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Original Article

Comparison of plan dosimetry on multi-targeted lung radiotherapy: A phantom-based computational study using IMRT and VMAT

Muhammad Isa Khan [a, b], Jalil ur Rehman [c], Muhammad Afzal [d], James C.L. Chow [b, e, *]

[a] Department of Physics, University of Gujrat, Pakistan
[b] Radiation Medicine Program, Princess Margaret Cancer Centre, University Health Network, ON, Canada
[c] Department of Physics, Khawaja Farid University of Engineering and Information Technology, Rahim Yar Khan, Pakistan
[d] Department of Physics, The Islamia University Bahawalpur Pakistan, Pakistan
[e] Department of Radiation Oncology, University of Toronto, ON, Canada

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ABSTRACT

This work analyzed the dosimetric difference between the intensity modulated radiotherapy (IMRT), partial/single/double-arc volumetric modulated arc therapy (PA/SA/DA-VMAT) techniques in treatment planning for treating more than one target of lung cancer at different isocenters. IMRT and VMAT plans at different isocenters were created systematically using a Harold heterogeneous lung phantom. The conformity index (CI), homogeneity index (HI), gradient index (GI), dose-volume histogram and mean and maximum dose of the PTV were calculated and analyzed. Furthermore, the dose-volume histogram and mean and maximum doses of the OARs such as right lung, contralateral lung and non GTV were determined from the plans. The IMRT plans showed the superior target dose coverage, higher mean and maximum values than other VMAT techniques. PA-VMAT technique shows more lung sparing and DA-VMAT increases the $V_{5/10/20}$ values of contralateral lung than other VMAT and IMRT techniques. The IMRT technique achieves highly conformal dose distribution to the target than other VMAT techniques. Comparing to the IMRT plans, the higher $V_{5/10/20}$ and mean lung dose were observed in the contralateral lung in the DA-VMAT.

1. Introduction

The main objective of external beam radiotherapy (EBRT) is to deliver a homogeneous radiation dose to the tumor target, while minimizing the dose to surrounding organs-at-risks (OARs) [1]. Three-dimensional conformal radiotherapy (3DCRT) is an example of EBRT and it includes direction of multiple radiation beams conformed to the shape of the target [2]. The intensity modulated radiotherapy (IMRT) is an advanced form of 3DCRT that combines intensity modulated beams leading to the construction of highly conformal dose distribution. Some of the benefits of IMRT over 3DCRT are the improved conformity for target volume that has complex shape, and better sparing of OARs [3–7].

Recently, volumetric modulated arc therapy (VMAT) was introduced to replace the classical 3DCRT [8–10]. The VMAT system can deliver a highly conformal radiation dose to the target using one or two arcs, although complex shaped targets may require more arcs, and the delivery technique allows the simultaneous variation of gantry rotation speed, dose rate and multileaf collimator (MLC) leaf positions. Furthermore, radiotherapy for lung cancer can be challenging since the target is surrounded by a healthy lung tissue, a radiosensitive organ that has a low radiation tolerance.

The published data in Ref. [11] on VMAT (RapidArc and SmartArc) planning studies of lung cancer show that VMAT techniques have clear superiority over 3DCRT with regard to improving dose conformity and sparing of OARs. However, dosimetric differences between VMAT and IMRT planning studies are less distinct. Specifically, the data indicates that for lung tumor VMAT and IMRT provide equivalent dose homogeneity, dose conformity and target volume coverage [12–19].

The aim of this study is to provide information about the dose distribution by changing the position of isocenter when more than one targets treated with IMRT, partial arc (PA) VMAT, single arc (SA) VMAT, and double arc (DA) VMAT techniques.

* Corresponding author.. Radiation Medicine Program, Princess Margaret Cancer Centre, University Health Network, ON, Canada.
E-mail address: james.chow@rmp.uhn.ca (J.C.L. Chow).

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Table 1
DV control points for the PTVs, Non GTV, left and right lung, spinal cord for all studied techniques.

Volume of interest	DV control point (cGy)
PTV1, PTV2, PTV3	$D_{99} \geq 6600$
	Maximum dose to 1 $cm^3 \leq 6900$
Non GTV	$D_{25} \leq 2000$
	$D_5 \leq 500$
Left lung	$D_{15} \leq 2000$
Right Lung	$D_{25} \leq 2000$
Spinal cord 3 mm	Maximum dose to 1 $cm^3 \leq 4000$

