD) | P-Value |
|---|---|---|---|---|---|
| **Minimum (cGy)** | 55.02 ± 12.02 | 59.73 ± 12.30 | 4.7 ± 0.94 | 6.67 ± 0.30 | <0.0001 (cord) |
| **Mean (cGy)** | 646.04 ± 29.70 | 696.34 ± 87.03 | 596.62 ± 175.72 | 672.43 ± 260.41 | 0.0325 (cord) |
| **Maximum (cGy)** | 4698.83 ± 148.79 | 5044.24 ± 154.25 | 3677.11 ± 117.13 | 3560.34 ± 123.81 | 0.0360 (heart) |

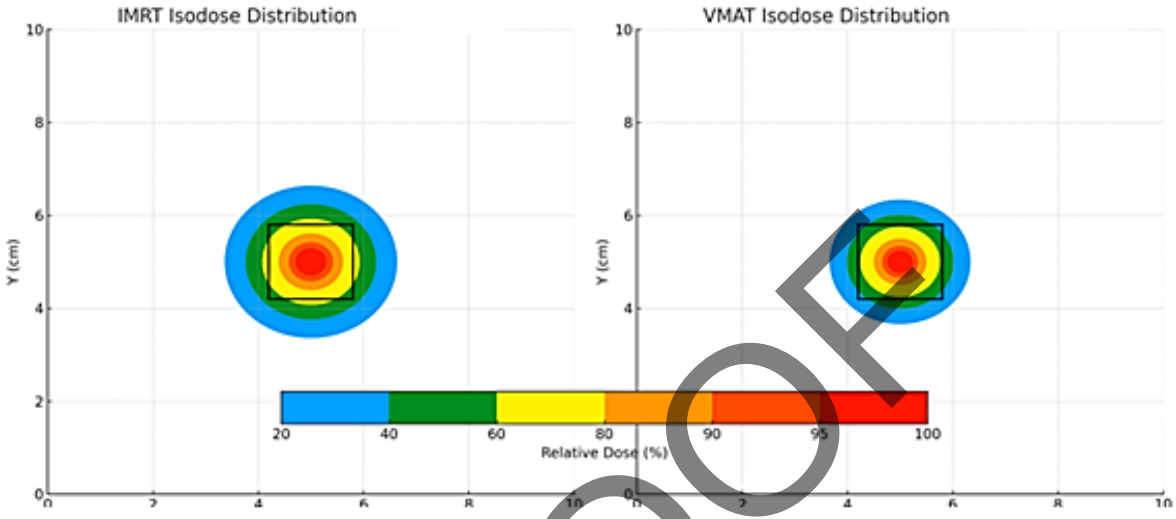


**Figure 4.** Schematic isodose distribution images for an IMRT and VMAT

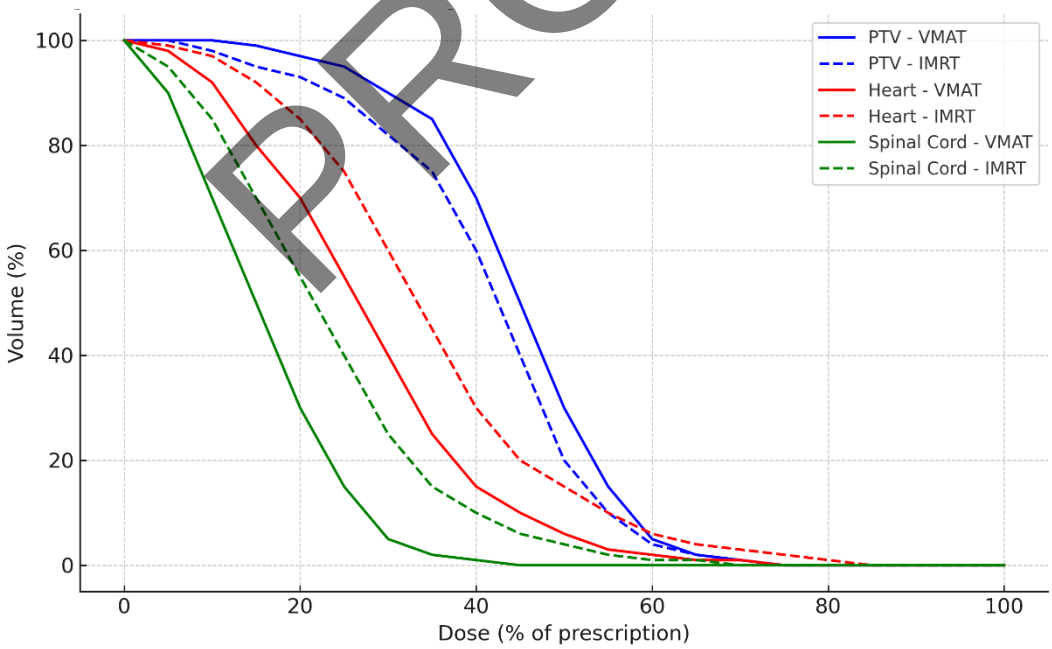


**Figure 5.** Dose-volume Histogram (DVH) for PTV and OARs (VMAT vs IMRT)

volume of the heart receiving moderate to high doses was reduced in VMAT, and the volume of the spinal cord exposed to high doses was also significantly lower. These findings provide quantitative and graphical support for the superior conformity and

organ-sparing capabilities of VMAT compared to IMRT.

A subgroup analysis was performed according to tumor laterality (Table 4). As expected, left-sided tumors were associated with significantly higher cardiac doses compared with right-sided cases. The mean heart dose was 14.6 ± 3.1 Gy with VMAT and 16.8 ± 3.4 Gy with IMRT for left-sided tumors, versus 6.2 ± 2.1 Gy and 7.4 ± 2.5 Gy, respectively, for right-sided tumors ($p < 0.001$). Similarly, the maximum heart dose was nearly twice as high for left-sided tumors compared to right-sided ones. In contrast, lung dose parameters (V20, V5, and mean lung dose) and spinal cord Dmax did not differ significantly between laterality groups ($p > 0.05$). Importantly, VMAT consistently provided superior PTV coverage, conformity, and homogeneity over IMRT for both left- and right-sided tumors.

