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Dosimetric effect of limited aperture multileaf collimator on VMAT plan quality: A study of prostate and head-and-neck cancers

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ABSTRACT

Aim: The aim of study was to evaluate the dosimetric effect of collimator-rotation on VMAT plan quality, when using limited aperture multileaf collimator of Elekta Beam Modulator^{TM} providing a maximum aperture of 21 cm × 16 cm.

Background: The increased use of VMAT technique to deliver IMRT from conventional to very specialized treatments present a challenge in plan optimization. In this study VMAT plans were optimized for prostate and head and neck cancers using Elekta Beam-Modulator^{TM}, whereas previous studies were reported for conventional Linac aperture.

Materials and methods: VMAT plans for nine of each prostate and head-and-neck cancer patients were produced using the 6 MV photon beam for Elekta-SynergyS® Linac using Pinnacle^3 treatment planning system. Single arc, dual arc and two combined independent-single arcs were optimized for collimator angles (C) 0°, 90° and 0°–90° (0°–90°; i.e. the first-arc was assigned C0° and second-arc was assigned C90°). A treatment plan comparison was performed among C0°, C90° and C(0°–90°) for single-arc dual-arc and two independent-single-arcs VMAT techniques to evaluate the influence of extreme collimator rotations (C0° and 90°) on VMAT plan quality. Plan evaluation criteria included the target coverage, conformity index, homogeneity index and doses to organs at risk. A 'two-sided student *t*-test' ($p \leq 0.05$) was used to determine if there was a significant difference in dose volume indices of plans.

Results: For both prostate and head-and-neck, plan quality at collimator angles C0° and C(0°–90°) was clinically acceptable for all VMAT-techniques, except SA for head-and-neck. Poorer target coverage, higher normal tissue doses and significant *p*-values were observed for collimator angle 90° when compared with C0° and C(0°–90°).

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Conclusions: A collimator rotation of 0° provided significantly better target coverage and sparing of organs-at-risk than a collimator rotation of 90° for all VMAT techniques.

1. Background

The radical challenge of radiotherapy is to deliver highly conformal dose distributions to the planning target volume (PTV) while maintaining maximum sparing of organs at risk (OARs). Several intensity modulated radiotherapy (IMRT) delivery techniques were proposed in early 1990s.[1,2] The method of VMAT to deliver IMRT[3] offers dosimetric and efficient delivery advantages over previous techniques. The optimum VMAT dose distributions and efficient delivery generally depend on the choice of equipment, optimization algorithm and user selectable planning parameters (i.e. number of arcs, collimator angle, gantry angle spacing and delivery time). Many authors reported treatment plan optimization among single arc VMAT, dual arc VMAT[4–6] and their comparison with 3-dimentional conformal radiotherapy (3DCRT) and static field IMRT techniques[7–11] for different tumor locations. Using different treatment planning systems (TPS), these plans were simulated for Varian (Varian Medical Systems, Palo Alto, CA) and Elekta (Elekta Ltd, Crawley, UK) linear accelerators (Linac) with conventional 40 cm × 40 cm apertures.[4–11] In a computer modeled study, the analysis of the parking problem (leaf-parked-gaps for closed leaf pairs) and the associated challenge in plan optimization is discussed by Web[12] for the Beam Modulator™ collimation system (Elekta Ltd, Crawley, UK), limited to a maximum field size of 21 cm × 16 cm.

In this study, three VMAT techniques were optimized for two different collimator rotations, and its influence on VMAT plan quality was investigated. Moreover, beam delivery efficiency in terms of monitor units was also recorded. The increased use of VMAT technique to deliver IMRT from conventional to very specialized treatments, like stereotactic-body-radiotherapy (SBRT)/stereotactic-radio-surgery (SRS)[13] presents a challenge in plan optimization. This study will help treatment planners in plan optimization, users of Beam Modulator™ collimation system.

2. Aim

In the search of optimal planning strategies, the specific aim of the study was to investigate the weakness and strength of two extreme collimator rotations and their mix, and how it influence the VMAT plan quality, when using SynergyS® (Elekta Ltd, Crawley, UK) Linac equipped with the Beam Modulator™ limited to maximum apertures of 21 cm × 16 cm.

3. Materials and methods

A retrospective VMAT planning study of nine prostate and nine head-and-neck cancer patients was carried out. For prostate cancer patients, the PTV comprises prostate gland plus half of the seminal vesicles with prescribed dose (PD) of 78 Gy (2 Gy/fraction), while the rectum and bladder were delineated as OARs. The PTV78 was defined from respective CTV by adding a standard margin of 0.7 cm transverse and 0.9 cm in craniocaudal directions.[14] For head-and-neck, a heterogeneous group of nine cancer patients with different target geometries and prescribed doses for the carcinoma of the oropharynx, hypopharynx, oral cavity and larynx 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 $\text{PTV}_{\text{boost}}/\text{PTV}_{\text{elective}}$, respectively. On the physical examination with endoscopy and imaging, the primary and neck nodes gross tumor volume (GTV) were all gross disease. The clinical target volume (CTV) was extended 5 mm over the GTV to account for the microscopic spread of disease, and finally the planning target volume was drawn on CTV plus 3 mm. Where appropriate, organs at risk were identified on each scan segment: the parotid glands, oral cavity, mandible, larynx, spinal cord and brainstem.[15]

The SynergyS® Linac equipped with a Beam Modulator™ MLC collimation system has 40 leaf pairs each of a nominal width corresponding to 4 mm at the isocentre. The maximum field size is 21 cm (along the leaf direction) by 16 cm (perpendicular to the leaf movement direction) in the isocentre plane.[12] For VMAT delivery SynergyS®, specific parameters integrated in the SmartArc™ module include: 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. The VMAT plans were optimized for a 6 MV photon beam using the SmartArc™ module[16,17] in the Pinnacle^3 TPS (version 9.2, Philips Healthcare). The performance of the SmartArc™ module has been reported by several authors.[5,17]