2. Materials and methods

2.1. Planning Schemes

This study was established to compare the dose distribution when there are more than one target under different radiotherapy techniques. The main focus was on coverage of all targets (PTV1, PTV2, and PTV3) and sparing of OARs such as non GTV, left lung and right lung. Five-field (beam angles: 120°, 225°, 300°, 0° and 270°) were used for IMRT, partial arc (180° − 0°), single arc (180° - 179.9°) and dual arc with angles (180° - 179.9°, 179.9° − 180°) were used for VMAT. The internal organ motion, patient setup uncertainty and sub-clinical disease spread are accounted by the margin between the GTV and PTV. This margin (e.g. 0.5 cm) is necessary to ensure an acceptable dose coverage at the tumour under the uncertainties caused by the internal organ motion of lungs (i.e. patient's breathing). In this study, the closest distance between two targets was 1 cm considering the margins from the GTV to PTV was set to 0.5 cm. Since this study was to compare the plan dosimetry between VMAT and IMRT, the target size was set unchanged.

The Harold phantom developed by Chiarot et al. [20] was used for this study. Computed tomography (CT) images were taken from the Toshiba scanner (Aquilion ONE TSX-301A; Toshiba medical systems, USA) containing 512 × 512 pixels in each slice. The Harold phantom was irradiated by a 120 kVp photon beam with 300 mA current perpendicular to the phantom surface. After the CT simulation, digital imaging and communication in medicine (DICOM) CT images were transferred to the Pinnacle treatment planning system (TPS) for contouring and planning preparation. PTV1, PTV2, PTV3, non GTV, left lung, right lung and spinal cord were contoured on the TPS.

The radiotherapy techniques such as 5-field IMRT, partial arc (PA-VMAT), single arc (SA-VMAT) and double arc (DA-VMAT) plans were all designed to achieve conformal dose distribution while sparing dose to OARs. The crucial distinction is that the number of isocenters was proportional to numbers of PTVs in all studied radiotherapy techniques. The isocenter was placed at the center of each PTV and at the center of three PTVs for studied radiotherapy techniques, respectively. PTV1, PTV2 and PTV3 were too close to be separated, thus being treated and evaluated as a whole in these studied techniques.

2.2. VMAT plan and treatment delivery

For planning the patient, a Synergy S® linear accelerator with an energy of 6 MV, equipped with beam modulator head, an iViewGT electronic portal imaging device, and on board cone-beam CT XVI was used for IMRT, partial arc, single arc, and double arc VMAT delivery. There were no moveable jaws and the maximum field size was 16 cm × 21 cm. Although dose rate can be varied in VMAT, it was binned to 600 MU/min for each VMAT plan.

Smart-arc prostate VMAT plans were generated on Pinnacle (Philips, Version 9.2.0, Fitchburg, WI, 53711–4910, and U.S.A) TPS with ACQSim^{3TM} and were optimized with the direct machine parameter optimization (DMPO) algorithm. The isocenter was positioned differently such as on the center of all targets, on the PTV1, PTV2 and PTV3 for all studied delivery techniques. These plans were set up in 33 fractions for 66 Gy minimum doses to the CTV. All calculations were performed using adaptive convolve (AC) having a calculation grid spacing of 0.25 cm**.** In order to make fair comparisons, no modification was done throughout the optimization to the dose-volume constraints and weighting. Dose-volume histogram (DVH) control points are given in Table 1.

2.3. Dosimetric evaluation

The dosimetric comparison was carried out using the following parameters such as conformity index (CI), homogeneity index (HI) and gradient index (GI) when isocenter is at the center of PTVs, PTV1, PTV2 and PTV3 for all studied techniques as shown in Table 2. Maximum dose (D_{max}) and mean dose (D_{mean}) are also computed for this dosimetric comparison as shown in Table 3 for all studied techniques.

By definition, RTOG CI is the volume of the target receiving >98% of the prescribed dose divided by the volume of the PTV which has an optimal value of 1. HI is defined as the dose received by 5% of the PTV minus the dose received by 95% of the PTV divided by the mean dose (its optimal value is 0) as shown in Equation (1) [21].

$$HI = \frac{D_5 - D_{95}}{D_{mean}} \quad (1)$$

GI is defined as the ratio of volume covered by at least a given percentage of the prescribed dose [18]. Mathematically, GI in this study is expressed in (2) as:

$$GI = \frac{V_{50}}{V_{100}} \quad (2)$$

where V_{50} is the volume covered by 50% of the prescribed dose. A value closer to unity embodies a faster dose fall-off in normal tissue, which may indicate a lower dose to critical structures.

2.4. Dose-volume histogram (DVH) evaluation

Dose-volume histogram plots were used to provide quantitative comparisons among all different techniques for all targets and

Table 2
Dosimetric results of conformity index, homogeneity index, and gradient index when isocenter is at the center of all PTVs, PTV1, PTV2 and PTV3 for all studied techniques.

