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ORIGINAL ARTICLE

Comparing four volumetric modulated arc therapy beam arrangements for the treatment of early-stage prostate cancer

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Abstract

Introduction: This study compared four different volumetric modulated arc therapy (VMAT) beam arrangements for the treatment of early-stage prostate cancer examining plan quality and the impact on a radiotherapy department's resources. **Methods:** Twenty prostate cases were retrospectively planned using four VMAT beam arrangements (1) a partial arc (PA), (2) one arc (1A), (3) one arc plus a partial arc (1A + PA) and (4) two arcs (2A). The quality of the dose distributions generated were compared by examining the overall plan quality, the homogeneity and conformity to the planning target volume (PTV), the number of monitor units and the dose delivered to the organs at risk. Departmental resources were considered by recording the planning time and beam delivery time. **Results:** Each technique produced a plan of similar quality that was considered adequate for treatment; though some differences were noted. The 1A, 1A + PA and 2A plans demonstrated a better conformity to the PTV which correlated to improved sparing of the rectum in the 60–70 Gy range for the 1A + PA and 2A techniques. The time needed to generate the plans was different for each technique ranging from 13.1 min for 1A + PA to 17.8 min for 1A. The PA beam delivery time was fastest with a mean time of 0.9 min. Beam-on times then increased with an increase in the number of arcs up to an average of 2.2 min for the 2A technique. **Conclusion:** Which VMAT technique is best suited for clinical implementation for the treatment of prostate cancer may be dictated by the individual patient and the availability of departmental resources.

Introduction

Perhaps understatedly, volumetric modulated arc therapy (VMAT) was first introduced in 2008 as a novel radiotherapy technique where treatment is delivered efficiently and accurately using a modulated arc.[1] More specifically, VMAT treatment is delivered using a cone beam that rotates around the patient. The cone beam is modulated by the intertwining of dynamic multi-leaf collimators (MLCs), variable dose rates, and gantry speeds to generate high-quality dose distributions in a single optimised arc around the patient.[2]

Since being introduced, it is now well established that VMAT is capable of producing a dosimetric plan of similar or improved quality compared to intensity modulated radiation therapy (IMRT) for the treatment of early-stage prostate cancer.[3] A previous study by our group supported this by demonstrating that when using either 5-field IMRT or VMAT with one and two arcs, a dose distribution that meets departmental planning guidelines was successfully produced for 20 prostate cancer cases. The overall quality of the IMRT and VMAT plans produced were similar. Importantly, beam delivery times were reduced when using VMAT with one arc and

the number of monitor units (MUs) required to deliver a fraction of treatment was lower for both VMAT techniques compared to IMRT.[4]

On the basis of these findings the Fraser Valley Centre (FVC) of the British Columbia Cancer Agency (BCCA) is considering implementing VMAT for the radical treatment of prostate cancer to take advantage of the reduced treatment time to increase patient throughput in the department.

A decision has to be made on which VMAT beam arrangement is best suited for clinical implementation. In previous publications from the current authors, IMRT was compared to VMAT with either one or two arcs.[4,5] Similar studies have been performed by others that also examine the use of one and/or two treatment arcs.[3,6–17] Other authors have reported using partial arcs (PA) or a mix of full and PAs to treat the prostate.[6,15,18,19] While some of these studies may have considered up to two different VMAT beam arrangements, to the best of our knowledge there is no study that compares a variety of VMAT techniques.

This study compared four different VMAT beam arrangements to aid in the decision as to which technique to implement clinically for the treatment of early-stage prostate cancer. The factors effecting the decision as to which technique to implement will be considered including plan quality and the impact on departmental planning and treatment resources.

Methods

Approval for this study was provided by the University of Newcastle, Australia, Human Research Ethics Committee (approval number: H-2011-0073) and the British Columbia Cancer Agency, Canada, Research Ethics Board (approval number: H11-00108).

Cases and plans

The study used de-identified CT data sets from 20 patients that had been previously treated at the FVC of the BCCA with IMRT to the prostate only. The presentation history of the 20 cases used has been described previously.[5]

Dose distributions were generated retrospectively for each data set using four VMAT beam arrangements (detailed below). All planning was done by the same radiation therapist using v10.0 (PRO10.0.28) of Varian Medical Systems *Eclipse* planning software (which includes *RapidArc)*. The planning was done on the same computer which uses an XP (SP3) operating system, 16 processors (2.3 GHz each) and 24 GB of RAM. Each plan was prescribed 74 Gy in 37 fractions and intended to meet the FVC prostate IMRT planning guidelines outlined in Table 1.

Table 1. The Fraser Valley Centre specific planning objectives for intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) treatments of the prostate.