## 4. Discussion

The most common side effects of radiotherapy for lung cancers are Radiation-Induced Pneumonitis (RIP), which produces significant morbidity and fatality. RIP incidence is inversely related to the dose of ionizing radiation received by the lungs [15, 16]. Previous studies have shown that DVH-lung dosimetric metrics, including mean lung dose, pulmonary volume 20, and pulmonary volume 30, have been directly linked to tRIP [17].

This study reveals a substantial variation between IMRT and VMAT in terms of the 95% PTV, maximum, and minimum values. Our study reported a 95% PTV coverage of 98.52% for VMAT versus 97.40% for IMRT (p = 0.0443). This aligns with Jiang *et al.* (2011) [16], who observed 98.3% vs. 96.4% for VMAT and IMRT, respectively.

Recent studies [18-20] have investigated the difference in dosimetric and clinical characteristics of VMAT versus IMRT. The VMAT approach is superior to IMRT in various solid tumor types, particularly those with a complex target volume. The current research investigated dosimetric discrepancies and effectiveness between IMRT and VMAT treatment planning techniques for lung cancer.

The current analysis demonstrates that VMAT achieves 95% greater HI and CI to the PTV than IMRT. Our CI values (0.93 for VMAT and 0.78 for IMRT) are consistent with those reported by Wu *et al.* (2009) [21], who found improved conformity with VMAT in complex target geometries (CI > 0.90).

Our results agreed with Jiang *et al.* [16], who found that in treatment planning for locally advanced lung cancer, a single arc VMAT plan achieves improved CI and HI (all the better at the p-value of 0.05), and even a partial arc VMAT plan may accomplish this dose distribution in Comparison to the IMRT plans. This is consistent with Scorsetti *et al.* [22] investigations.

The relatively low values of the Homogeneity Index (HI) reported for both VMAT and IMRT are consistent with expectations based on the calculation method.

