Comparison of three Radiotherapy Techniques Volumetric Modulated Arc Therapy with Variable and Constant Dose Rate and Intensity-Modulated Radiotherapy for the Irradiation of Five Cancer Sites

Varsha Raghunathji Gedam (PhD Candidate)[1,2]*, Anirudh Pradhan (PhD)[3]

[1]Department of Medical Physics, Delhi State Cancer Institute, Dilshad Garden-110095, Delhi, India
[2]Department of Physics, GLA University, Mathura-281406, Uttar Pradesh, India
[3]Centre for Cosmology, Astrophysics, and Space Science, GLA University, Mathura-281406, Uttar Pradesh, India

ABSTRACT

Background: Volumetric modulated arc therapy (VMAT) is mostly considered due to its superior tumor coverage and sparing of organs at risk (OAR) with shorter treatment delivery time.

Objective: This study aimed to explore the feasibility and potential benefits of VMAT with a constant dose rate (CDR).

Material and Methods: In this analytical study, 75 cancer patients (15 from each cancer) were selected. Step and shoot intensity-modulated radiation therapy (S&S IMRT), CDR, and VDR VMAT (variable dose rate VMAT) plans were generated for each patient using the Monte Carlo algorithm on the Monaco treatment planning system for 6 MV photon energy. For dosimetric comparison, some variables were compared, including doses to the planning target volume (PTV), OAR, homogeneity index, conformity index (CI), treatment delivery time, and monitor units.

Results: CI was higher in CDR and VDR VMAT plans compared to IMRT without any significant variation for PTV coverage V95 and PTV mean dose. In the sparing of OAR, no significant variation was found between CDR, VDR, and IMRT for the brain, head-neck, oesophagus, lung, and prostate. The treatment delivery time was reduced more, i.e., by up to 72-80% in the CDR VMAT technique compared to IMRT.

Conclusion: CDR VMAT technique generates a clinically acceptable plan in terms of PTV coverage, dose conformity, and OAR sparing as IMRT and VDR VMAT in all five cancer sites.

Keywords

Radiotherapy; Head and Neck; Brain; Prostate; Esophagus; Lung

Introduction

Intensity-modulated radiation therapy (IMRT) is mostly considered a treatment for many cancer cases due to its advantage in planning target volume (PTV) coverage and organ-at-risk OAR (organ-at-risk) sparing [1-3]. IMRT delivers radiation through a linear accelerator (Linac) fitted with a multileaf collimator (MLC) and also uses an inverse planning method to deliver non-uniform beam intensities from fixed gantry angles. However, the IMRT technique requires a longer treatment de-

*Corresponding author:
Varsha Raghunathji Gedam
Department of Medical Physics, Delhi State Cancer Institute, Dilshad Garden-110095, Delhi, India
E-mail: varshadhargave@gmail.com

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livery time, leading to intra-fraction positional error. This intra-fraction motion could impact underdose or overdose to PTV and also overdose to OAR.

The volumetric modulated arc therapy (VMAT) technique has been known more due to its dosimetric advantages in terms of PTV coverage and OAR sparing with lower monitor units and shorter treatment delivery time [4-6]. Moreover, VMAT delivers radiation through a continuously rotating arc with varying dose rates, gantry speed, and MLC motions. However, VMAT is considered better than IMRT for various tumor sites [7-9], it requires advanced machine or hardware or software upgrades in Linac, resulting in less feasible use in low-and-middle-income countries (LMIC) due to financial constraints.

The VMAT with variable dose rate (VDR VMAT) machine is more expensive as the cost is more compared to Co-60 and conventional Linac. However, VMAT with constant dose rate (CDR VMAT) technique can be implemented on conventional Linac without any extra expenditure to the institute, leading to producing clinically acceptable plans with shorter treatment delivery time.

The VMAT with constant dose rate technique is more beneficial in LMIC due to cost-effectiveness, similar results as the IMRT and VDR-VMAT, and the capability of using existing Linac. However, it has a constant dose rate. CDR VMAT provides a similar quality plan as IMRT or VDR-VMAT [10-18]. The advantages of CDR VMAT are as follows: 1) the treatment on existing Linac with the shorter treatment delivery time, leading to increased patient throughput, and 2) the reduction of intra-fraction motion errors, resulting in better quality treatment. To the best of our knowledge, the current study is the first study with five different treatment sites for the validation of the CDR VMAT technique in radiotherapy practice.

This study aimed to explore the feasibility and potential benefits of the CDR VMAT technique based on its dosimetric comparison with IMRT and VDR VMAT for 5 complex cancer sites, including, brain, head-neck, lung, oesophagus, and prostate.

