

Validation of the relative insensitivity of volumetric-modulated arc therapy (VMAT) plan quality to gantry space resolution

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ABSTRACT

Volumetric-modulated arc therapy (VMAT) is an efficient form of radiotherapy used to deliver intensity-modulated radiotherapy beams. The aim of this study was to investigate the relative insensitivity of VMAT plan quality to gantry angle spacing (GS). Most previous VMAT planning and dosimetric work for GS resolution has been conducted for single arc VMAT. In this work, a quantitative comparison of dose–volume indices (DIs) was made for partial-, single- and double-arc VMAT plans optimized at 2°, 3° and 4° GS, representing a large variation in deliverable multileaf collimator segments. VMAT plans of six prostate cancer and six head-and-neck cancer patients were simulated for an Elekta SynergyS[®] Linac (Elekta Ltd, Crawley, UK), using the SmartArc[™] module of Pinnacle³ TPS, (version 9.2, Philips Healthcare). All optimization techniques generated clinically acceptable VMAT plans, except for the single-arc for the head-and-neck cancer patients. Plan quality was assessed by comparing the DIs for the planning target volume, organs at risk and normal tissue. A GS of 2°, with finest resolution and consequently highest intensity modulation, was considered to be the reference, and this was compared with GS 3° and 4°. The differences between the majority of reference DIs and compared DIs were <2%. The metrics, such as treatment plan optimization time and pretreatment (phantom) dosimetric calculation time, supported the use of a GS of 4°. The ArcCHECK[™] phantom–measured dosimetric agreement verifications resulted in a >95.0% passing rate, using the criteria for γ (3%, 3 mm). In conclusion, a GS of 4° is an optimal choice for minimal usage of planning resources without compromise of plan quality.

KEYWORDS: multiple VMAT techniques, gantry angle space, plan quality

INTRODUCTION

In the last few decades, there have been significant technological advances in therapeutic and diagnostic radiology. The need for (i) more conformal and accurate dose delivery, (ii) tumor dose escalation for better locoregional tumor control, yet improved sparing of organs at risk (OARs), and (iii) efficient treatment delivery systems has focused researchers in these areas. Volumetric modulated arc therapy (VMAT) proposed by Otto [1] is currently the most efficient method used for the delivery of IMRT beams. VMAT exploits the simultaneous movement of various mechanical variables, e.g. use of 360° gantry angles, multileaf collimator (MLC) and static or

variable dose rate, for intensity modulation. The VMAT plan optimization module allows the selection of various planning parameters, including number of arcs, gantry angle spacing (GS), estimated treatment delivery time, and collimator angle. Bortfeld *et al.* [2], Otto *et al.* [3], Verbakel *et al.* [4] and Zhang *et al.* [5] discussed and compared the advantages of the VMAT technique versus conventional IMRT and concluded that VMAT is more efficient in the delivery of planned doses than conventional IMRT, while maintaining comparable or better plan quality.

Feygelman *et al.* [6] investigated the effect of control point (CP) spacing (i.e. GS) on dosimetric accuracy for single-arc (SA) VMAT,

using the SmartArc™ module in combination with the Trilogy Linac (Varian Medical Systems, Palo Alto, CA) and concluded that 4° spacing was a good compromise between calculation speed and accuracy, whereas 6° spacing exhibited large dosimetric errors. Mihaylov *et al.* [7] evaluated the effect of GS resolution on VMAT plan quality in a single modulated arc optimization at various CP spacing. They reported that all optimized plans were clinically acceptable, and differences were within $\pm 3\%$ between the majority of referenced and compared dose–volume indices (DIs). They concluded that 4° GS resolution seems to be a balanced alternative between plan quality and plan complexity. Treutwein *et al.* [8] reported that 4° GS was better in a planning and dosimetric study using the Oncentra® MasterPlan treatment planning system (TPS) (Nucletron B.V., Veenendaal, The Netherlands). Tyagi *et al.* [9] recommended the use of 4° and 6° GS with appropriate leaf speed and maximum delivery time in SA for adequate planning target volume (PTV) coverage.

The focus of our study was the search for optimal user-selectable VMAT planning parameters and their influence on plan quality. Most of the planning and dosimetric work for GS was conducted for SA VMAT. In this work, partial-arc (PA), SA and double-arc (DA) VMAT plans were optimized at 2°, 3° and 4° GS, representing a large variation in deliverable MLC segments. It provides a detailed evaluation of GS influence on VMAT plan quality, quantified in terms of DIs for deliverable multiple VMAT schemes. Moreover, delivered monitor units (MUs), dose optimization and calculation times, and plan delivery efficiency for a range of GSs were also noted for the Elekta SynergyS® Linac (Elekta Ltd, Crawley, UK).

MATERIALS AND METHODS

Patient selection

Six each of prostate cancer and head-and-neck cancer patients were selected, with various target (tumor) geometries and prescribed doses (PDs). The regions of interest (ROIs)—PTVs and organs at risk (OARs)—were delineated [10–12] by a radiation oncologist on each computed tomography (CT) slice, and plans were reviewed after optimization. The PD for prostate cancer ranged over 74–78 Gy for PTV_{boost} (which includes the prostate gland plus half of the seminal vesicles), with 2 Gy per fraction, whereas the PD for all head-and-neck cancer plans was 60 and 54 Gy for PTV_{boost} and PTV_{elective}, with 2 Gy and 1.80 Gy per fraction for the simultaneously integrated boost (SIB), respectively. PTV_{boost} and PTV_{elective} represent the high- and low-risk volumes for postoperative head-and-neck cancer cases. The details of PTVs, OARs and PDs for individual patients are given in Table 1.

