RESEARCH ARTICLE

Radiotherapy of prostate and head-and-neck tumour: An optimal treatment planning comparison for intensity modulated radiotherapy and volumetric modulated arctherapy techniques

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Abstract

Objective: To evaluate and compare merits between intensity modulated radiotherapy and volumetric modulated arc-therapy radiotherapy techniques to determine which technique can achieve better treatment plan quality and efficient delivery.

Method: The retrospective study was conducted at the Radiation Oncology Department of SanBorotlo Hospital, Vicenza, Italy, in 2019, and comprised data from Jan 2019 to Dec 2019 related to prostate and head-and-neck patients in whom Pinnacle³ treatment planning system was used for optimisation with different prescribed doses and target geometries for intensity modulated radiotherapy and volumetric modulated arc-therapy techniques. Treatment plans were simulated using 6MV photon beam of SynergyS® Linac (Linear accelerator). The plan quality was evaluated using dose-volume indices for planning target-volume and organs-at-risk. ArcCHECK™ phantom was used for dose agreement verification between planed and delivered doses.

Results: Data of 8 patients was analysed. Intensity modulated radiotherapy and volumetric modulated arc-therapy treatment plan quality for prostate was found to be similar, but volumetric modulated arc-therapy had significant results for maximum dose (p=0.005). Intensity modulated radiotherapy and volumetric modulated arc-therapy plans for head-and-neck achieved adequate target coverage and sparing of organs at risk, and produced clinically acceptable treatment plans. The percentage of target coverage (p=0.001), dose maximum (p=0.013) and conformity index (p=0.000) were significant. A significant gain for all planning target volume dose-volume indices was noted (p<0.05). Volumetric modulated arc-therapy obtained better plan with significant values and improved sparing of organs at risk compared to intensity modulated radiotherapy for both prostate and head-and-neck treatments while maintaining doses to the organs at risk (p<0.05).

Conclusion: Dynamic arc mode of beam delivery provided increased degrees of freedom of volumetric modulated arc-therapy beam intensity modulation, depicting superior dose distribution than intensity modulated radiotherapy.

Keywords: IMRT, VMAT, Radiotherapy, Treatment planning. (JPMA 72: 16; 2023)

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Introduction

Since the early 1990s, the innovation of multileaf collimator (MLC) and introduction of intensity modulation in radiotherapy treatment planning helped researchers to overcome the radical challenge of delivering highly conformal doses to planning target volume (PTV) while maintaining organs-at-risk (OARs) doses. Intensity modulated radiotherapy (IMRT) is a treatment technique able to create steep dose gradients that can well conform complex-shaped PTVs by sparing OARs.[1-3] The arc based an efficient intensity modulated beam delivery technique, known as volumetric modulated arc therapy (VMAT), has been proposed.[4] It is a recent addition in the technological armamentarium of Intensity modulated beam delivery techniques. A number of studies have compared standard IMRT and VMAT techniques for different tumour sites in order to highlight the potential advantages in both techniques.[5-9] Some studies have reported the dosimetric impact of user selectable planning parameters on the final dose distribution of IMRT[10] and VMAT treatment plans, and have recommended user selectable planning parameters.[10-15]

The current study was planned to evaluate and compare the merits of IMRT and VMAT techniques to determine which technique can achieve better treatment plan quality and efficient delivery.

Materials and Methods

The retrospective study was conducted at the Radiation Oncology Department of SanBorotlo Hospital, Vicenza, Italy, in 2019, and comprised data from Jan 2019 to Dec 2019 related to prostate and head-and-neck patients

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comprising different prescribed doses (PDs) and tumour geometries previously treated with standard IMRT technique. Data was retrieved and randomly selected from computerised medical records. These patients were re-planned using VMAT technique by adopting recommended user selectable planning parameters[10-15] in order to obtain optimal treatment plan quality. One step-and-shoot (SS) IMRT and one dual-arc (DA) VMAT treatment plan of each prostate and head-and-neck patient was generated.

On segmented computed tomography (CT) scans, the regions of interest (ROI) comprising PTVs, OARs and normal body tissue were delineated by radiation oncologists following standard published guidelines[16,17] for prostate and head-and-neck radiotherapy. The mean volumes of PTV_{boost}, $PTV_{elective(s)}$, OAR and PDs for selected prostate and head-and-neck tumours were noted. All prostate patients were prescribed a dose of 78Gy for PTVboost to be delivered in 39 equal treatment fractions. In case of head-and-neck treatment, two equal sets of patients were selected to deliver prescribed doses by means of simultaneous integrated boost (SIB). The first set of patients contained three PTVs with prescribed doses of 70Gy, 60Gy and 56Gy defined for PTV_{boost}, $PTV_{elective\ 1}$ and $PT_{Velective\ 2}$, respectively. The second set of patients had two PTVs with prescribed doses of 60Gy and 54Gy defined for PTV_{boost} and $PTV_{elective\ 1}$, respectively.

