

Optimisation of user-selectable volumetric modulated arc therapy (VMAT) planning parameters: VMAT arcs for prostate and head-and-neck cancers

Ghulam Murtaza,¹ Zaheer Abbas Gillani,² Shahid Mehmood,³ Jalil Ur Rehman,⁴ Ehsan Ullah Khan⁵

Abstract

Objective: To evaluate different VMAT planning techniques for a multi-leaf collimator (MLC) providing maximum aperture of $21 \times 16 \text{ cm}^2$.

Methods: A VMAT planning study of nine prostate and nine head-and-neck cancer patients was carried out. The patients were previously treated with Intensity Modulated Radiotherapy (IMRT) technique during 2014-15, at radiation oncology SanBortolo Hospital, Vicenza, Italy. Three VMAT plans for each of prostate and head-and-neck cancer patient were optimized using Pinnacle treatment planning system for 6MV photon beam from Elekta SynergyS[®] Linac system. Single arc, dual arc and combined two independent-single-arcs were optimized for collimator angle 45° . VMAT treatment planning comparison was made among single-arc dual-arc and combined two independent-single-arcs. The student's t-test (two-sided) with $p \leq 0.05$ was applied for significant difference between dose volume indices of plans.

Results: All VMAT techniques produced clinically acceptable plans for prostate, while for head-and-neck, DA and ISAs significantly improved target coverage compared to SA. Single arc is sufficient for prostate, while inefficient in case of head-and-neck dose-planning. In spite of having different VMAT optimization approach dual arc and two combined independent-single-arcs provided very similar target coverage, while dual arc improved sparing of organs-at-risk. Similar treatment delivery times were observed for DA and ISAs VMAT techniques.

Conclusion: Single arc is sufficient for prostate, while inefficient in case of head-and-neck dose-planning. Dual arc and two combined independent-single-arcs provided similar PTV coverage, while DA provided better sparing of organs at risk.

Keywords: VMAT, Treatment planning, Limited aperture collimation system. (JPMA 71: 1093; 2021)

DOI: <https://doi.org/10.47391/JPMA.710>

Introduction

Accurate radiation dose delivery is vital for the challenge of radical radiotherapy to ensure optimal target coverage with maximal healthy tissue sparing. The method of Volumetric Modulated Arc Therapy (VMAT) to deliver Intensity Modulated Radiotherapy (IMRT) is most widely used novel technique at present.¹ In the study of hepatic malignancies VMAT offers dosimetric and delivery-efficiency advantages over tomotherapy and IMRT.² A dosimetric study for pelvic and nasal malignancies explains added advantages of VMAT over IMRT for different cancers.^{3,4} The physical and dosimetric aspects of a multileaf collimation system and leaf sequencing algorithms enhanced the intensity modulation of delivered beams.^{5,6} Several authors have reported VMAT

treatment plan optimization studies for prostate,⁷ head-and-neck⁸ and their comparison with IMRT using conventional Linear accelerators (Linac) with $40 \times 40 \text{ cm}^2$ aperture. These studies combined different treatment planning systems (TPS).⁹ Author reported the impact of gantry space resolution on VMAT plan quality for limited aperture multileaf collimator (MLC) 'Elekta Beam-Modulator™', and concluded that a gantry space of 4° is an optimal choice for minimal usage of planning resources without compromising treatment plan quality.¹⁰

A recent study reported the dosimetric effect of limited aperture multileaf collimator on VMAT plan quality.¹¹ They concluded that plan quality at collimator angles $C0^\circ$ and $C(0^\circ - 90^\circ)$ was clinically acceptable for all VMAT-techniques for both prostate and head-and-neck except single-arc for head-and-neck. The significant p-values were observed for collimator angle 90° with higher normal tissue doses, poorer target coverage when compared with $C0^\circ$ and $C(0^\circ - 90^\circ)$. Both studies showed that limited aperture MLC have different results in plan optimization compared to conventional $40 \times 40 \text{ cm}^2$ MLC aperture.^{10,11}

In terms of treatment plan quality, three VMAT techniques

¹Department of Medical Imaging, School of Health Sciences, University of Management and Technology, Lahore, ²Department of Physics, Baluchistan University of Information Technology, Engineering and Management Sciences, Quetta, ⁴Department of Physics, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan ³Department of Oncology, Combined Military Hospital, Rawalpindi, ⁵Department of Mathematics, NAMAL INSTITUTE Mianwali, Pakistan.

