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DOSIMETRIC EVALUATION STUDY OF 10-MV FFF USED IN SBRT FOR LUNG TUMOURS[†]

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Purpose: The objective of this research was to conduct a comparative and dosimetric analysis of three different radiotherapy techniques used in lung stereotactic body radiotherapy (SBRT), the three-dimensional conformal radiotherapy (3DCRT), intensity-modulated radiation therapy (IMRT), and volumetric modulated arc therapy (VMAT), using a 10 MV flattening filter-free (FFF) photon beam. ***Materials and methods:*** The present study employed computed tomography (CT) images of a humanoid phantom for the purpose of treatment planning. The gross tumour volumes (GTVs) delineated in both the central and peripheral positions of the lungs. The determination of Planning Target Volumes (PTVs) involved the addition of a margin of 0.5 cm to the Gross Tumour Volume (GTV). Three-dimensional conformal radiotherapy (3DCRT), intensity-modulated radiation therapy (IMRT), and volumetric modulated arc therapy (VMAT) treatment plans produced employing a 10-megavolt (MV) flattening filter-free (FFF) photon beam. The calculation of dosage for all plans Performed using the anisotropic analytical algorithm (AAA). ***Results:*** IMRT and VMAT had better PTV dose conformation than 3DCRT for both central and peripheral targets. PTV conformity improved in VMAT compared to IMRT, and CI values were acceptable for VMAT, IMRT, and 3DCRT plans. VMAT plans had slightly better CI than IMRT, with better results in peripheral lung PTVs compared to central PTVs. VMAT and IMRT are superior for treating HDV and D2cm, with lower HDV for peripheral lung tumours. Both 3DCRT and IMRT improved outcomes for peripheral lung PTVs, while VMAT was better for central lung PTVs. The former proved better with less low lung doses and improved D2cm results. 3DCRT plans demonstrated higher precision in dose distribution than VMAT and IMRT plans, with superior average GI values. VMAT and IMRT had higher HI, Dmax, and D2% than 3DCRT. VMAT plans compared to IMRT plans, with similar HI values for central lung PTVs. VMAT better spares OARs than other techniques, but V20 and V30 lung doses were lower with 3DCRT. VMAT increases lung dose, but OAR stays below thresholds. ***Conclusion***: The investigation found that all three treatment techniques can deliver SBRT plans that meet RTOG dose constraints. However, VMAT is a better treatment strategy than IMRT and 3DCRT for both peripheral and central lung PTVs, based on dosimetric indices like CI, D2cm, HI, and HDV. The study found that 3DCRT improves dosimetric indices, especially gradient index (GI), more than VMAT. Despite the need for more monitor units (MUs) in VMAT plans, treatment time reduced due to faster gantry velocity and higher dose rates (2400cGy/min) via free flatting filter energy.
Keywords: *3DCRT; IMRT; VMAT; Lung cancer; Dosimetric comparison; SBRT*
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INTRODUCTION

Stereotactic body radiation therapy (SBRT) is a type of radiation therapy that delivers high doses of radiation to a small, well-defined target in the body while minimizing the radiation dose to surrounding healthy tissue. SBRT is often used to treat tumours in the lung, liver, spine, and other areas of the body. There are several types of radiation therapy techniques that can be used to deliver SBRT, including 3D conformal radiation therapy (3DCRT), intensity-modulated radiation therapy (IMRT), and volumetric modulated arc therapy (VMAT) [1].

SBRT is a commonly used treatment option for non-small cell lung cancer (NSCLC), particularly for patients who are not candidates for surgery or traditional radiation therapy. NSCLC is the most common type of lung cancer, accounting for about 85% of all lung cancer cases [2]. SBRT delivers high doses of radiation to the tumour in a highly targeted and precise manner, while minimizing the dose to surrounding healthy tissue. This can be particularly important for NSCLC, as the lungs and surrounding organs are highly sensitive to radiation.

Studies have shown that SBRT can be an effective treatment option for NSCLC, with high rates of local tumour control and good overall survival rates. In fact, SBRT has been shown to have similar outcomes to surgery for early-stage NSCLC, with lower rates of complications and shorter recovery times [3].

SBRT is typically delivered over a few treatment sessions. The number of treatment sessions and the radiation dose delivered will depend on the size and location of the tumour, as well as the patient's overall health and treatment goals [4].

Typically, flattening filter (FF) photon beams are employed in all of these therapeutic techniques. In recent times, an alternative choice for FF beams called flattening filter-free (FFF) beams has been made available FFF beams offer a significant benefit over FF in terms of a dose rate that is between two to four times greater [5].

Overall, SBRT can be an important treatment option for patients with NSCLC, particularly those who are not candidates for surgery or traditional radiation therapy. However, as with any cancer treatment, the decision to use SBRT should be made in consultation with a multidisciplinary team of healthcare professionals, including radiation oncologists, medical oncologists, and pulmonologists.

