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A Retrospective Planning Analysis Comparing Volumetric-Modulated Arc Therapy (VMAT) to Intensity-Modulated Radiation Therapy (IMRT) for Radiotherapy Treatment of Prostate Cancer

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ABSTRACT

Purpose: This study aims to compare intensity-modulated radiation therapy (IMRT) to volumetric-modulated arc therapy (VMAT) for the treatment of prostate cancer. Particular focus was placed on the impact IMRT and VMAT have on departmental planning and treatment resources.

Materials and Methods: Twenty prostate cancer cases were retrospectively planned to compare 5-field IMRT to VMAT using a single arc (VMAT-1A) and 2 arcs (VMAT-2A). The impact on departmental resources was assessed by comparing the time needed to generate the dose distributions and to deliver the treatment plan. A comparison of plan quality was also performed by comparing homogeneity, conformity, the number of monitor units (MUs), and dose to the organs at risk.

Results: IMRT and VMAT-2A were able to produce adequate plans for all cases. Using VMAT-1A, planning guidelines were achieved in 8 of the 20 cases. IMRT provided an improved dose distribution and the best homogeneity to the planning target volume. Also, the IMRT plans were generated significantly faster than both VMAT techniques. VMAT planning provided significantly improved conformity and used significantly fewer monitor units than IMRT. VMAT-1A treatments were significantly faster than both IMRT and VMAT-2A. VMAT plans delivered lower dose to the bladder and heads of femur, and an increased dose to the rectum in the low dose region.

Conclusion: IMRT may have an advantage over VMAT for the treatment of prostate cancers. This is primarily due to the uncertainty of achieving planning guidelines using VMAT and the extended time needed to generate the VMAT plans.

RÉSUMÉ

But: Cette étude vise à comparer la radiothérapie conformationnelle avec modulation d'intensité de dose (RCMI) et l'irradiation avec modulation d'intensité volumétrique par arcthérapie (VMAT) pour le traitement du cancer de la prostate. Un accent particulier a été mis sur les effets de la RCMI et de la VMAT sur les ressources de planification et de traitement du service.

Matériel et méthodes: Vingt dossiers de cancer de la prostate ont fait l'objet d'une planification rétrospective afin de comparer la RCMI à cinq champs à la VMAT utilisant un seul arc (VMAT-1A) et deux arcs (VMAT-2A). L'incidence sur les ressources du service a été évaluée en comparant le temps requis pour produire la distribution de dose et exécuter le plan de traitement. Une comparaison de la qualité des plans a aussi été effectuée en rapprochant l'homogénéité, la conformité, le nombre d'unités de surveillance et la dose aux organes à risque.

Résultats: La RCMI et la VMAT-2A ont donné lieu à des plans adéquats pour tous les cas. Avec la VMAT-1A, des directives de planification ont été produites pour 8 des 20 cas. La RCMI a fourni une distribution de dose améliorée et la meilleure homogénéité du volume cible de planification. Par ailleurs, la RCMI a permis de générer des plans beaucoup plus rapidement que les deux techniques VMAT. La planification VMAT a permis d'améliorer la conformité de façon marquée et a utilisé beaucoup moins d'unités de surveillance que la RCMI. Les traitements VMAT-1A ont été significativement plus rapides que les traitements RCMI et VMAT-2A. Les plans VMAT permettent une dose réduite à la vessie et aux têtes de fémurs, et une dose augmentée au rectum dans la région de faible dose.

Conclusion: La RCMI pourrait avoir un avantage sur la VMAT pour le traitement du cancer de la prostate, en raison

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principalement de l'incertitude qui subsiste sur l'atteinte des directives de planification lors de l'utilisation de la technique VMAT et du délai supplémentaire nécessaire pour générer les plans VMAT.

Keywords: IMRT; VMAT; radiation therapy; prostate

Introduction

Intensity-modulated radiation therapy (IMRT) was introduced in the early 1990s and represented a major shift in modern radiotherapy over the pre-existing techniques of 2-dimensional radiation therapy and 3-dimensional conformal radiation therapy [1]. IMRT has enabled the delivery of a highly conformal dose distribution to the target while limiting dose to surrounding tissues and organs [2–4]. The advantages of IMRT come at a cost of increased treatment times and monitor units (MUs), resulting in a greater integral body dose from leakage and scatter radiation, increasing the risk of developing a secondary malignancy [5, 6].

On a linear accelerator, IMRT is conventionally delivered at fixed gantry angles using either the step-and-shoot or sliding window technique [7]. In 2008, Otto reported a novel form of IMRT called volumetric-modulated arc therapy (VMAT) [8]. In VMAT, treatment is delivered using a cone beam that rotates around the patient. The cone beam is modulated by the intertwining of dynamic multileaf collimators (MLCs), variable dose rates, and gantry speeds to generate IMRT quality dose distributions in a single optimized arc around the patient [9].