Equipment

The beam data for the Elekta SynergyS® Linac equipped with a Beam Modulator was used for simulation and delivery of the VMAT plans. The MLC has 40 leaf pairs, each of nominal width 4 mm; diaphragms limit the maximum field size to 21 cm (along the leaf direction) by 16 cm (perpendicular to the leaf movement direction) projected to the isocentre; and there are no moveable jaws. The VMAT plans were optimized for a 6 MV photon beam, using

the SmartArc™ module [13] in the Pinnacle³ TPS (version 9.2, Philips Healthcare). The performance of the SmartArc™ module has been reported by several authors elsewhere. Some of the SynergyS® specific parameters integrated in SmartArc™ module for VMAT delivery include: maximum gantry speed of 5.5°/s, maximum leaf speed of 2.4 cm/s and five fixed dose rate levels of 35, 75, 150, 300 and 600 MU/min. In the SmartArc™ module, the user can define VMAT parameters, e.g. gantry start and stop angles, rotation direction, GS (2°, 3° or 4° spacing between subsequent CPs), maximum delivery time (MDT), and number and type of arcs. A leaf motion constraint of 0.469 cm/degree of gantry angle was used. A detailed description of the optimization algorithm has been published by Bzdusek *et al.* [13], in which the full collapsed cone convolution superposition (CCCS) algorithm was used for calculation, followed by additional segment weight optimization [6, 14, 15]. At the end of the optimization process, the resultant deliverable dynamic arc beam is achieved within the commissioned parameters of the Linac machine.

VMAT planning and objectives

Optimization of multiple VMAT schemes at GS of 2°, 3° and 4° was performed to quantify the magnitude of variation among various DIs and its effect on VMAT plan quality in terms of target coverage and sparing of OARs. The prostate cancer plans were optimized for PA, SA and DA VMAT schemes, whereas the head-and-neck cancer plans were optimized for SA and DA VMAT schemes at GS 2°, 3° and 4°. A MDT of 90 s (per arc) for prostate cancer and of 110 s (per arc) for head-and-neck cancer [16], and a collimator angle (C) of 45° were selected for optimal dose distribution [4, 8]. Start/stop gantry angles of 179°/181° for SA and DA, and 225°/135° for PA VMAT were selected. A calculation grid size of 3 mm in all three directions was set for all optimization schemes.

The following flat treatment planning objectives were defined for all PTVs: 95% of the PD should cover at least 95% of the PTV volume, the conformity index ($CI = V_{95\%}/V_{PTV}$; here V_{PTV} represents the volume of the PTV) should be $\geq 95\%$, $D_{mean} \geq PD$, for OARs (rectum: $V_{50\text{ Gy}} < 50\%$, i.e. the rectum volume irradiated by 50 Gy should be $< 50\%$, and similarly $V_{70\text{ Gy}} < 20\%$) for prostate cancer cases. The mean dose of either parotids should remain < 27 Gy ($D_{mean} < 27$ Gy) or the volume of parotids irradiated by 30 Gy should be $< 50\%$ ($V_{30\text{ Gy}} < 50\%$) for head-and-neck cancer cases. In order to make a rigorous comparison of the impact of GS, a similar well-optimized set of ‘Dose–Volume Objectives’ (DVOs) was used for all VMAT schemes (DVOs were optimized separately for prostate and head-and-neck cancer). DI-based comparison was made for each GS.

Analysis

The purpose of the study was to note and compare dose variations among various GSs at various fractions of volumes-of-interest. Therefore, doses were noted and compared quantitatively for a fixed fraction of volume ($D_{x\%}$), for all volumes-of-interest. Dose–volume histogram (DVH) data was used for analysis. All radiation doses were noted in the standard unit Gray (Gy) and the volume in cubic centimeters (cm^3). In the case of prostate cancer: PTV DIs, $D_{95\%}$,

Table 1. Summary of individual prostate cancer and head-and-neck cancer patient characteristics in terms of PTV, OARs and PD

Patient no.	Prostate cancer			Head-and-neck cancer				
	PTV _{boost} (cm ³)	PD (Gy)	rectum (cm ³)	PTV _{boost} (cm ³)	PTV _{elective} (cm ³)	PD (Gy) (boost/elective)	Right parotid volume (cm ³)	Left parotid volume (cm ³)
P1	120.57	74	84.06	204.82	169.36	60/54	10.08	11.51
P2	106.95	78	35.36	244.61	28.40	60/54	10.92	10.17
P3	142.23	74	41.82	255.67	66.07	60/54	32.02	21.56
P4	160.62	76	69.61	115.32	136.89	60/54	14.40	13.83
P5	102.87	78	33.30	230.53	166.34	60/54	10.08	11.51
P6	105.82	78	41.27	100.14	94.59	60/54	13.18	14.04

PTV = planning target volume, PD = prescribed dose, OAR = organ at risk.