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MATERIALS AND METHODS

When developing and testing treatment plans for SBRT using 10FFF for NSCLC, a common approach is to use a humanoid phantom. A humanoid phantom is a human-shaped object made of materials that mimic human tissue, and it is used to simulate the effects of radiation on the body. Here are some general material and methods for SBRT using 10FFF for NSCLC with a humanoid phantom:

1. Humanoid phantom

A humanoid phantom made of tissue-equivalent materials is used to simulate the human body shown in Figure (1). The phantom should be of a similar size and shape to the patient being treated. Polyurethane material was used to create artificial muscles and soft tissue. A substance that is similar to soft tissue in terms of its atomic properties.

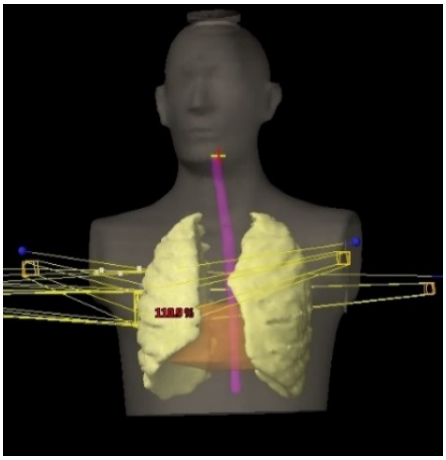

Figure 1. Humanoid phantom

Polyurethane simulated muscle and soft tissue, while a lower density material with the same effective atomic number as soft tissue was used for lungs. The phantom is a 175 cm, 73.5 kg male body sliced at 2.5 cm intervals. [6,7]

Simulation: A CT scan of 25mm slices of the phantom is performed to create a 3D image of the phantom. This image is used to develop a treatment plan, similar to what would be done for a patient. The radiation oncologist and medical physicist work together to develop the treatment plan using specialized software.

2. Characteristics of Treatment Planning

The image registration and contouring tasks were carried out through utilization of the Eclipse 15.6 treatment planning system, which was developed by Varian Medical Systems, Palo Alto, California, United States. The treatment plan is developed using the CT scan image and other information about the tumour. The goal is to deliver a high dose of radiation to the tumour while minimizing exposure to surrounding healthy tissue. The use of 10FFF beams may require adjustments to the treatment plan to optimize dose delivery.

3. Delineation and characteristics of the tumor

The delineation of the gross tumour volumes (GTVs) took place in two locations within the lungs: central and peripheral regions. To mimic the impact of a lung tumour on the phantom, GTV was provided with a skeletal muscle substance possessing a mass density of 1.05 $g \cdot cm^{-3}$ and a CT number of 48 HU. The volume for planning purposes, referred to as the PTV, was acquired by incorporating a margin of 0.5cm to the GTV. 30 PTVs were defined, with 15 being located in each of the lungs. A group of 15 distinct tumour sizes ranging from 1.7 cc to 99.6 cc and located at the same central point were known as PTVs. The volumes of these PTVs differed from one another. Both PTVs were used to contour both tumour locations. The volume of the 15 PTVs in each location (central or peripheral) of the lungs are shown in Table 1.

Table 1. Volumes of fifteen lesions at central and peripheral lung

Target No	Central target volume cm^3	Peripheral target volume cm^3
1	1.7	1.7
2	2.5	2.5
3	3.6	3.6
4	4.5	4.5
5	5.8	5.8
6	7.2	7.2
7	9.6	9.6
8	14.4	14.4
9	22.5	22.5
10	41	41
11	63.2	63.2
12	74.4	74.4
13	87.3	87.3
14	91.8	91.8
15	99.6	99.6

4. Treatment Planning Techniques

This study evaluates the techniques of 3DCRT, IMRT and VMAT planning when performing SBRT for lung tumours. The Eclipse TPS (version 15.6) was utilized to produce the treatment plans. For planning purposes, a 10-MV FFF photon beam was derived from a True Beam linear accelerator manufactured by Varian Medical Systems, Inc. located in Palo Alto, CA, USA. High-definition multi-leaf collimators comprised of 120 leaves were employed to establish field apertures. The

plans were subjected to radiation dose calculations using the AAA algorithm with dose rate 2400MU/min. The plans underwent normalization to ensure that the prescribed dose encompassed 95% of the planning target volume (PTV) [8].

Three-dimensional conformal radiation therapy (3DCRT), intensity-modulated radiation therapy (IMRT), and volumetric modulated arc therapy (VMAT) are all forms of radiation therapy used to treat cancer. Each treatment technique employs different methods to deliver radiation to the cancerous cells while sparing surrounding healthy tissue.

a. 3DCRT

Three-dimensional conformal radiation therapy (3DCRT) is a type of external beam radiation therapy that uses multiple beams of radiation to deliver high doses of radiation to the tumour while sparing surrounding healthy tissue. The beams a shaped using collimators to match the shape of the tumour and delivered from different angles [9,10].