Correspondence: Ghulam Murtaza. Email: faqeergm@gmail.com

single-arc (SA), dual-arc (DA) and combined two independent-single-arcs (ISAs) were compared. VMAT plan optimization was done for 'ElektaSynergyS[®]' (Elekta Ltd, Crawley, UK) Linac providing maximum aperture $21 \times 16 \text{ cm}^2$ (Beam-Modulator™). The study focused in the search of optimal user selectable VMAT planning parameters for limited aperture MLC of 'Elekta Beam-Modulator™', and to assess the potential combination of Beam-Modulator™ and SmartArc™ module of the Pinnacle Treatment Planning System (version 9.2, Philips Healthcare).³

Material and Methods

A VMAT planning study of nine prostate and nine head-and-neck cancer patients was carried out on patients previously treated using the technique of Intensity Modulated Radiotherapy (IMRT) during 2014-15, at medical physics department of radiation oncology division SanBortolo hospital, Vicenza, Italy. In case of prostate cancer patients, the planning target volume (PTV) comprised of prostate gland plus half of the seminal vesicles with prescribed dose (PD) of 78 Gy (2 Gy/fraction), while the delineated organs-at-risk (OARs) were rectum and bladder. The PTV78 was defined from CTV by adding a standard margin of 0.7 cm transverse and 0.9 cm in craniocaudal directions for all patients. In case of head-and-neck cancers, a group of nine patients with different target geometries and prescribed doses for carcinoma of oral cavity, hypopharynx, larynx and oropharynx was considered. Five treatments were planned for 70/60 Gy (2/1.71 Gy/fraction), and four (post operative) treatments were planned for 60/54 Gy (2/1.8 Gy/fraction) for PTVboost/PTVelective respectively. Primary and neck nodes gross tumour volume (GTV) were all gross disease on physical examination with endoscopy and imaging. Usually clinical target volume (CTV) was the GTV plus 5 mm for the microscopic spread of disease, and finally the planning target volume was CTV plus 3 mm. Organs at risk were identified on each scan segmented where appropriate: larynx, oral-cavity, mandible, brainstem, spinal cord, and parotid glands.

In the SynergyS[®] Linac collimation system (Beam Modulator™) has 40 leaf pairs, each of a nominal width 4mm at the isocentre. The 21cm (along the leaf direction) by 16cm (perpendicular to the leaf movement direction) in isocentreplane is the maximum field size.¹² Using the SmartArc™ module¹³ Pinnacle³ TPS (version 9.2, Philips Healthcare) VMAT plans were simulated for a 6MV photon beam. In this study, for VMAT delivery, SynergyS[®] specific parameters integrated in the SmartArc™ module includes: maximum gantry speed of 5.5°/s, maximum leaf speed of 2.4 cm/s, leaf motion

constraint of 0.469 cm/° and five fixed dose rate levels of 35, 75, 150, 300 and 600 MU/min.

Three VMAT plans for each of prostate and head-and-neck patient were optimized by invoking the same set of well optimized dose-volume-objective (DVO) functions, to make a rigorous comparison among different VMAT techniques. It was planned to achieve acceptable target dose coverage ($D_{95\%} \geq 95\%$) for the PTV(boost) however, this ($D_{95\%} \geq 95\%$) constraint was not strictly followed for PTV(elective). Dose volume constraints for PTV and OARs were noted in the data tables.

Single arc (SA), dual arc (DA) and two 'independent single arcs' (ISAs) VMAT techniques were optimized both for prostate and head-and-neck cancers. An arc length of 181° - 179° (clockwise) for prostate and 185° - 175° (clockwise) for head-and-neck, a collimator (C) angle of 45°¹⁴ gantry space (GS) resolution of 4° (4° spacing between subsequent gantry control points),¹⁰ and a maximum delivery time (MDT) of 90 seconds for prostate and 110 seconds for head-and-neck¹⁵ were selected. In the SmartArc™ module, if the user defines plan optimization parameters in a single arc of 360° (clockwise) and select the option of 'two-arcs' then a second arc (counter-clockwise) with same planning parameters will be added automatically, providing the setup of a dual arc VMAT plan. In a dual arc mode, one arc will focus to the left and one to the right side of targets divided by OARs as described by author,¹⁶ which reduced the leaf opening over the OAR and thereby the dose delivered to it. Two 'independent' single arcs (ISAs) of 360 (clockwise and counter-clockwise) coupled in a single optimization process could provide another 'dual arc like' setup. In ISAs both arcs are simultaneously optimized and each arc focuses on the PTV independently, thereby producing similar segments.