$D_{2\%}$, $V_{95\%}$, dose homogeneity index ($HI = (D_{2\%} - D_{98\%})/D_{50\%}$) and mean dose (D_{mean}) for rectum: $D_{1\text{ cm}^3}$, $D_{40\%}$ and $D_{70\%}$, for bladder: $D_{70\%}$, and for surround: $D_{30\%}$, $D_{70\%}$ and D_{mean} were noted for evaluation. The surround is defined as: surround = body outline minus (PTV and OARs). In the case of head-and-neck cancer, the PTV DIs were $D_{95\%}$, $D_{1\text{ cm}^3}$, $V_{95\%}$, HI and D_{mean} ; for both (right and left) parotids: $V_{30\text{ Gy}}$, D_{mean} , and the surround D_{mean} were noted for evaluation. Briefly, $D_{x\%}$ values represent doses for a fixed fraction of the volume, $V_{x\%}$ values represent volume at particular percentage of PD, and $V_{x\text{ Gy}}$ values represent the fraction of volume for a fixed amount of dose, obtained from the corresponding DVHs. A 'two-sided student *t*-test', assuming unequal variances with statistical significance set to $P \leq 0.05$, was used to test for significant difference between DIs of plans with different GSs.

The dose distributions obtained with maximum CPs at GS 2° were used as the reference for calculating the difference for a GS of 3° and a GS of 4°. If the differences were >2% for the PTV DIs, the respective values were highlighted. Mihaylov *et al.* [7] used the criteria of $\pm 3\%$ as the surrogate for clinical significance. Delivered MUs, beam optimization and calculation time and delivery times were also analyzed. Dosimetric validation was performed for randomly selected plans (three prostate cancer and three head-and-neck cancer plans) and all measurements were done in a single session. The corresponding TPS-calculated dose distributions of each plan were recalculated [exported in SNC Patient software version 6.2 (Sun Nuclear Inc, Melbourne, FL)] and delivered to an ArcCHECK™ phantom using an Elekta SynergyS® linear accelerator. Both TPS-calculated and phantom-measured doses were compared using 3D gamma (γ) analysis [17]. The global γ indices using the Van Dyk criteria [18] were computed for 3 mm/3% and considered clinically acceptable if γ_{global} (3%/3 mm) was $\geq 95\%$. The dosimetric measurements were made in absolute dose mode with a low-dose threshold of 10 cGy, to restrict our analysis to the clinically relevant areas.

Ethical statement

The studies followed were in accordance with the ethical standards approved by the responsible committee of the hospital.

RESULTS

Summaries of the results for PTV and OARs DIs of prostate cancer and head-and-neck cancer optimized at a GS of 2°, 3° and 4° for PA, SA and DA VMAT schemes are presented in Tables 2, 3, 4, 6 and 7. The efficiency parameters in terms of MUs, optimization time, delivery time and number of CPs are noted in Table 5 for all VMAT schemes. The treatment-planning objectives were achieved by all VMAT schemes, except SA for head-and-neck cancer.

Prostate

The results for the prostate PTV DIs (Tables 2, 3 and 6) show that differences between the reference (2°) and compared (3° and 4°) DIs were $\leq 2\%$, except the HI, for all VMAT schemes. For the majority of the compared values, a GS of 4° showed a trend toward comparable or increased target coverage ($D_{95\%}$) and CI, reduced tail doses ($D_{2\%}$), and increased HI, compared with a GS of 2° or 3°. In the majority of patients, the HI for a GS of 4° was higher than for a GS of 2° or 3°, and varied between 3 and 16% [highest value (0.074) bold-italic in Table 6, Patient 4]. The majority of DI results ($D_{1\text{ cm}^3}$, $D_{40\%}$ and $D_{70\%}$ for rectum; $D_{70\%}$ for bladder; and $D_{30\%}$, $D_{70\%}$ and D_{mean} for surround) were within 2%. The rectum constraints of $V_{30\text{ Gy}}$ and $V_{70\text{ Gy}}$ were well below the maximum limits defined in the planning objectives (data not presented here).

Head-and-neck cancer

The PTV DIs for head-and-neck cancer presented in Tables 4 and 7 for DA and SA VMAT schemes show that the differences between the reference (2°) and compared (3° and 4°) DIs were <2%, except for the HI. For the majority of patients, a GS of 4° showed comparable or better target coverage ($D_{95\%}$) and CI for PTV_{boost} and PTV_{elective}, similar tail doses ($D_{1\text{ cm}^3}$), and higher HI, compared with a GS of 2° and 3°. The HI for a GS of 4° was higher than the for a GS of 2° or 3°, varying between 3 and 7% in the majority of patients. Generally, the DI for $V_{30\text{ Gy}}$ resulted in better sparing of the parotid for a GS of 4° compared with that for a GS of 2° or 3°; comparable D_{mean} values for the surround were noted. The left parotid (Patients 3 and 4), and right and left parotids (Patient 5)

Table 2. Summary of DIs of PTVs and OARs for six prostate cancer patients optimized for the dual-arc VMAT scheme