		Isocenter is at Center	Isocenter is at PTV1	Isocenter is at PTV2	Isocenter is at PTV3
IMRT	CI (mean)	0.94	0.92	0.91	0.95
	HI (mean)	0.12	0.06	0.07	0.07
	GI (mean)	1.19	1.19	1.19	1.19
PA-VMAT	HI (mean)	0.14	0.14	0.13	0.12
SA-VMAT	HI (mean)	0.14	0.13	0.15	0.15
DA-VMAT	HI (mean)	0.14	0.14	0.13	0.12

Table 3
Maximum and mean doses to IMRT, partial arc VMAT, single arc VMAT and dual arc VMAT.

			IMRT	Partial Arc VMAT	Single Arc VMAT	Dual Arc VMAT
D_{mean} (Gy)	Center	PTV1	62.80	53.73	53.33	53.10
		PTV2	62.88	53.21	53.80	53.79
		PTV3	63.26	54.82	53.63	53.29
	PTV1	PTV1	62.84	53.92	53.40	53.01
		PTV2	62.90	53.79	53.86	53.63
		PTV3	63.25	54.82	53.78	53.48
	PTV2	PTV1	62.81	54.20	53.66	53.32
		PTV2	62.93	52.83	53.84	53.47
		PTV3	63.31	54.66	53.74	53.71
	PTV3	PTV1	62.84	54.41	53.38	53.30
		PTV2	62.91	53.41	53.79	53.73
		PTV3	63.29	54.86	53.58	53.71
D_{max} (Gy)	Center	PTV1	69.18	60.56	59.90	59.76
		PTV2	69.34	59.87	60.03	60.17
		PTV3	69.09	61.03	59.90	59.76
	PTV1	PTV1	69.24	60.69	60.07	59.41
		PTV2	69.53	60.92	60.07	59.59
		PTV3	69.31	61.14	60.13	59.49
	PTV2	PTV1	69.13	60.96	60.21	59.48
		PTV2	69.28	60.02	60.12	59.47
		PTV3	69.27	60.95	60.12	59.90
	PTV3	PTV1	69.04	61.05	59.85	59.97
		PTV2	69.41	60.30	59.80	59.93
		PTV3	69.26	61.23	59.82	59.92

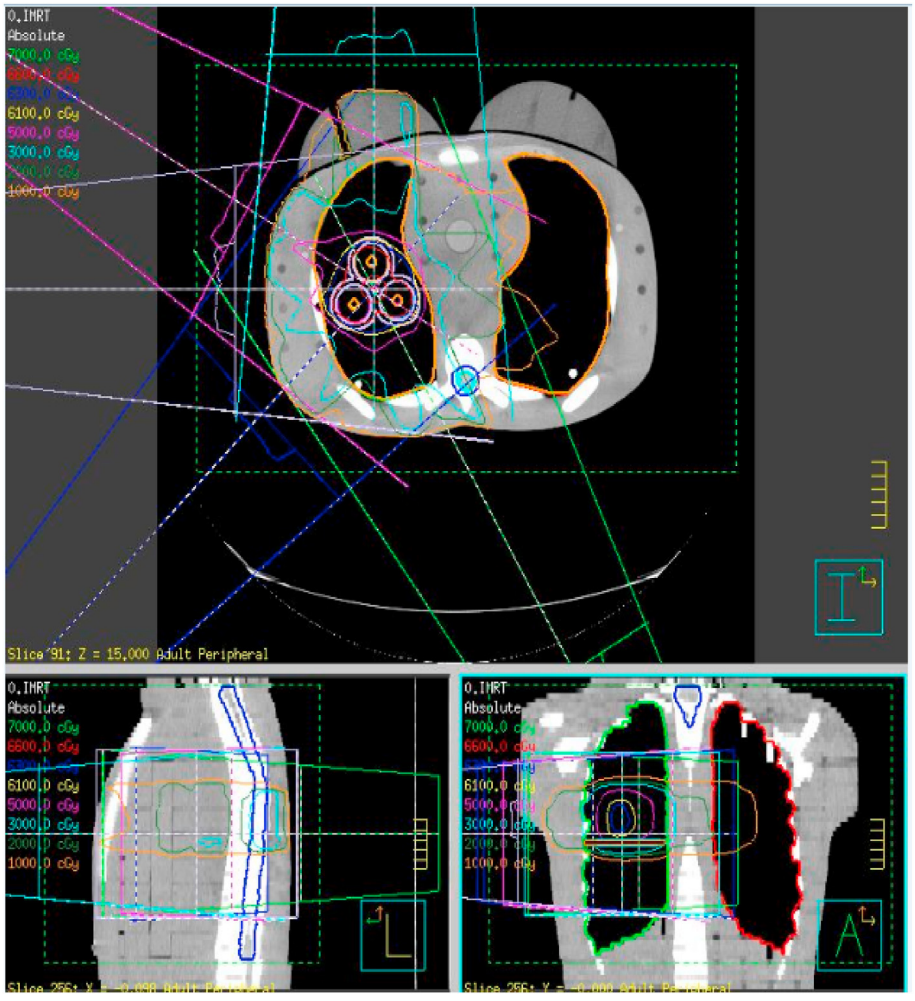

Fig. 1. The isodose distribution of IMRT when isocenter is at center of the three PTVs.