Volume/organ at risk (OAR)	Dose constraint
Planning target volume (PTV)	• 99% of the volume to get ≥ 95% of the prescription • Minimum dose > 90% of the prescription • Mean dose >99% of the prescription • Maximum dose <107% of the prescription • The maximum dose must be within the PTV
Rectum	<65% of the volume to receive 50 Gy <55% of the volume to receive 60 Gy <25% of the volume to receive 70 Gy <15% of the volume to receive 75 Gy <5% of the volume to receive 78 Gy
Bladder	<50% of the volume to receive 65 Gy <35% of the volume to receive 70 Gy <25% of the volume to receive 75 Gy <15% of the volume to receive 80 Gy

Gy, dose in gray.

CT simulation

The original CT data sets were obtained on a Phillips Brilliance Big Bore scanner using 2 mm slices with the patient in a supine position. Patients were instructed to have a full bladder at time of simulation and treatment, however, bowel preparation to ensure an empty bowel was not performed.

Contouring

All original contours from the actual treatment plans were transferred onto the de-identified data sets.

A radiation oncologist contoured the prostate, bladder and rectum distally from the rectosigmoid flexure to the anus. A planning target volume (PTV) was generated by expanding the prostate contour with a 10 mm margin in all directions. If the data set included prostate fiducial markers, the PTV was created using a 6 mm margin to the prostate posteriorly to spare additional rectal tissue from receiving radiation dose.

Optimisation structures were created for the PTV, rectum and bladder. A PTV_{opti} was created by copying the PTV and extending the contour superiorly and inferiorly by one slice. The size of the PTV_{opti} on the new superior and inferior slices was reduced by half. The creation of the PTV_{opti} was done to allow the superior and inferior ends of the PTV to receive adequate dose

coverage via primary and scatter dose. $Rectum_{opti}$ and $Bladder_{opti}$ structures were created by subtracting the rectum and bladder structures from the PTV_{opti} plus a 3-mm margin.

In addition to the contours transferred from the original planning data, the heads of femur were also contoured. The dose to the heads of femur are not routinely considered for IMRT planning at FVC but were considered in this study. The heads of femur were contoured superiorly from the caudal ishial tuberosity.

A couch structure was added to the plans so that beam attenuation from the treatment couch was considered. The couch structure was added using the pre-defined couch structures available within the Varian *Eclipse* software.

VMAT planning

In this study, dose distributions were generated retrospectively for each data set using four VMAT beam arrangements: (1) PA, (2) one arc, (3) one arc plus a partial arc and (4) two arcs (Fig. 1).

(1) The PA method utilised an arc that started with the gantry at 135° and rotated in a counter clockwise (CCW) direction stopping at 225°, for a total 270° degree arc (Fig. 1A). The arc deliberately avoided treating through the rectum from the posterior direction. The collimator was set at 45° to minimise MLC tongue and groove effect.[20]

(2) The one arc (1A) technique utilised one complete CCW rotation to deliver radiation treatment (Fig. 1B). The gantry start angle was 179° and the stop angle was 181°. As for PA, the collimator was set to 45°.

(3) The third technique combined one full arc plus a partial arc (1A + PA) (Fig. 1C). The PA was delivered as described above. The additional one arc was delivered with the gantry moving in the opposite clockwise (CW) direction from 181° to 179°. For this additional arc the collimator was flipped to 135° to increase modulation.

(4) The two-arc plan (2A) combined both a complete CCW rotation and a full CW gantry rotation for treatment (Fig. 1D). The parameters for the first arc were identical to the 1A technique. The second arc had the gantry rotating in the opposite direction to minimise set-up time. The gantry start angle was 181° and a stop angle of 179°. For the second arc, the collimator was set to 135° to increase modulation.

Planning templates defining the beam parameters and the initial optimisation objectives were created to expedite the planning process. Importantly, the initial optimisation objectives used for VMAT planning were the same for each of the four beam arrangements, however, these objectives were adjusted during optimisation to achieve the best plan. VMAT calculations utilised the anisotropic analytical algorithm (AAA) with heterogeneity correction on and a 2.5 mm calculation grid.