3.1. *Treatment planning*

Seven VMAT plans for each of the prostate and head-and-neck patients were optimized. In order to make a pure comparison among different collimator rotations, all plans were generated by invoking the same set of well optimized (separately, for prostate and head-and-neck) dose-volume-objective (DVO) functions. It was planned to achieve acceptable target dose coverage (D95% ≥95%) for the PTV (boost); however, this (D95% ≥95%) constraint was not strictly followed for PTV (elective). Dose volume constraints (clinical objectives) for target coverage (PTV)[18] and OARs[19] are 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 gantry space (GS) resolution of 4° (4° spacing between subsequent gantry control points),[20] and a maximum delivery time (MDT) of 90 s for prostate and 110 s for head-and-neck[21] were selected.

3.1.1. *Influence of field orientation on VMAT plan quality*

For the investigation of the influence of MLC field orientation (collimator rotation) on VMAT plan quality two (extreme) collimator angles C0° and C90° were considered providing different MLC travel directions and maximum aperture unlike conventional 40 cm × 40 cm apertures. In order to insure the consistency of results, these two collimator rotations were optimized for single-arc (SA), dual-arc (DA) and two combined independent-single-arcs (ISAs) VMAT techniques. In the situation of collimator angle 0° when the leaf motion is perpendicular to the rotational axis of the gantry, the larger field aperture (21 cm) remains in the direction of gantry motion. Conversely, at collimator angle 90° the leaf motion is parallel to the rotational axis of gantry and the smaller field aperture (16 cm) is in the direction of gantry motion. At present, the SmartArc^{TM} module does not allow a change of collimator angle in the second half of a DA technique. However, for ISAs the user can select different collimator angles for each individual arc. For prostate, each of the VMAT techniques (SA, DA and ISAs) were optimized for both C0° and C90° (each individual arc had the same angle in the clockwise and counter clockwise direction). Moreover, for prostate one ISAs plan was optimized at C(0°–90°) (i.e. the first arc was assigned C0° and the other was assigned C90°), purpose of this arc combination was to evaluate the effect of combined small and large aperture in a single optimization process. Similarly, for head-and-neck each of the VMAT techniques (SA, DA and ISAs) were optimized for C0°, C90° and C(0°–90°) as above.

3.2. *Plan evaluation criteria, statistical analysis and dosimetry*

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 the following dose indices: D95%, D2%, D1cc, 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 (Dmean) for parotids. The CI compares the 95% isodose volume with the PTV volume, has an optimal value of '1', and it is calculated as:

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

HI defines the dose uniformity within the PTV, with the optimal value of '0' and is calculated as[18]:

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

A 'two-sided student *t*-test' assuming unequal variances with statistical significance set to $p \leq 0.05$ was used to check the significant differences between dose indices of plans among different collimator rotations, and are marked in bold italic when significant.

Dosimetric validation was performed between phantom measured and TPS calculated doses for randomly selected VMAT plans. SA, DA and ISAs VMAT plans for each of the three prostate and head-and-neck cases were selected for collimator angle 0°, 90° and (0°–90°). All measurements were performed in a single session using the ArcCHECK^{TM} phantom and SNC patient software (version 6.2, Sun Nuclear Inc., Melbourne, FL).[22] Van Dyk et al.[23] distance-to-agreement (DTA) criteria of gamma local ($\gamma_{\text{-local}}$) 3%/3 mm ≥90% was used for comparison. The dosimetric measurements were made in absolute dose mode with a low-dose threshold of 10 cGy.

4. Results

The dose-volume indices (DIs) of the PTV and OARs (V_{xGy}) were normalized to prescribed doses and volumes except HI, and the CI is presented in percentage. The DIs summary of prostate PTV OARs and calculated MUs are noted in Table 1. The DIs summary of head-and-neck PTV and OARs are not presented here, whereas their calculated *p*-values are reported in Table 2. The doses for head-and-neck OARs; brainstem, oral cavity, mandible and larynx were clinically acceptable and well below the defined constraint limit and not reported in the data tables. The calculated gamma-index of planned and delivered doses is noted in Table 3.

All of the VMAT techniques (SA, DA, ISAs) optimized for C0° and ISAs optimized for C(0°–90°) achieved the planning objectives for prostate and head-and-neck, except SA (C0°) for head-and-neck plans. The majority of the VMAT techniques optimized for C90° failed to achieve the planning objectives both for the prostate (Table 1) and head-and-neck, except a few. Significant *p*-values were noted between C0° and C90°, and between C(0°–90°) and C90° for individual VMAT techniques except for prostate and head-and-neck, between C(0°–90°) and C0° for ISAs (Table 2). Less target dose coverage (D95%), poorer CI, and higher tails doses (D2%) were observed at C90° for all VMAT techniques compared to C0°. The PTV dose inhomogeneity at C90° was 45%, 52% and 51% higher than C0° for SA, DA and ISAs, respectively. A histogram comparison of individual patient data sets for ISAs VMAT technique optimized for C0°, C90° and C(0°–90°) for prostate planning are shown in Fig. 1. Similarly, the histogram comparison of individual patient data sets for SA VMAT technique for C0° and C90° for head-and-neck planning is shown in Fig. 2.