Plan quality was assessed by examining the ability of each planning technique to achieve defined clinical objectives. PTV doses were collected for a fixed fraction of volume using following dose indices: $D_{95\%}$, $D_{2\%}$, D_{1cc} , Conformity index (CI) and Homogeneity index (HI). Doses to the OARs were collected in the form of percentage volume of an organ receiving x-dose (V_xGy) and mean dose (D_{mean}) for parotids. The CI compares the 95% isodose volume with the covered PTV volume, has an optimal value of '1', and is calculated as:

$$CI = V_{95\%} / V_{PTV}$$

HI defines dose uniformity within the PTV, with the optimal value of '0' and is calculated as:

$$HI = D_{2\%} - D_{98\%} / D_{50\%}$$

It is assumed that dual arc VMAT, due to its involved focusing process,¹⁶ would provide comparable or better plan quality in terms of target coverage and sparing of organs at risk, than two independent single arcs. A 'two-sided student t-test' assuming unequal variances with statistical significance set to $p \leq 0.05$ was used to check significant differences between dose indices of plans; among different VMAT techniques.¹⁷

Dosimetric validation was performed between phantom measured and TPS calculated doses for randomly selected VMAT plans (DA and ISAs VMAT plans for two prostate and two head and neck cases were selected. All measurements were performed in a single session using

the ArcCHECK™ phantom and SNC Patient software (version 6.2, Sun Nuclear Inc, Melbourne, FL).¹⁷ Van Dyk¹⁸ distance-to-agreement (DTA) (dose difference is normalized to global maximum) criteria of gamma global (γ -global) 3%/3 mm $\geq 95\%$ was used for comparison. The dosimetric measurements were made in absolute dose mode with a low-dose threshold of 10 cGy.

Results

The dose-volume indices (DIs) of the PTV (D95%, D2%, D1cc) and OARs (VxGy) were normalized to prescribed doses and volumes except HI. The CI is presented in percentage. Averages (and ranges) for observed DIs for prostate and head-and-neck PTV and OARs doses are

Table-1: Summary of dose-volume indices (min - max) of prostate and head-and-neck PTV and OARs for VMAT techniques (average over 9-patients), MUs and gamma global (Γ) (average over 2-patients).

Disease location	Arc type	Planning Target Volume (PTV(boost)) (Dose Indices in %)				Rectum			Bladder		MUs	< Γ > global (%)
		D95% ($\geq 95\%$)	D2% ($\leq 107\%$)	CI (%)	HI	V50Gy (%) ($\leq 50\%V$)	V65Gy (%) ($\leq 25\%V$)	V70Gy (%) ($\leq 20\%V$)	V40Gy (%) ($\leq 50\%V$)	V70Gy (%) ($\leq 25\%V$)		
Prostate	SA	96 (95.3 – 96.8)	104 (102 – 106)	98.5 (95.8 – 100)	0.089 (0.059 – 0.134)	19.7 (17.4 – 22.6)	10.1 (8.0 – 13.3)	6.3 (4.2 – 7.7)	26.6 (15.9 – 37.2)	9.7 (5.2 – 14.8)	426	
	DA	96.3 (95.5 – 97.5)	103 (102 – 105)	99.6 (98.6 – 100)	0.079 (0.066 – 0.098)	18.8 (16.0 – 22.9)	9.2 (6.9 – 11.7)	6 (4.0 – 7.5)	25.8 (15.3 – 35.9)	9.4 (5.1 – 14.7)	490	99.7
	ISAs	96.6 (95.8 – 97.8)	103 (101 – 105)	99.5 (97.6 – 100)	0.077 (0.052 – 0.105)	19.7 (17.1 – 24.4)	9.5 (7.3 – 12.8)	6 (3.2 – 8.1)	26.2 (14.1 – 35.2)	9.8 (5.0 – 14.6)	467	99.5
		Planning Target Volume (PTV(boost)) (Dose Indices in %)				Spinal cord D0.5cc (≤ 45 Gy)	Parotid (right)		Parotid (left)		MUs	< Γ > global (%)
		D95% ($\geq 95\%$)	D1cc (%) ($\leq 110\%$)	CI (%)	HI		V30Gy (%) ($\leq 50\%V$)	Mean Dose (≤ 27 Gy)	V30Gy (%) ($\leq 50\%V$)	Mean Dose (≤ 27 Gy)		
Head-n-Neck	SA	95 (93.5 – 96.4)	110 (107 – 113)	94.8 (91.7 – 97.5)	0.157 (0.110 – 0.204)	34.5 (31.2 – 36.6)	32.5 (17.9 – 53.0)	26 (23.7 – 27.9)	34.5 (20.2 – 46.6)	25.7 (19.3 – 27.8)	474	
	DA	96.5 (95.2 – 97.6)	109 (106 – 111)	97.4 (95.4 – 98.7)	0.131 (0.096 – 0.152)	32.7 (30.6 – 35.6)	35.9 (25.8 – 50.9)	27 (26.5 – 27.4)	36.1 (27.0 – 42.9)	25.8 (20.8 – 27.9)	548	97.4
	ISAs	96.3 (95.1 – 97.3)	109 (106 – 111)	97.2 (95.2 – 98.6)	0.13 (0.098 – 0.146)	33.6 (31.2 – 35.3)	35.4 (26.6 – 50.2)	26.6 (26.1 – 27.2)	34.7 (22.7 – 44.1)	25.7 (19.9 – 27.6)	502	96.8