Where D2% and D98% represent the near-maximum and near-minimum doses received by the PTV, and D50% denotes the median dose. This formula is sensitive to the dose uniformity within the target and typically yields values between 0.0 and 0.2 for homogeneous plans. The lower HI observed in VMAT (0.05 ± 0.01) compared to IMRT (0.11 ± 0.06)



**Table 4.** Dosimetric laterality effect comparison of VMAT and IMRT plans for left- versus right-sided lung tumors

| Parameter | Left Lung VMAT (mean ± SD) | Left Lung IMRT (mean ± SD) | Right Lung VMAT (mean ± SD) | Right Lung IMRT (mean ± SD) | p-value (laterality effect) |
|---|---|---|---|---|---|
| **PTV95% (%)** | 98.6 ± 1.5 | 97.5 ± 2.2 | 98.4 ± 1.8 | 97.3 ± 2.6 | 0.72 |
| **CI** | 0.94 ± 0.05 | 0.79 ± 0.08 | 0.92 ± 0.06 | 0.77 ± 0.09 | 0.68 |
| **HI** | 0.05 ± 0.01 | 0.11 ± 0.05 | 0.05 ± 0.02 | 0.12 ± 0.06 | 0.82 |
| **Heart $D_{max}$ (Gy)** | 47.9 ± 3.2 | 50.8 ± 3.5 | 24.2 ± 2.8 | 26.1 ± 3.1 | <0.001 |
| **Heart $D_{mean}$ (Gy)** | 14.6 ± 3.1 | 16.8 ± 3.4 | 6.2 ± 2.1 | 7.4 ± 2.5 | <0.001 |
| **Lung V20 (%)** | 28.1 ± 5.6 | 29.3 ± 5.8 | 27.5 ± 5.3 | 28.7 ± 5.5 | 0.59 |
| **Lung V5 (%)** | 55.8 ± 7.9 | 58.6 ± 8.2 | 54.6 ± 7.6 | 57.2 ± 7.9 | 0.51 |
| **MLD (Gy)** | 15.2 ± 2.8 | 16.3 ± 3.0 | 14.8 ± 2.7 | 15.7 ± 2.9 | 0.64 |
| **Spinal cord $D_{max}$ (Gy)** | 39.5 ± 4.2 | 41.2 ± 4.5 | 38.9 ± 4.1 | 40.8 ± 4.4 | 0.71 |

confirms that VMAT achieved a more uniform dose distribution across the PTV, consistent with its known delivery efficiency and planning flexibility [22].

Dosimetric parameters in current research seem to be obtainable from planning. The number of segments utilized in the plan and Monitor Units (MUs) per percentage of each plan was included in this study, along with the outcomes of the segment and MU count. IMRT had more segments and monitor units than VMAT. We observed significantly fewer MUs with VMAT (393.5 ± 87.9) compared to IMRT (457.9 ± 85.9). Similar reductions were noted by Scorsetti *et al.* (2010) [15], who reported a ~15% MU reduction with VMAT.

In addition to the dosimetric analysis, our findings were consistent with those of other studies [23-25]. They reveal a shorter treatment time when single and partial VMAT arc approaches were used. Increasing patient satisfaction and comfort while decreasing intrafraction variance would benefit the VMAT approach. It may assist patients in withstanding a whole treatment session, especially those who are ill or in discomfort.

Compared to IMRT, the VMAT method of treatment planning reduces the total dose to all organs, which is particularly beneficial in areas close to the lung where organs such as the contralateral lung, liver, heart, and spinal cord are at risk. VMAT provides a significantly lower minimum, maximum, and mean dosage to the contralateral lung compared to IMRT. There was only a significant change in the minimal dosage for the liver. While only the maximum dosage differs considerably between IMRT and VMAT for the heart, the minimum and mean doses reaching the spinal cord were significantly greater with IMRT than with VMAT. In our study, the mean heart dose was reduced by approximately 50 cGy in VMAT plans. In comparison, the spinal cord dose was reduced by approximately 76 cGy, consistent with trends observed in other dosimetric comparisons for thoracic targets.

Tumor laterality is an important determinant of organ-at-risk exposure in thoracic radiotherapy, particularly for cardiac structures. In our cohort, left-sided tumors were associated with significantly higher heart doses than right-sided tumors, both in terms of maximum and mean dose, consistent with previous reports and QUANTEC recommendations [14]. Elevated cardiac dose in left-sided cases reflects the anatomical proximity of the heart to the left lung, which has been well documented as a factor contributing to increased risk of late cardiotoxicity. Despite these differences, our results demonstrate that VMAT maintained dosimetric advantages over IMRT for both laterality subgroups, achieving superior conformity, homogeneity, and target coverage while still reducing cardiac exposure relative to IMRT. Lung and spinal cord doses were not significantly influenced by laterality, suggesting that the primary dosimetric trade-off is cardiac sparing. These findings reinforce the clinical importance of careful heart dose evaluation, particularly for left-sided tumors, and support the preferential use of VMAT in such scenarios where minimizing high-dose cardiac exposure is critical.