The dose volume histogram (DVH) of PTV and OARs for a prostate case is shown in Fig. 3 ("red" curves for PTV, "green" for bladder and "pink" for rectum). Dual arc at C0° is considered to be a reference to compare with three different VMAT techniques optimized at C90°. Dual-arc at C0° (thick solid line) is compared to single-arc at C90° (thin solid line), dual-arc at C90° (thin dashed line) and two independent single arcs at C90° (thick dashed line). Target coverage and sparing of OARs is better at C0° than C90°.

Fig. 4(a–c) shows the dose distribution for prostate case in a typical transverse slice (same slice) for SA, DA and ISAs VMAT techniques optimized for C0° (left hand side) and C90° (right hand side) in each sub-figure. It is evident that C0° provided a better target coverage, higher conformity, less hotspot dose, less spread of low-dose-bath and better sparing of OARs than C90°.

Table 1 – Summary of dose-volume indices (min–max) of prostate PTV and OARs for VMAT techniques at C0°, C90° and C(0°–90°) (average over 9 patients).

Arc type	Collimator angle	Planning target volume (dose indices in %)				Rectum			Bladder		MUs
		D95% (≥95%PD)	D2% (≤107%PD)	CI (%)	HI	V50 Gy (≤50%V)	V65 Gy (≤25%V)	V70 Gy (≤20%V)	V40 Gy (≤50%V)	V70 Gy (≤25%V)	
SA	0°	96.5 (95.5–97.3)	103 (101–105)	99.2 (97.3–100)	0.076 (0.050–0.107)	20.8 (17.9–24.8)	10.8 (8.9–14.0)	7.3 (6.0–8.3)	25.4 (14.9–34.2)	10.3 (5.6–16.0)	458
SA	90°	94.0 (91.0–95.1)	104 (101–107)	93.4 (85.8–97.0)	0.120 (0.082–0.193)	19.9 (18.1–22.4	8.6 (7.2–10.0)	4.8 (2.9–6.5)	26.6 (16.8–35.6)	9.2 (5.4–14.7)	398
DA	0°	96.6 (96.2–97.3)	103 (102–105)	99.6 (99.4–100)	0.076 (0.062–0.090)	19.7 (17.4–25.6)	10.0 (7.6–13.4)	6.8 (4.7–8.5)	25.2 (14.6–35.0)	10.5 (5.7–16.3)	515
DA	90°	94.8 (91.9–96.5)	106 (102–110)	95.1 (82.4–99.3)	0.129 (0.084–0.206)	19.3 (14.2–28.4	7.6 (5.7–9.9)	3.9 (2.3–6.3)	26.9 (15.5–35.6)	9.1 (4.7–15.0)	473
ISAs	0°	96.7 (95.1–98.0)	105 (103–109)	99.2 (96.8–100)	0.091 (0.061–0.188)	21.1 (18.1–26.2	10.6 (8.2–14.5)	7.1 (5.0–9.6)	25.7 (15.3–36.1)	10.6 (5.4–16.7)	504
ISAs	90°	92.7 (90.1–95.3)	106 (102–108)	91.4 (85.2–96.8)	0.154 (0.100–0.197)	20.3 (18.1–25.6	7.4 (3.8–9.8)	4.0 (1.2–6.7)	28.4 (16.7–35.6)	7.8 (3.8–14.0)	438
ISAs	0°–90°	96.4 (95.5–97.8)	103 (101–105)	99.3 (98.2–100.0)	0.073 (0.047–0.098)	19.3 (16.0–22.5)	9.0 (6.0–12.3)	5.6 (3.0–8.2)	24.6 (14.0–33.0)	10.2 (4.9–16.0)	478

Table 2 – Summary of calculated *p*-values among collimator angles C0°, C90° and C(0°–90°) for different VMAT techniques for prostate and head-and-neck plans.

Disease location	Arc type	Collimator angle	Dose indices (PTV (boost))				Dose indices (PTV (elective))	
			D95%	D2%	CI	HI	D95%	CI
Prostate	SA	0° vs 90°	**0.00**	0.28	**0.00**	**0.00**	–	–
	DA	0° vs 90°	**0.00**	**0.00**	**0.02**	**0.00**	–	–
	ISAs	0° vs 90°	**0.00**	0.15	**0.00**	**0.00**	–	–
	ISAs	(0°–90°) vs 0°	0.40	**0.04**	0.71	0.22	–	–
	ISAs	(0°–90°) vs 90°	**0.00**	**0.00**	**0.00**	**0.00**	–	–
			D95%	D1cc	CI	HI	D95%	CI
Head-and-neck	SA	0° vs 90°	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	DA	0° vs 90°	**0.00**	0.81	**0.00**	**0.00**	**0.00**	**0.00**
	ISAs	0° vs 90°	**0.03**	0.42	**0.03**	**0.05**	**0.00**	**0.00**
	ISAs	(0°–90°) vs 0°	0.90	0.89	0.90	0.93	0.87	0.95
	ISAs	(0°–90°) vs 90°	**0.04**	0.44	**0.05**	0.07	**0.00**	**0.00**

Table 3 – Gamma index of delivered versus planned (calculated) doses for different collimator angles, for three of each prostate and head-and-neck patients.