Material and Methods

In this analytical study, 75 cancer patients participated, who were referred to the radiotherapy department at Delhi State Cancer Institute, Dilshad Garden, Delhi from January 2018 to October 2021 with the diagnosis of brain, head-neck, lung, oesophagus, and prostate by convenience sampling. A total of 15 patients were randomly selected from each cancer site, and each patient was immobilized with a thermoplastic cast and simulated on a computed tomographic (CT) simulator (SOMATOM, SIEMENS, Germany) in a supine position. The 3-mm slices were acquired for all cases. The radiation oncologist delineated the target volumes and OAR structures in the monacosim contouring station (ELEKTA, Crawley, UK) for each site.

Radiotherapy Treatment Planning

For 75 patients, 225 plans, including 75 VDR VMAT, 75 CDR VMAT, and 75 IMRT were designed using the Monte Carlo algorithm on Monaco (Elekta Medical Solutions) treatment planning system version 5.11.01. This planning was used to prescript 54 Gy in 30 fractions for the brain, 60 Gy in 30 fractions for the lung, 78 Gy in 39 fractions for the prostate, 45 Gy in 25 fractions for oesophagus, and 70/63/54 Gy in 35 fractions for head-neck cases. Step and shoot IMRT (S&S IMRT) plans were created using 5–9 fields for 6 MV Oncor Expression Linac.

The VDR-VMAT plans for the brain, lung, oesophagus, and prostate were designed using one coplanar arc of 360˚, consisting of clockwise and counter-clockwise rotation. Head-neck plans were created and computed using dual coplanar arcs of 360˚ rotation for a maximum dose rate 320 MU/min with the gantry angle increment 20˚/30˚, collimator an-

gle 5˚, 0.5 cm segment width, medium fluence smoothening, and 3 mm grid size.

CDR-VMAT plans were generated by setting the gantry angle increment to 20˚/30˚, collimator angle to 5˚, 0.5 cm segment width, medium fluence smoothening, and 3-mm grid size, and a constant dose rate of 320 MU/min was selected for calculation. The VDR and CDR VMAT plans were generated for 6 MV photon energy of Clinac 600 C Varian Linac (Varian Medical Systems CA, USA).

The IMRT, VDR VMAT, and CDR VMAT plans were optimized to achieve the dose constraints, presented in Table 1. In Monaco, biological optimization is a two-step process, in which a finite-size pencil beam algorithm was used for the fluence optimization of beams in step one, and a Monte Carlo algorithm was used for the segmentation optimization in the second step. The Monte Carlo algorithm uses XVMC code19 for dose calculation, based on the virtual energy fluence model.

Three techniques were dosimetrically compared based on the evaluation of dose-volume-histogram (DVH) parameters, the maximum dose to PTV (D2), the mean dose to PTV, and PTV coverage. The plan quality was analyzed by comparing the homogeneity index (HI) and conformity index (CI). The dose conformity was calculated by using the formula given by Paddick [19] as follows:

$$CI = \frac{TV_{RI}}{TV} \times \frac{TV_{RI}}{V_{RI}} \qquad (1)$$

where TV is the target volume, TV_{RI} is the target volume encompassed by reference isodose, and V_{RI} is the volume of the reference isodose. CI, closer to 1, shows more conformed dose distribution to the tumor. The dose homoge-

Table 1: The organs at risk (OAR) dose constraints for the brain, head-neck, lung, oesophagus, and prostate.

Brain	Head-neck	Lung	Oesophagus	Prostate
Max Dose	Max Dose	Max Dose	Max Dose	
Lens <8 Gy	Lens <8 Gy	Spinal cord <45 Gy	Spinal cord <45 Gy	Rectum V50<50%
Brainstem <54 Gy	Brainstem <54 Gy	Both lungs V20<35%	Both lungs V20<35%	V60<35%
Optic nerve <54 Gy	Optic nerve <54 Gy	V30<20%	V30<20%	V65<25%
Optic chiasm <54 Gy	Optic chiasm <54 Gy	Mean dose <20 Gy	Mean dose <20 Gy	V70<20%
Eyes Mean dose <35 Gy	Spinal cord <45 Gy	Heart Mean dose <26 Gy	Heart Mean dose <26 Gy	V75<15%
	Eyes Mean dose <35 Gy	V30<46%	V30<46%	Bladder V65<50%
	Parotid Mean dose <26 Gy			V70<35%
				V75<25%
				V80<15%
				Femoral Head V40<40%

neity was calculated by using formula (2), as follows:

$$HI = \frac{D_2 - D_{98}}{D_{50}} \qquad (2)$$

Where D_{50} is the dose covering 50% of PTV, D_2 is the dose covering 2% of PTV, and D_{98} is the dose covering 98% of PTV. *HI* nearer to zero shows a more homogeneous dose distribution inside the tumor.

