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

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Objectives: Volumetric-modulated arc therapy (VMAT) is becoming an increasingly utilised modality for treating a variety of anatomical sites. However, the efficacy of single-arc VMAT to treat prostate cancer suspicious for extraprostatic extension was heretofore unknown. In this work, we report our institutional experience with single-arc VMAT and fixed-beam intensity-modulated radiation therapy (IMRT) for prostate cancer patients treated for seminal vesicle and/or lymph node involvement.

Methods: Single-arc VMAT and 7- or 9-field IMRT treatment plans were compared for 10 prostate cancer patients treated for seminal vesicle involvement and/or lymph node involvement. All treatment plans were constructed using the Philips Pinnacle treatment planning system (v.9.0, Fitchburg, WI) and delivered on an Elekta Infinity radiotherapy accelerator (Crawley, UK). Resulting plans were compared using metrics that characterised dosimetry and delivery efficiency.

Results: No statistically significant differences in target coverage, target homogeneity or normal tissue doses were noted between the plans ($p > 0.05$). For prostate patients treated for seminal vesicle involvement, VMAT plans were delivered in 1.4 ± 0.1 min (vs 9.5 ± 2.4 min for fixed-beam IMRT) ($p < 0.01$) and required approximately 20% fewer monitor units ($p = 0.01$). For prostate patients treated for lymph node involvement, VMAT plans were delivered in 1.4 ± 0.1 min (vs 11.7 ± 1.3 min for fixed-beam IMRT) ($p < 0.01$) and required approximately 45% fewer monitor units ($p < 0.01$).

Conclusion: Single-arc VMAT plans were dosimetrically equivalent to fixed-beam IMRT plans with significantly improved delivery efficiency.

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The evolution and widespread implementation of intensity-modulated radiation therapy (IMRT) has enabled the delivery of highly conformal doses to target structures [1, 2]. Recent advances in treatment planning optimisation and accelerator delivery technology have fuelled a growing interest in maintaining IMRT-quality treatment plans while dramatically decreasing the time and monitor unit (MU) requirements for treatment delivery, the benefits of which are well documented [3–5]. Volumetric-modulated arc therapy (VMAT), in which continuous modulation of the multileaf collimator (MLC), dose rate and gantry speed are utilised to deliver highly conformal dose distributions in a short period of time and with fewer MUs, offers such a solution [3]. However, debate has arisen regarding the efficacy and potential benefits of VMAT [5–8], particularly as it relates to the relationship between plan quality and the number of arcs required to deliver IMRT-quality plans. As such,

the theoretical advantages of single-arc rotational IMRT have not yet been fully demonstrated clinically.

Studies reporting the equivalence of single-arc VMAT and IMRT in the pelvis have concentrated on relatively simple, single-dose targets such as the prostate or prostate bed [4, 9], while studies that have examined more complex pelvic target geometries have yielded mixed results. In a retrospective planning study, Guckenberger et al [10] found that VMAT plans including a simultaneously delivered integrate boost could improve target coverage and homogeneity for prostate cancer cases. However, their study was conducted with an early research release of treatment planning software and resulting plans were neither clinically delivered nor verified. More recently, Yoo et al [11] found that fixed-beam IMRT plans were superior to one- and two-arc VMAT when considering target volumes that included the prostate, seminal vesicles and/or pelvic lymph nodes. However, their study was conducted using the Varian Medical Systems (Palo Alto, CA) treatment planning system and delivery technology. There have been no studies to date that have conducted a similar clinical investigation using competing hardware and software configurations. Such

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studies are prudent given the marked differences between treatment planning and delivery approaches among radiotherapy vendors.

In this work, we report on our institutional experience comparing fixed-beam IMRT and single-arc VMAT plans produced using the Philips Pinnacle treatment planning system (v.9.0, Fitchburg, WI) and delivered by the Elekta treatment control system (Crawley, UK) for 10 prostate patients treated for seminal vesicle and/or lymph node involvement. Resulting plans were compared on the basis of quantitative dosimetric metrics and delivery efficiency.