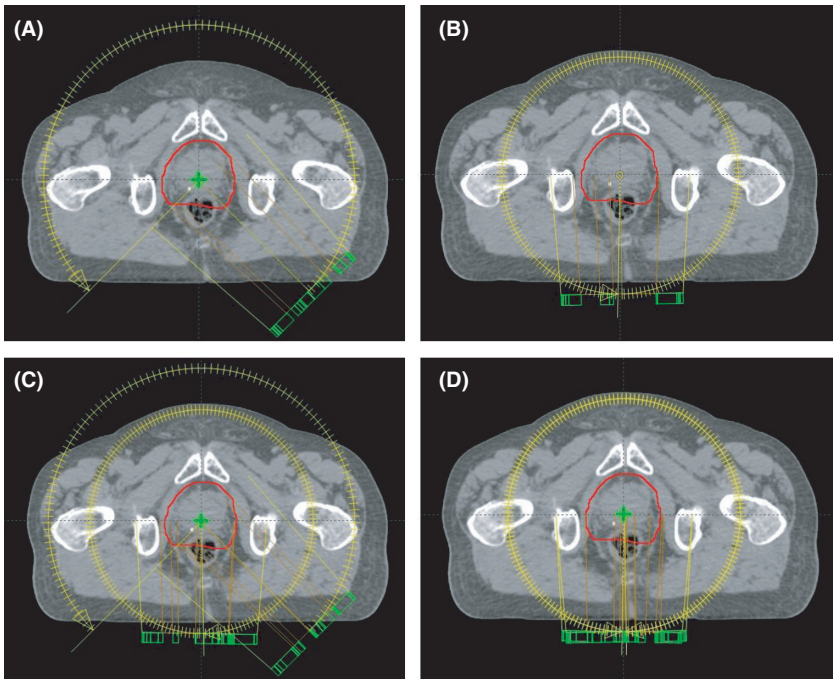

Figure 1. An example case displaying the planning target volume (in red) and the beam arrangement for the (A) partial arc (PA), (B) one arc (1A), (C) one arc plus a partial arc (1A + PA) and (d) two-arc (2A) volumetric modulated arc therapy (VMAT) techniques.

Analysis

Plan quality

A dose distribution was considered acceptable for treatment if able to meet the FVC prostate planning guidelines outlined in Table 1.

The plan quality was quantitatively assessed by calculating the homogeneity index (HI) and conformity number (CN) for each plan. The HI is defined as:

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

where D_n is the dose covering n of the target volume.

A HI value closer to zero indicates more homogeneous dose coverage within the PTV.

Dose conformity evaluates the dose fit of the PTV relative to the volume covered by the prescription dose.[16] Ideally the prescribed dose should fit tightly to the PTV, therefore reducing the side effects incurred by treating surrounding tissues and organs. The CN simultaneously takes into account irradiation of the PTV and irradiation of healthy tissues. The CN is defined as:

$$\mathrm{CN} = \frac{V_{\mathrm{TPress}}}{\mathrm{PTV}} \times \frac{V_{\mathrm{TPres}}}{V_{\mathrm{Pres}}}$$

where V_{Pres} is the total volume receiving the prescription, PTV is the planning target volume and V_{TPres} is the target volume covered by the prescription).[21]

A CN value closer to 1, indicates that the dose distribution fits more tightly to the PTV preserving healthy tissue.

Dose to organs at risk

The dose to the organs at risk (OAR) was compared by determining the percentage volume (V) of an organ receiving n dose (V_n). To get a complete understanding of how each VMAT beam arrangement impacts on dose delivered across the rectum and bladder, the V_5, V_{15}, V_{20}, V_{30}, V_{40}, V_{50}, V_{60}, V_{65}, and V_{70} were recorded. For each of the left and right heads on femur, the V_{20}, V_{30} and V_{40} were measured.

Planning time

The time taken to generate a dose distribution for each technique was recorded in minutes (min). For the purposes of this study, planning time does not include the time needed to perform contouring as this is considered neutral for each of the VMAT techniques. Instead, time measurement includes a sum of the time to place fields, plan optimisation, dose calculation and the period of evaluation of the final dose distribution to assess if the planning guidelines were achieved.

Beam delivery time

The time taken to deliver the treatment fields for the PA, 1A, 1A + PA and 2A plans was measured and recorded. This was done by running all four treatment plans for each of the 20 cases in standby mode on a Varian TrueBeam linear accelerator (linac). Time measurement was started at the initial beam-on and was ended when the final MU was delivered. The treatment time does include the time taken to move parameters such as gantry and collimator angles during treatment and between fields. However, the automation feature of the TrueBeam machine was used to minimise the delay due to collimator and gantry movement between treatment arcs. The measured treatment time does not include patient set up time or the time that may be needed to verify treatment position.

Number of MUs

The total number of MUs needed to deliver each treatment plan was summed and recorded.

Statistical analysis

A sample size of 20 cases was calculated to give a power of at least 0.8 at the 95% level. Statistical analysis was conducted using Graphpad InStat version 3 for windows (www.graphpad.com). The data were analysed first to test for normality, and if it passed it was analysed for statistical difference with the repeated measures analysis of variance (RM ANOVA). A RM ANOVA test was chosen as the same data sets were used for each treatment option. To be statistically different the values needed to be significant at the 95% level (i.e. $P < 0.05$).

Results

Each VMAT beam arrangement trialled, PA, 1A, 1A + PA and 2A, was able to produce an acceptable plan meeting the department guidelines for all 20 cases. An example of one case showing the dose volume histogram (DVH) for the PTV, rectum, bladder and heads of femur, for each of the four techniques is presented in Figure 2.