Treatment delivery parameters, including monitor units (MU) and treatment delivery time, were evaluated and compared for CDR, VDR VMAT, and IMRT. For OAR evaluation, mean doses, maximum doses, and volume doses were compared for all five tumor sites. OAR dose constraints for plan optimization for all five sites are presented in Table 1.

Statistical analysis

For statistical analysis, IBM SPSS software (version 20, IBM Corporation) was used, and Tables 2 and 3 are presented with mean±standard deviation. The CDR VMAT, VDR VMAT, and S&S IMRT were statistically compared by using paired samples t-test using the *P*-value<0.05, which was statistically significant.

Results

Table 2 shows PTV and MU, in which all PTV parameters were comparable in all five treatment sites, i.e., the brain, head-neck, lung, oesophagus, and prostate. The CI was higher in VDR and CDR VMAT plans than IMRT for all five cancer sites. Both VMAT (VDR and CDR) and IMRT plans were homogeneous. The PTV coverage V95 was more than 95%, and all OAR parameters were comparable for all five tumor sites in all three techniques. The detailed OAR parameters of comparison are noted in Table 3. In the study of brain cases, PTV coverage V95 was 97.35±1.42% in the IMRT, 98.15±1.33% in VDR VMAT, and 97.54±1.38% in the CDR VMAT. The difference in PTV mean dose, maximum dose, HI, CI, and OAR parameters were not significant between CDR, VDR, and IMRT.

In head-neck cases, the PTV coverage V95 of PTV70, PTV63, and PTV54 were 97.0±1.16%, 98.34±1.15%, and 97.86±1.16% in IMRT, 97.37±1.16%, 98.93±1.1%, and 98.25±1.16% in VDR VMAT, and 97.0±1.62%, 98.68±1.16%, and 97.87±1.16% in CDR VMAT, with no statistically significant difference. The OAR doses in the head-neck, such as the brainstem, optic chiasm, and optic nerve had no significant difference in CDR, VDR, and IMRT. The contra-lateral parotid mean dose was comparatively higher in VDR (23.29±13.72 Gy) and CDR VMAT (22.63±12.61 Gy) compared to 18.43±11.03 Gy in IMRT. Similarly, the ipsilateral parotid mean dose was comparatively higher in VDR (39.23±11.86 Gy) and CDR VMAT (38.69±12.51 Gy) compared to 33.66±9.05 Gy in IMRT.

For lung cases, PTV coverage (V95) was obtained higher 99.49±0.35% in VDR VMAT compared to 99.11±0.72% in CDR VMAT (*P*=0.01) and 98.42±0.99% in IMRT (*P*=0.016). Furthermore, VDR and CDR VMAT plans were obtained more conformed than IMRT plans. The lower PTV maximum dose (D2) was obtained in IMRT vs. VDR and CDR VMAT. Dose homogeneity was superior in VDR VMAT compared to the remaining two techniques. V20 of both lungs was higher 32.84±14.71% in VDR VMAT and 33.85±14.37% in CDR VMAT (*P*=0.06) compared to 30.73±14.05% in IMRT (*P*=0.011), which were lower than its constraint (V20<35%). The other OAR doses heart, contralateral, and both lungs did not significantly change in CDR, VDR, and IMRT.

In Oesophagus cases, VMAT plans had more conformed dose distribution than IMRT plans since CI was higher 0.852±0.06 in VDR VMAT and 0.84±0.061 in CDR compared to 0.825±0.07 in IMRT. The doses to the lung, heart, and spinal cord were also obtained with no significant difference. In prostate cases, the PTV coverage V95 was 98.2±1.16% in IMRT,

Table 2: Comparison of planning target volume (PTV) parameters and monitor units (MUs)