Methods and materials

Patients

This study included 10 patients treated at our institution for prostate cancer between February 2010 and July 2010. Patients were divided into two subgroups: five patients treated for seminal vesicle involvement and five treated for regional lymph node involvement (it should be noted that the lymph node planning target volume (PTV) was typically drawn to include the seminal vesicles). Each patient underwent CT imaging prior to treatment. A commercially available endorectal balloon (Radiadyne, Houston, TX) was employed for immobilisation during simulation and fraction delivery in all patients. Following import into the treatment planning system, a radiation oncologist delineated the planning targets and critical structures. Target volumes were defined as PTV1, which included the prostate or prostate bed, and PTV2, which included the seminal vesicles or lymph nodes. Defined critical structures included the rectum, bladder and femoral heads. Table 1 details the PTV volumes and dose prescriptions for each patient.

Treatment planning

Our current institutional procedure for prostate treatment planning is to construct fixed-beam IMRT and VMAT treatment plans for each patient, utilising the VMAT plan for treatment delivery only if it is judged by the radiation oncologist to be equal to or better than the fixed-beam IMRT plan. All treatment plans were constructed using version 9.0 of the Philips Pinnacle

treatment planning system. All IMRT plans were “step and shoot”, utilised 6 MV beams and consisted of seven fields for patients treated for seminal vesicle involvement and seven or nine fields for patients treated for lymph node involvement. Gantry angles were selected manually with an approximate geometric spacing of 40–60° with consideration given to normal tissue avoidance. The direct machine parameter optimisation module of the Pinnacle was used for inverse planning with a maximum of 10 segments per field. VMAT plans were constructed using the SmartArc module [12], and utilised 6 MV beams, a single 350° arc (beginning at 175° and rotating counterclockwise to 185°) and a static collimator angle of 45°. For SmartArc optimisation, the final gantry spacing was set to $\Delta=4^\circ$ with the maximum delivery time set to 90 s, and maximum leaf motion constrained to 4 mm per degree of gantry rotation. Planning objectives were determined using a combination of institutional guidelines and specifications from the radiation oncologist. All plans were produced using methods consistent with our clinical workflow and timelines, with no particular attention given to patient selection or optimisation of treatment technique other than meeting the planning objectives. At the conclusion of the planning process, the radiation oncologist reviewed and approved each plan on the basis of clinical acceptability. Following physician approval, all plans were transferred to a cylindrical solid water phantom (Cheese Phantom; TomoTherapy, Inc., Madison, WI) for the purpose of patient-specific quality assurance measurements using film (EDR-2; Eastman Kodak Co., Rochester, NY) and a calibrated cylindrical ion chamber (A1SL; Standard Imaging, Madison, WI).

All plans were constructed for delivery on an Elekta Infinity radiotherapy accelerator utilising the Desktop Pro R7.0x control system. The Elekta Infinity system features an 80-leaf MLC with 1 cm leaf widths and delivers VMAT plans using discretely variable dose rates (*i.e.* 500, 250, 125, 63, 37 MU min⁻¹) and continuously variable gantry speed [13].

Plan evaluation

Fixed-beam IMRT and VMAT plans were compared using dosimetric quantities for the PTVs and normal tissues. PTV metrics included $V_{98\%}$ (the percentage of the PTV encompassed by the 98% isodose line) and the maximum dose, $D_{\max}$. The conformity index (CI) was