Since 2008, VMAT has rapidly attained widespread use. Published literature has reported the use of VMAT to treat various anatomical sites, most commonly; prostate, head and neck cancers, intercranial tumors, anal canal, breast cancers, and stereotactic body radiation therapy of the lung and abdomen. The majority of publications agree that VMAT reduces both treatment time and monitor units significantly when compared to conventional IMRT techniques [10]. This allows for quicker treatment times which improves patient comfort and allows for more time to be dedicated to patient care and support.

In mid-2010, the Fraser Valley Centre (FVC) of the British Columbia Cancer Agency, Canada, upgraded its infrastructure to be able to deliver VMAT treatments using Varian Medical Systems RapidArc^{TM}. To progress the development of VMAT treatments at FVC, the current study was undertaken to retrospectively compare single-arc and dual-arc VMAT plans to the FVC standard fixed field IMRT for the treatment of localized prostate cancers. The comparison of IMRT and VMAT focuses on their impact within the planning and treatment resources in our department, but also examines the quality of the treatment plans produced using these techniques.

Prostate cancer was specifically selected for our department's initial foray into VMAT planning for two reasons. First, the prostate is a relatively simple anatomical site on which to perform radiotherapy planning. It was therefore considered that generating a dose distribution for prostate treatments could provide a less complex experience when using VMAT for the first time. Second, and more importantly, treatment of early stage prostate cancers accounts for a high volume of work at our centre (approximately 10% of workload in 2010). If VMAT was demonstrated in this study to reduce treatment times as reported previously, VMAT treatment of prostate cancers could have the greatest potential to increase patient throughput and reduce the waitlist for our department.

Materials and 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 Research Ethics Board (approval number: H11-00108).

Cases and Plans

This study used deidentified computed tomography datasets from 20 patients that had been treated between July 2009 and September 2010 at FVC with IMRT to the prostate only (Table 1).

The original IMRT treatment plans were not used in this study. Instead, the IMRT plan was redone to establish consistency for comparison to VMAT planning. Two VMAT plans were generated for each dataset; a VMAT single-arc plan and a VMAT distribution using two arcs. All planning was done by the same radiation therapist using Varian Medical Systems Eclipse planning software version 8.6 (v8.6). Each plan was prescribed 7400 cGy in 37 fractions and intended to meet the FVC prostate IMRT planning guidelines outlined in Table 2.

CT Simulation

The original CT datasets 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 deidentified datasets.

A radiation oncologist contoured the prostate, bladder, and rectum from the sigmoid colon 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 dataset 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.

Table 1
The presentation history and contoured volumes of the 20 cases used in this study

	Age	Weight (kg)	Stage (TNM)	PTV Volume (cm^3)	Bladder Volume (cm^3)	Rectum Volume (cm^3)
Case 1	84	73.7	T3a NX M0	212.5	108.7	84.2
Case 2	67	83.5	TX N0 M0	216.9	823.7	63.5
Case 3	65	107.3	T2 N0 M0	132.8	171.3	51.8
Case 4	73	87.5	T2a	222.7	515.6	124.1
Case 5	62	79.5	T2 NX M0	249.1	266.1	78.2
Case 6	65	110	T1c N0 M0	141.4	317.7	51.1
Case 7	76	87	T2a NX M0	249.9	158.1	101.5
Case 8	74	67.4	T1c NX M0	152.9	208.5	143.5
Case 9	71	71.4	T2b	283.5	537.8	98.9
Case 10	75	118	T2b N0 M0	221.2	541	49.2
Case 11	72	64	T2a NX MX	190.3	338.4	63
Case 12	75	73.6	T2b N0 M0	137	255.9	46.3
Case 13	68	96.5	T1c N0 M0	181.5	79.5	168.6
Case 14	76	75.5	T2a	261.1	159.1	45.5
Case 15	69	78	T1c NX M0	139.9	51.5	50.1
Case 16	69	84.6	T2a	152	363.2	111.1
Case 17	61	92.4	T2a N0 M0	227.5	133.1	42.7
Case 18	80	80	T2a	66.9	239.8	63.4
Case 19	72	110	T2b	155.1	277.4	157.1
Case 20	82	88.7	T2a NX M0	142.1	182	97.5

Optimization 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 ischial tuberosity.