Parameters	S&S IMRT (mean±SD)	CDR VMAT (mean±SD)	VDR VMAT (mean±SD)	*P*-value IMRT vs CDR	*P*-value CDR vs VDR
Brain					
PTV V95 (%)	97.35±1.42	97.54±1.38	98.15±1.33	0.543	0.456
PTV max (D2 Gy)	55.88±0.49	56.72±0.77	56.23±0.56	<0.001	0.512
PTV mean (Gy)	54.27±0.60	54.35±0.56	54.41±0.60	0.655	0.689
PCI	0.896±0.06	0.903±0.06	0.916±0.06	0.473	0.367
HI	0.087±0.02	0.102±0.02	0.084±0.02	0.014	0.016
MU	361.64±77.4	531.98±96.1	466.26±77.4	<0.001	<0.001
Head-neck					
PTV 70 V95 (%)	97.0±1.16	97.0±1.62	97.37±1.16	0.984	0.421
PTV 63 V95 (%)	98.34±1.15	98.68±1.16	98.93±1.1	0.322	0.498
PTV 54 V95 (%)	97.86±1.16	97.87±1.16	98.25±1.16	0.979	0.435
PTV max (D2 Gy)	73.29±0.42	75.94±0.76	74.67±0.42	0.004	0.001
PTV mean (Gy)	70.32±0.27	70.67±0.32	70.24±0.27	0.342	0.392
PCI	0.817±0.74	0.822±.713	0.828±0.74	0.682	0.682
HI	0.168±0.06	0.185±0.06	0.182±0.06	0.076	0.372
MU	826.49±287.3	848.07±350.3	823.34±221.2	0.711	0.534
Lung					
PTV V95 (%)	98.42±0.99	99.11±0.72	99.49±0.35	0.016	0.01
PTV max (D2 Gy)	63.42±0.54	64.18±0.51	64.04±0.55	<0.001	0.366
PTV mean (Gy)	61.15±0.46	61.51±0.48	61.88±0.37	0.024	0.026
PCI	0.867±0.059	0.873±0.068	0.874±0.06	0.724	0.654
HI	0.096±0.018	0.099±0.018	0.096±0.016	0.352	0.002
MU	512.25±115.5	849.67±252.2	644.43±144.1	<0.001	<0.001
Oesophagus					
PTV V95 (%)	98.77±0.66	98.73±0.9	99.14±0.53	0.86	0.41
PTV max (D2 Gy)	47.3±0.23	47.57±0.35	47.63±0.31	0.004	0.062
PTV mean (Gy)	45.7±0.34	45.73±0.32	45.81±0.36	0.759	0.783
PCI	0.825±0.07	0.84±0.061	0.852±0.07	0.042	0.064
HI	0.14±0.20	0.093±0.014	0.092±0.012	0.386	0.686
MU	443.39±98.9	572.62±115.9	492.65±68.8	<0.001	<0.001
Prostate					
PTV V95 (%)	98.2±1.16	98.4±1.11	99.1±0.96	0.516	0.465
PTV max (D2 Gy)	82.37±0.41	83.6±0.84	82.16±0.48	<0.001	<0.001
PTV mean (Gy)	79.58±0.67	79.51±0.44	79.83±0.53	0.79	0.673
PCI	0.82±0.047	0.83±0.048	0.84±0.047	0.751	0.732
HI	0.097±0.015	0.116±0.018	0.095±0.014	0.002	0.002
MU	740.12±202.5	988.07±199.7	826.46±108.3	<0.001	<0.001

S&S IMRT: Step and shoot intensity-modulated radiation therapy, CDR VMAT: Volumetric modulated arc therapy with constant dose rate, VDR VMAT: Volumetric modulated arc therapy with variable dose rate, PTV: Planning target volume, PCI: Paddick conformity index, HI: Homogeneity index, V95 (%): Percentage of volume cover the 95% of the prescribed dose, MU: Monitor units, SD: Standard deviation

Table 3: The organ at risk comparison between volumetric modulated arc therapy with constant dose rate (CDR VMAT), volumetric modulated arc therapy with variable dose rate (VDR VMAT), and intensity-modulated radiation therapy (IMRT)