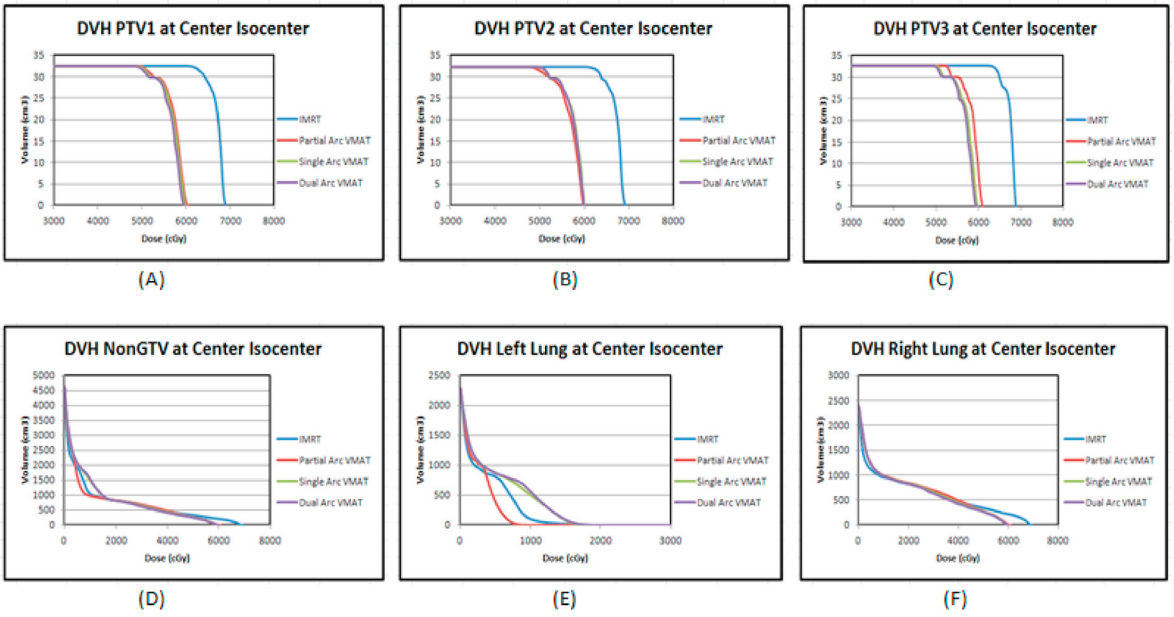

Fig. 2. (A–F): DVH of PTV1, PTV2, PTV3, Non GTV, Left lung and Right lung when isocenter is at the center for IMRT, partial arc, single arc and dual arc techniques.

OARs. The DVH data for each technique was gathered from Pinnacle[3] with a bin size of 0.01 Gy. All targets and organ specific individual DVHs for each studied techniques were calculated.

3. Results

This study has been carried out on a Harold phantom and clinically acceptable IMRT plans satisfying a minimum of 98% prescribed coverage to PTV and a goal of minimum dose to OARs were achieved but the coverage to the PTV was partially under-dosed with studied PA-VMAT, SA-VMAT and DA-VMAT techniques. It was used to make this work repeatable and typical, though it is not statically significant. Fig. 1 shows the isodose distribution of IMRT when isocenter is placed at center of three PTVs and PTV1 is sketched at the top, PTV2 is at the right and PTV3 at the left side.