3DCRT using 5- fields involves delivering radiation to the tumour using five different beams, which aimed at the tumour from different angles. The goal of using multiple beams is to maximize the dose of radiation delivered to the tumour while minimizing the dose to healthy surrounding tissue.

b. IMRT

Intensity-modulated radiation therapy (IMRT) is a type of external beam radiation therapy that uses multiple beams of radiation with varying intensities to deliver precise doses of radiation to the tumour while minimizing the dose to surrounding healthy tissue. This achieved by using a collimator with movable leaves that can shape the radiation beam to conform to the shape of the tumour. [11,12]

IMRT using 7- fields involves delivering radiation to the tumour using seven different beams, which aimed at the tumour from different angles. The intensity of each beam modulated using specialized software to deliver different amounts of radiation to various parts of the tumour. This allows for precise dose delivery to the tumour while sparing surrounding healthy tissue. The treatment planned to use specialized software that calculates the optimal beam angles, beam intensities, and leaf positions for delivering the radiation.

c. VMAT

Volumetric modulated arc therapy (VMAT) is a type of external beam radiation therapy that uses a single or multiple arcs of radiation to deliver precise doses of radiation to the tumour while sparing surrounding healthy tissue. The beam shaped using a collimator with movable leaves, similar to IMRT.

VMAT using two full arcs involves delivering radiation to the tumour using two full arcs of radiation to central lung tumour and two half arcs for peripheral lung tumour, which aimed at the tumour from different angles. The collimator leaves move continuously during the delivery of the radiation to modulate the intensity of the beam and shape it to conform to the shape of the tumour. This allows for precise dose delivery to the tumour while sparing surrounding healthy tissue [13,14].

5. Dosimetric Plan Evaluation Indices

i. The conformity index (CI): defined as the ratio of the prescribed dose volume (VPD) to the volume of the planning target receiving the prescribed dose or more (PTVPD). The planned ideal ratio was to be below 1.2 [15].

$$\boldsymbol{CI = \frac{VPD}{PTVPD}} \tag{1}$$

ii. High dose volume (HDV): refers to the volume of tissue that receives a radiation dose above a certain threshold. The threshold dose used to define HDV varies depending on the clinical situation, but it is typically higher than the prescribed dose and can range from 105% to 150% of the prescribed dose [16].

iii. low-dose location (D2cm):is the maximum dose administered to healthy tissue situated at a distance of 2 cm from the planning target volume (PTV) in all directions [17,18].

iv. The gradient index (GI): is the ratio between the volume which receives 50% of the prescribed dose (V50PD) to the volume of prescription isodose (PTV V100%) [19,20].

$$\boldsymbol{GI = \frac{Vol\,(50\%)}{PTV\,V100\%}} \tag{2}$$

v. Homogeneity Index (HI): is an objective tool used to analyse the uniformity of dose distribution in the target volume. HI basically indicates the ratio between the maximum and minimum dose in the target volume and the lower value indicates a more homogenous dose distribution within this volume.

$$\boldsymbol{HI = \frac{D2\%-D98\%}{D50\%}} \tag{3}$$

vi. Maximum dose (Dmax): is the maximum point dose located inside the PTV.

vii. A monitor unit (MU):is a unit of measurement used in radiation therapy to quantify the amount of radiation delivered to a patient. One monitor unit is equal to the amount of charge that is required to produce one cGy of dose in a water phantom.

viii. Beam on time (BOT): the time when a radiation beam used to deliver a set number of monitor units [16,19].

$$\boldsymbol{BOT} = \frac{\boldsymbol{Total\ monitor\ unit}}{\boldsymbol{Dose\ rate\ (2400cGy/min)}} \quad (4)$$

6. Organ at risk constrains

The dose tolerances for Lungs, Oesophagus, Heart, and spinal cord illustrated in Table 2.

Table 2. Organ at risk dose constrains

Structure	Metric	Tolerance (5 fractions)
Both lungs	V20%	10 Gy
	Dmean	8 Gy
Esophagus	D0.01cc	35 Gy
Heart	D0.01cc	29 Gy
Spinal cord	D0.035	25.3 Gy

RESULTS

A set of clinically appropriate plans of volumetric-modulated arc therapy VMAT, IMRT, and 3DCRT were successfully developed for all 15 cases. The dosimetry data pertaining to all Stereotactic Body Radiation Therapy (SBRT) plans were derived through the process of Dose-Volume Histogram (DVH) analysis. Subsequently, a comparison was made between the plans for the three techniques through the utilization of these indices. Table 7 presents the dosimetry outcomes for the treatment plans utilizing 3DCRT, IMRT, and VMAT for the combined lung targets, encompassing all planning target volumes (PTVs) situated in both peripheral and central regions of the lungs. The results of the study were subjected to separate evaluations based on the location of the lung tumour, namely the central and peripheral lung planning target volumes, which are presented in Tables 3-5 respectively. Figure 1 illustrates the axial plane dose allocation in three distinct treatment approaches, 3DCRT, IMRT, and VMAT, for the Planning Target Volume (PTV) encompassing both central and peripheral regions.