Patients	Disease location	SA		DA		ISAs		
		0°	90°	0°	90°	0°	90°	0°–90°
1	Prostate	96.4%	98.9%	97.6%	99.6%	98.3%	99.2%	98.6%
	Head-and-neck	92.9%	91.9%	92.8%	93.8%	93.9%	92.2%	95.9%
2	Prostate	95.3%	99.8%	97.1%	98.7%	97.2%	98.3%	97.5%
	Head-and-neck	91.9%	93.1%	91.8%	92.6%	90.5%	92.5%	93.9%
3	Prostate	97.6%	98.7%	96.6%	99.3%	97.8%	99.8%	97.3%
	Head-and-neck	93.5%	92.4%	92.8%	91.8%	92.6%	93.9%	94.2%

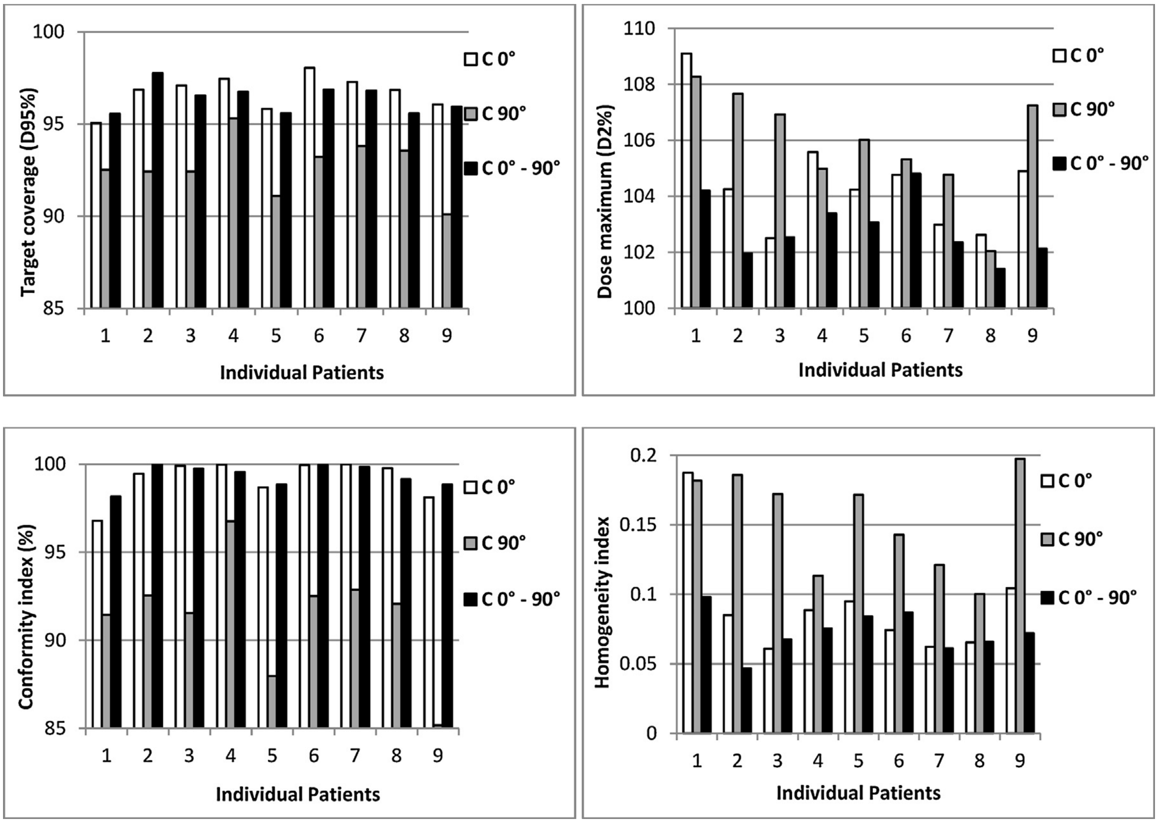

Fig. 1 – Comparison of individual patient data sets for prostate PTV dose-volume indices (D95%, D2%, CI, HI) optimized at C0°, C90° and C(0°–90°) for ISAs.