The results for the planning time, beam delivery time, number of MUs, HI and CN are presented in Table 2. Overall the plan quality of each technique was similar with some observable differences. The measured homogeneity was similar for the 1A, 1A + PA and 2A

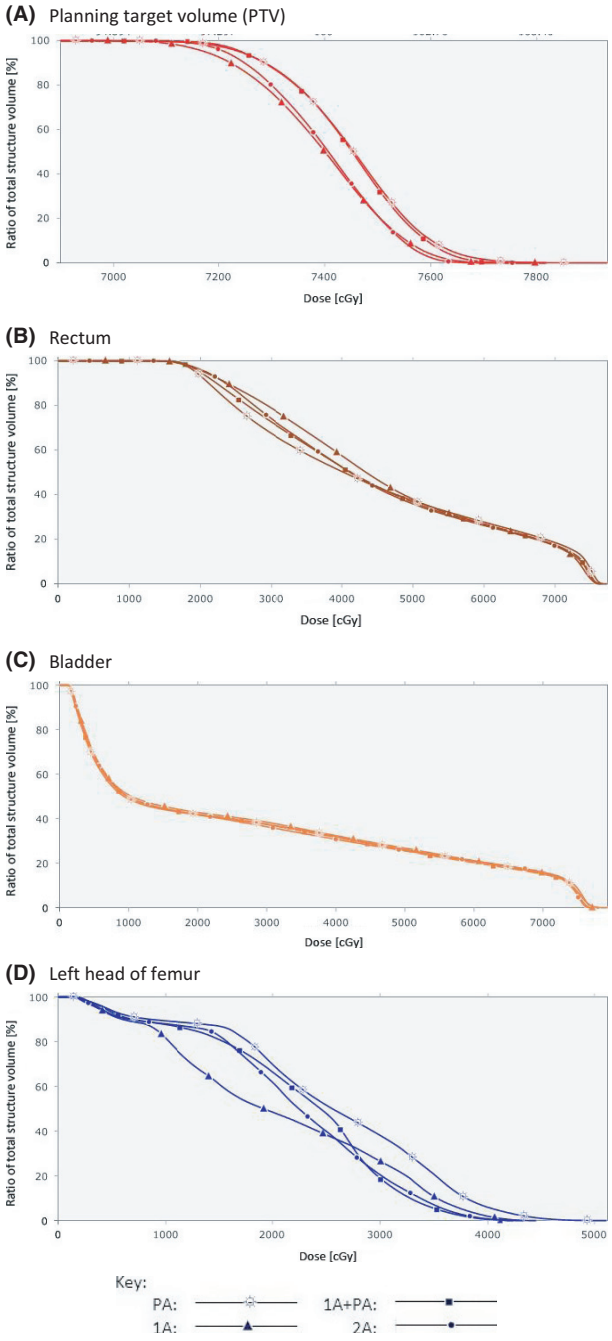

Figure 2. A series of dose volume histograms (DVHs) for an example case (Case 5) that plots the dose in cGy against the ratio of total structure volume (%) for the (A) planning target volume (PTV), (B) rectum, (C) bladder and (D) left head of femur for the partial arc (PA), one arc (1A), one arc plus a partial arc (1A + PA) and two-arc (2A) volumetric modulated arc therapy techniques.

techniques. These were significantly better than that observed for the PA arrangement (Table 2).

The conformity to the PTV as reported by the CN is similar for the 1A, 1A + PA and 2A techniques. These techniques demonstrate improved conformity compared to the PA technique, with the 1A + PA and 2A techniques being significantly better than the PA beam arrangement (Table 2).

The mean number of MUs required to deliver the 1A and 2A treatments are similar (460 and 470). Significantly more MUs are required to deliver PA (496) and 1A + PA (489) plans (Table 2).

The time required to generate a dose distribution for each beam arrangement is presented in Table 2. It was hypothesised that the PA dose distributions would be produced in the fastest time and that 2A plans would require the most time to generate. Unexpectedly, the 1A + PA plans were produced the fastest taking an average time of 13.1 min. The 1A plans took the longest mean time to generate (17.8 min). The PA and 2A plans required a mean time of 13.4 and 14.4 min respectively. Figure 3 drills down the overall planning time presented in Table 2, into the portion of time needed for plan optimisation and the time for plan calculation. The average time used for optimisation is lowest for the PA plans and increases as the number of treatments arcs (gantry rotation) increases. As such the 2A plans needed the most time to optimise. The 1A + PA and 2A plans require less time to calculate compared to the PA and 1A technique.

The mean beam delivery time recorded on the TrueBeam unit increases as the number of treatment arcs (gantry rotation) is increased (Table 2). Beam delivery time was fastest using the PA technique, requiring 0.9 min. The 1A technique was the next fastest requiring 1.0 min followed by the 1A + PA technique which required an average time of 1.9 min. The 2A arrangement took the longest with a mean time of 2.2 min.

The dose delivered to the rectum is presented in Table 3 and an example DVH from an actual case is presented in Figure 2B. From this data there is a trend for the PA technique to provide a greater sparing of tissue in the V_{15}–V_{30} range. In the V_{60}–V_{70} range the 1A + PA and 2A techniques provide the best sparing of rectal tissue.

As can be seen in Figure 2C, the dose delivered to the bladder is very similar for each of the four VMAT beam arrangements. The statistical differences between the techniques and the dose they deliver to the bladder is assessed in Table 4. In the V_{40}–V_{70} range, each technique delivers a similar dose to the bladder with the only statistical difference being that the 1A technique delivers more dose to the bladder compared to the 1A + PA technique.