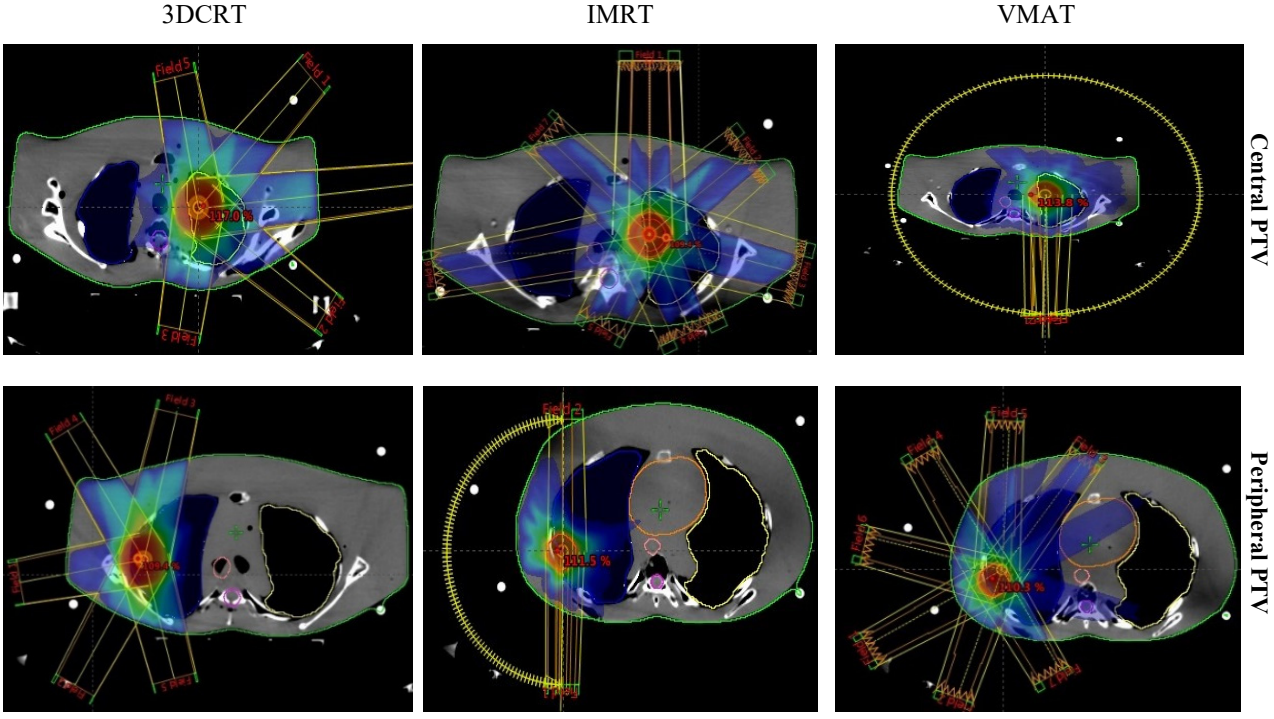

Figure 1. Dose distribution for the three planning techniques in the axial plane both peripheral and central

Table 3. Dosimetric differences in plan parameters between three treatment techniques for central lung PTV

Parameters	3-DCRT	IMRT	VMAT	P-VALUE		
				3DCRT/ IMRT	3DCRT/ VMAT	IMRT/VMAT
HI	0.18±0.03	0.21±0.02	0.21±0.023	0.17	0.13	0.48
CI	1.17±1.3	1.07±0.08	1.04 ±0.06	0.032	0.029	0.034
GI	3.2±0.65	3.42±0.84	4.1±0.47	0.42	0.004	0.003
DMAX%	115±5	117±4	118±5	0.003	0.003	0.009

Parameters	3-DCRT	IMRT	VMAT	P-VALUE		
				3DCRT/ IMRT	3DCRT/ VMAT	IMRT/VMAT
D2%	112±4	113±2	115±3	0.004	0.002	0.003
D2CM%	57±8.3	43.6±5	38±6	0.004	0.003	0.002
HDV%	1.7±0.46	0.44±0.53	0.37±.26	0.003	0.003	0.006
BOT(MIN)	1.54±0.9	1.98±1.2	1.82±0.7	0.005	.008	0.003
MUs	3703±322	4747±534	4367±253	0.003	0.003	0.002

1. Maximum dose (Dmax)and Minimum dose(D2%)
   The results from the statistical analysis for Maximum dose (Dmax)and Minimum dose (D2%) indicated a remarkable variation ($p<0.05$) among the various techniques, except for the p-value associated with maximum dose (Dmax) when comparing the IMRT and VMAT techniques in relation to central lung PTVs. Notably, the calculated p-value for this comparison was found to be 0.09 Table 3.
2. Homogeneity Index (HI)
   Homogeneity index (HI) comparison for central lung PTVs, revealed a significant difference could not be established between three different techniques ($p>0.05$) Table.3, while yielded significant differences ($p<0.05$) between three different techniques for peripheral and combined lung PTVs Table.5,7.