The values of CI, HI and GI when isocenter is at center of all PTVs, PTV1, PTV2 and PTV3 for all studied techniques such as IMRT, PA-VMAT, SA-VMAT and DA-VMAT are shown in Table 2. The table shows that PTV coverage was found in acceptable range for just IMRT technique. The higher mean value (0.95) and lower mean value (0.91) of CI was found when isocenter is placed at PTV3 and PTV2, respectively. The lower mean value of HI was found 0.06 when isocenter is placed at PTV1 for IMRT. The values of GI were remain the same wherever isocenter is placed for IMRT. The DVHs of Figs. 2–5 show the actual volumes of the targets and critical

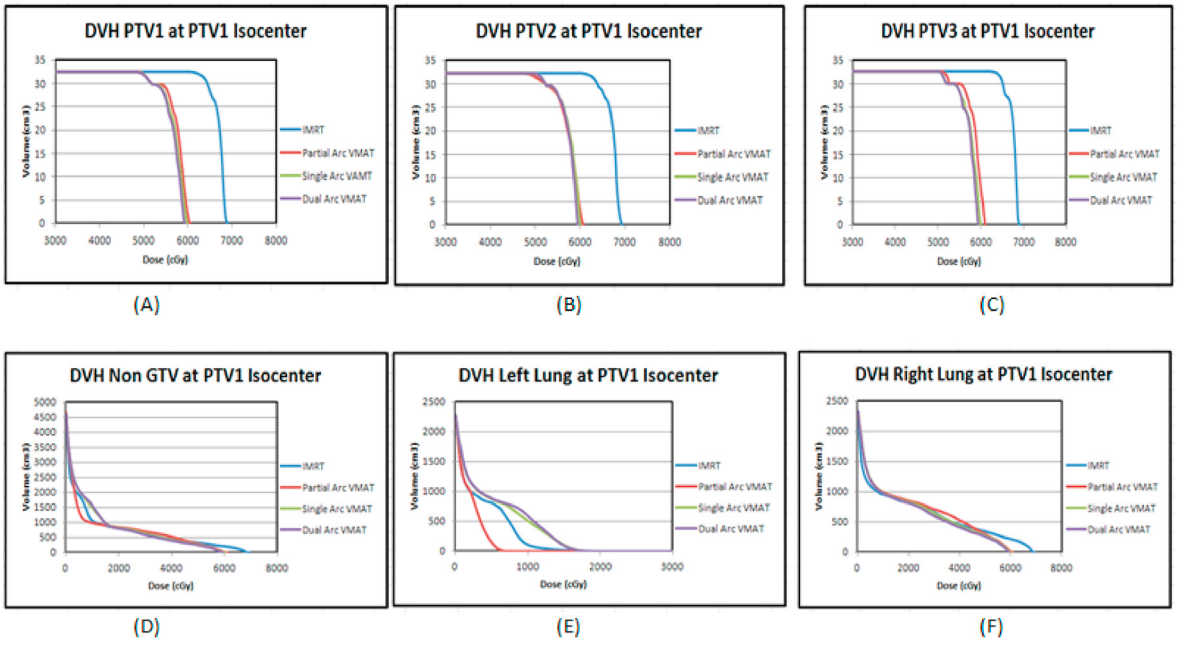

Fig. 3. (A–F): DVH of PTV1, PTV2, PTV3, Non GTV, Left lung, Right lung when isocenter is at PTV1 for IMRT, partial arc, single arc and dual arc VMAT techniques.