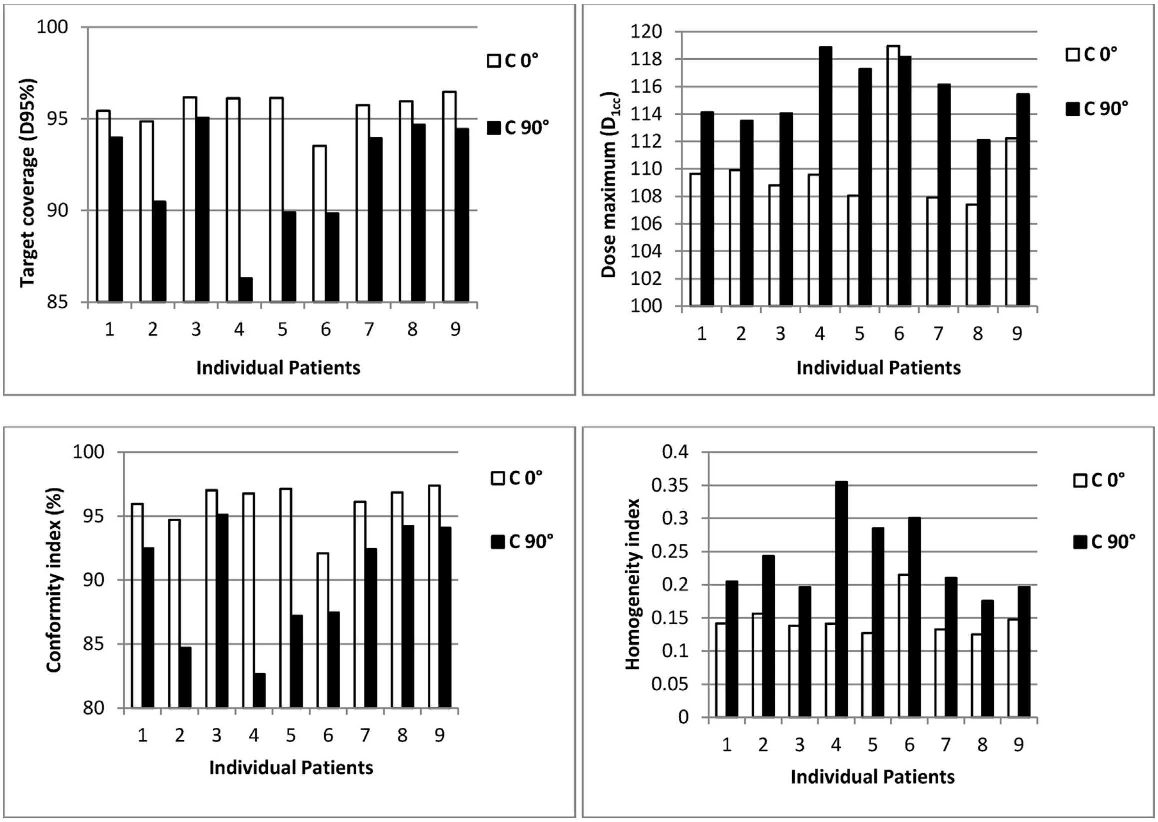

Fig. 2 – Comparison of individual patient data sets for head-and-neck PTV (boost) dose-volume indices (D95%, D1cc, CI, HI) optimized at C0° and C90° for single arc.

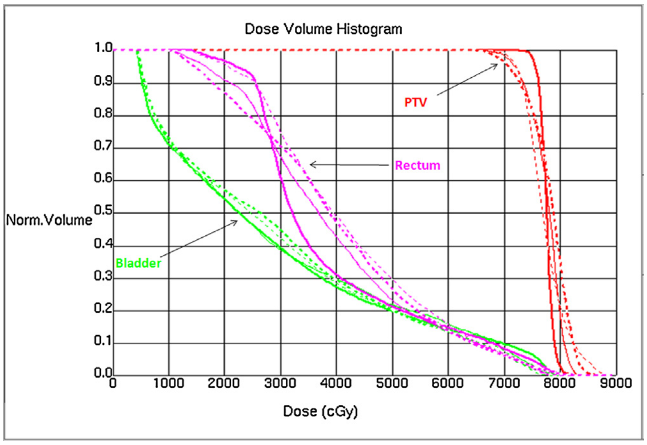

Fig. 3 – A representative prostate case showing the mean DVH for the PTV and OARs comparing different VMAT techniques for C0° and C90°: dual-arc C0° (thick solid line) compared to single arc C90° (thin solid line), dual arc C90° (thin dashed line) and two independent single arcs C90° (thick dashed line) "red" curves for PTV, "green" for bladder and "pink" for rectum.

Fig. 5(a–c) shows the three consecutive control points produced by the SA, DA and ISAs VMAT techniques for C0° (upper row) and C90° (lower row) in each sub-figure, optimized for a prostate patient. C0° is the situation when the direction of MLC motion is perpendicular to the rotational axes of the gantry. Here, MLC parked-gaps are seldom found, whereas for C90° almost every control point showed MLC parked gaps.

5. Discussions

In this study, three different VMAT techniques were optimized for two extreme collimator rotations 0° and 90°, demonstrating different aperture widths and MLC travel direction for an Elekta SynergyS® Linac (Beam Modulator™) with a maximum field size of 21 cm × 16 cm. The results were assessed quantitatively and qualitatively in terms of VMAT plan quality using the same dose volume objectives and algorithm. Most of the earlier VMAT plan optimization studies presented in the literature were based on the use of Linac(s) with apertures of 40 cm × 40 cm.

Limited field aperture of the Beam Modulator™, nominal gantry speed, leaf speed limitations per degree of gantry angle and multiple geometries of ROIs create a challenge for dynamic dose delivery. All VMAT techniques (SA, DA, ISAs) optimized for C0° produced clinically acceptable plans for the prostate, whereas DA and ISAs techniques at C0° achieved planning objectives for head-and-neck except SA C0°. In this study, single arc (C0°) produced sufficient plan quality for prostate treatment which is consistent with the previous findings[4,6]; however, DA (C0°) and ISAs (C0°, C0°–C90°)