Table (4). Comparison of doses to organs at risk for central lung PTV

organs	parameters	3-DCRT	IMRT	VMAT	P-VALUE		
					3DCRT/ IMRT	3DCRT/ VMAT	IMRT/ VMAT
Both lungs	V20%	4.3±2.3	5.2±3.1	4.01±1.9	0.05	0.162	0.045
	Dmean	3.1±1.8	2.28±2.1	2.7±2.3	0.022	0.033	0.134
Esophagus	D 0.1cc, (Gy)	16.33±2.6	17.8±4.4	13.4±2.8	0.43	0.003	0.002
Heart	D 0.1cc, (Gy)	17.6±1.13	5.4±1.9	3.7±1.8	0.003	0.002	0.003
Spinal cord	D0.035	14.3±2.5	11.7±1.8	10.3±1.6	0.03	0.003	0.002

3. Conformity Index (CI)
   The present study observed a significant improvement in the mean conformity index (CI) values for IMRT and volumetric arc therapy (VMAT) in the combined lung planning target volume (PTV) as compared to (3DCRT). Furthermore, the peripheral lung PTV demonstrated superior CI values as compared to the central lung PTV. all PTV apparatuses fulfilled the corresponding Radiotherapy Oncology Group (RTOG) standards via the utilization of three different techniques. Four smaller planning target volumes (PTVs) were initially scheduled to be delineated within the central lung region using (3DCRT) techniques. However, these PTVs obtain minor deviations. The statistical test conducted for individual comparisons indicated statistically significant differences ($P < 0.05$) among the various techniques Tables 3,5,7.

Table 5. Dosimetric differences in plan parameters between three treatment techniques for peripheral lung PTV

parameters	3-DCRT	IMRT	VMAT	P-VALUE		
				3DCRT/ IMRT	3DCRT/ VMAT	IMRT/ VMAT
HI	0.17±0.06	0.23±0.02	0.22±0.03	0.003	0.003	0.002
CI	1.09±0.08	1.07±0.08	1.04 ±0.06	0.003	0.002	0.003
GI	3.06±0.45	3.3±0.76	3.8±0.39	0.003	0.004	0.174
DMAX%	113±4	116±5	116±7	0.003	0.003	0.005
D2%	110±7	111±5	114±4	0.003	0.003	0.002
D2CM%	52±9	40.6±7	38±5	0.088	0.014	0.19
HDV%	1.1±0.87	0.4±0.77	0.32±.66	0.006	0.003	0.002
BOT(MIN)	1.35±1.04	1.79±0.8	1.65±0.95	0.006	0.003	0.003
MUs	3238±243	4287±435	3956±383	0.003	0.003	0.002

4. High dose volume (HDV)and Low dose location (D2cm)
   The mean values of high-dose volume (HDV) and 2cm dose distance (D2cm) were optimized via VMAT and IMRT techniques for the combined lung planning target volume (PTV). Except for IMRT, which exhibited superior D2cm in comparison to VMAT and (3DCRT) for peripheral lung planning target volumes (PTVs), both central and peripheral lung PTVs illustrated a comparable objective towards the incorporation of the entire lung PTVs. The statistical analysis performed to compare the HDV and D2cm techniques revealed a significant difference with a p-value of less than 0. 05, similar to the Conformity Index (CI) procedure. However, it is observed that the p-values obtained for the D2cm technique in the evaluation of peripheral lung Planning Target Volumes (PTVs) did not yield statistically significant differences between the various techniques investigated ($p>0.05$) Tables 5.

Table 6. Comparison of doses to organs at risk for peripheral lung PTV

organs	parameters	3-DCRT	IMRT	VMAT	P-VALUE		
					3DCRT/IMRT	3DCRT/VMAT	IMRT/VMAT
Both lungs	V20%	4.7±2.8	5.6±3.5	5.91±2.2	0.003	0.003	0.007
	Dmean	3.7±2.3	3.2±1.8	3.7±2.6	0.005	0.003	0.005
Esophagus	(Gy) D0.1cc	4.6±1.6	5.4±1.2	3.8±1.6	0.006	0.003	0.003
Heart	(Gy) D0.1cc	2.2±2.6	2.8±2.2	3.3±1.5	0.003	0.003	0.003
Spinal cord	Dmax (Gy)	7.3±2.6	6.7±3.1	5.6±2.34	0.08	0.003	0.003

5. Gradient Index (GI):
The statistical analysis indicated significant differences ($p < 0.05$) among the gradient index (GI) outcomes observed in the three investigated techniques. However, it should be noted that the p-values for GI outcomes in central lung planning target volumes (PTVs) between (3DCRT) and IMRT plans, as well as in peripheral lung PTVs between IMRT and VMAT plans, were found to be non-significant ($p = 0.427$ and 0.134, respectively) Tables 3,5.