The dose delivered to the heads of femur is presented in Figure 2D and Table 5. At all levels measured, the PA technique delivers a higher dose to the heads of femur.

Table 2. Summary data representing the mean planning time, treatment time, monitor units required, homogeneity index and conformity number for the partial arc (PA), one arc (1A), one arc plus partial arc (1A + PA) and two-arc (2A) plans.

	Mean (95% confidence interval)				*P* values (*N* = 20) (calculated with RM ANOVA)					
	PA	1A	1A + PA	2A	PA vs. 1A	PA vs. 1A + PA	PA vs. 2A	1A vs. 1A + PA	1A vs. 2A	1A + PA vs. 2A
Planning time (min)	13.4 (12.8–13.9)	17.8 (17.2–18.5)	13.1 (12.5–13.7)	14.4 (13.8–15)	***	ns	***	***	***	***
Beam delivery time (min)	0.9 (0.9–0.9)	1.0 (1.0–1.0)	1.9 (1.9–1.9)	2.2 (2.1–2.2)	ns	***	***	ns	***	ns
Monitor units	495.5 (479.9–513.9)	457 (446.9–474.1)	485 (472–506.4)	454.5 (452.9–486.2)	***	ns	**	***	ns	*
Homogeneity index	0.073 (0.070–0.074)	0.068 (0.066–0.071)	0.069 (0.066–0.072)	0.066 (0.064–0.068)	**	*	***	ns	ns	*
Conformity number	0.851 (0.84–0.86)	0.853 (0.85–0.86)	0.857 (0.85–0.86)	0.854 (0.85–0.86)	ns	*	*	ns	ns	ns

ns, not significant ($P > 0.05$).
*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

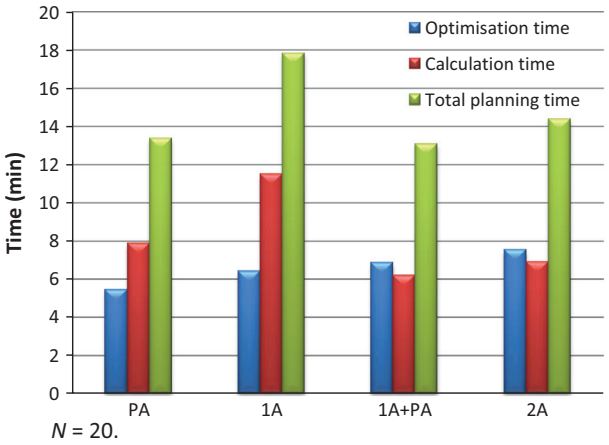

Figure 3. The average optimisation, calculation and total planning time (in minutes) required for the; partial arc (PA), one arc (1A), one arc plus a partial arc (1A + PA) and two-arc (2A) volumetric modulated arc therapy (VMAT) techniques.

Discussion

This study examined plan quality and the impact on a radiation therapy department's resources for four different VMAT beam arrangements for the treatment of early-stage prostate cancer. The four beam arrangements examined were: (1) a partial arc (PA), (2) one arc (1A), (3) one arc plus a partial arc (1A + PA) and (4) two arcs (2A). Each technique was able to produce an acceptable plan as defined by the departmental planning guidelines.

The time required to generate a dose distribution was different for each beam arrangement. The 1A + PA plans were produced the fastest in a mean time of 13.1 min. The next fastest were the PA plans followed by the 2A technique requiring an average time of 13.4 and 14.4 min. The 1A plans took the longest mean time to generate (17.8 min).

The results obtained for the time required to generate a treatment plan were unexpected by the authors who hypothesised that the planning time would correlate with the number of control points being used to generate each plan. In Varian Medical Systems VMAT planning software, a control point is used approximately every 2° of gantry rotation during the optimisation and calculation processes. In this study the PA, 1A, 1A + PA and 2A plans used 113, 178, 291 and 356 control points. The authors, therefore, hypothesised the planning time from fastest to slowest would be PA, 1A, 1A + PA, then 2A. The hypothesised trend was observed when comparing the time needed for plan optimisation, however, this trend is not observed in the measured calculation time (Fig. 3). Instead, the calculation time of the two techniques with the greatest number of control points, 1A + PA and 2A, is the fastest. This observation can be explained by the way the FVC's network for VMAT calculations is configured. The dosimetry department is set up so that when a VMAT plan utilises one arc or less, the calculation is performed by the local Eclipse workstation only. When more than one arc is utilised within a plan, the calculation is not only performed by the local workstation but is also farmed out to other available Eclipse workstations thus reducing the time needed for calculation. Presumably, if the calculation network is reconfigured so that all VMAT calculations are farmed out to other available Eclipse workstations, the plans with the least number of control points would be calculated in the fastest time. This is an important

Table 3. The mean dose to the rectum delivered by the partial arc (PA), one arc (1A), one arc plus partial arc (1A + PA) and two-arc (2A) plans The dose to the organ at risk is presented as the percentage volume (V) of the organ receiving n dose in gray (V_n).