Table 1. Planning target volumes and prescriptions

Patient	Prostate + seminal vesicles				Prostate + seminal vesicles + lymph nodes			
	PTV1		PTV2		PTV1		PTV2	
	Volume (ml)	Rx (Gy)	Volume (ml)	Rx (Gy)	Volume (ml)	Rx (Gy)	Volume (ml)	Rx (Gy)
1	273.2	76	34.2	56	75.6	68	124.2	58
2	139.2	66	107.9	56	68.3	62	457.4	55
3	184.0	78	86.4	56	132.1	68	312.0	58
4	210.5	76	21.2	56	104.4	68	163.5	58
5	240.4	78	41.0	72	111.7	66	200.6	56
Mean $\pm$ SD	209.5 $\pm$ 37.1	-	58.1 $\pm$ 37.1	-	98.4 $\pm$ 26.3	-	251.5 $\pm$ 134.7	-

PTV1, planning target volume including prostate or prostate bed; PTV2, planning target volume including seminal vesicles or lymph nodes; Rx, prescription dose; SD, standard deviation.

computed for the prostate PTV using the method of Paddick [14], given by

$$CI = \frac{TV_{PIV}^2}{TV \times PIV} \quad (1)$$

where TV_{PIV} represents the volume of the prostate PTV within the prescription isodose line, TV denotes the volume of the prostate PTV and PIV denotes the volume encompassed by the prescription isodose line. Values of CI are dimensionless, have a value of 1 for an ideal treatment, and decrease as the prescription isodose line encompasses larger volumes outside the PTV. The dose homogeneity index (DHI) was also computed for each PTV volume such that

$$DHI = \frac{D_{max} - D_{min}}{D_{Rx}} \quad (2)$$

where D_{max} represents the dose to 1% of the PTV, D_{min} denotes the dose to 99% of the PTV and D_{Rx} denotes the prescribed dose. Values of DHI are dimensionless, have a value of 0 for an ideal treatment and increase as dose to the PTV becomes less uniform.

Normal tissue metrics were also compared for plan evaluation: the mean organ dose, $V_{40\text{ Gy}}$ and $V_{65\text{ Gy}}$ for the bladder; the mean organ dose, $V_{40\text{ Gy}}$ and $V_{70\text{ Gy}}$ for the rectum; and the maximum dose to the right and left femoral heads [15, 16]. The $V_{30\text{ Gy}}$ for the whole pelvis was also compared.

Fixed-beam IMRT and VMAT plans were also compared on the basis of delivery efficiency. Metrics used to characterise delivery efficiency included (1) the total number of MU required for treatment delivery and (2) the treatment delivery time. The treatment delivery time was defined as the time elapsing between initiation of the first beam and completion of the final beam. For VMAT plans, treatment delivery time was recorded directly from the control system during quality assurance. For fixed-beam IMRT plans, treatment delivery time was measured manually with a stopwatch, and included the time required for gantry rotation between beams and intersegment MLC leaf motion.

Differences in dosimetric and delivery efficiency metrics were evaluated for statistical significance ($p < 0.05$) using the two-tailed Student's paired t -test. Prior to application of the Student's t -test, the data were verified to be normally distributed using a quantile-quantile plot.

Results

Dose distributions for a single patient treated for lymph node involvement are shown in Figure 1 and are representative of all 10 patients. The figure shown is a comparison of a seven-field IMRT plan (Figure 1a,b) and a VMAT plan (Figure 1c,d) in the axial and coronal planes. The corresponding dose volume histograms (DVHs) are shown in Figure 2. In general, the two plans were similar in the high-dose regions, with the VMAT plan showing slightly better conformity in the axial plane and better dose homogeneity within the lymph node PTV (DHI=0.24 and 0.24 for IMRT and VMAT, respectively). In the

low-dose regions (less than 45 Gy) the VMAT plan produced more rounded distributions than the equivalent IMRT plan, which was to be expected given the rotational delivery of VMAT. The IMRT plan delivered slightly less dose to the rectum ($D_{mean}=35.4$ and 37.3 Gy for IMRT and VMAT, respectively) with both plans delivering similar doses to the bladder ($D_{mean}=42.1$ and 41.6 Gy for IMRT and VMAT, respectively).