ROI	DI	Patient no. (prescribed dose)																	
		Patient 1 (74 Gy)			Patient 2 (74 Gy)			Patient 3 (76 Gy)			Patient 4 (78 Gy)			Patient 5 (78 Gy)			Patient 6 (78 Gy)		
		Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing		
		2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°
PTV	D _{95%} (Gy)	72.48	72.70	72.58	72.28	72.02	71.96	74.06	74.07	73.86	75.92	75.84	76.63	76.54	76.58	76.58	75.90	75.92	75.68
	D _{2%} (Gy)	77.56	77.88	77.22	76.78	76.32	76.10	79.67	79.63	79.62	81.42	81.01	81.69	81.64	80.80	81.10	79.98	79.94	79.46
	HI	0.074	0.075	0.067	0.066	0.063	0.064	0.082	0.082	0.082	0.078	0.073	0.070	0.069	0.058	0.062	0.061	0.059	0.058
	D _{mean} (Gy)	74.55	74.86	74.45	74.19	73.91	73.83	76.56	76.40	76.28	78.20	77.89	78.58	78.62	78.45	78.53	77.71	77.76	77.49
	CI	0.998	0.998	0.998	0.997	0.994	0.992	0.993	0.992	0.994	0.993	0.992	0.997	1.000	1.000	1.000	0.993	0.993	0.991
Rectum	D _{1cm³} (Gy)	72.20	72.30	72.24	70.66	69.82	69.62	73.08	73.20	73.08	71.51	71.58	72.86	73.94	73.80	73.54	73.88	73.91	73.48
	D _{40%} (Gy)	42.98	43.49	43.57	42.16	41.38	42.82	44.40	44.92	45.61	44.70	43.70	44.00	44.41	44.66	43.80	42.18	42.82	44.25
	D _{70%} (Gy)	5.560	6.520	6.800	30.61	30.14	30.73	32.82	33.52	33.93	34.60	34.27	34.86	33.42	33.51	32.74	27.30	27.82	28.88
Bladder	D _{70%} (Gy)	9.190	9.070	9.370	11.40	10.98	10.81	29.68	30.31	30.65	7.340	7.350	7.410	16.42	16.64	16.70	4.440	4.520	4.540
Surround	D _{30%} (Gy)	16.34	16.44	16.26	17.17	17.39	17.52	17.55	17.34	17.16	16.48	16.55	16.85	17.28	17.18	17.22	15.24	15.26	15.25
	D _{70%} (Gy)	3.760	3.770	3.780	5.000	5.040	5.020	4.740	4.620	4.660	3.030	3.050	3.050	4.260	4.290	4.330	3.100	3.160	3.120
	D _{mean} (Gy)	12.55	12.58	12.52	13.41	13.51	13.50	13.34	13.20	13.14	12.01	12.08	12.17	13.22	13.25	13.29	11.33	11.47	11.40

Differences of >2% for the PTV DIs have been highlighted. DI = dose-volume index, CI = conformity index, HI = homogeneity index, OAR = organ at risk, ROI = region of interest, PTV = planning target volume, VMAT = volumetric-modulated arc therapy.

Table 3. Summary for DIs of PTV and OARs for six prostate cancer patients optimized for the partial-arc VMAT scheme

ROI	DI	Patient no. (prescribed dose)																	
		Patient 1 (74 Gy)			Patient 2 (74 Gy)			Patient 3 (76 Gy)			Patient 4 (78 Gy)			Patient 5 (78 Gy)			Patient 6 (78 Gy)		
		Gantry Spacing			Gantry Spacing			Gantry Spacing			Gantry Spacing			Gantry Spacing			Gantry Spacing		
		2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°
PTV	D _{95%} (Gy)	71.65	71.74	71.74	71.54	71.5	71.55	73.29	73.40	73.31	75.36	75.58	75.68	76.72	76.32	76.28	74.81	74.92	74.84
	D _{2%} (Gy)	75.58	75.65	75.56	75.57	75.50	75.49	78.72	78.52	78.58	80.78	80.17	80.53	80.20	80.08	80.07	79.26	79.02	79.05
	HI	0.060	0.059	0.057	0.063	0.064	0.064	0.083	0.076	0.078	0.080	0.069	0.073	0.050	0.053	0.053	0.068	0.066	0.068
	D _{mean} (Gy)	73.44	73.43	73.39	73.43	73.37	73.39	75.99	75.89	75.84	78.00	77.82	77.84	78.11	77.88	77.70	77.14	77.09	77.05
	CI	0.993	0.996	0.996	0.989	0.987	0.988	0.980	0.986	0.985	0.985	0.989	0.988	1.000	0.999	1.000	0.976	0.974	0.972
Rectum	D _{1 cm₃} (Gy)	72.08	72.30	72.28	71.06	70.94	71.20	73.26	73.08	73.14	74.68	74.64	74.40	74.30	74.06	74.08	73.90	73.85	73.54
	D _{40%} (Gy)	33.74	32.92	32.46	43.30	43.48	43.36	39.85	40.82	40.84	44.40	45.20	44.30	43.44	44.74	43.92	46.42	46.30	45.54
	D _{70%} (Gy)	8.920	8.920	8.710	26.04	25.72	25.58	25.50	26.30	26.44	32.60	32.00	32.25	28.34	30.16	28.88	27.39	27.06	26.76
Bladder	D _{70%} (Gy)	11.29	11.42	11.25	8.904	8.724	8.603	30.36	30.88	30.67	7.202	7.134	7.072	14.54	15.42	14.20	4.242	4.193	4.124
Surround	D _{30%} (Gy)	18.22	18.74	18.54	17.82	18.04	18.20	18.84	19.36	19.88	16.08	16.70	16.44	17.92	17.40	17.86	15.17	15.84	15.48
	D _{70%} (Gy)	4.221	4.323	4.324	5.052	5.124	5.103	4.824	4.762	4.871	2.892	2.921	2.874	4.233	4.172	4.214	3.101	3.102	3.063
	D _{mean} (Gy)	13.62	13.76	13.82	13.51	13.62	13.65	13.842	13.93	13.74	12.04	12.16	12.02	13.47	13.26	13.40	11.66	11.78	11.65

Differences of >2% for the PTV DIs have been highlighted. DI = dose-volume index, HI = homogeneity index, CI = conformity index, OAR = organ at risk, ROI = region of interest, PTV = planning target volume, VMAT = volumetric-modulated arc therapy.