Table-2: Summary of calculated p-values among SA, DA and ISAs VMAT techniques for prostate and head and neck plans.

Disease location	Arc type	Dose Indices (PTV(boost))				Dose Indices (PTV(elective))		
		D95%	D2%	CI	HI	D95%	D2%	CI
Prostate	SA vs DA	0.30	0.53	0.06	0.20	-	-	-
	SA vs ISAs	0.06	0.58	0.09	0.13	-	-	-
	DA vs ISAs	0.30	0.99	0.69	0.61	-	-	-
		D95%	D1cc	CI	HI	D95%	D1cc	CI
Head n Neck	SA vs DA	0.00	0.35	0.00	0.02	0.01	0.02	0.02
	SA vs ISAs	0.00	0.15	0.01	0.02	0.06	0.06	0.11
	DA vs ISAs	0.66	0.52	0.65	0.88	0.50	0.50	0.34

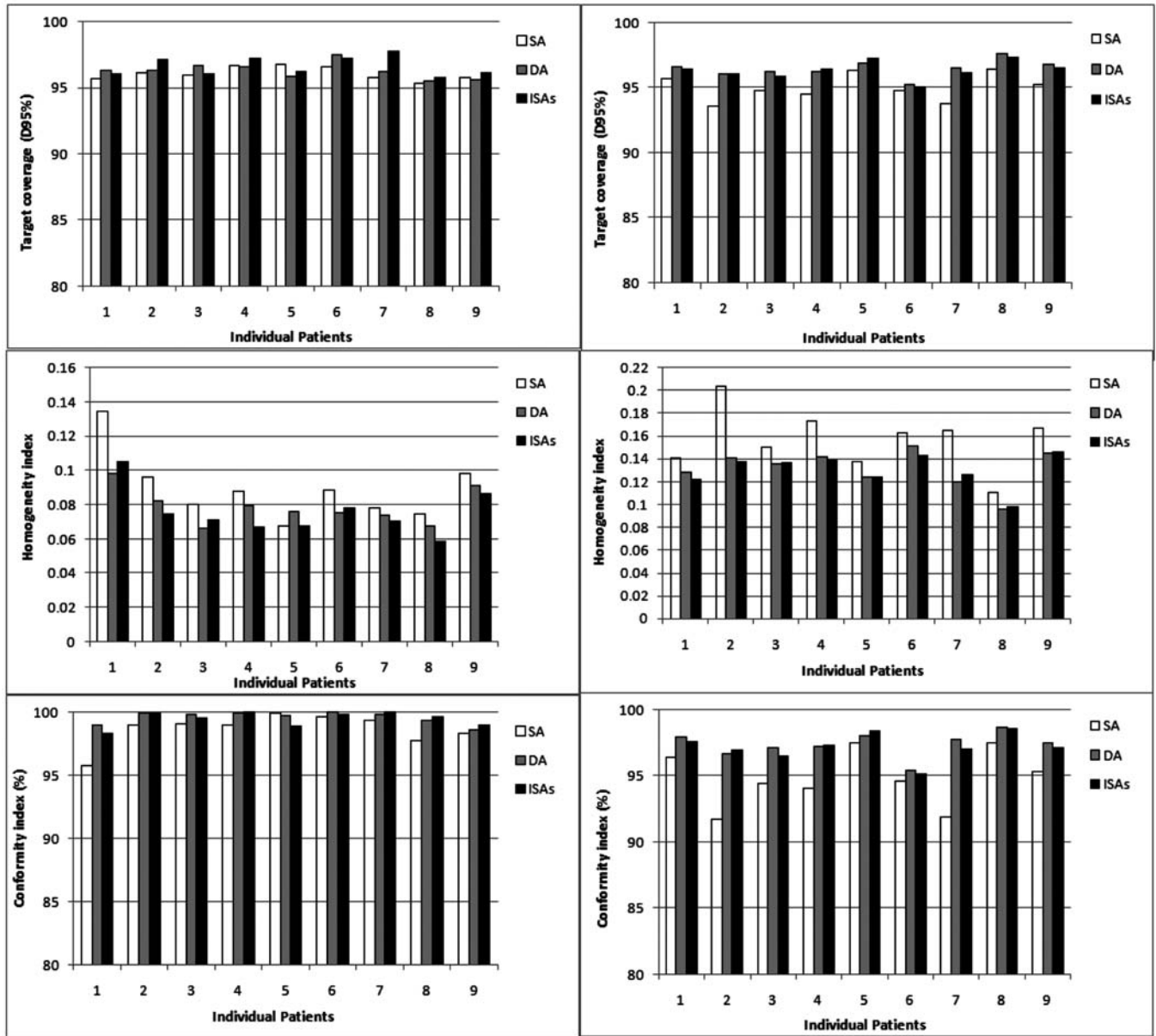


Figure-1: Comparison of individual patient data sets for prostate PTV_{boost} (left column) and Head-and-Neck PTV_{boost} (right column), dose-volume indices (D95%, HI, CI₁) optimized for SA, DA and ISAs VMAT arcs.

noted in Table-1 for different VMAT techniques, and their respective p-values in Table-2. The doses for head-and-neck organs at risk (larynx, mandible oral cavity and brainstem) were well below from defined constraints and clinical acceptable. Therefore, were not reported in the data tables, except spinal cord and parotid glands.

All VMAT techniques produced clinically acceptable plans for prostate (Table-1) and no significant differences were observed between DA and ISAs for PTV metrics (Table-2). It was observed that DA spared more rectum volume in

medium ($V_{50\text{Gy}}$), ($V_{65\text{Gy}}$) and high dose ($V_{70\text{Gy}}$) regions than ISAs (Table-1). SA could not achieve the target coverage ($D95\% \geq 95\%$) in some of head-and-neck cases (Table-1 (SA 95.0 (93.5 - 96.4)) for PTV (boost). DA showed a trend of better target coverage and conformity index compared to ISAs for head-and-neck with similar sparing of OARs (Table-1), however their comparing p-values were not significant (Table-2). SA produced similar plans to DA and ISAs for prostate (Table-1), while for head-and-neck, DA and ISAs significantly improved target coverage compared to SA (Table-2). DA used 5% and 9% higher