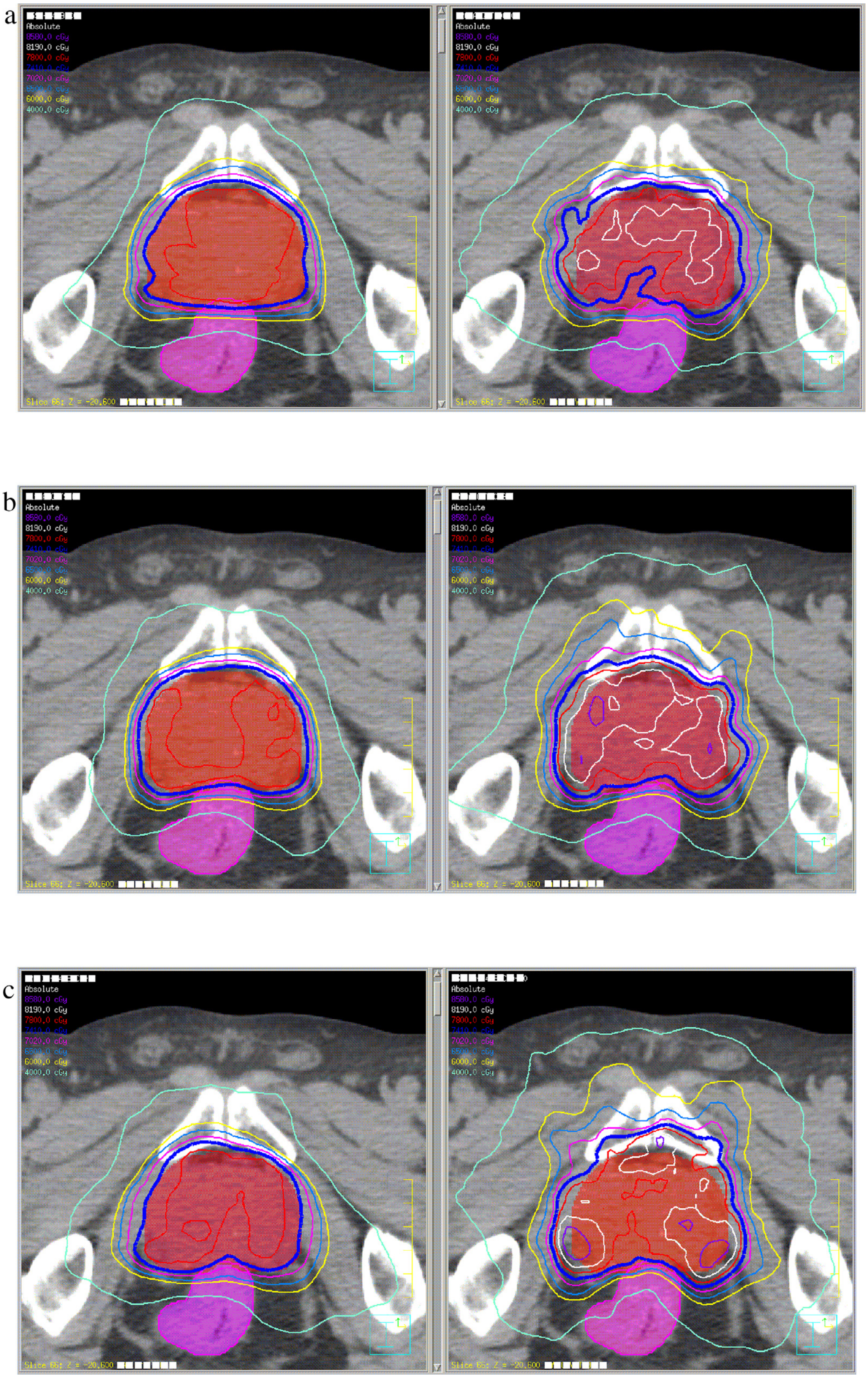

Fig. 4 – (a–c) A representative prostate case showing the dose distribution in a typical transverse slice for SA, DA and ISAs VMAT techniques optimized for C0° (left hand side) and C90° (right hand side) in each sub-figure.

improved target coverage, better sparing the OARs at the cost of increased beam delivery times in terms of higher calculated MUs. In many cases, single-arc optimized at C0° could not achieve optimal target coverage in contrast to the results of Bertelsen et al.[5] that recommended the use of single-arc for the treatment of head-and-neck tumors treated at Elekta Linac (Synergy) with 40 cm × 40 cm aperture. None of the VMAT techniques could achieve the defined planning objectives at C90° for both prostate and head-and-neck tumors. For C90°, higher normal tissue doses (Fig. 4a–c) and maximum doses ($D_{\max} = \text{D2\%}$) for the PTV compared to C0° (Table 1) were noted, and significant *p*-values were observed for PTV dose-volume indices between C0°and C90° (Table 2). Webb[12] and Bedford[24] have demonstrated that in some cases, ideal dose delivery would require the ability to deliver two (or more) distinct apertures for a specific gantry angle, but with VMAT this is not possible because of continuous gantry motion. Consequently, Webb reported on the possibility of 'under' and 'over' irradiation of ROIs in VMAT and showed how the need for multiple apertures for optimal dose delivery may depend on the collimator rotations which in effect could favor one collimator rotation (C0°) with respect to another (C90°).

Another reason for the observed differences between C0° and C90° might be that the optimal target (PTV) coverage at specific gantry positions can require dose delivery at two or more separate parts of the PTV along one leaf pair. At C90° (i.e., largest aperture of the MLC (21 cm) in the craniocaudal direction) due to a limited leaf speed, the optimizer has limited freedom of dose modulation for defining multiple segments within consecutive control points by one leaf pair. In this configuration, only a part of the PTV is exposed at each gantry angle. Conversely, at C0° one leaf pair can provide multiple segments in consecutive control points, which provide improved intensity modulation, hence, increased target coverage, conformity and dose homogeneity.[8]

Larger MLC apertures per-dose-delivery segment and prominent MLC parked gaps were observed for almost every control point at C90° for all VMAT techniques (Fig. 5a–c), while, seldom, a few MLC parked gaps were observed at C0°. The reason might be that C90° prohibits the fitting of MLC segments to ROIs without violating the leaf-speed constraints. In practice, for a VMAT delivery the MLC segments are engineered to be transitive gradually through the consecutive control points without any abrupt transition and violation of leaves speed.[24] Therefore leaf-speed of (maximum) 0.469 cm/° can be a limiting factor. Possibly, the over-irradiation of the PTV and OARs at C90° compared to C0° was caused by a combination of the effects of parked gaps and less optimal leaf fitting. Note that, there are no backup jaws in the Beam Modulator™ and field shaping is achieved only with the MLCs. Consequently, C90° resulted in less target coverage, less conformity, increased dose inhomogeneity and higher hotspots doses than C0°.