Organ-at-risk	Parameters	S&S IMRT (mean±SD)	CDR VMAT (mean±SD)	VDR VMAT (mean±SD)	*P*-value IMRT vs CDR	*P*-value CDR vs VDR
Brain						
Lt lens	Max dose (Gy)	4.12±2.05	5.12±2.5	5.06±2.1	0.03	0.122
Rt lens	Max dose (Gy)	3.98±1.62	4.13±2.32	3.98±1.64	0.57	0.063
Brain Stem	Max dose (Gy)	52.07±10.54	52.94±12.05	52.27±9.96	0.149	0.652
Rt Optic nerve	Max dose (Gy)	32.04±19.85	31.55±19.66	31.42±19.76	0.472	0.823
Lt Optic nerve	Max dose (Gy)	34.76±19.64	35.9±19.35	34.26±18.43	0.122	0.08
Optic chiasm	Max dose (Gy)	42.60±18.32	43.04±19.13	42.54±18.36	0.268	0.468
Brain	Mean dose (Gy)	26.42±6.15	26.66±5.86	26.46±5.6	0.391	0.236
LT Eyes	Mean dose (Gy)	8.75±7.05	9.3±7.38	8.92±6.84	0.112	0.427
RT Eyes	Mean dose (Gy)	7.67±5.33	8.72±6.45	7.64±5.13	0.162	0.134
Head-neck						
Lt lens	Max dose (Gy)	3.73±2.05	3.96±3.41	3.83±2.01	0.780	0.697
Rt lens	Max dose (Gy)	4.12±1.84	5.0±4.24	4.26±3.12	0.386	0.493
Brain Stem	Max dose (Gy)	35.61±12	36.06±12.08	35.83±12.34	0.655	0.231
Optic chiasm	Max dose (Gy)	24.2±25.22	27.03±25.55	25.16±25.29	0.055	0.063
Rt Optic nerve	Max dose (Gy)	16.13±19.22	16.92±20.75	16.13±19.22	0.567	0.567
Lt Optic nerve	Max dose (Gy)	12.58±16.91	12.89±17.79	12.58±16.91	0.596	0.596
Spinal cord	Max dose (Gy)	40.55±5.89	41.98±4.73	41.64±5.95	0.521	0.468
Mandible	Max dose (Gy)	68.85±6.12	69.32±6.43	68.85±6.32	0.664	0.714
RT Eyes	Mean dose (Gy)	4.39±3.04	5.49±5.51	4.83±3.21	0.226	0.226
LT Eyes	Mean dose (Gy)	3.34±2.06	3.89±3.35	3.34±2.06	0.355	0.536
Contra-lat Parotid	Mean dose (Gy)	18.43±11.03	22.63±12.61	23.29±13.72	<0.001	0.623
Ipsi-lat Parotid	Mean dose (Gy)	33.66±9.05	38.69±12.51	39.23±11.86	0.031	0.043
Lung						
Spinal cord	Max dose (Gy)	37.55±11.92	38.07±11.33	37.4±12.1	0.27	0.353
Both Lung	V20 (%)	30.73±14.05	33.85±14.37	32.84±14.71	0.011	0.06
	V30 (%)	24.23±10.14	25.34±10.31	24.6±10.17	0.104	0.036
	V40 (%)	19.03±7.88	19.02±7.45	18.75±7.6	0.973	0.36
	Mean dose (Gy)	18.96±6.22	19.25±6.29	19.03±6.47	0.064	0.23
Heart	Mean dose (Gy)	16.01±11.37	16.55±11.74	16.62±11.82	0.253	0.66
	V30 (%)	20.47±18.71	21.7±19.91	21.19±19.61	0.172	0.185
Oesophagus						
Spinal cord	Max dose (Gy)	32.37±5.02	32.21±5.6	31.58±6.36	0.84	0.627
Lt Lung	Mean dose (Gy)	11.17±3.51	11.09±3.32	10.65±3.56	0.681	0.338
Rt Lung	Mean dose (Gy)	12.05±4.24	11.79±4.21	11.63±4.21	0.083	0.078
Both lung	Mean dose (Gy)	11.61±3.67	11.45±3.58	11.24±3.56	0.120	0.119
	V20 (%)	18.72±8.32	17.61±7.3	17.39±7.57	0.107	0.216
Heart	Mean dose (Gy)	9.93±7.18	10.29±7.74	9.91±7.18	0.244	0.235
	V30 (%)	7.4±9.3	7.56±10.55	7.58±9.7	0.78	0.214

Organ-at-risk	Parameters	S&S IMRT (mean±SD)	CDR VMAT (mean±SD)	VDR VMAT (mean±SD)	*P*-value IMRT vs CDR	*P*-value CDR vs VDR
Prostate						
Rectum	V50 (%)	37.43±14.4	38.66±13.85	37.63±14.32	0.125	0.094
	V60 (%)	27.02±13.18	26.45±12.67	25.62±12.76	0.452	0.732
	V65 (%)	21.15±12.19	21.34±11.79	21.13±12.06	0.302	0.326
	V70 (%)	17.03±10.9	16.22±10.82	16.11±11.17	0.305	0.112
	V75 (%)	10.84±8.34	10.22±9.33	10.56±8.8	0.479	0.319
Bladder	V65 (%)	22.4±6.75	23.34±8.6	23.07±7.63	0.366	0.348
	V70 (%)	17.67±6.18	18.7±8.26	17.13±7.32	0.331	0.296
	V75 (%)	11.7±5.11	13.3±7.43	12.2±5.64	0.231	0.274
	V80 (%)	2.2±2.9	4.47±3.72	2.8±3.1	0.073	0.081
Rt Femoral Head	Mean dose (Gy)	17.36±3.34	17.19±3.35	17.12±3.32	0.772	0.806
	V40 (%)	0.55±1.65	0.51±1.65	0.57±1.78	0.29	0.572
Lt Femoral Head	Mean dose (Gy)	17.66±3.06	17.23±2.74	17.66±3.06	0.571	0.613
	V40 (%)	0.7±1.6	0.5±1.3	0.72±1.5	0.467	0.684

Vx (%): Percentage of volume covering the x Gy dose (x= 20, 30, 40, ….), SD: Standard deviation, S&S IMRT: Step and Shoot intensity-modulated radiation therapy, CDR VMAT: Volumetric modulated arc therapy with constant dose rate, VDR VMAT: Volumetric modulated arc therapy with variable dose rate, Lt: left, Rt: right

99.1±0.96% in VDR VMAT, and 98.4±1.11% in CDR VMAT.