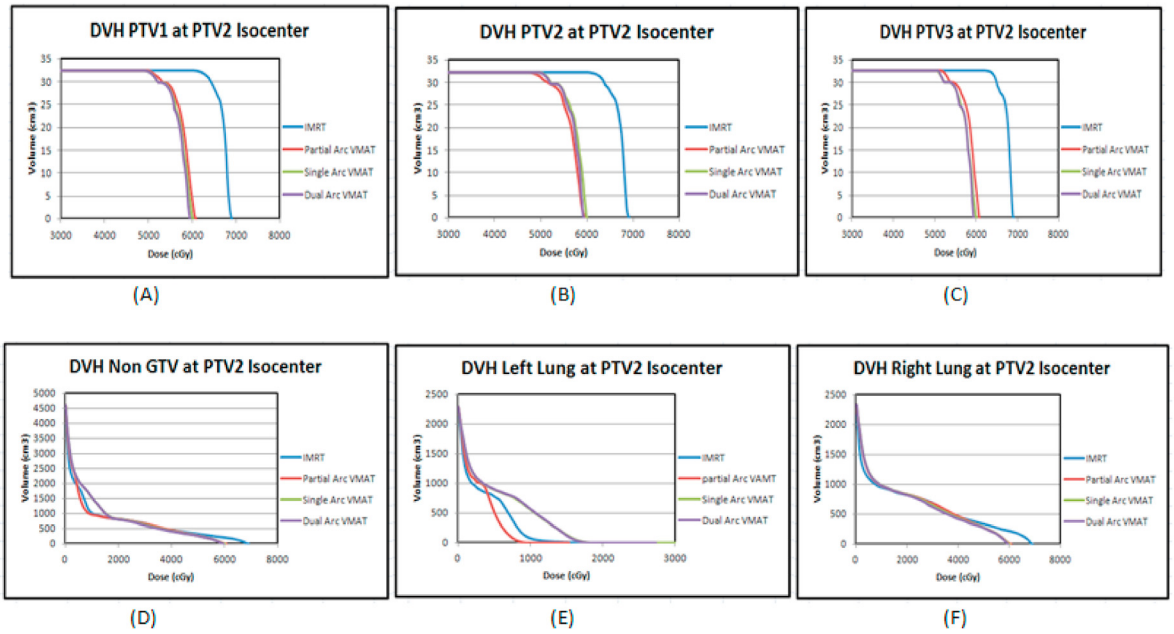

Fig. 4. (A–F): DVH of PTV1, PTV2, PTV3, Non GTV, Left lung, Right lung when isocenter is at PTV2 for IMRT, partial arc, single arc and dual arc VMAT techniques.

organs. This provided more information in justifying the variation of DV, when different radiation dose delivery techniques (i.e. IMRT and VMAT) were used in the study.

The maximum and means doses to IMRT, PA-VMAT, SA-VMAT and DA-VMAT plans, when isocenter is at the center of the three PTVs, PTV1, PTV2, and PTV3, are shown in Table 3.

The DVHs of the PTV1, PTV2, PTV3, Non GTV, Left lung, Right lung are shown in Figs. 2–5, when isocenter is at the center of the three PTVs, PTV1, PTV2 and PTV3 for all studied techniques. Comparing IMRT and other VMAT plans, PA-VMAT plans show advantages in dose sparing of the contralateral lung.

The planning dose objectives of the Non GTV, agree well with the prescribed dose; their mean, maximum, D_5 and D_{25} were shown in Table 4. The dose to both lungs was found to be within the acceptable range; their mean, maximum, D_{15}, D_{25}, V_5, V_{10} and V_{15} were calculated and shown in Table 4.

4. Discussion

4.1. Dose-volume indices

The PTV conformity index CI calculated for IMRT versus PA-VMAT, SA-VMAT and DA-VMAT techniques are shown in Table 2. The IMRT plans show a higher and tighter confirmation of the high dose region to the target volumes than other studied techniques. The higher mean value of CI was found when isocenter was placed at PTV3 and its mean

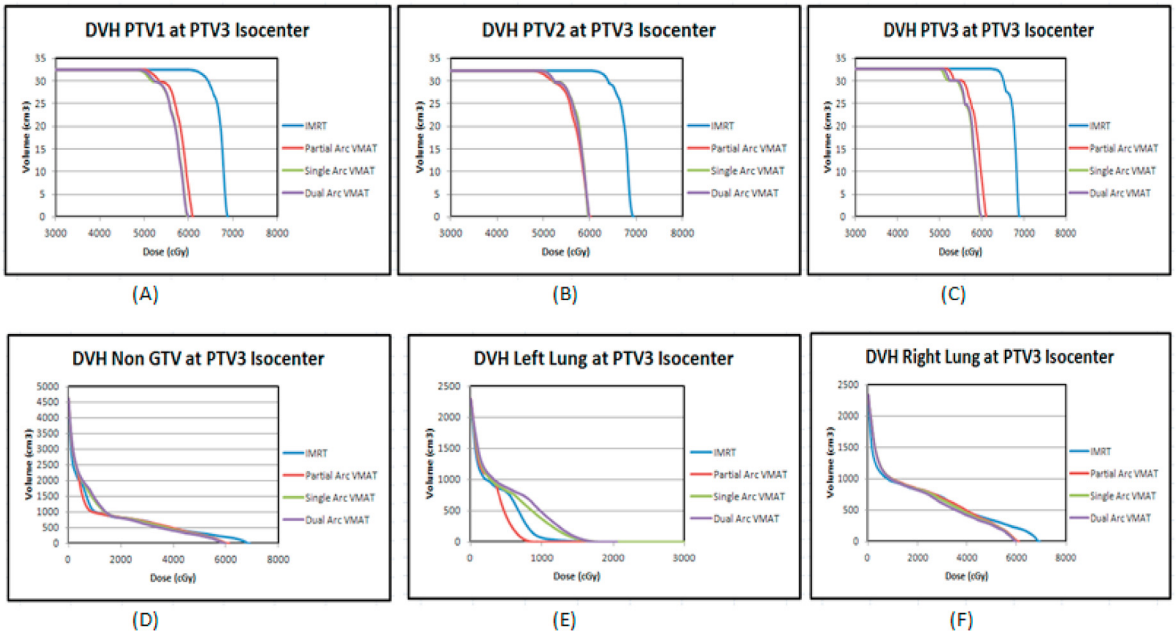

Fig. 5. (A–F): DVH of PTV1, PTV2, PTV3, Non GTV, Left lung, Right lung when isocenter is at PTV3 for IMRT, partial arc, single arc and dual arc VMAT technique.