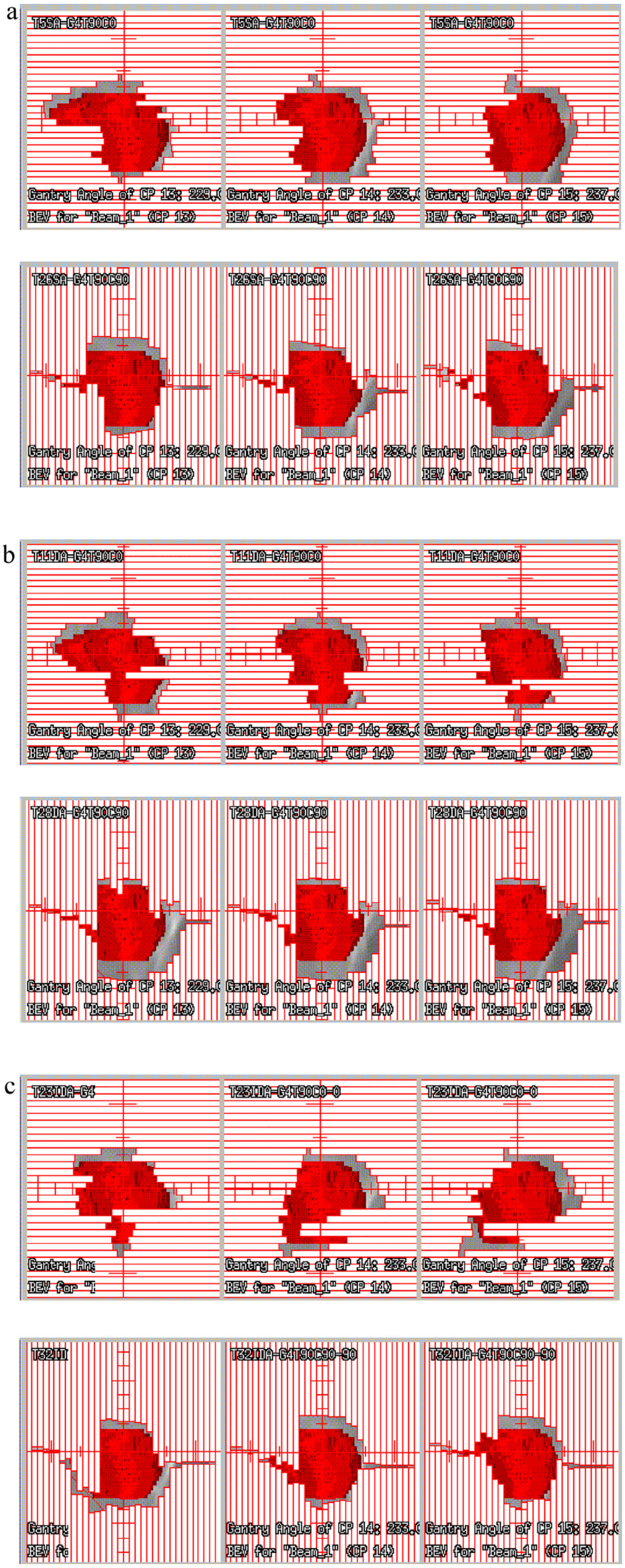

Fig. 5 – (a–c) A representative prostate case showing three consecutive control points produced by the SA (a), DA (b) and ISAs (c) VMAT techniques for C0° (upper row) and C90° (lower row) in each sub-figure.

Two combined independent single arcs (ISAs) coupled in a single optimization process were therefore used to investigate the effect of different aperture widths on VMAT plan quality. ISAs C(0°–90°) was optimized for both prostate and head-and-neck VMAT planning (first arc (clockwise) with C0° and second arc (counter clockwise) with C90°) providing an orthogonal collimator angle setup. The results of ISAs C(0°–90°) showed similar target coverage, but better sparing of OARs compared to SA, DA and ISAs optimized for C0° (Table 1). Significant *p*-values for dose volume indices difference were observed when ISAs C(0°–90°) was compared with the same arc (ISAs) optimized for C90° (Table 2). The results of ISAs C(0°–90°) confirmed that C90° probably due to limited leaf speed and smaller aperture in the direction of gantry motion provides less modulation space. In the configuration of mixed C0° and C90° collimator angle the MLC motion of the two arcs is perpendicular, which tends to diminish the cumulative leakage effects and provide a balance of 'under' and 'over' irradiation[12] with optimal target coverage.

Mancosu et al.[25] recommended the use of combined independent single arcs with two different collimator angles (close to but not exactly C90°): Arc1-C80° and Arc2-C280° for the treatment of vertebral metastases using Varian Eclipse TPS (version 8.6) and 2100-DHX Varian Linac with an aperture of 40 × 40. The study of Mancosu differs from ours in terms of target geometry (a small more cylindrical target geometry – vertebrae – where MLC leaves have a shorter distance to travel) and maximum width of the MLC aperture. Perhaps, limited field aperture of the Beam Modulator^{TM}, issue of leaf-parked-gaps and leaf speed limitations per degree of gantry angle can be the reasons for the failure of C90° for all VMAT techniques in achieving the planning objectives in contrast to the Mancosu et al.[25] finding. The same well optimized set of dose-volume-objectives (DVO) was used for all plan optimizations. In some of the cases, like "Fig. 1 patient-5" and "Fig. 2 patient-4", the optimizer was not forced to achieve planning objective (target coverage) by changing DVO, conversely unacceptable hotspot doses, increased dose inhomogeneity and deterioration of doses on the slices toward periphery of PTV were noted.

Dual arc setup (both DA and ISAs) calculated higher MUs than single-arc, when comparing for respective collimator angles of 0°, 90° and (0°–90°) (Table 1), which confirms the previous findings.[4] Two 'independent' single arcs (ISAs) of 360° (clockwise and counter-clockwise) coupled in a single optimization process provide another 'dual-arc-like' setup, where both arcs simultaneously optimize, and each arc focuses on the PTV independently. ISAs at C0° delivered 2.14% less MUs than DA (C0°), also ISAs at C(0°–90°) delivered 5.16% and 7.18% less MUs than ISAs (C0°) and DA (C0°), respectively. Although C90° in the case of Beam Modulator^{TM} is not preferred for plan optimization, ISAs at C90° continued to keep a similar trend over DA C90° by calculating 8% less MUs. For all VMAT techniques, fewer MUs were required at C90° compared to C0°, possibly because of larger mean MLC aperture per segment. Therefore, ISAs at C(0°–90°) can be used as an alternative to DA with similar target coverage, improved sparing of OARs and less calculated MUs. Independent dosimetric verification performed for randomly selected VMAT plans ensured that the calculated dose distributions could be delivered as planned. All selected plans passed the defined criteria of $\gamma_{\text{-local}}$ (3%/3 mm) ≥90%, results noted in Table 3. Majority of the delivered plans showed a trend of higher gamma passing rate for C90° over C0°, possibly due to less beam-modulation and larger mean MLC aperture.