Being limitation of study the prostate plus half seminal-vesicles tumours were considered for study and prostate tumours involving lymph nodes (LNs) were excluded. Likewise, head-and-neck tumours only planned for SIB were considered. Tumours <15cm craniocaudal extension and either of the diagonal length of PTVs equal or <15cm were considered due to limited MLC aperture (21x16 cm^2).[15]

Elekta SynergyS® (Elekta Ltd, Crawley, United Kingdom) medical linear accelerator containing Beam Modulator™ MLC system was used for treatment delivery. The treatment plans were simulated for 6MV photon beam of this medical linear accelerator. The SmartArc™ module[18] from Pinnacle[3] version 9.2 (Philips Healthcare) treatment planning system (TPS) was used for the optimisation of both IMRT and VMAT plans. The physical properties and dosimetric features of Beam Modulator™ MLC system[12-15] and TPS SmartArc™ module in Pinnacle[3] [18] have already been described. A well-optimised set of user selectable planning parameters was used for treatment plan optimisation of IMRT and VMAT.[10-15] The standard IMRT clinical objectives for PTV and OAR[19,20] were also used for VMAT treatment plan optimisation. Both treatment planning techniques used the same original PTV for prostate and head-and-neck tumours.

The SS IMRT plans were generated at standard collimator position for prostate and head-and-neck cases using five (0º, 45º 105º, 255º and 315º) and seven (0º, 51º, 102º, 153º, 204º, 255º, 306º) fields, respectively. The number of segments 30 and 50 per angle were used for plan optimisation of prostate and head-and-neck treatments, respectively. Nominal dose of 300MU/min was set for SynergyS Linac.

DA VMAT plans were optimised in clockwise and counter-clockwise directions for prostate and head-and-neck treatments. The start and stop gantry angles of VMAT arc for prostate were set at 181° and 179º and for head-and-neck at 183º and 177º.[21]

Radiation oncologists reviewed all IMRT and VMAT plans in order to verify the appropriateness of PTV and OAR dose coverage. To quantify in terms treatment plan quality, the differences between IMRT and VMAT was carried out. PTV dose indices (DIs) D95%V, D2%V, D1cc, conformity index (CI) and homogeneity index (HI) Dmean were evaluated[19] from dose-volume-histogram (DVH) data sets. Partial volume doses to the OARs were collected and evaluated as per the recommendations.[20] It allowed deducing the optimal technique with statistical significance set at $p \leq 0.05$ using two-sided student t-test. The dosimetric verification between TPS calculated and delivered treatment plans was done in a single session for the selected cases using the ArcCHECK™ phantom and SNC patient software version 6.2 (Sun Nuclear Inc. Melbourne FL).[22] The distance-to-agreement (DTA) criteria of gamma local (γ-local) 3%/3mm ≥95% for prostate, and ≥90% for head-and-neck23 was used for comparison.

Results

Data of 8 patients was analysed. The mean volumes of PTV_{boost}, $PTV_{elective(s)}$, OAR and PDs for selected prostate and head-and-neck tumours were noted (Table 1). Besides, standard IMRT clinical objectives for PTV and OAR were used for VMAT treatment plan optimisation (Table 2).

All IMRT and VMAT plans optimised for both prostate and head-and-neck achieved satisfactory target coverage and sparing of OAR. The obtained OAR partial volume dose (VxGy) values for both IMRT and VMAT techniques were well below the dose limits. IMRT and VMAT treatment plan quality for prostate was found to be similar, but VMAT had significant results for maximum dose (p=0.005). IMRT and VMAT plans for head-and-neck achieved adequate target coverage and sparing of OARs, and produced clinically acceptable treatment plans. The percentage of target coverage (p=0.001), dose maximum (p=0.013) and conformity index (p=0.000) were significant. A significant

Table-1: The mean values and ranges (min-max) of planning target volumes (PTVs), organs at risk (OAR) and prescribed doses for head-and-neck and prostate patients. Region of interest (ROI) volumes are presented in cm^3 (n=8).