Table 4
The mean, maximum, D_5, D_{15}, D_{25}, V_5, V_{10} and V_{15} for Non GTV, contralateral lung and right lung for IMRT and VMAT techniques.

	Isocenter at		IMRT	Partial arc (PA)	Single arc (SA)	Dual arc (DA)
Non GTV	Center	D_5 (Gy)	57.8	51.8	51.8	51.25
		D_{25}(Gy)	11.9	6.9	13.1	12.95
		D_{mean} (Gy)	10.73	10.16	11.11	11
		D_{max} (Gy)	69.34	60.99	60.03	60.17
	PTV1	D_5 (Gy)	57.15	52.6	51.3	59.9
		D_{25}(Gy)	8.78	6.08	12.65	13.3
		D_{mean} (Gy)	10.72	10.12	11.10	10.93
		D_{max} (Gy)	69.51	61.14	60.14	59.59
	PTV2	D_5 (Gy)	57.6	52.5	52	51.95
		D_{25}(Gy)	8.7	7.2	13.6	13.55
		D_{mean} (Gy)	10.62	10.15	11.23	11.09
		D_{max} (Gy)	69.28	60.99	60.21	59.50
	PTV3	D_5 (Gy)	57.9	29.2	51.7	26.15
		D_{25} (Gy)	8.5	7	12.5	12.5
		D_{mean} (Gy)	10.75	10.29	10.90	10.87
		D_{max} (Gy)	69.39	61.23	59.86	59.97
L-Lung/Contralateral lung	Center	D_{15} (Gy)	8.1	5.3	11.95	12
		D_{mean} (Gy)	3.58	2.66	4.96	5.1
		D_{max} (Gy)	22.8	10.09	18.46	19.46
		V_5 (%)	39.3	43.2	43.2	43.1
		V_{10} (%)	10	5.2	34.4	31.1
		V_{20} (%)	2.9	0	10	10
	PTV1	D_{15} (Gy)	8.3	4.1	12.1	12.45
		D_{mean} (Gy)	3.65	2.05	5.04	5.24
		D_{max} (Gy)	23.45	8.5	19.05	19.17
		V_5 (%)	39.6	25.3	43.6	44.2
		V_{10} (%)	28.9	4	34.8	35.7
		V_{20} (%)	3	0	18.1	20.6
	PTV2	D_{15} (Gy)	7.7	5.7	12.55	12.6
		D_{mean} (Gy)	3.43	2.88	5.28	5.32
		D_{max} (Gy)	21.67	10.28	19.51	19.03
		V_5 (%)	38.5	43.4	44.3	44.6
		V_{10} (%)	25.4	8	35.8	36.1
		V_{20} (%)	1	0	19.9	12.7
	PTV3	D_{15} (Gy)	7.55	5.4	10.5	11.35
		D_{mean} (Gy)	3.40	27.26	4.46	4.91
		D_{max} (Gy)	21.9	98.97	19.47	18.71
		V_5 (%)	39	42.5	42	44
		V_{10} (%)	24	6	31.5	34.6
		V_{20} (%)	1	0	6	8.1
R-Lung	Center	D_{25} (Gy)	32.8	35.2	33	31.6
		D_{mean} (Gy)	17.82	17.53	17.16	16.83
		D_{max} (Gy)	69.34	61.03	60.03	60.17
		V_5 (%)	50.9	59	59.6	59.3
		V_{10} (%)	43.4	45.8	46.1	45.9
		V_{20} (%)	39.3	39	38.7	38.5
	PTV1	D_{25} (Gy)	32.7	37.2	32.2	30.35
		D_{mean} (Gy)	17.71	18.05	17.08	16.56
		D_{max} (Gy)	69.53	61.14	60.14	59.59
		V_5 (%)	50.9	59.3	59.5	59.1
		V_{10} (%)	43.4	46.3	46	45.7
		V_{20} (%)	38.1	39.4	38.6	38.2
	PTV2	D_{25} (Gy)	33	34.2	32.2	31
		D_{mean} (Gy)	17.74	17.31	17.11	16.80
		D_{max} (Gy)	89.28	60.99	60.21	59.50
		V_5(%)	51	58.4	69.3	59.31
		V_{10} (%)	43.1	45.3	46.1	45.9
		V_{20} (%)	38	38.2	38.7	38.6
	PTV3	D_{25} (Gy)	33.9	35.4	33.35	31.25
		D_{mean} (Gy)	18.01	17.73	17.25	16.76
		D_{max} (Gy)	69.41	61.23	59.86	59.97
		V_5 (%)	51.8	59.2	59.4	59.1
		V_{10} (%)	43.4	43	46.1	45.9
		V_{20} (%)	38.4	39.3	38.7	39.8