6. Conclusions

In conclusion, a collimator rotation of 0° provided a better target coverage and sparing of OARs than a collimator rotation of 90° for VMAT plan optimization when using limited field size of 21 cm × 16 cm of Beam Modulator^{TM}. Orthogonal collimator angle(s) setup (i.e. a combination of C0°and C90°) tended to diminish the cumulative radiation leakage effects and provided a balance for under and over irradiation, with optimal target coverage, improved sparing of OARs and less delivered monitor units. Thus, optimal choice of VMAT arc and collimator rotation is another degree of freedom to improve the beam intensity modulation in order to obtain desired PTV dose distributions and sparing of organs at risk.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Conflict of interest

None declared.

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REFERENCES

1. Bortfeld TR, Boyer AL, Schlegel W, Kahler L, Waldron TJ. Realisation and verification of three-dimensional conformal radiotherapy with modulated fields. *Int J Radiat Oncol Biol Phys* 1994;**30**:899–908.
2. Spirou SV, Chui CS. Generation of arbitrary intensity profiles by combining the scanning beam with dynamic multileaf collimation. *Med Phys* 1996;**23**:1–8.
3. Otto K. Volumetric modulated arc therapy IMRT in a single arc. *Med Phys* 2008;**35**:310–7.
4. Guckenberger M, Richter A, Krieger T, et al. Is a single arc sufficient in volumetric-modulated arc therapy (VMAT) for complex-shaped target volumes. *Radiother Oncol* 2009;**93**:259–65.

5. 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.
6. Kjær-Kristoffersen F, Ohlhues L, Medin J, Korreman S. RapidArc volumetric modulated therapy planning for prostate cancer patients. *Acta Oncol* 2009;**48**:227–32.
7. Fontenot JD, King ML, Johnson SA, Wood CG, Price MJ, Lo KK. Single-arc volumetric-modulated arc therapy can provide dose distributions equivalent to fixed-beam intensity-modulated radiation therapy for prostatic irradiation with seminal vesicle and/or lymph node involvement. *BJR* 2012;**85**:231–6.
8. Verbakel WF, Cuijpers JP, Hoffmans D, 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**(1):252–9.
9. Xu H, Hatcher G. Treatment planning study of volumetric modulated arc therapy and three dimensional field-in-field techniques for left chest-wall cancers with regional lymph nodes. *Rep Pract Oncol Radiother* 2016;**21**(6):517–24.
10. Palma D, Vollans E, James K, et al. Volumetric modulated arc therapy for delivery of prostate radiotherapy: comparison with intensity-modulated radiotherapy and three-dimensional conformal radiotherapy. *Int J Radiat Oncol Biol Phys* 2008;**72**:996–1001.
11. Kumar SAS, Vivekanandan N, Sriram P. A study on conventional IMRT and RapidArc treatment planning techniques for head and neck cancers. *Rep Pract Oncol Radiother* 2012;**17**(3):168–75.
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. Amendola BE, Amendola M, Perez N, Iglesias A, Wu X. Volumetric-modulated arc therapy with RapidArc: an evaluation of treatment delivery efficiency. *Rep Pract Oncol Radiother* 2013;**18**(6):383–6.
14. Boehmer D, Maingon P, Poortmans P, et al. Guidelines for primary radiotherapy of patients with prostate cancer. *Radiother Oncol* 2006;**79**:259–69.
15. Grégoire V, Levendag P, Ang KK, et al. CT based delineation of lymph node levels and related CTVs in the node-negative neck, DAHANCA, EORTC, GORTEC, NCIC, RTOG Consensus Guidelines. *Radiother Oncol* 2003;**69**:227–36.
16. 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.
17. Eriksson K, Friberger H, Sterner E, Blumenthal C. *Volumetric modulated arc therapy (VMAT) optimization with RayArc*. Stockholm: RaySearch White Paper; 2009. p. 1–16.
18. International Commission on Radiation Units and Measurements Report 83. Prescribing, recording, and reporting photon-beam intensity modulated radiation therapy (IMRT). *J ICRU* 2010:10.
19. Marks LB, Yorke ED, Jackson A, et al. Use of normal tissue complication probability models in the clinic. *Int J Radiat Oncol Biol Phys* 2010;**76**(3 Suppl.):S10–9.
20. 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, http://dx.doi.org/10.1093/jrr/rrw114.
21. 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). *Strahlentherapie und Onkologie* 2011;**187**(12):812–9.
22. Thiyagarajan R, Nambiraj A, Sinha SN, et al. Analyzing the performance of ArcCHECK diode array detector for VMAT plan. *Rep Pract Oncol Radiother* 2016;**21**(1):50–6.
23. 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.
24. Bedford JL. Treatment planning for volumetric modulated arc therapy. *Med Phys* 2009;**36**:5128–38.
25. Mancosu P, Cozzi L, Fogliata A, et al. Collimator angle influence on dose distribution optimization for vertebral metastases using volumetric modulated arc therapy. *Med Phys* 2010;**37**(8):4133–7.