Table 4. Summary for DIs of PTV and OARs for six head-and-neck cancer patients optimized for the dual arc VMAT scheme

ROI	DI	Patient no. (prescribed doses)																	
		Patient 1 (60/54)			Patient 2 (60/54)			Patient 3 (60/54)			Patient 4 (60/54)			Patient 5 (60/54)			Patient 6 (60/54)		
		Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing		
		2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°
PTV _{boost}	D _{95%} (Gy)	57.42	57.80	58.28	57.37	57.36	57.14	57.94	57.86	57.92	58.39	58.53	58.53	58.10	58.18	58.06	57.63	57.70	57.90
	D _{1 cm³} (Gy)	66.90	67.96	68.18	66.08	66.20	66.44	65.74	65.38	65.22	64.10	63.92	63.70	66.76	66.66	66.74	65.24	65.50	64.82
	HI	0.189	0.195	0.189	0.149	0.148	0.152	0.125	0.123	0.120	0.102	0.097	0.096	0.144	0.140	0.144	0.156	0.159	0.145
	D _{mean} (Gy)	60.28	60.92	60.93	60.98	60.97	60.98	60.77	60.86	60.80	60.83	60.87	60.88	61.71	61.66	61.62	60.70	61.06	61.00
	CI	0.955	0.956	0.958	0.961	0.961	0.954	0.978	0.977	0.978	0.986	0.988	0.987	0.976	0.978	0.975	0.957	0.960	0.976
PTV _{elective}	D _{95%} (Gy)	51.43	51.38	51.50	53.55	54.07	53.59	53.07	53.31	53.24	52.70	52.54	52.58	51.74	52.02	52.08	51.83	52.15	52.01
	D _{mean} (Gy)	55.93	55.83	55.66	56.63	56.83	56.28	55.08	55.29	55.16	55.79	55.64	55.58	55.24	55.33	55.34	55.42	55.45	55.18
Parotid (Rt.)	V _{30 Gy} (cm ³)	3.532	3.831	3.604	3.092	2.772	2.824	4.991	5.404	5.942	0.554	0.561	0.584	nr	nr	nr	5.842	6.093	5.904
	D _{mean} (Gy)	27.43	27.44	27.23	27.11	26.47	26.57	13.64	14.15	14.40	7.521	7.614	7.572	nr	nr	nr	26.10	27.19	26.83
Parotid (Lt.)	V _{30Gy} (cm ³)	4.142	3.891	3.674	2.712	2.662	2.754	nr	nr	nr	nr	nr	nr	nr	nr	nr	2.463	2.462	2.481
	D _{mean} (Gy)	28.01	27.62	26.97	27.04	26.59	26.38	nr	nr	nr	nr	nr	nr	nr	nr	nr	12.88	13.12	12.86
Surround	D _{mean} (Gy)	30.79	31.06	30.66	11.23	11.35	11.27	10.60	10.66	10.62	10.47	10.50	10.41	22.42	22.58	22.56	16.41	16.39	16.23

Differences of >2% for the PTV DIs have been highlighted. DI = dose-volume index, OAR = organ at risk, ROI = region of interest, HI = homogeneity index, CI = conformity index, PTV = planning target volume, VMAT = volumetric-modulated arc therapy, 'nr' = either no parotid involvement or negligible DI values, not reported.

Table 5. Summary of efficiency parameters of six prostate cancer and head-and-neck cancer patients optimized for VMAT schemes

Tumor site	Arc type	Index	Patient 1			Patient 2			Patient 3			Patient 4			Patient 5			Patient 6			
			Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing			
			2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	
Prostate	SA	MUs	334	333	331	383	380	373	364	363	363	397	388	376	386	368	365	391	384	381	
		Opti. time (min)	22	14	11	26	18	13	16	11	9	16	11	9	20	14	11	33	23	18	
		Deli. time (s)	nr	nr	nr	nr	nr	nr	107	104	107	108	112	107	110	105	113	nr	nr	nr	
		γ (3%, 3 mm)	nr	nr	nr	nr	nr	nr	98.6	99.1	99.5	98.5	98.8	99.5	99.4	98.9	99.7	nr	nr	nr	
		Control points	180	121	91	180	121	91	180	121	91	180	121	91	180	121	91	180	121	91	
	DA	MUs	384	384	379	441	440	430	409	404	404	452	457	445	432	427	430	443	442	427	
		Opti. time (min)	33	27	20	48	30	24	30	19	15	30	19	15	39	29	20	58	39	31	
		Deli. time (s)	nr	nr	nr	nr	nr	nr	194	180	180	231	240	232	178	174	177	nr	nr	nr	
		γ (3%, 3 mm)	nr	nr	nr	nr	nr	nr	99.8	100	100	99.6	99.8	100	99.9	100	99.9	nr	nr	nr	
		Control points	360	242	182	360	242	182	360	242	182	360	242	182	360	242	182	360	242	182	
	PA	MUs	342	345	346	361	361	362	349	346	346	353	352	354	359	354	358	376	380	380	
		Opti. time (min)	17	12	9	23	13	11	13	9	7	13	9	7	17	12	9	25	17	14	
		Control points	136	91	69	136	91	69	136	91	69	136	91	69	136	91	69	136	91	69	
	Head and neck	SA	MUs	791	788	800	436	424	438	403	389	406	477	469	469	475	454	458	419	412	403
			Opti. time (min)	22	17	11	11	9	6	15	12	8	14	11	7	10	7	5	12	8	6
Deli. time (s)			nr	nr	nr	151	140	143	163	133	150	nr	nr	nr	nr	nr	nr	140	141	140	
γ (3%, 3 mm)			nr	nr	nr	96.4	95.6	95.4	95.8	96.7	97.7	nr	nr	nr	nr	nr	nr	96.8	95.9	97.2	
Control points			180	121	91	180	121	91	180	121	91	180	121	91	180	121	91	180	121	91	
DA		MUs	1107	1020	1037	520	510	494	470	465	457	552	538	528	543	542	541	451	448	449	
		Opti. time (min)	40	33	21	24	17	12	32	22	16	28	19	15	19	13	9	23	15	11	