	Head and Neck		Prostate	
ROI (cm^3)	3 PTV	2PTV	ROI (cm^3)	
(PTV_{boost})	136.9	175.4	(PTV_{boost})	80.7
	(83.3 – 189.3)	(100 – 255.7)		(53.4 – 107)
$PTV_{elective\ 1}$	118.4	116	---	---
	(89.5 – 142.8)	(66 – 166.3)		
$PTV_{elective\ 2}$	113.7		---	---
	(67.5 – 165.5)			
Parotid	18.1	19.9	Rectum	42.5
(right)	(10.0 – 29.1)	(13.2 – 32.0)		(28.9 – 54)
Parotid	14.7	16.5	Bladder	141
(left)	(10.4 – 27.3)	(13.8 – 21.6)		(94.7 – 256.4)
PD (Gy)	70/60/56	60/54		78

Table-2: Summary of dose-volume indices mean and range (min-max) of head-and-neck and prostate planning target volumes (PTVs) and organs at risk (OAR) for intensity modulated radiotherapy (IMRT) and volumetric modulated arctherapy (VMAT) techniques.

	Head and Neck						Prostate			
	3 PTV			2 PTV						
Region of Interest	**IMRT**	**VMAT**	***p*-value**	**IMRT**	**VMAT**	***p*-value**	**Region of Interest**	**IMRT**	**VMAT**	***p*-value**
PTVboost							PTVboost			
$D_{95\%V}$ (%)	95.2	96.3	**0.001**	95.6	96.3	0.244	D95%V (%)	96.0	96.3	0.447
	(95.1 – 95.4)	(96.0 – 96.6)		(95.2 – 96.1)	(94.8 – 97.6)			(94.8 - 96.8)	(95.5 - 97.5)	
D_{1cc} (%)	106	110	**0.013**	105	109	**0.032**	D2%V (%)	102	103	**0.005**
	(105 - 108)	(109 – 110)		(104 - 106)	(106 – 111)			(101 - 103)	(102 - 104)	
CI (%)	91.9	97.3	**0.001**	94.1	97.3	**0.033**	CI (%)	98.8	99.7	0.130
	(90.5 – 92.5)	(96.7 – 97.9)		(92.8 – 95.5)	(94.7 – 98.7)			(96.2 - 99.9)	(98.6 - 100)	
HI	0.13	0.14	0.502	0.11	0.13	0.341	HI	0.067	0.076	0.125
	(0.12 – 0.14)	(0.13 – 0.14)		(0.11 – 0.12)	(0.10 – 0.15)			(0.049 - 0.087)	(0.066 - 0.091)	
$PTV_{elective\ 1}$										
$D_{95\%V}$ (%)	94.0	96.7	**0.001**	95.0	97.2	0.060		--	--	
	(93.5 – 94.6)	(96.5 – 97.0)		(93.8 – 97.0)	(96.3 – 98.7)					
CI (%)	92.5	97.5	**0.001**	94.7	98.2	0.154		--	--	
	(91.6 – 94.1)	(97.1 – 97.9)		(91.6 – 99.7)	(97.2 – 99.9)					
$PTV_{elective\ 2}$							--	--		
$D_{95\%V}$ (%)	94.8	97.7	**0.003**	--	--			--	--	
	(94 – 95.3)	(97.0 – 98.9)								
CI (%)	94.3	98.6	**0.002**	--	--			--	--	
	(92.7 – 95.7)	(98.1 – 99.7)								
Organs at Risk (OAR)							**Organs at Risk (OAR)**			
Parotid (right)*							Bladder			
V30Gy (%) (≤ 50%V)	39.8	41.0		45.5	44.8		V40Gy (≤ 50%V)	26.3	25.8	
	(31.0 – 48.6)	(31.0 – 50.9)		(45.5 – 45.5)	(44.8 – 44.8)			(17.0 – 34.0)	(15.3 – 35.9)	
Mean Dose (≤ 27Gy)	26.52	27.21		25.68	26.83		V70Gy (≤ 25%V)	8.7	9.4	
	(26.32 – 27.71)	(26.98 – 27.44)		(25.68 – 25.68)	(26.83 – 26.83)			(5.1 – 13.5)	(5.1 – 14.7)	
Parotid (left)*							Rectum			
V30Gy (%) (≤ 50%V)	37.6	36.6		--	--		V50Gy (≤ 50%V)	20.3	18.8	
	x(29.0 – 42.2)	(33.2 – 40.8)						(18.0 – 23.7)	(16.0 – 22.9)	
Mean Dose (≤ 27Gy)	25.38	25.62		--	--		V65Gy (≤ 25%V)	10.4	9.2	
(20.68 – 26.98)	(20.84 – 27.96)							(8.7 – 13.6)	(6.9 – 11.7)	
--	--			--	--		V70Gy (≤ 20%V)	6.7	6.0	
								(5.5 – 8.5)	(4.0 – 7.5)	
$<\Gamma>$* global (%)	93.0	97.4		--	--			99.9	99.7	