No significant difference was observed in doses of the bladder, rectum, and femoral head with a *P*-value>0.05.

The total number of MU per fraction and the time to deliver the plan were also compared, showing the number of MU per fraction was significantly higher in CDR VMAT compared to VDR and IMRT with a *P*-value<0.001 in the brain, lung, oesophagus, and prostate, except head-neck. In head-neck, MU was obtained 826.49±287.29 in IMRT, 823.34±221.2 in VDR, and 848.07±350.32 in CDR with no significant variation (*P*-value>0.05). However, treatment delivery time was lower in VDR and CDR VMAT compared to IMRT.

Figure 1 shows a comparison of CI and HI among IMRT, CDR VMAT, and VDR VMAT in the brain, head-neck, lung, oesophagus, and prostate.

The isodose distribution on the axial slice for IMRT, VDR VMAT, and CDR VMAT techniques is shown in the brain, head-neck, lung, oesophagus, and prostate (Figure 2).

The CDR VMAT reduced the treatment time to 72-80% compared to IMRT, leading to reducing the average treatment time of 10.78 min (76%) in brain cases, 17.96 min (72%) in head-neck, 12.88 min (79%) in the lung, 12.18 min (78%) in oesophagus, and 15.5 min (80%) in prostate compared to IMRT.

Discussion

This study aimed to explore the feasibility and potential benefits of the CDR VMAT technique by dosimetric comparison of the CDR with VDR VMAT and IMRT for five cancers, as follows: brain, head-neck, lung, oesophagus, and prostate. The CDR VMAT technique provided a clinically acceptable plan, such as IMRT and VDR-VMAT [10-18]. The current study shows that the CDR VMAT technique produces a clinically acceptable plan as IMRT and VDR VMAT for nearly all tumor sites with optimum PTV coverage, more conformed dose distribution, and minimal doses to OAR.

The obtaining results of brain tumors show that the CDR VMAT plan was the clinically

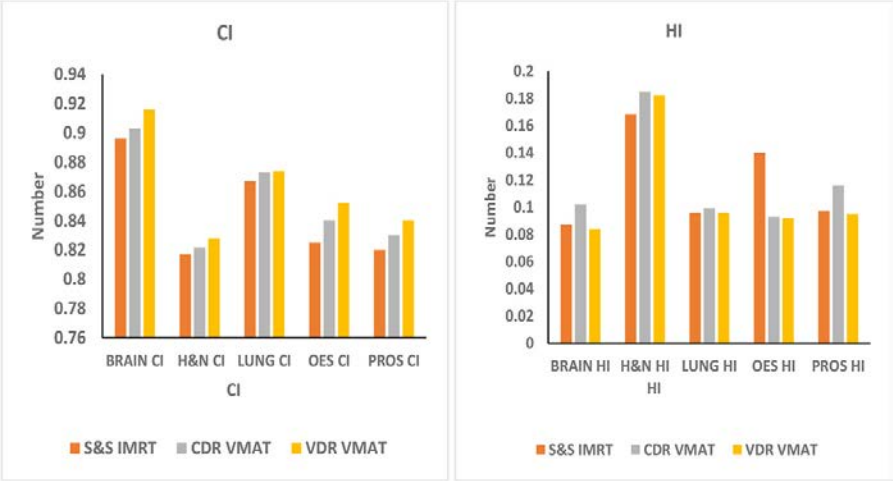

Figure 1: Comparison of conformity index (CI) and homogeneity index (HI) among step-and-shoot intensity-modulated radiation therapy, volumetric modulated arc therapy with constant dose rate, and volumetric modulated arc therapy with variable dose rate in brain, head-neck, lung, oesophagus, and prostate. (S&S IMRT: Step and Shoot intensity-modulated radiation therapy, CDR VMAT: Volumetric modulated arc therapy with constant dose rate, VDR VMAT: Volumetric modulated arc therapy with variable dose rate)

acceptable plan due to achieving all dose constraints (Table 1). CI was higher than IMRT for the CDR and VDR VMAT techniques. The PTV coverage was similar in all three techniques, and the OAR parameters were also comparable. However, the left lens maximum dose and PTV maximum dose (D2) dose were significantly less in IMRT compared to CDR and VDR VMAT but within the tolerance limit.

The dose distribution in CDR and VDR VMAT plans was observed more conformed with higher CI in head-neck cases than in IMRT. However, the contralateral parotid and ipsilateral parotid mean doses were significantly higher in VDR and CDR VMAT. The PTV maximum dose (D2) was less in IMRT and VDR compared to CDR VMAT. MU was also comparable in CDR, VDR, and IMRT techniques. However, treatment delivery time was significantly shorter in CDR VMAT (6.84 min vs. 24.8 min) than in IMRT.