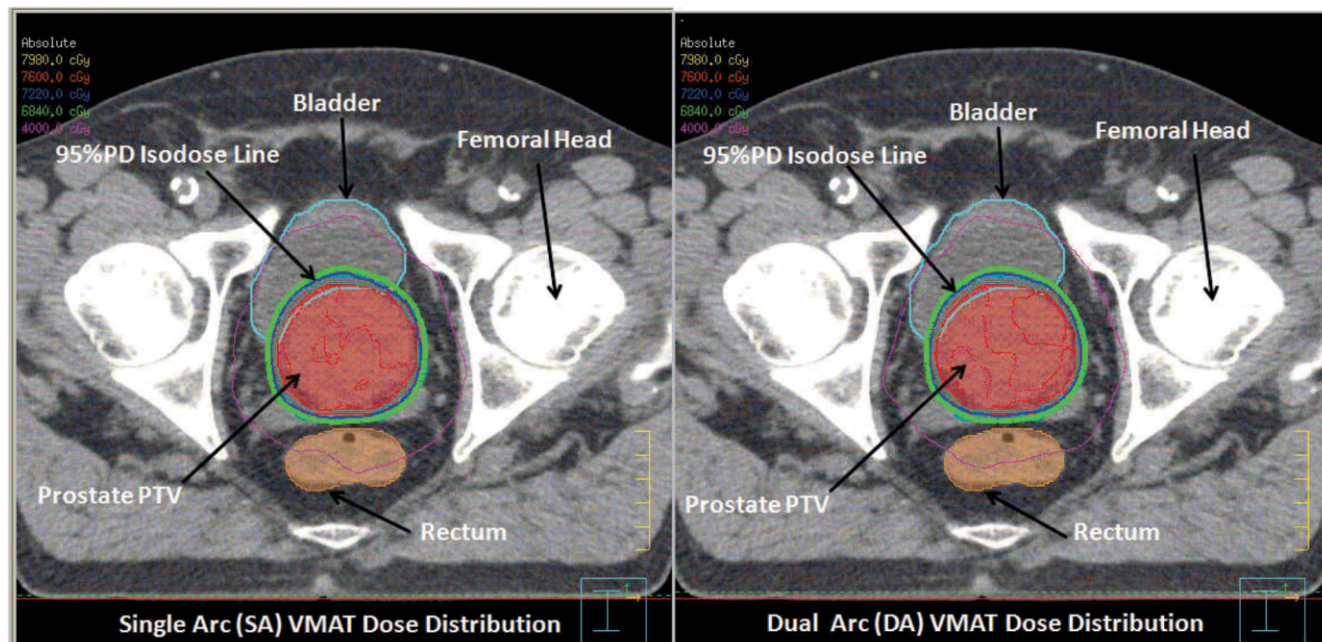


Figure-2: A representative prostate case showing the dose distribution in a typical transverse slice for single and dual arc VMAT techniques. Thick-blue isodose-line indicates the 95% of PD to cover at least 95% of PTV_{boost} (red-contour), whereas pink-contour is for rectum.

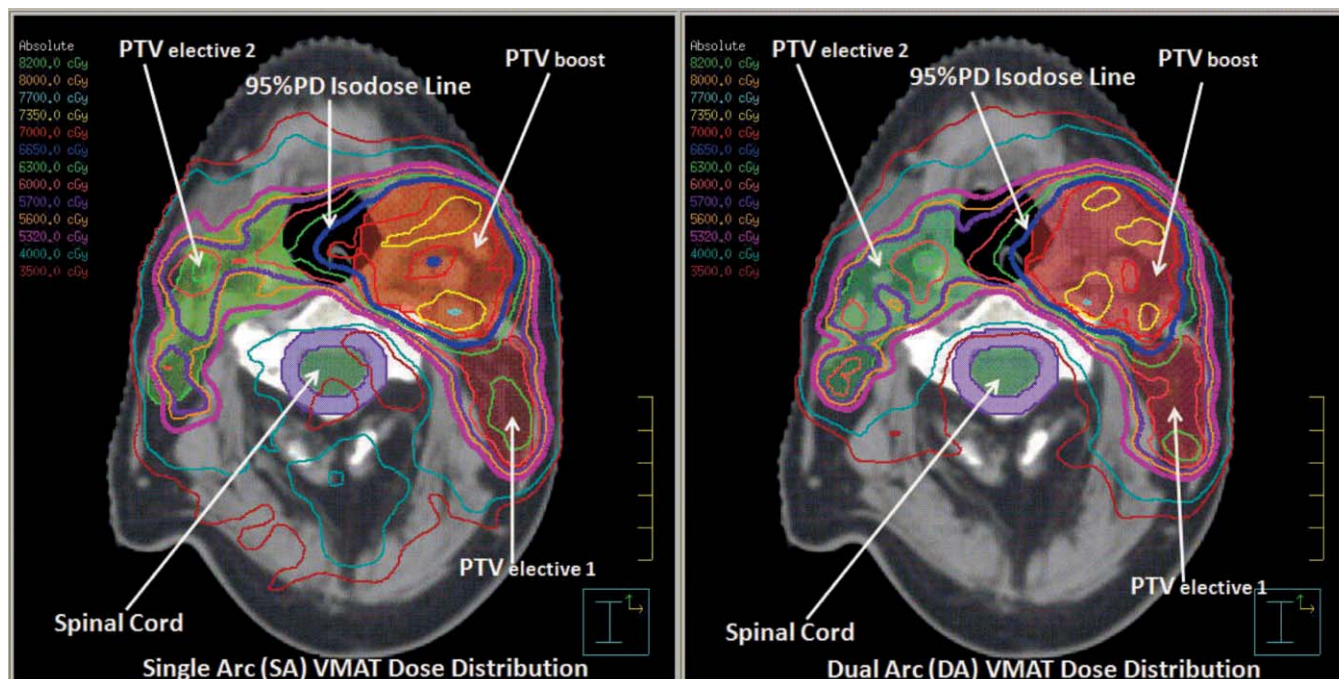


Figure-3: A representative Head-and-Neck case showing the dose distribution in a typical transverse slice for single and dual arc VMAT techniques. Thick-blue isodose-line indicates the 95% of PD to cover at least 95% of PTV_{boost} (red-contour), brown-contour is for PTV_{elective1} and green-contour is for PTV_{elective2}.

monitor units than ISAs, for prostate and head-and-neck plans, respectively (Table-1).

The histogram based comparison of individual patient

data sets for prostate (left column) and Head-and-Neck (right column) dose-volume indices (D95%, HI, CI,) are shown in Figure-1 for different VMAT arcs. Whereas for prostate and head-and-neck, the dose distributions in a

typical transverse slice for SA and DA VMAT techniques are shown in Figure-2 and Figure-3, respectively.