gain for all PTV dose-volume indices was noted ($p<0.05$). VMAT obtained better plan with significant values and improved sparing of OARs compared to IMRT for both prostate and head-and-neck treatments while maintaining doses to the OARs ($p<0.05$).

Discussion

The current study provided a treatment planning analysis between IMRT and VMAT. The treatment plans were obtained for a set of recommended user selectable optimisation parameters. The VMAT solution was implemented using SmatArc™ module of Pinnacle³ TPS and Elekta SynergyS® linear accelerator. Due to limited MLC aperture (21x16 cm^2)[15] the tumours less than <15cm craniocaudal extension and either of the diagonal length of PTVs equal or less than <15cm were considered for treatment planning and vice versa. In case of tumour extension larger than >15cm, the Linac with MLC aperture (40 x 40 cm^2) will be used for treatment delivery.

In prostate cases, both IMRT and VMAT produced clinically acceptable treatment plans. The percentage of target coverage (D95%), dose maximum (D2%) and CI were higher for VMAT than IMRT (Table 2, Figure 1). Owing to inherited advantage of arc delivery mode, VMAT had a gain for target coverage (D95%V) and CI. The difference between IMRT and VMAT techniques for prostate PTV DIs

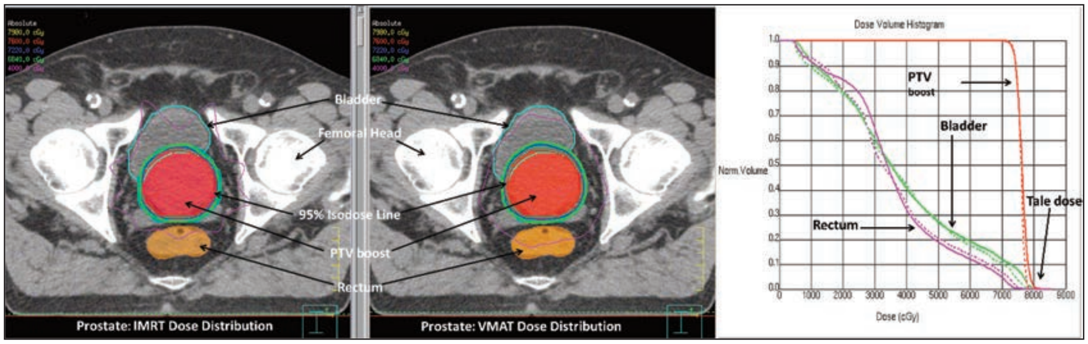

Figure-1: A representative case of prostate dose distribution in specific computed tomography (CT) slice for intensity modulated radiotherapy (IMRT) and volumetric modulated arc-therapy (VMAT). The thick green isodose line in left and middle images represents 90% of prescribed dose (PD), and thin blue isodose line represents 95% of PD covering whole of the PTVboost. Dose-volume histograms (DVH) on the right side shows planning target volume (PTV) and organs at risk (OAR) (bladder and rectum). Solid-lines represent VMAT, and dotted lines represent IMRT results.