	Mean (%) (95% confidence interval)				*P* values (*N* = 20) (calculated with RM ANOVA)					
	PA	1A	1A + PA	2A	PA vs. 1A	PA vs. 1A + PA	PA vs. 2A	1A vs. 1A + PA	1A vs. 2A	1A + PA vs 2A
V_5	89.4 (84.8–94.2)	89.9 (85.3–94.5)	89.9 (85.2–94.6)	90.0 (92.8–94.7)	*	*	**	ns	ns	ns
V_{15}	74.4 (63.0–80.8)	75.8 (69.6–82.0)	75.7 (69.6–81.7)	75.6 (69.5–81.7)	**	*	*	ns	ns	ns
V_{20}	68.3 (61.6–75.1)	72.4 (66.3–78.5)	71.6 (65.8–77.5)	72.3 (66.3–78.3)	***	***	***	ns	ns	ns
V_{30}	54.0 (47.0–61.0)	61.9 (56.3–67.4)	57.3 (51.3–63.0)	60.7 (55.7–65.7)	***	*	***	**	ns	*
V_{40}	41.4 (35.1–47.8)	46.4 (41.4–51.6)	41.0 (35.4–46.7)	44.0 (39.2–49.0)	***	ns	ns	***	ns	*
V_{50}	29.9 (24.6–35.1)	31.0 (26.6–35.4)	28.5 (23.6–33.5)	29.6 (25.1–34.2)	ns	ns	ns	***	ns	ns
V_{60}	21.4 (17.1–25.3)	21.3 (17.1–25.4)	20.4 (16.1–24.6)	20.7 (16.5–24.9)	ns	***	*	**	ns	ns
V_{65}	17.6 (13.6–21.5)	17.2 (13.4–21.0)	16.8 (12.9–20.7)	16.9 (13.0–20.7)	ns	***	***	*	ns	ns
V_{70}	13.4 (10.1–16.8)	12.7 (9.4–16.0)	12.6 (9.3–15.9)	12.6 (9.2–15.9)	*	**	**	ns	ns	ns
V_{75}	3.8 (2.1–5.6)	1.9 (0.9–2.8)	1.9 (0.9–2.9)	1.9 (0.8–3.1)	***	***	***	ns	ns	ns

ns, not significant ($P > 0.05$).
*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

Table 4. The mean dose to the bladder delivered by the partial arc (PA), one arc (1A), one arc plus partial arc (1A + PA) and two-arc (2A) plans The dose to the organ at risk is presented as the percentage volume (V) of the organ receiving n dose in gray (V_n).

	Mean (%) (95% confidence interval)				*P* values (*N* = 20) (calculated with RM ANOVA)					
	PA	1A	1A + PA	2A	PA vs. 1A	PA vs. 1A + PA	PA vs. 2A	1A vs. 1A + PA	1A vs. 2A	1A + PA vs 2A
V_5	66.4 (56.0–76.7)	68.4 (58.3–78.6)	68.0 (57.8–78.2)	68.7 (58.6–78.2)	***	***	***	ns	ns	*
V_{15}	48.1 (36.6–60.0)	49.8 (37.8–61.8)	49.3 (37.5–61.1)	50.0 (38.0–62.0)	***	ns	***	ns	ns	ns
V_{20}	44.4 (32.9–55.9)	45.8 (34.1–57.5)	45.2 (33.8–56.6)	45.9 (34.1–57.7)	***	ns	***	ns	ns	ns
V_{30}	35.9 (25.6–46.2)	37.4 (26.7–48.2)	36.4 (26.2–46.6)	37.0 (26.4–47.7)	***	ns	*	ns	ns	ns
V_{40}	28.3 (19.5–37.0)	29.3 (20.2–38.4)	27.9 (19.5–36.3)	28.6 (19.8–37.3)	ns	ns	ns	ns	ns	ns
V_{50}	22.0 (14.8–29.2)	22.7 (15.3–30.1)	21.5 (14.6–28.4)	22.0 (14.9–29.1)	ns	ns	ns	**	ns	ns
V_{60}	17.4 (11.6–23.3)	17.8 (11.8–23.8)	17.0 (11.3–22.6)	17.3 (11.5–23.1)	ns	ns	ns	***	ns	ns
V_{65}	15.3 (10.1–20.5)	15.5 (10.2–20.8)	14.9 (9.9–19.8)	15.2 (10.0–20.3)	ns	ns	ns	*	ns	ns
V_{70}	12.8 (8.4–17.2)	12.9 (8.5–17.3)	12.5 (8.3–16.7)	12.7 (8.4–17.1)	ns	ns	ns	*	ns	ns
V_{75}	5.9 (3.8–8.1)	4.3 (2.8–5.8)	5.2 (3.3–7.0)	4.6 (2.9–6.4)	***	ns	**	*	ns	ns

ns, not significant ($P > 0.05$).
*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

Table 5. The mean dose to the heads of femur delivered by the partial arc (PA), one arc (1A), one arc plus partial arc (1A + PA) and two-arc (2A) plans The dose to the organ at risk is presented as the percentage volume (V) of the organ receiving n dose in gray (V_n).