Discussions

In this study, three different VMAT arcs are assessed quantitatively and qualitatively in terms of VMAT plan quality using the same dose volume objectives and algorithm, demonstrating the use of ElektaSynergyS® Linac equipped with a Beam Modulator™, which has the maximum field size of $21 \times 16 \text{ cm}^2$. Whereas most of the earlier VMAT plan optimization studies presented in literature were simulated for Linac(s) with apertures of $40 \times 40 \text{ cm}^2$.

The target coverage for dual arc (DA) and two combined independent single arcs (ISAs) were found to be very similar and plans were clinically acceptable for both prostate and head-and-neck cases. This might be due to similar available modulation space, equal number of control points and similar angle of collimation. Briefly, irradiated partial volumes of OARs for both prostate and head-and-neck at fixed amount of dose were well below from their respective tolerance levels. The spinal cord dose constraints were achieved for all VMAT techniques using a single maximum dose objective. The calculated p-values did not show any significant variation between DA and ISAs VMAT techniques in terms of target coverage for both organs.

In case of prostate, a notable advantage of DA over ISAs was better, sparing of rectum volumes 4.8% and 3.3% in the medium ($V_{50\text{Gy}}$) and high dose ($V_{65\text{Gy}}$) regions, respectively. The DA technique provided better sparing of OARs by focusing on one half of PTV for each arc, thereby minimizing the leaf opening over the OARs, as reported earlier.¹⁶ The dose diminution in medium and high dose regions for rectum-volumes by DA might reduce rectum side effects.¹⁹ Single arc VMAT produced all clinically acceptable plans for prostate and is considered sufficient for dose planning in our study; however, DA and ISAs improved target coverage and sparing of OARs, but at the cost of increased plan-optimization and arc-delivery times.

In case of head-and-neck, DA and ISAs significantly improved the target dose coverage, conformity and HI over SA. The significant p-values were noted in, similar results have been reported by authors for the optimization of SA and DA.⁸ The magnitude of parotid sparing ($V_{30\text{Gy}}$) and mean-dose between DA and ISAs were comparable for head-and-neck plans. SA might be an appropriate treatment planning solution for simple cases. But for complicated tumour sites like head-and-neck where multiple PTVs and organs at risk are defined, multiple modulated arcs provide better treatment plans at the cost of increased plan-optimization and delivery

time.²⁰ The author recommended the use of SA for head-and-neck planning when using Linac aperture of $40 \times 40 \text{ cm}^2$.⁹ Whereas in our results, SA is inefficient in achieving treatment planning goals (D95%, HI, CI,) in majority of cases, when using limited aperture MLC of Beam Modulator™, and the spread of low-dose-bath is higher for SA compared to DA and ISAs.

In general DA and ISAs techniques provided higher degrees of freedom while optimizing both arcs simultaneously compared to SA. It is supported by other studies reported that a second arc adds more degrees of freedom of possible leaf positions thus providing better treatment plans than single arc.⁸ In complicated dose planning sites like head-and-neck, ISAs could be used an alternative to DA, provided DA failed to achieve dose-planning objectives. Dual arc required more MUs than ISAs, which in turn used more monitor units than single arc. In this study, a similar arc delivery time was noted between DA and ISAs VMAT techniques for individual planned organs. An independent dosimetric verification was performed for randomly selected VMAT plans to ensure that the calculated dose distributions could be delivered as planned. All selected plans passed the defined criteria of γ -global (3%/3 mm) $\geq 95\%$ and their average results were noted.

Conclusions

Single arc is sufficient for prostate, while inefficient in case of head-and-neck dose-planning, while using 'Elekta Beam-Modulator' collimation system. Dual arc and two combined independent-single-arcs provided similar PTV coverage, while DA provided better sparing of organs at risk. In complicated dose-planning cases ISAs can be used an alternative to DA. Similar treatment delivery times were observed for DA and ISAs VMAT techniques. Thus, optimal choice of VMAT arc is another degree of freedom in order to obtain desired PTV dose distributions and sparing of organs at risk.

Disclaimer: This is a study of VMAT radiotherapy planning using well optimized 'planning objectives', previously treated using the technique of Intensity Modulated Radiotherapy (IMRT). This research was a part of PhD thesis research project.

Conflict of Interest: None.

Source of Funding: This research work was supported under the educational grant STEP fellowship programme of 'Abdus-Salam ICTP Trieste Italy' and 'IAEA Vienna Austria'.