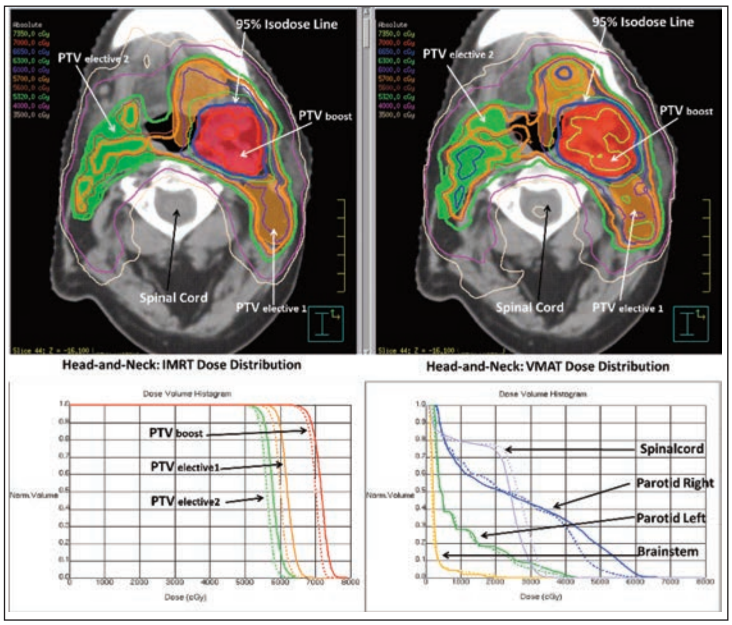

Figure-1: A representative case (Row-1) for head-and-neck dose distribution in specific computer tomography (CT) slice for intensity modulated radiotherapy (IMRT) and volumetric modulated arc-therapy. The thin green isodose line represents 90% of prescribed dose (PD) and thick blue isodose line represents 95% of PD covering whole of the PTVboost. The appropriate target coverage for both planning target volume (PTV)elective1 and PTVelective2 were achieved in terms of their PDs. Row-2 shows dose-volume histograms (DVH) for PTVs and organs at risk (OAR). Solid-lines represent VMAT and dotted-lines represent IMRT results.

were not significant except for dose maximum (D2%) (Table 2). From DVH (Figure1), a trend of higher doses (D2%) for prostate VMAT was significant (p=0.005). Consequently, at the centre of PTV, the PD (100% isodose line) for VMAT will have more target coverage and higher absolute dose value per unit volume than IMRT. The sparing of OAR volumes (rectum and bladder) at particular dose level (VxGy) were comparable or slightly better for VMAT than IMRT (Table 2, Figure 1) and individual patient data not reported here. The findings coincide with the earlier studies[5,6,9] related to different tumours using other treatment planning systems and delivery machines.

In head-and-neck cases, all IMRT and VMAT plans optimised achieved adequate target coverage and sparing of OARs. and produced clinically acceptable treatment plans. The percentage of target coverage (D95%), dose maximum (D1%) and CI were significant for VMAT comared to IMRT (Table 2, Figure 2). The gain for all PTVs dose volume indices, including PTVboost and PTVelective(s) was significant. Owing to inherited advantage of arc delivery mode, VMAT had a gain for target coverage (D95%V) and CI. The difference between IMRT and VMAT techniques for head-and-neck PTV DIs were significant (Table 2). From DVH (Figure 2), a trend of higher doses (D1%) for head-and-neck VMAT was noted to be significant (p=0.013). Consequently, it is evident at the centre of PTV, the PD (100% isodose line) for VMAT plan had more target coverage and higher absolute dose value per unit volume than IMRT. For example, at the centre of PTV (Figure 2), 105% isodose line of PD was evident for VMAT plan. It makes VMAT favourable for stereotactic body radiotherapy (SBRT) treatments, where larger amount of radiation doses are planned and delivered with few fractions with high treatment delivery accuracy.[24]

The sparing of OAR volumes (right and left parotids, spinal-cord and brain-stem) at particular dose level (VxGy) were comparable or better for VMAT than IMRT, particularly for spinal-cord and right-parotid (Table 2, Figure 2). For example, from OAR DVH at 70% volume of spinal-cord, the VMAT planned a dose of about 2100cGy (solid-line), whereas IMRT planned a dose of about 2500cGy (dotted-line). The findings were consistent with published studies.[7-9] Due to more conformal nature compared to dynamic arc mode of VMAT, however, IMRT attained better homogeneity index for both prostate and head-and-neck treatment planning. The VMAT is a more efficient treatment delivery technique compared to IMRT in terms of delivered monitor units and total treatment delivery time.[25]

Independent dosimetric verification to ensure safe treatment delivery is vital while using advanced technologies for the accurate and highly conformal dose distributions in radiotherapy treatments. For selected IMRT and VMAT plans, the dose agreement verification was compared between TPS calculated and machine delivered doses. The dosimetric measurements passed the set quality assurance criteria of γ-global (3%/3mm) ≥90% for IMRT and ≥95% for VMAT (Table 2).

Conclusion

VMAT provided more degrees of freedom of treatment beam intensity modulation owing to its arc mode of delivery and advantage of combining simultaneous movement of different mechanical variables. VMAT provided comparable or better treatment plan quality compared to IMRT for both prostate and head-and-neck treatment planning. A gain in PTV dose volume indices was noted for VMAT over IMRT while maintaining doses to the OARs.

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Author Contribution:
GM: Concept, design of the manuscript