Table 7. Dosimetric differences in plan parameters between three treatment techniques for combined lung PTV

parameters	3-DCRT	IMRT	VMAT	P-VALUE		
				3DCRT/IMRT	3DCRT/VMAT	IMRT/VMAT
HI	0.025±0.05	0.28±0.04	0.27±0.02	0.003	0.002	0.002
CI	1.08±0.08	1.06±0.08	1.03 ±0.06	0.002	0.002	0.002
GI	3.16±0.75	3.34±0.66	3.7±0.45	0.002	0.003	0.003
DMAX%	115±4.6	118±3.3	118±4.4	0.003	0.003	0.003
D2%	113±5.4	116±4.6	115±3.6	0.001	0.001	0.002
D2CM%	49.3±5.3	43.6±6.6	40.6±4.5	0.001	0.001	0.007
HDV%	1.2±0.24	0.49±0.44	0.42±.75	0.001	0.001	0.001
BOT(MIN)	1.5±0.84	1.9±1.02	1.75±0.9	0.001	0.001	0.002
MUs	3603±356	4544±544	4188±311	0.002	0.003	0.003

6. Monitor Unit (MU)and Beam on Time (BOT)
When compared to 3DCRT, the mean MU values for central lung tumours increased by 28.2% with IMRT and 17.9% with VMAT; and 32.39% with IMRT and 22.17% with VMAT for peripheral lung tumours and MU values for combined lung tumours increased by 26.11% with IMRT and 16.23% with VMAT. Similar to monitor unit (MU) Compared with 3DCRT, mean beam on time (BOT) values for central lung tumours increased by 32.5% with IMRT and 18.18% with VMAT; 32.5% with IMRT and 22.2% with VMAT for peripheral lung tumours and combined lung tumours with BOT values increased by 26.7% for IMRT and 16.7% for VMAT Tables 3,5,7.

Table 8. Comparison of doses to organs at risk for combined lung PTV

organs	parameters	3-DCRT	IMRT	VMAT	P-VALUE		
					3DCRT/IMRT	3DCRT/VMAT	IMRT/VMAT
Both lungs	V20%	4.5±2.8	5.6±2.4	4.41±2.6	0.001	0.001	0.273
	Dmean	3.7±2.4	3.3±2.8	2.9±3.3	0.002	0.030	0.223
esophagus	Dmax (Gy)	14.5±5.6	15.8±5.9	11.4±4.6	0.09	0.001	0.001
Heart	Dmax (Gy)	11.6±6.8	4.2±4.2	3.05±1.8	0.05	0.04	0.001
Spinal cord	Dmax (Gy)	11.3±3.5	10.2±3.8	8.6±2.8	0.03	0.003	0.002

7. Organ at Risk Dose limits
All three treatment techniques satisfactorily followed to the dose limits of the organs-at-risk (OAR). The statistical test was conducted for V20 and Dmax in various organs including the spinal cord, oesophagus, and heart, and revealed significant differences amongst different techniques ($p < 0.05$), except for specific instances where p-values for Dmax (spinal cord and oesophagus) between 3DCRT and IMRT for peripheral lung PTVs Table 6 and Dmax (oesophagus) between 3DCRT and IMRT for combined and central lung PTVs ($p > 0.05$) Tables 4,8. Additionally, V20 (lung) between IMRT and VMAT for combined lung PTVs, Dmean (lung) between IMRT and VMAT for combined lung and central lung PTVs, and V20 (lung) between 3DCRT and VMAT for central lung PTVs also exhibited p-values greater than 0.05 Tables 4,8.

DISCUSSION

The aim of the current investigation was to conduct a comparative evaluation of the 3D conformal radiotherapy (3DCRT), intensity-modulated radiotherapy (IMRT), and volumetric arc therapy (VMAT) planning methodologies regarding their suitability for SBRT treatment of lung tumours using 10-MV FFF. Both the VMAT and intensity modulated radiation therapy IMRT techniques have demonstrated superior conformal delivery of prescribed doses to the planning target volume (PTV) for both central and peripheral lung targets in comparison to the traditional (3DCRT) approach. The conformity of the planned target volume (PTV) dose in VMAT plans demonstrated a minor enhancement in comparison to that of modulated radiation therapy (MRT). The conformity index (CI) values of VMAT, IMRT, and 3DCRT plans were found to be within the clinically acceptable limit (CI <1.2) which specified in the Radiation Therapy Oncology Group (RTOG) protocols. However, minor deviations in the CI values (CI>1.5) were observed for the 3DCRT plans designed for the smallest planning target volumes (PTVs) - PTV 1{1.7cc}, PTV 2{2.5cc}, PTV 3{3.6cc}, and PTV 4{4.5cc} - located in the central and peripheral lung PTVs, respectively. The IMRT and VMAT plans demonstrated superior conformity index (CI) outcomes in comparison to the (3DCRT) plans. A marginal enhancement in the conformity index (CI) was noted in the VMAT plans when compared with those of the IMRT plans. The peripheral lung planning target volumes (PTVs) exhibited a superior conformity index (CI) in comparison to the central lung PTVs.