Continued

Table 5. Continued

Tumor site	Arc type	Index	Patient 1		Patient 2		Patient 3		Patient 4		Patient 5		Patient 6				
			Gantry spacing		Gantry spacing		Gantry spacing		Gantry spacing		Gantry spacing		Gantry spacing				
			2°	3°	2°	3°	2°	3°	2°	3°	2°	3°	2°	3°			
		Deli. time (s)	nr	nr	230	212	218	223	231	233	nr	nr	nr	nr	214	219	229
		γ (3%, 3 mm)	nr	nr	95.8	97.5	96.4	99.7	98.4	96.3	nr	nr	nr	nr	96.7	97.1	97.6
		Control points	360	242	182	360	242	182	360	242	182	360	242	182	360	242	182

Dose calculation and optimization (Opti.) time reported in minutes and delivery (Deli.) time in seconds. DI = dose-volume index, VMAT = volumetric-modulated arc therapy, MUs = monitor units, SA = single-arc, DA = dual-arc, PA = partial-arc, only three patients were selected for the reporting of dosimetric measurement and delivery time measurement for both prostate and head-and-neck, for SA, DA, PA.

received negligible doses; therefore, their DIs are not reported in Tables 4 and 7. In all head-and-neck cancer plans, the brainstem and spinal cord doses were well below the defined limits, and they are not reported in the data tables.

P-values were calculated for a GS of 2° vs 3° and for a GS of 2° vs 4° for the prostate (PTV; D_{95%}, D_{2%}, HI, V_{95%}, rectum; D_{40%}, D_{70%}) and head-and-neck (PTV; D_{95%}, D_{1 cm³}, HI, V_{95%}) DIs, and none of the P-values indicated any statistically significant difference. The average beam delivery time per arc (in seconds) on Linac for each GS for the various VMAT arcs was as follows—prostate: SA 2° (108 s), 3° (107 s), 4° (109 s), DA 2° (201 s), 3° (198 s), 4° (196 s); and head-and-neck: SA 2° (151 s), 3° (138 s), 4° (144 s), DA 2° (222 s), 3° (221 s), 4° (227 s). A summary of MUs, dose calculation and optimization time, estimated delivery time and number of CPs is presented in Table 5. In the majority of the plans, the MUs at a GS of 4° were comparable with or less than those for a GS of 2° or 3°, with the exception of a few. The optimization and calculation times for a GS of 2° was almost double compared with a GS of 4° for both prostate cancer and head-and-neck cancer for the respective VMAT schemes. All of the selected VMAT plans for dosimetric validation passed the clinically accepted quality assurance criteria of γ-global (3%/3 mm) ≥95% for 2°, 3° and 4° GS, and the results are listed in Table 5.

DISCUSSION

In plan optimization, DVOs are defined for all ROIs (PTVs and OARs) that play a key role in the final dose distribution of the treatment plans. To make a rigorous comparison, we used a well-optimized similar set of DVOs for the optimization of all VMAT plans. The quantitative and qualitative measures of the obtained dose distributions for the three GSs optimized for multiple VMAT schemes were clinically acceptable, except for the SA VMAT plan for head-and-neck cancer. This planning study comprised the optimization of PA, SA and DA VMAT plans compared with SA as reported by Mihaylov *et al.* [7]. The number of CPs in PA and DA is 1.3 times smaller and 2 times greater than SA, respectively, which translate into MLC segments accordingly. A minimum of 69 MLC segments was used in our study while, Wu *et al.* [19] reported that VMAT plans require ~70 or more MLC segments for adequate PTV coverage and OARs dose distribution.

The differences in DIs between gantry space resolution of 2°, 3° and 4° were <2%. The majority of the DIs obtained favored a GS of 4° compared with a GS of 2° or 3°, with a few exceptions. The differences in DIs, such as target coverage (D_{95%}), CI and tail doses (D_{2%}), were generally very small, ~1 Gy between GSs, but were certainly in the favor of a GS of 4°. Our SA VMAT results were very similar to the results reported by Mihaylov *et al.* [7]. The higher absolute gains for HI were found at a GS of 4° compared with a GS of 2° or 3°, and this might be due to the larger number of MLC segments and smaller number of CPs, as Palma *et al.* [3] reported a higher HI for 3D-CRT compared with IMRT and VMAT, and several authors reported a higher HI for IMRT versus VMAT [4, 5]. Tyagi *et al.* reported [9] that since larger GSs generate a smaller number of CPs, therefore the SmartArc™ module tends to use a larger field size (larger MLC segments) to provide adequate PTV coverage. A larger field