	Mean (%) (95% confidence interval)				*P* values (*N* = 20) (calculated with RM ANOVA)					
	PA	1A	1A + PA	2A	PA vs. 1A	PA vs. 1A + PA	PA vs. 2A	1A vs. 1A + PA	1A vs. 2A	1A + PA vs 2A
LT Femur										
V_{20}	50.6 (42.9–58.4)	30.1 (22.8–37.4)	46.8 (36.6–56.9)	30.4 (20.9–39.8)	***	ns	***	***	ns	***
V_{30}	18.2 (12.5–23.9)	5.8 (2.2–9.4)	9.3 (4.6–14.0)	3.6 (0.6–3.7)	***	*	***	ns	ns	*
V_{40}	2.6 (1.0–4.2)	0.3 (−0.1 to 0.8)	0.4 (−0.3 to 0.1)	0.1 (−0.4 to 0.1)	***	**	***	ns	ns	ns
RT Femur										
V_{20}	56.2 (48.6–63.8)	41.2 (29.9–52.5)	39.0 (30.8–47.3)	34.4 (26.0–42.8)	*	***	***	ns	ns	ns
V_{30}	15.7 (9.6–21.3)	7.8 (2.7–12.7)	5.9 (3.1–8.8)	6.3 (2.5–10.0)	**	**	***	ns	ns	ns
V_{40}	2.3 (0.6–4.0)	0.4 (−0.05 to 0.9)	0.4 (−0.04 to 0.8)	0.4 (−0.08 to 0.8)	*	*	*	ns	ns	ns

ns, not significant ($P > 0.05$).
*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

consideration for any radiation therapy department considering implementing VMAT.

Although it was demonstrated that there were some statistical differences in the mean time needed to generate a plan for each of the four VMAT styles, in reality there was less than 5 min difference between the fastest and slowest technique. Importantly, the planning time reported in this study includes the time to place fields, plan optimisation, dose calculation and the time needed to review the plan. It could be argued the observed difference in planning time of 5 min is insignificant from a resource management perspective, especially if you were also to consider the additional time required for contouring and quality assurance checks.

Overall, the quality of the plans produced were similar for each technique, however, there were some noted difference between the beam arrangements.

The homogeneity across the PTV as determined by the HI was similar for the 1A, 1A + PA and 2A techniques. The HI for these techniques was significantly better than that observed for the PA arrangement. This observation is in agreement with previous findings from this group and the reports of others who have demonstrated that the homogeneity across the PTV is improved as more gantry angles or arcs are used for treatment.[4,5,19] Although statistical differences in the HI have been determined here, the actual values are similar and, therefore, the clinical significance of such small differences remains unclear.

The 1A and 2A techniques require the fewest number of MUs to deliver a single fraction of treatment. Significantly, more MUs are required to deliver the PA and 1A + PA plans. The significance of the number of MUs used in a treatment becomes important when considering the theoretical risk of inducing secondary malignancies as a consequence of radiation treatment. A greater number of MUs may result in an increase in the whole body dose due to an increase in scatter and leakage radiation.[22] In turn, the increased whole body dose theoretically increases the risk of developing secondary malignancies.[23] Secondary malignancy induction is an important consideration for prostate cancers patients who have a significant chance of long term survival.[6,24] On the basis of the results presented in this study, patients being treated with one or two arcs may hypothetically have a reduced risk of generating a treatment-related secondary malignancy than patients treated using either PA or 1A + PA which require a greater number of MUs.

Any improvement in dose conformity observed using VMAT may increase the potential of dose escalation without increasing treatment-related morbidities associated with radiation exposure to surrounding tissues. Importantly, dose escalation has been demonstrated to improve local control of prostate cancer.[15,25–28] The conformity to the PTV as reported by the CN is similar for the 1A, 1A + PA and 2A techniques. These are shown to be improved compared to the PA technique. The improved conformity observed using VMAT techniques with relatively more arcs is a consequence of a treatment that delivers dose from more gantry angles. In this study, a significant improvement in CN was not observed as the number of arcs used for treatment is increased above one arc. The PTV used here contains the prostate only and is relatively spherical, without irregularities in shape. For this PTV it has been demonstrated here that an increase in the number of arcs/gantry angle used beyond one arc does not improve the conformity of the plan. It may be reasonable to expect that a more irregularly shaped PTV, such as those including the seminal vesicles, may become more conformal as a greater number of arcs/gantry angle are used for treatment. Sale and Moloney compared VMAT treatments using one or two arcs to irregularly shaped PTVs for post-prostatectomy patients or a prostate PTV that includes the seminal vesicles. They report that the conformity is improved for these more complex PTVs using two arcs compared to the single-arc technique.[29]