Regarding the OARs, our results partially disagreed with the study by Jiang *et al.* [14]. Other organs at risk (spinal cord, heart, and esophagus) did not show significant variation between the IMRT and VMAT regimens for treating locally advanced lung malignancies.

Various researchers have indicated that plans generated using the VMAT technique are superior to those generated using the IMRT technique in treating lung cancer. According to Jiang *et al.*, the VMAT shows better outcomes than the IMRT technique for locally advanced patients with lung cancer, offering improved PTV coverage. Findings from their research show that the Man Lung Dose (MLD) in VMAT designs is significantly lower than the MLD in IMRT plans. Previous studies show that VMAT regimens are the most effective for stage III NSCLC patients [22, 26]. The different volume goal scenarios may be a factor in why this is the case. Researchers found that central lung cancer patients who were treated with PTVs that included the mediastinal lymphatic drainage region had different outcomes than those who were treated with PTVs that did not include this area. This was because the PTV did not cover this region.

Tumor location within the lung lobes may also affect dosimetric outcomes, as the proximity of the target volume to critical structures varies by site. Upper lobe tumors are generally situated farther from the heart. They may therefore result in lower cardiac

exposure, whereas lower lobe tumors are often closer to the heart, esophagus, and diaphragm, potentially leading to higher doses to these structures. Several studies have shown that lobe-specific tumor location can influence both cardiac and pulmonary dose distribution in radiotherapy for lung cancer [13, 27]. Although our cohort was not sufficiently powered for a lobe-based subgroup analysis, this remains an important consideration for individualized treatment planning.

The appropriateness of the planning approach may change based on the tumor's stage, location, size, dose-tolerance criteria, and OARs. However, the current research has limitations due to the limited number of participants, which makes the findings less credible. In addition, different planning procedures using extra beams may have been investigated for IMRT; however, incorporating such variations might increase the complexity of the plan, albeit with a more extended treatment period. To effectively address these issues, further clinical research is required.

### 4.1. Study Limitations and Future Directions

This study has several limitations. First, it was a single-center retrospective analysis with a relatively small cohort of 30 patients, which may limit the generalizability of the findings. Second, respiratory motion management with 4D-CT was not systematically incorporated, meaning that intra- and inter-fraction tumor motion could not be fully assessed. Third, the study was limited to dosimetric endpoints without clinical correlation; thus, toxicity outcomes such as radiation pneumonitis or late cardiac effects were not evaluated. Fourth, the sample size was insufficient to conduct robust subgroup analyses based on tumor lobe location or detailed comorbidity profiles, which may further influence organ-at-risk exposure.

Future research should include larger, multi-institutional cohorts with prospective data collection to validate the dosimetric advantages of VMAT over IMRT. Incorporation of advanced motion management strategies, such as 4D-CT, deep inspiration breath-hold, or gating, will allow for more accurate assessment of respiratory effects. Furthermore, integrating clinical endpoints, such as treatment-related toxicity and survival, is essential to establish the translational relevance of dosimetric findings. Finally, exploring patient-specific factors such as tumor laterality, lobe location, and comorbidity burden in larger datasets may refine treatment individualization and improve therapeutic outcomes.

## 5. Conclusion

This study demonstrates that volumetric modulated arc therapy (VMAT) offers dosimetric advantages over intensity modulated radiotherapy (IMRT) in the treatment of unilateral lung cancer, providing improved conformity, homogeneity, and treatment efficiency. Importantly, VMAT also reduced cardiac and spinal cord exposure, which may have meaningful clinical implications, particularly for left-sided tumors. However, lung dose parameters were similar between techniques, and subgroup analyses suggest that anatomical factors such as tumor laterality remain important determinants of OAR exposure. As a single-center dosimetric study, our findings are limited by sample size, the absence of motion management data for all patients, and the lack of clinical outcome correlation. Future studies with larger patient populations, incorporation of 4D imaging, and long-term toxicity follow-up are warranted to validate these results and better define the role of VMAT in routine practice.

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