Furthermore, the obtained results were consistent with those of Didona et al. [11], who compared 15 head-neck plans and showed VMAT plans were comparable to IMRT and VDR-VMAT with a higher number of monitor units and significantly shorter average delivery time. The treatment delivery time of CDR VMAT was shorter compared to IMRT in the present study. However, the number of monitor units was not significantly different in CDR, VDR, and IMRT. Yu et al. [12] compared the constant dose rate VMAT (CDR-VMAT) technique to VDR-VMAT and MCO-VMAT for nasopharyngeal cancer and showed CDR VMAT was similar to VDR in terms of PTV coverage and OAR sparing.

In the current study, VDR and CDR VMAT plans conformed dose distribution since CI was higher than IMRT for prostate cases. However, dose homogeneity and PTV maximum dose were less in IMRT than in VDR and CDR VMAT. The obtained results were similar to previous studies in terms of a higher number of MU and shorter treatment delivery time for prostate cancer [13-15]. McGarry et al. [13] observed that dose homogeneity and conformity were not significantly different in CDR, VDR, and IMRT plans for

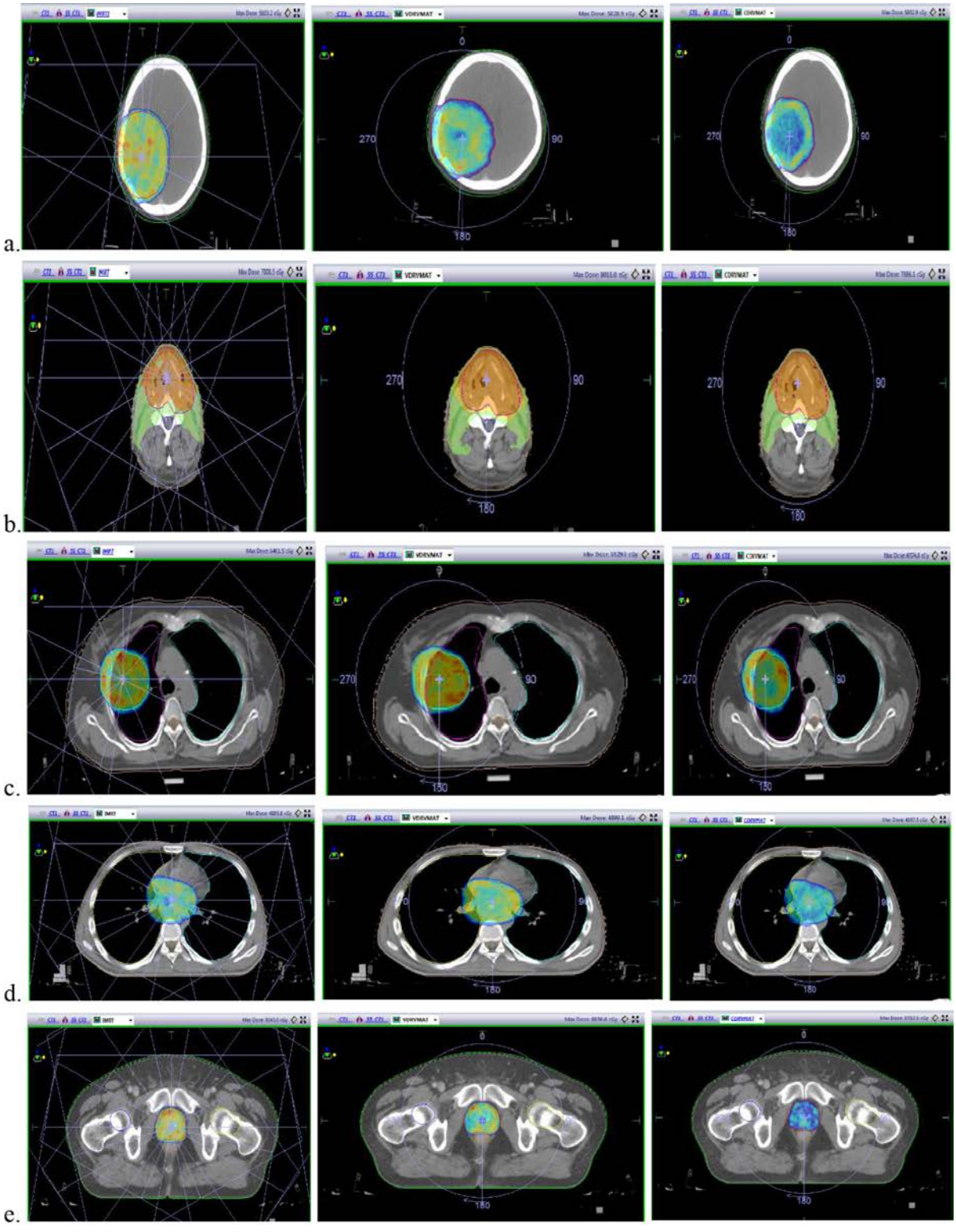

Figure 2: Dose distribution on an axial slice (with color wash from 95-107%) in a. brain, b. head-neck, c. lung, d. oesophagus, and e. prostate site for step-and-shoot intensity-modulated radiation therapy, volumetric modulated arc therapy with variable dose rate, and volumetric modulated arc therapy with constant dose rate.