For the treatment of HDV and D2cm, both VMAT and IMRT have revealed superior outcomes compared to 3DCRT. The results of the volumetric analysis indicated a lower high dose volume (HDV) for peripheral lung tumours in comparison to central lung tumours across all three techniques employed in the SBRT treatment plans. The study revealed a linear increase in D2cm with a rise in PTV volumes for both 3DCRT and VMAT techniques. On the other hand, IMRT obtained a notable elevation in D2cm especially for smaller PTV volumes, whereas a was observed for larger PTV volumes. The present study yielded that both 3DCRT and IMRT demonstrated enhanced D2cm outcomes for peripheral lung planning target volumes (PTVs), whereas VMAT showed superior enhancements in D2cm outcomes for central lung PTVs. The present study employed VMAT to administer radiotherapy to patients with centrally and peripherally located primary lung tumours. Specifically, the treatment plan for central lung planning target volumes (PTVs) involved the use of two full coplanar arcs, whereas two half arcs were employed for peripheral lung PTVs. The superior performance of the former approach was attributed to the reduction of low lung doses, thereby improving the D2cm outcomes for central PTVs. When compared to (3DCRT), IMRT and VMAT demonstrated enhanced D2cm outcomes for peripheral and central lung planning target volumes (PTVs). The optimal D2cm was attained through the utilization of VMAT for centrally located lung planning target volumes (PTVs).

The Gradient Index (GI) values of the three-dimensional conformal radiotherapy (3DCRT) plans demonstrated a comparatively higher precision in dose distribution, as opposed to the VMAT and IMRT plans. Moreover, the average GI values of the 3DCRT plans were found to be significantly superior.

The results indicated that the IMRT plans exhibited a superior dose fall-off in the normal tissue compared to the VMAT plans, as evidenced by lower dose values. This outcome was anticipated due to the utilization of non-coplanar (3DCRT) and non-coplanar IMRT, as they attenuate beam overlap from the targeted tumour region. This contrasted with the coplanar VMAT techniques [13, 17].

The present study identifies that the measures of homogeneity index (HI), maximum dose (Dmax), and dose to 2% volume (D2%) attained greater values in both VMAT and intensity modulated radiation therapy IMRT plans compared to those obtained through (3DCRT). A marginal enhancement in the homogeneity index was noted through our observation.

The maximum dose (Dmax) and Dose received by 2% of the volume (D2%) in association with the VMAT plans were compared with those of the Intensity Modulated Radiation Therapy IMRT plans. Notably, the central lung Planning Target Volumes (PTVs) exhibited similar Homogeneity Index (HI) values in both the IMRT and VMAT plans. A heightened level of dosage heterogeneity within the planning target volume (PTV) has the potential to result in a subsequent decline in dosage within healthy tissues [15]. Prior academic research has indicated that an elevated Homogeneity Index (HI) exhibits a negative correlation with the Gastrointestinal Index (GI) (referencing studies 22 and 23). The utilization of the HI parameter as an indicator of plan quality appears promising, however, the existing literature on SBRT has yet to offer any guidance on the optimal HI value for the PTV dose [17, 19]. At present, it appears that the HI parameter demonstrates restricted utility in the optimization of a lung SBRT plan. However, the analysis of dose-volume histograms (DVHs) and dose distribution within axial CT sections remains an important part of the plan review.

VMAT has been found to offer substantial advantages in terms of dose-sparing to the organs at risk (OARs) in comparison to other treatment planning techniques. It should be noted, though, that the V20 and Dmean of the lung dose were significantly lower for the plans conducted using three-dimensional conformal radiotherapy (3DCRT). The disparity in outcomes could be attributed to the non-coplanar beam arrangement utilized in the 3DCRT plans. The increased pulmonary dose observed with VMAT can be attributed to the volumetric distribution of the dose within the planning target volume (PTV) by the rotational arcs. Nevertheless, the administered doses of organ-at-risk (OAR) in each treatment modality were deemed to be substantially lower than the accepted clinical thresholds. IMRT yielded superior outcomes in comparison to (3DCRT) in general. To comprehensively assess the functionality of Organs-At-Risk (OARs), their individual performance analysed with respect to both central and peripheral regions.

The target volumes of the lungs, known as lung Planning Target Volumes (PTVs), are a significant aspect of radiation therapy planning for various thoracic malignancies. Upon analysis, it was found that the VMAT technique outperformed

all other techniques. It was noted that in the context of peripheral tumours, 3-Dimensional Conformal Radiation Therapy (3DCRT) demonstrated certain enhancements in contrast to Intensity Modulated Radiation Therapy (IMRT). Nonetheless, none of the examined locations proved to be universally optimal for all organs at risk (OARs) with the usage of (3DCRT).

When comparing with the 3DCRT, both IMRT and VMAT demonstrated a higher value in terms of the monitor units (MUs) required for treatment delivery. However, VMAT exhibited a superior improvement over IMRT. Our investigation revealed that even though a greater number of Monitor Units (MUs) were necessary for VMAT techniques, the duration of treatment was less than that for (3DCRT). The present study indicates that the dose rate of flatting filter free energy (FFF) beams may be between two to four times greater when compared to conventional FF beams. Consequently, the implementation of FFF-based free flatting filter (FFF) 3D conformal radiotherapy (3DCRT) has resulted in a slightly shorter treatment duration than that observed for FFF-based intensity modulated radiotherapy IMRT in clinical trials. In the case of (FFF) VMAT plans, the treatment delivery time is primarily constrained by the rotational speed of the gantry, rather than the dose rate. Accelerated delivery may potentially decrease the likelihood of intra-fractional setup inaccuracies, which have been reported to occur in treatment procedures lasting over 15 minutes [7, 12].