Table 2 compares the results of the fixed-beam IMRT and VMAT plans with respect to a variety of dosimetric metrics. Values are presented as means for the five patients in each subgroup: prostate and seminal vesicles or prostate and lymph nodes.

Target volumes

Target volume metrics were similar across treatment plans, showing no statistically significant differences. For the prostate patients treated for seminal vesicle involvement, both plans showed a similar $V_{98\%}$ for PTV1 and PTV2. Values of DHI for PTV1 and PTV2 were also similar. Differences in CI were small and not statistically significant. Likewise, for prostate patients treated for lymph node involvement, differences in $V_{98\%}$ were statistically insignificant for PTV1 and PTV2. Values of DHI and CI also did not show any statistically significant differences.

Normal tissues

Normal tissue metrics were also similar across plans. For all patients, differences in D_{mean} and $V_{40\text{ Gy}}$ in the rectum and bladder were small and not statistically significant. Differences in $V_{70\text{ Gy}}$ and $V_{65\text{ Gy}}$ for the rectum and bladder, respectively, were small and insignificant for both subgroups. It should be noted that the mean $V_{70\text{ Gy}}$ and $V_{65\text{ Gy}}$ for the rectum and bladder, respectively, were lower for the patients treated for lymph node involvement than in those treated for seminal vesicle involvement because of differences in the prescription dose. Differences in $V_{40\text{ Gy}}$ for the whole pelvis were not statistically significant in either subgroup. For patients treated for seminal vesicle involvement, the VMAT plans provided lower maximum doses to the femoral heads (a decrease of approximately 3 Gy to both right ($p=0.01$) and left ($p=0.03$) femoral head structures). However, no significant differences were observed in patients treated for lymph node involvement in either the right or left femoral heads.

Delivery efficiency

Table 3 shows the resulting metrics utilised for comparison of delivery efficiency between fixed-beam IMRT and VMAT plans. In general, the VMAT plans were significantly more efficient than the fixed-beam IMRT plans in each subgroup. In patients treated for seminal vesicle involvement, the VMAT plans delivered 20% lower MU ($p=0.01$) and achieved a reduction in treatment delivery time of 8.1 min ($p<0.01$). Similarly, in patients treated for lymph node involvement, VMAT plans

Figure 1. (a) Axial and (a) coronal views of dose distributions for a volumetric-modulated arc therapy plan and (c) axial and (d) coronal a seven-field, fixed-beam intensity-modulated radiation therapy plan. Isodose contours are 30, 45, 56, 60, 66 and 68 Gy. The orange-shaded region indicates the prostate planning target volume (PTV) (66 Gy prescription) and the purple-shaded region indicates the lymph node PTV (56 Gy prescription).

Figure 2. Dose-volume histogram comparisons for the dose distributions shown in Figure 1. IMRT, intensity-modulated radiation therapy; PTV1, planning target volume including prostate or prostate bed; PTV2, planning target volume including seminal vesicles or lymph nodes; VMAT, volumetric-modulated arc therapy.