References

1. Otto K. Volumetric modulated arc therapy, IMRT in a single arc. *Med Phys.*2008; 35:310-7.
2. Bota K, Lock M, Ahmad B, Fisher B, Yartsev S, Wong E, et al. Dosimetric Comparison of Volumetric Modulated Arc Therapy, Tomotherapy, and Intensity Modulated Radiation Therapy for Radiation Dose Escalation of Hepatic Malignancies. *Int J Radiat Oncol Biol Phys.* 2014; 90: S381-2.
3. Jain S, Babaiah M, Mohanty P, Mirza A, Ramalingam K. Volumetric Modulated Arc Therapy (VMAT) Versus Intensity Modulated Radiation Therapy (IMRT) in Pelvic Malignancies: A Dosimetric Analysis. *Int J Radiat Oncol Biol Phys.* 2013; 87:S752.
4. Liu X, Huang E, Wang Y, He Y, Luo H, Zhong M, et al. Dosimetric comparison of helical tomotherapy, VMAT, fixed-field IMRT and 3D-conformal radiotherapy for stage I-II nasal natural killer T-cell lymphoma. *Radiat Oncol.* 2017; 12:76.
5. LoSasso T, Chui CS, Ling CC. Physical and dosimetric aspects of a multileaf collimation system used in the dynamic mode for Implementing intensity modulated radiotherapy. *Med Phys.* 1998; 25:1919-27.
6. Xia P, Verhey LJ. Multileaf collimator leaf sequencing algorithm for intensity modulated beams with multiple static segments. *Med Phys.* 1998; 25:1424-34.
7. Kristoffersen KF, Ohlhues L, Medin J, Korreman S. Rapid Arc volumetric modulated therapy planning for prostate cancer patients. *Acta Oncol.* 2009; 22:227-32.
8. Verbakel WF, Cuijpers JP, Hoffmans D, Bieker M, Slotman BJ, Senan S. et al. Volumetric intensity-modulated arc therapy vs conventional IMRT in head-and-neck cancer. A comparative planning and dosimetric study. *Int J Radiat Oncol Biol Phys.* 2009; 74:252-9.
9. Bertelsen A, Hansen CR, Johansen J, Brink C. Single Arc Volumetric Modulated Arc Therapy of head and neck cancer. *Radiother Oncol.*2010; 95:142-8.
10. Murtaza G, Cora S, Khan EU. Validation of the Relative Insensitivity of Volumetric-Modulated Arc Therapy (VMAT) Plan Quality to Gantry Space Resolution. *J Radiat Res.*2016; 58:579-90.
11. Murtaza G, Mehmood S, Rasul S, Murtaza I, Khan EU. Dosimetric effect of limited aperture multileaf collimator on VMAT plan quality: A study of prostate and head-and-neck cancers. *Rep Pract Oncol Radiother.*2018; 23:189-98.
12. Webb S. Does the option to rotate the Elekta Beam Modulator MLC during VMAT IMRT delivery confer advantage? - A study of 'parked gaps'. *Phys Med Biol.*2010; 55:303-19.
13. Bzdusek K, Friberger H, Eriksson K, Hårdemark B, Robinson D, Kaus M. Development and evaluation of an efficient approach to volumetric arc therapy planning. *Med Phys.*2009; 36:2328-39.
14. Treutwein M, Hipp M, Koelbl O, Dobler B. Searching standard parameters for volumetric modulated arc therapy (VMAT) of prostate cancer. *Radiat Oncol.*2012; 7:108.
15. Pasler M, Wirtz H, Lutterbach J. Impact of gantry rotation time on plan quality and dosimetric verification--volumetric modulated arc therapy (VMAT) vs. intensity modulated radiotherapy (IMRT).*Strahlenther Onkol.* 2011; 187:812-9.
16. Eriksson K, Friberger H, Sterner E, Blumenthal C. Volumetric Modulated Arc Therapy (VMAT) optimization with Ray Arc. Stockholm. Ray Search White Paper. 2009; 1-16.
17. Chaswa V, Weldon M, Gupta N, Chakravarti A, Ronga Y. Commissioning and comprehensive evaluation of the Arc CHECK cylindrical diode array for VMAT pre-treatment delivery QA. *J Appl Clin Med Phys.* 2014; 15:212-25.
18. Van Dyk J, Barnett RB, Cygler JE, Shragge PC. Commissioning and quality assurance of treatment planning computers. *Int J Radiat Oncol Biol Phys.*1993; 26: 261-73.
19. Dröge LH, Weber HE, Guhlich M, Leu M, Conradi LC, Gaedcke J, et al. Reduced toxicity in the treatment of locally advanced rectal cancer: a comparison of volumetric modulated arc therapy and 3D conformal radiotherapy. *BMC Cancer.* 2015; 15:750.
20. Bedford JL. Treatment planning for volumetric modulated arc therapy. *Med Phys.*2009; 36:5128-38