lower value was found when isocenter was at PTV2 for IMRT. The HI mean value of the IMRT when isocenter was placed at PTV1 was lower on the average of 0.6% than rest of the techniques. The higher mean HI value was found 0.15 for SA-VMAT and DA-VMAT. GI remains with the same results and show no difference by changing the isocenter. Overall, the difference is very small to be reported for IMRT but no CI and GI values were found for rest of the studied techniques. This may be due to lower coverage of the PTV in SA-VMAT, PA-VMAT, and DA-VMAT techniques. The coverage was not good due to variation in lung density or maybe on inhomogeneity correction.

4.2. Dose-volume criteria, maximum and mean dose

Mean dose-volume criteria, maximum and mean dose are the important parameters for plan evaluation. Mean doses of IMRT were found (84.4%), (84.6%), (84.5%) and (84.7%) higher than all

other studied VMAT techniques, when isocenter is placed at the center of three PTVs, PTV1, PTV2 and PTV3, respectively. For the mean D_5, D_{25} and D_{mean} of the non GTV, all the techniques satisfied the corresponding dose volume criteria. The mean D_5 of non GTV is found lower (on the average of 0.41%, 0.54%, 0.47% and 0.44%) for PA-VMAT, when isocenter is placed at the center of all PTVs, PTV1, PTV2, and PTV3 than other study techniques. D_{mean} found to be lower on the average of 0.08% for PA than other studied techniques at the placement of isocenter at different places. The mean D_5 of the non GTV is found lower for DA-VMAT. However, higher D_{25} and D_{mean} values were found for SA and higher D_5 values were found for IMRT than other studied techniques.

D_{15} and D_{mean} of left lung were found lower for PA-VMAT on the average of (0.55%, 0.67%, 0.54%, 0.52% and 0.47%, 0.6%, 0.45%, 0.45%) than other studied techniques when isocenter is placed at the center of three PTVs, PTV1, PTV2 and PTV3. The higher values of D_{15} and D_{mean} of left lung were found for DA-VMAT than all other studied techniques. DA-VMAT shows lower percentage values of right lung than all other studied techniques and the higher values were found for PA-VMAT as given in Table 3.

4.3. Dose-volume histogram

Figs. 2–5 (A-C) show the average DVH of all targets (PTV1, PTV2 and PTV3) at different isocenters using all studied techniques. The dose range in Figs. 2–5 (A-C) begin at 30 Gy rather than 0 Gy to focus on the drop-off region of the curve. IMRT showed higher PTV coverage than other studied techniques, when isocenter is placed at center of all PTVs, PTV1, PTV2 and PTV3. PA-VMAT shows lower doses to left lung and non GTV than all studied techniques as illustrated in DVHs for different isocenters, whereas DA-VMAT shows lower doses to right lung.

4.4. Contralateral lung

Jiang et al. [22] conducted the retrospective study of 12 locally advanced lung cancer patients and analyzed the differences between IMRT and single/partial-arc Smart-arc (SA/PA-smartArc) techniques in treatment planning. The SA-SmartArc plans showed the superior target dose coverage and comparable target dose (minimum, mean and maximum). For the total and contralateral lung, in comparison to IMRT plans, the V (5 Gy) and V (10 Gy) values were higher; whereas the V (20 Gy) and V (30 Gy) values as well as mean lung doses were lower in the SmartArc plans. Rao et al. [23] showed that the V_{20} value was slightly higher in the Smart Arc plans than in the IMRT plans.

For contralateral left lung, a lower value of V_5 was achieved in IMRT plans: however, a small increase in V_5 value to contralateral left lung was obtained in DA-VMAT plans compared to IMRT plans. It can be seen in Table 3 that V_{20} values are higher in DA-VAMT plans than IMRT or other techniques. However, lower V_{20} values were found in PA-VMAT plans. Overall, for the contralateral lung, in comparison to IMRT plans, the V_5, V_{10} and V_{20} values were higher in DA-VMAT plans. This foundation is correlated with the study of McGrath et al. among lung cancer patients [24].

5. Conclusions

In this treatment plan dosimetric analysis, IMRT plans show more optimal target coverage than other VMAT techniques. Compared to IMRT and other VMAT techniques, DA-VMAT increases the $V_{5/10/20}$ values to contralateral lung. PA-VMAT technique shows more sparing of contralateral lung than other VMAT and IMRT plans. Considering target motion, VMAT plan for lung cancer is more effective compared to IMRT because VMAT improved the dose delivery efficiency and shortened the treatment time.

Financial disclosure

None declared.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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