Table 2. Summary dosimetric comparison of VMAT and fixed-beam IMRT plans

Structure	Metric	IMRT	VMAT	p-value
<i>Prostate + seminal vesicles</i>				
PTV1	V _{98%} (%)	97.4 ± 2.2	96.7 ± 2.1	0.41
	D _{max} (%)	104.6 ± 2.3	103.8 ± 1.3	0.41
	DHI	0.089 ± 0.058	0.075 ± 0.028	0.53
	CI	0.86 ± 0.05	0.84 ± 0.02	0.70
PTV2	V _{98%} (%)	98.3 ± 1.6	98.0 ± 2.5	0.60
	DHI	0.32 ± 0.17	0.31 ± 0.15	0.21
Rectum	D _{mean} (Gy)	41.8 ± 8.8	42.5 ± 8.7	0.14
	V _{40 Gy} (%)	49.7 ± 21.0	50.0 ± 21.6	0.71
	V _{70 Gy} (%)	12.5 ± 11.3	11.7 ± 11.5	0.24
Bladder	D _{mean} (Gy)	36.1 ± 8.8	35.9 ± 9.0	0.65
	V _{40 Gy} (%)	39.8 ± 15.0	38.7 ± 14.7	0.20
	V _{65 Gy} (%)	18.0 ± 7.8	17.1 ± 7.6	0.06
Right femoral head	D _{max} (Gy)	48.0 ± 3.6	44.9 ± 3.5	0.01
Left femoral head	D _{max} (Gy)	48.3 ± 3.8	45.3 ± 2.4	0.03
Body	V _{30 Gy} (cm ³)	2170.4 ± 964.3	1910 ± 699.3	0.11
<i>Prostate + lymph nodes</i>				
PTV1	V _{98%} (%)	99.1 ± 1.0	99.5 ± 0.6	0.53
	D _{max} (%)	103.9 ± 1.8	103.0 ± 0.5	0.26
	DHI	0.057 ± 0.023	0.045 ± 0.010	0.31
	CI	0.85 ± 0.04	0.85 ± 0.01	0.91
PTV2	V _{98%} (%)	97.3 ± 2.0	96.8 ± 3.6	0.82
	DHI	0.22 ± 0.05	0.20 ± 0.02	0.43
Rectum	D _{mean} (Gy)	42.6 ± 7.1	43.1 ± 6.8	0.31
	V _{40 Gy} (%)	59.7 ± 20.9	60.9 ± 21.4	0.21
	V _{70 Gy} (%)	0.2 ± 0.4	0.1 ± 0.3	0.61
Bladder	D _{mean} (Gy)	42.4 ± 11.0	42.2 ± 11.4	0.54
	V _{40 Gy} (%)	57.6 ± 19.4	57.7 ± 21.9	0.96
	V _{65 Gy} (%)	11.3 ± 8.2	11.5 ± 9.2	0.84
Right femoral head	D _{max} (Gy)	49.6 ± 2.4	46.8 ± 2.1	0.14
Left femoral head	D _{max} (Gy)	48.0 ± 1.4	47.3 ± 3.0	0.64
Body	V _{30 Gy} (cm ³)	1764.2 ± 586.2	1943.6 ± 867.3	0.41

CI, conformity index; DHI, dose homogeneity index; Dmax, maximum dose; Dmean, mean dose; IMRT, intensity-modulated radiation therapy; PTV1, planning target volume including the prostate or prostate bed; PTV2, planning target volume including the seminal vesicles or lymph nodes; VMAT, volumetric-modulated arc therapy; V30 Gy, volume irradiated to 30 Gy; V40 Gy, volume irradiated to 40 Gy; V65 Gy, volume irradiated to 65 Gy; V70 Gy, volume irradiated to 70 Gy; V98, the planning target volume encompassed by the 98 isodose line.

The mean values of the five patients in each subgroup are shown with ± 1 SD. The p-values were computed using the two-tailed Student's paired t-test.

delivered 45% lower MU ($p < 0.01$) and achieved a reduction in treatment delivery time of 10.3 min ($p < 0.01$). Appropriate execution of all planned treatments was verified via quality assurance measurements, with ion chamber measurements typically agreeing with calculated values within 3%, and >95% of points measured with film agreeing with calculated values using a 3% dose difference or 3 mm distance to agreement criteria.

Table 3. Summary delivery efficiency comparison of volumetric-modulated arc therapy (VMAT) and fixed-beam intensity-modulated radiation therapy (IMRT) plans

Metric	IMRT	VMAT	p-value
<i>Prostate + seminal vesicles</i>			
MU	586.6 ± 131.8	467.6 ± 91.3	0.01
Delivery time (min)	9.5 ± 2.4	1.4 ± 0.1	<0.01
<i>Prostate + lymph nodes</i>			
MU	769.2 ± 116.9	435.2 ± 47.8	<0.01
Delivery time (min)	11.7 ± 1.3	1.4 ± 0.1	<0.01

IMRT, intensity-modulated radiation therapy; MU, monitor units; VMAT, volumetric-modulated arc therapy.