Table 6. Summary of DIs of PTV and OARs for six prostate cancer patients optimized for the single-arc VMAT scheme

ROI	DI	Patient no. (prescribed doses)																	
		Patient 1 (74 Gy)			Patient 2 (74 Gy)			Patient 3 (76 Gy)			Patient 4 (78 Gy)			Patient 5 (78 Gy)			Patient 6 (78 Gy)		
		Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing		
		2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°
PTV	D _{95%} (Gy)	71.62	71.76	71.81	71.35	71.91	72.07	74.13	74.00	74.08	75.18	75.52	75.63	76.04	76.06	76.10	75.46	75.30	75.28
	D _{2%} (Gy)	75.20	75.24	75.28	76.28	76.30	76.22	79.62	79.21	79.13	82.13	81.32	80.50	81.14	80.54	80.37	79.80	79.38	79.16
	HI	0.055	0.054	0.053	0.072	0.066	0.063	0.081	0.076	0.074	0.087	0.084	0.074	0.070	0.066	0.062	0.067	0.061	0.059
	D _{mean} (Gy)	73.51	73.56	73.54	73.62	73.76	73.86	76.57	76.30	76.25	78.37	78.18	77.95	78.14	78.14	78.08	77.44	77.23	77.31
	CI	0.996	0.997	0.998	0.991	0.995	0.996	0.996	0.995	0.996	0.988	0.987	0.991	0.999	0.996	0.997	0.987	0.988	0.986
Rectum	D _{1 cm³} (Gy)	72.36	72.06	71.98	70.44	70.66	70.51	73.15	73.08	73.13	74.06	74.13	73.20	73.42	73.03	73.24	73.62	73.56	73.51
	D _{40%} (Gy)	40.98	40.84	41.02	41.96	42.08	44.54	45.78	45.68	45.82	44.07	44.20	44.40	42.66	44.82	45.19	42.92	44.65	45.82
	D _{70%} (Gy)	6.982	7.021	7.122	29.15	29.84	32.50	33.78	33.54	33.74	32.80	33.60	34.00	29.68	32.46	32.64	27.44	30.03	30.93
Bladder	D _{70%} (Gy)	10.36	10.35	10.31	11.30	11.09	11.46	31.74	31.84	31.36	7.372	7.434	7.242	17.80	17.50	17.22	4.413	4.461	4.463
Surround	D _{30%} (Gy)	17.70	17.66	17.44	18.05	17.59	16.98	17.44	17.35	17.45	16.93	16.98	16.93	17.85	17.50	17.38	16.12	15.90	15.64
	D _{70%} (Gy)	4.014	4.024	4.004	4.971	4.962	4.902	4.831	4.802	4.863	2.972	2.961	2.921	4.262	4.151	4.152	3.144	3.121	3.082
	D _{mean} (Gy)	13.18	13.17	13.06	13.56	13.45	13.21	13.33	13.25	13.32	12.26	12.25	12.20	13.36	13.11	13.11	11.61	11.54	11.46

Differences of >2% for the PTV DIs have been highlighted. DI = dose-volume index, OAR = organ at risk, ROI = region of interest, PTV = planning target volume, HI = homogeneity index, CI = conformity index, VMAT = volumetric-modulated arc therapy.

Table 7. Summary of DIs of PTV and OARs of six head-and-neck cancer patients optimized for the single-arc VMAT scheme

ROI	DI	Patient no. (prescribed doses)																	
		Patient 1 (60/54)			Patient 2 (60/54)			Patient 3 (60/54)			Patient 4 (60/54)			Patient 5 (60/54)			Patient 6 (60/54)		
		Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing			Gantry spacing		
		2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°	2°	3°	4°
PTV _{boost}	D _{95%} (Gy)	56.14	56.02	56.26	56.34	56.83	56.87	54.99	55.80	56.28	57.70	57.74	57.82	57.26	57.24	57.12	55.58	55.70	56.32
	D _{1 cm³} (Gy)	68.84	68.80	69.32	67.10	66.76	66.50	68.04	67.08	65.72	63.92	64.26	63.92	67.44	67.45	67.60	65.36	64.58	67.88
	HI	0.212	0.207	0.209	0.181	0.169	0.166	0.217	0.191	0.165	0.115	0.117	0.111	0.164	0.163	0.171	0.181	0.163	0.201
	D _{mean} (Gy)	61.53	61.18	61.23	61.20	61.29	61.20	61.06	60.58	60.48	60.70	60.76	60.63	61.40	61.49	61.43	60.47	60.41	61.35
	CI	0.920	0.914	0.923	0.927	0.945	0.946	0.880	0.894	0.919	0.971	0.973	0.975	0.957	0.957	0.953	0.890	0.903	0.928
PTV _{elective}	D _{95%} (Gy)	49.34	49.64	49.82	52.88	53.00	53.16	51.56	52.26	52.43	52.24	52.12	52.00	51.16	51.18	51.10	50.12	49.80	50.40
	D _{mean} (Gy)	55.40	55.08	55.15	56.41	55.79	55.78	55.77	55.44	55.29	55.41	55.37	55.08	55.50	55.47	55.36	55.31	55.09	55.37
Parotid (Rt.)	V _{30 Gy} (cm ³)	5.071	4.822	4.753	3.114	3.032	2.921	8.622	10.91	10.99	1.041	1.052	1.004	nr	nr	nr	6.182	6.081	6.004
	D _{mean} (Gy)	30.66	30.04	29.25	26.37	26.98	26.54	17.23	19.87	20.15	9.242	9.372	9.063	nr	nr	nr	27.38	27.12	25.78
Parotid (Lt.)	V _{30 Gy} (cm ³)	4.041	3.491	2.922	2.151	2.382	2.054	nr	nr	nr	nr	nr	nr	nr	nr	nr	2.612	2.521	2.562
	D _{mean} (Gy)	28.93	28.86	27.77	26.31	27.44	25.92	nr	nr	nr	nr	nr	nr	nr	nr	nr	14.00	13.72	13.52
Surround	D _{mean} (Gy)	30.32	29.95	30.04	11.25	11.24	11.33	10.56	10.62	10.48	10.77	10.71	10.65	22.90	22.69	22.67	17.00	16.75	16.57