CONCLUSIONS

The results of this investigation indicate that the three treatment techniques could deliver conformal stereotactic body radiation therapy (SBRT) plans while satisfying the dose constraints specified by the Radiation Therapy Oncology Group (RTOG). Conversely, by assessing dosimetric indices, including conformity index (CI), 2 cm away from the planning target volume (D2cm), homogeneity index (HI), and high dose volume (HDV), VMAT demonstrates a more favourable treatment strategy compared to IMRT and (3DCRT) for treating both peripheral and central lung planning target volumes (PTVs). The present study observed a significant enhancement in dosimetric indices, particularly the gradient index (GI), with the implementation of three-dimensional conformal radiotherapy (3DCRT) over volumetric modulated arc therapy (VMAT). The present observation evidently indicates that, despite the increased demand for higher monitor units (MUs) involved within VMAT plans compared to Three-Dimensional Conformal Radiotherapy (3DCRT), the administration time for treatment is significantly reduced due to the superior gantry velocity employed in the VMAT technique and using free flatting filter energy that increase dose rate to 2400cGy/min.

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ДОЗИМЕТРИЧНЕ ОЦІНЮВАННЯ 10-MV FFF, ВИКОРИСТАНОГО У SBRT ДЛЯ ПУХЛИН ЛЕГЕНЬ

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Мета: Метою цього дослідження було проведення порівняльного та дозиметричного аналізу трьох різних методів променевої терапії, які використовуються в стереотаксичній променевій терапії легенів (SBRT), тривимірній конформній променевій терапії (3DCRT), променевій терапії з модуляцією інтенсивності (IMRT) та об'ємно-модульованій дуговій терапії (VMAT) з використанням пучка фотонів 10 MB без фільтра (FFF). **Матеріали та методи**. У цьому дослідженні з метою планування лікування використовували зображення гуманоїдного фантома за допомогою комп'ютерної томографії (КТ). Великі об'єми пухлини (GTVs), окреслені як у центральному, так і в периферичному положеннях легень. Визначення планових цільових об'ємів (PTV) передбачало додавання запасу в 0,5 см до загального об'єму пухлини (GTV). Тривимірна конформна променева терапія (3DCRT), інтенсивно-модульована променева терапія (IMRT) і об'ємно-модульована дугова терапія (VMAT), створені з використанням 10-мегавольтного (MV) вирівнюючого пучка фотонів без фільтра (FFF). Розрахунок дозування для всіх планів виконується за допомогою анізотропного аналітичного алгоритму (AAA). Результати: IMRT і VMAT мали кращу конформацію дози PTV, ніж 3DCRT як для центральних, так і для периферичних мішеней. Відповідність PTV покращилася у VMAT порівняно з IMRT, а значення CI були прийнятними для планів VMAT, IMRT і 3DCRT. Плани VMAT мали дещо кращий ДІ, ніж IMRT, з кращими результатами в PTV периферичних легенів порівняно з центральними PTV. VMAT та IMRT кращі для лікування HDV та D2cm, з нижчим HDV для периферичних пухлин легень. Як 3DCRT, так і IMRT покращили результати для PTV периферичних легенів, тоді як VMAT був кращим для центральних PTV легенів. Перший виявився кращим з менш низькими дозами в легенях і покращив результати D2cm. Плани 3DCRT продемонстрували вищу точність розподілу дози, ніж плани VMAT та IMRT, з вищими середніми значеннями ГІ. VMAT і IMRT мали вищі HI, Dmax і D2%, ніж 3DCRT. Плани VMAT порівняно з планами IMRT, з подібними значеннями HI для центральних легеневих PTV. VMAT краще заощаджує OAP, ніж інші методи, але дози V20 і V30 у легенях були нижчими з 3DCRT. VMAT збільшує легеневу дозу, але OAR залишається нижче порогових значень. **Висновок:** дослідження виявило, що всі три методики лікування можуть забезпечити плани SBRT, які відповідають обмеженням дози RTOG. Однак VMAT є кращою стратегією лікування, ніж IMRT і 3DCRT, як для периферичних, так і для центральних легеневих PTV, заснованих на дозиметричних показниках, таких як CI, D2cm, HI і HDV. Дослідження показало, що 3DCRT покращує дозиметричні показники, особливо градієнтний індекс (GI), більше, ніж VMAT. Незважаючи на потребу в більшій кількості моніторів (MU) у планах VMAT, час лікування скоротився завдяки вищій швидкості гентрі та вищим потужністю дози (2400 сГр/хв) через вільну енергію фільтра.

Ключові слова: *3DCRT; IMRT; VMAT; Рак легенів; дозиметричне порівняння; SBRT*