Discussion

In this study, single-arc VMAT plans were found to be dosimetrically equivalent to seven- or nine-field fixed-beam IMRT plans for prostatic irradiation in cases with either seminal vesicle or pelvic lymph node involvement. No statistically significant differences in target coverage, target homogeneity or normal tissue doses were observed. VMAT plans were found to provide significantly improved delivery efficiency, as evaluated by (1) the total number of MU required for treatment delivery and (2) the treatment delivery time. The results of this study are consistent with previous investigations comparing VMAT plans with fixed-beam IMRT plans for irradiation of the prostate volume [4, 9, 10]. However, our results differ from those reported by Yoo et al [11], who concluded that one-arc and two-arc VMAT plans produced with the RapidArc system (Varian Medical Systems) were dosimetrically inferior and comparable, respectively, to seven-field IMRT for pelvic volumes that included the prostate and seminal vesicles. Moreover, their study concluded that two-arc plans produced with the RapidArc system were inferior to seven-field IMRT plans for volumes that included the prostate, seminal

vesicles and lymph nodes. One potential reason for differences between the outcomes of the studies may be attributable to differences in optimisation algorithms between treatment planning systems [3, 12]. Another possible explanation may reflect differences in the treated volumes, as the mean pelvic target volume (prostate, seminal vesicles, lymph nodes) was 769.9 ± 154.6 ml in the study by Yoo et al [11] compared with a mean pelvic volume of 350.0 ± 132.7 ml in the present study. Such differences reflect interpatient anatomical variations as well as differences in clinician preference and philosophy.

The primary strength of this work is derived from the clinical methodologies used during data collection. In order to maximise the clinical practicality of this work, no particular attention was given to patient selection or optimising and maximising the capabilities of each treatment technique. The plans presented and analysed in this study were the product of the routine daily activities of radiation oncologists, physicists and dosimetrists. Although it may be possible to improve each plan by applying individualised planning approaches that have been optimised for each case, such methods would not meet the requirements of efficiency and utility generally necessary in a clinical setting. The conclusions drawn within this study were derived from clinical workflow at our centre and have resulted in VMAT often being the treatment technique of choice for prostate targets that include the seminal vesicle and/or lymph nodes.

Our study also had several limitations. While usage of our clinical workflow to produce treatment plans for this study demonstrated clinical efficacy, it is possible that subsequent investigation of ideal planning objectives for each modality may lead to improvements that would increase the dosimetric quality of each treatment approach. Additionally, our study included patients with different dose prescriptions and fractionation schedules, rendering summary analysis of absolute dosimetric differences between plans difficult. An ideal study would include patients with identical treatment regimens, enabling analysis of population differences in target and normal tissue doses. However, as the stated purpose of our report was to investigate the potential equivalency of single-arc VMAT with fixed-beam IMRT (independent of dose prescription and fractionation pattern), we propose that variability in patient selection would not significantly influence our findings. Furthermore, while our study demonstrates the feasibility of a single arc for complex pelvic targets, further studies should investigate potential gains offered by the use of multiple arcs.

Conclusions

Single-arc VMAT treatments constructed with the Philips Pinnacle treatment planning system and delivered on an Elekta Infinity accelerator were compared with fixed-beam IMRT treatments for prostate patients treated for seminal vesicle and/or lymph node involvement. No

statistically significant differences in target coverage, target homogeneity or normal tissue doses were observed between the plans. For prostate patients treated for seminal vesicle and/or lymph node involvement, VMAT plans were delivered in significantly less time and required significantly less MU.

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