Differences of >2% for the PTV DIs have been highlighted. DI = dose-volume index, OAR = organ at risk, ROI = region of interest, PTV = planning target volume, VMAT = volumetric-modulated arc therapy, nr = either no parotid involvement or negligible DI values, not reported.

aperture tends to improve dose uniformity across the tumor volume, which potentially can lead to enhanced locoregional tumor control, as reported by some authors [20, 21]. All OARs and normal tissue (surround) show very little variation in the magnitude of the various DIs between the three GSs. Dose homogeneity for DA was higher than for SA for a similar set of planning parameters (i.e. gantry spaces) in the respective VMAT schemes.

Despite SA VMAT being optimized for head-and-neck cancer, it could not achieve the planning objectives; however, the majority of DI values were in the favor of a GS of 4° compared with a GS of 2° or 3°. In our results, better PTV coverage, higher HI, and improved sparing of OARs was achieved by DA compared with SA, because of increased degrees of freedom in terms of: number of arcs, CPs, leaf positions and delivery time; similar results were reported by other authors [4, 8]. The results for head-and-neck cancer SA VMAT plans in our study were in marked contrast to those reported by other investigators [7]. The reason might be the use of Linac(s) with different apertures—Mihaylov *et al.* [7] used a Linac with an aperture of 40 × 40 cm², whereas in this study VMAT plans were simulated for an Elekta Beam Modulator™ with a maximum aperture of 21 × 16 cm².

Dose calculation and optimization time in a VMAT plan is directly related to the number of CPs. For the respective arc selections, a GS of 4° and of 3° require ~50% and ~70% of the dose 'optimization-and-calculation' time, consumed by a GS of 2°. In the optimization of DA, a maximum of 58 and 40 min were recorded for prostate and head-and-neck cancer, respectively. Similar (pretreatment) ArcCHECK™ phantom dose calculation times were noted (as reported in Table 5) for the treatment plan optimization of the various VMAT arcs. Our dose calculation and optimization times were shorter than those reported by Mihaylov *et al.* [7] because of our efficient computer hardware set-up. In most of the VMAT plans, a GS of 4° achieved comparable or fewer MUs than a GS of 2° or 3°. Similar results were reported by Tyagi *et al.*, since larger GS generates a smaller number of CPs, which in turn helps in reducing the total MUs [9].

The average beam delivery time (Deli. time as reported in Table 5) per arc was observed to be higher compared with a MDT of 90 s (per arc) for prostate cancer and 110 s (per arc) for head-and-neck cancer used (being an objective) by the optimizer. The reason for this discrepancy is that the console software Precise Desktop® 7 automatically determines the fastest available combination of dose rate, gantry speed and leaf speed for the VMAT delivery. Consequently, it is not necessary that the delivery time per arc will be the same as the MDT used by the optimizer during plan optimization. Minor differences were found between the delivery time for the different GSs. Some of the dosimetric- and efficiency-related parameters [PTV dose inhomogeneity (higher radiation-dose variations across the target volume), MUs, optimization time and delivery time] were notably increased in head-and-neck cancer planning compared with prostate cancer planning, possibly due to the increased complexity of the plan. Practically, a GS of 2°, 3° and 4° did not show any significantly different effect on VMAT plan quality for selection of any number of arcs or MLC segments; however, dosimetric and efficiency metrics were in favor of a GS of 4°. Our study confirmed the previous results reported for SA [6–8] and provide a further detailed evaluation of the GS resolution effect for a

large number (2-fold) of MLC segments. Comparable phantom-measured dosimetric results for verification are noted for a GS of 2°, 3° and 4°, whereas DA showed a trend for a higher gamma passing rate compared with SA. We frequently use a GS of 4° for SA and DA VMAT schemes for treatment plan optimization of prostate tumors. In our experience, SA is not sufficient for the treatment of head-and-neck cancer tumors because of the limited field size of the Elekta MLC 'Beam Modulator™'; therefore, our choice is DA and a GS of 4° for treatment plan optimization of head-and-neck cancers in order to obtain clinically acceptable VMAT plans with the minimum beam calculation time.

In conclusion, GS is insensitive and practically has no significant effect on VMAT plan quality in the case of Pinnacle³ SmartArc™ module implementation. A GS of 4° showed comparable or better dosimetric indicators for plan quality, with least optimization and calculation time. Therefore, a GS of 4° is an optimal choice for minimal usage of planning resources without compromise of plan quality.

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CONFLICT OF INTEREST

None of the authors have any conflicts of interests.

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