Conformity to the PTV can in-part explains the dose levels being delivered to the rectum in this study. It has been demonstrated that when using the PA technique, a greater volume of rectal tissue receives 60–70 Gy compared to the 1A + PA and 2A techniques. This may be attributed to the 1A + PA and 2A techniques generating a more conformal dose to the PTV therefore sparing more of the rectal tissue. Increased sparing of rectal tissues in this dose range is critical as it has been reported that parts of the rectum receiving ≥60 Gy are more likely to experience acute and late side effects including moderate diarrhoea, excessive rectal mucus, rectal bleeding and obstruction.[30] Therefore VMAT treatments with the 1A + PA and 2A techniques may reduce the occurrence of these acute and late toxicities.

In the 15–30 Gy range, the PA technique actually spares more of the rectum than the other beam arrangements. This can be attributed to the geometry of the PA beam arrangement which avoids delivering dose to the PTV through the rectum.

The PA technique delivers more dose to the heads of femur at all levels measured. This is also due to the geometry of the PA beam arrangement. As the PA avoids the rectum it is forced to push more dose from other angles including those which treat through the heads of femur, delivering a greater dose to these OAR. An option not investigated here that could be used to reduce the dose delivered to the heads of femur would be to consider using avoidance sectors. Another option to reduce the dose to the heads of femur would be

to consider using couch rotations to create non-coplanar plans. If a non-coplanar technique is used, this would likely increase the time needed to deliver a treatment as additional time would be needed to enter the room to change the couch angle.

The mean beam delivery time on the TrueBeam unit was different for each technique. Beam delivery time was fastest using the PA technique requiring 0.9 min, while the 2A technique needed the most time (2.1 min). The beam delivery time correlated with the total gantry movement in each technique. As the amount of gantry movement increased, so too did the beam delivery time. The PA technique utilised the smallest total gantry rotation while the 2A techniques had the greatest total gantry rotation.

The significance of faster beam delivery is that there is less chance of intrafraction movement. Positioning studies have reported that reducing treatment time has the potential to increase prostate treatment accuracy.[10] That is, the longer a treatment lasts the higher the risk is of patient movement and anatomical deviation.[31,32] As discussed earlier, a more irregularly shaped treatment target may benefit from using multiple arcs to achieve the best dose distribution, however, this comes with the cost of an increased beam delivery time.

It is important to remember that the reported beam delivery time represents only a fraction of the time the patient is actually on the treatment couch. An overall treatment appointment also includes the time needed for patient positioning, portal imaging and general patient care. None the less, any reduction in the beam delivery time will increase patient comfort and reduce the chance of intrafraction movement. If the time needed for the overall treatment appointment can be reduced, it may be possible to increase patient throughput and reduce the wait list of radiation therapy department. Alternatively, the newly available time could be used to implement advanced image guidance radiation therapy (IGRT) techniques such as cone beam CT, without increasing the overall treatment appointment time.

The purpose of this study was to compare four different VMAT beam arrangements to aid our radiation therapy department in deciding which VMAT beam arrangement to implement clinically for the treatments of early-stage prostate cancer. As demonstrated here each technique has its own pros and cons. Quan et al. consider dual arcs superior to single arc in terms of a compromise between plan quality and delivery efficiency. Their group prefer the dual arc VMAT plans which provide improved rectal and bladder sparing which they consider outweighs the cost of increased treatment time compared to the single-arc technique.[3] Sale and Maloney elect to use the one arc technique for more spherical PTV structures (prostate only) and choose the two-arc technique when planning irregular PTV structures such as post-prostatectomy cases and where the seminal vesicles are included in the PTV.[29] The preferred technique at the BCCA is the 1A technique which is considered to provide an adequate dose distribution while still reducing the treatment time considerably compared to IMRT.

Conclusion

This study examines the plan quality of four different VMAT beam arrangements for the treatment of prostate cancer and their potential impact on a radiation therapy department's resources. Although statistical differences were noted, the four techniques considered: PA, 1A, 1A + PA and 2A, produced a dose distribution of similar quality that achieved the departmental planning guidelines. The conformity to the PTV was best for the 1A, 1A + PA and 2A techniques which translated to improved rectal sparing in the 1A + PA and 2A plans in the 60–70 Gy range. The improved conformity and reduced rectal dose observed using the 1A + PA and 2A techniques may allow for dose escalation without increasing rectal toxicity. However, the 1A + PA and 2A plans did have the longest beam delivery times, reducing patient comfort and increasing the chance of intrafraction movement. The PA and 1A + PA techniques also required the highest number of MUs to deliver a treatment fraction, increasing the theoretical risk of generating a radiation-induced secondary malignancy.

Ultimately, which VMAT technique is best suited for clinical implementation for the treatment of early-stage prostate cancer may be dictated by the individual patient and the availability of resources in each radiotherapy department.

Conflict of Interest

The authors declare no conflict of interest.

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