prostate cancer. Additionally, their results show that CDR was associated with significantly higher MU than IMRT, but delivery time was significantly less. Hatanaka et al. [14] studied 28 prostate cases and stated that CDR-VMAT plans were clinically equivalent to IMRT and VDR-VMAT.

For lung cases, PTV coverage V95 was higher 99.49±0.35% in VDR VMAT compared to 99.11±0.72% in CDR VMAT and 98.42±0.99% in IMRT. Furthermore, VDR and CDR VMAT plans were more conformed than IMRT plans. The lower PTV maximum dose (D2) was obtained in IMRT vs. VDR and CDR VMAT. Dose homogeneity was superior in VDR VMAT compared to the remaining two techniques. All OARs were comparable except lung V20, which was significantly higher in CDR and VDR VMAT but within the tolerance limit.

For oesophagus cases, VDR and CDR VMAT plans had a more conformed dose distribution with higher CI than IMRT and were more homogeneous than IMRT. The PTV coverage was similar in all the techniques. The right lung mean dose, both lungs mean dose, and both lung V20 were significantly lower in CDR and VDR VMAT compared to IMRT. Furthermore, other OARs were comparable, with no statistical difference.

In lung and oesophagus cases, lung pneumonitis is a major concern for radiotherapy treatment. The mean lung dose and lung V20 were the predictors for lung pneumonitis [20]. In the current study, lung mean dose and V20 were obtained lower than their constraint in both oesophagus and lung cases.

For all five sites, CDR VMAT provides clinically acceptable plans with better PTV coverage, more conformed dose distribution, and OAR sparing with a shorter treatment delivery time. The total number of MU was higher in CDR VMAT, but treatment delivery time was significantly shorter compared to IMRT. The average treatment delivery time significantly reduced (72-80%) from 14.2-24.8 min (S&S IMRT) to 3.42-6.84 min (CDR VMAT) in all five cancer sites, leading to reducing intra-fraction motion errors and improving patient comfort. The shorter treatment delivery time was beneficial in cases, such as prostate, lung, and oesophagus since organs are very sensitive to organ motion during treatment. This study demonstrated that the CDR VMAT technique produces clinically acceptable plans, such as VDR VMAT and IMRT for nearly all tumour sites. Therefore, this cost-effective technique is considered better for the patient and the institute to improve the patient's quality of life by better quality treatment for more patients.

Due to the unavailability of advanced technology in LMIC, LMIC can use this CDR VMAT technique to increase patient throughput with more conformed dose distribution and better PTV coverage with safe OAR. The shorter treatment delivery time may reduce intra-fraction motion error and increase patient throughput. Therefore, the VMAT with a constant dose rate could be the most promising treatment technique in radiotherapy practice in LMIC, resulting in helping treat a greater number of patients with quality treatment in LMIC and improving their quality of life.

The limitation of this study, the sample size was small (15 patients) from each site. The number of patients can be increased for better dosimetric and clinical evaluation. This study may help select the CDR VMAT technique for the treatment of nearly all types of cancer sites, in which VDR VMAT is not available for treatment and wanted to adopt the VMAT technique.

Conclusion

Based on comparing CDR, VDR, and IMRT techniques, the CDR VMAT technique can provide more conformed dose distribution, resulting in quality plans with good PTV coverage and sparing OAR as VDR VMAT and IMRT in all five tumour sites, such as brain, head-neck, lung, oesophagus, and prostate. Furthermore, the CDR VMAT may also re-

duce intra-fraction motion errors with a shorter treatment delivery time to improve patient comfort. Moreover, with these advantages and its cost-effectiveness, the CDR VMAT technique may be a promising treatment technique in radiotherapy practice in LMIC and offer benefits to the radiotherapy community.

Authors' Contribution

The idea was conceived by VR. Gedam. The article was designed and written by VR. Gedam. The data collection, analysis, and interpretation were done by VR. Gedam. A. Pradhan gathers the related literature and helps with data analysis and interpretation. A. Pradhan edited and reviewed the article. All the authors had read, modified, and approved the final manuscript.

Ethical Approval

Permission had been taken from Delhi State Cancer Institute, Dilshad Garden, Delhi to conduct the research and use the resources needed.

Conflict of Interest

None

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