Table 2
The planning objectives for IMRT and VMAT treatment of the prostate

Volume/ Organ at Risk (OAR)	Dose Constraint
Planning Target Volume (PTV)	-99% of the volume to get $\geq$ 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 50Gy
	<55% of the volume to receive 60Gy
	<25% of the volume to receive 70Gy
	<15% of the volume to receive 75Gy
	<5% of the volume to receive 78Gy
Bladder	<50% of the volume to receive 65Gy
	<35% of the volume to receive 70Gy
	<25% of the volume to receive 75Gy
	<15% of the volume to receive 80Gy

A couch structure was added to the plans so that beam attenuation from the treatment couch was considered. The couch structure was added differently for IMRT and VMAT planning due to different calculation algorithms being used for IMRT and VMAT (see the following section). For IMRT planning, the couch was contoured and combined with the body contour. For VMAT planning, a couch structure was added using the predefined couch structures available within the Varian Eclipse software.

IMRT

At our centre a 5-field sliding window IMRT technique is standardly used to treat the prostate. A template is used to expedite the planning process. The template defines the gantry angles of the five treatment fields as well as the optimization parameters. Each treatment beam uses 6-MV photons with the gantry angles fixed at 0°, 75°, 135°, 225°, and 285°. Dosimetric calculations were performed using the pencil beam convolution, with heterogeneity correction and a 5-mm calculation grid.

VMAT

VMAT plans were produced using Varian Medical Systems RapidArc software (v8.6). RapidArc is based on Otto's original VMAT optimization platform [8, 10–12].

In this study both single-arc and 2-arc VMAT plans were developed. Similarly to IMRT, plan templates defining beam parameters and the initial optimization objectives were created to expedite the planning process. The single arc technique (VMAT-1A) used one complete counterclockwise rotation to deliver radiation treatment. The gantry start angle was 179.9° and the stop angle was 180.1°. The collimator was set at 45° to minimize MLC tongue-and-groove effect [13].

The 2-arc plan (VMAT-2A) combined both a complete counterclockwise rotation and a full clockwise (CW) gantry

rotation for treatment. The parameters for the first arc were identical to the VMAT-1A technique. The second arc had the gantry rotating in the opposite direction to minimize setup time. The gantry start angle was 180.1° and a stop angle of 179.9°. For the second arc, the collimator rotation was set to 135° to increase modulation. Routinely at our centre, dose calculations are performed using the pencil beam convolution as described for IMRT. However, VMAT calculations necessitate using the anisotropic analytical algorithm. In this study, VMAT calculations used the anisotropic analytical algorithm with heterogeneity correction on and a 2.5-mm calculation grid.

Analysis

Plan Quality

Plan quality was assessed by examining the ability of each planning technique to achieve the dosimetric guidelines. This qualitative assessment was aided by comparing the dose volume histogram (DVH) for the IMRT, VMAT-1A, and VMAT-2A plans.

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

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

Where D_n = 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 [14]. Ideally the prescribed dose should fit tightly to the target volume, therefore reducing the side effects occurred by treating surrounding tissues and organs. The CN simultaneously takes into account irradiation of the target volume and irradiation of healthy tissues [15]. The CN is defined as

$$CN = \frac{V_{TPres}}{TV} \times \frac{V_{TPres}}{V_{Pres}}$$

Where V_{Pres} is the total volume receiving the prescription, TV is the target volume and V_{TPres} is the target volume covered by the prescription [16].

A CN value closer to one indicates that the dose distribution fits more tightly to the target volume preserving healthy tissue.

Dose to Organs at Risk (OAR)

The dose to the OAR was compared by determining the percentage volume (V) of an organ receiving n dose (V_n). To get a complete understanding of how IMRT and VMAT planning impacts on dose delivered across the rectum and bladder, the V_{15}, V_{20}, V_{30} (rectum only), V_{40}, V_{50}, V_{60}, V_{65} (bladder only), V_{70}, and V_{75} (bladder only) were recorded. For each of the left and right heads on femur, the V_{30} and V_{40} were measured.

Planning Time

The time taken to perform the dosimetric calculations for each plan was recorded. For the purposes of this study, planning time does not include the time needed to perform contouring as this is considered neutral for both IMRT and VMAT planning. Instead, time measurement includes a sum of the time to place fields, plan optimization, dose calculation, and the period of evaluation of the final dose distribution to assess if the planning guidelines were achieved.

Treatment Time

The time taken to treat the IMRT, VMAT-1A, and VMAT-2A plans was measured and recorded. This was done by running the treatment plan for all three techniques in standby mode on a Varian Trilogy linear accelerator. Time measurement was started at the initial beam-on and was ended when the final monitor unit was delivered. The treatment time does include the time taken to move parameters such as gantry and collimator angles during treatment and between fields. The measured treatment time does not include patient setup 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 using already published data 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 analyzed first to test for normality, and if it passed it was analyzed for statistical difference with the parametric paired *t*-test and repeated measures analysis of variance (ANOVA). If the data were not normal, then statistical difference was analyzed using Wilcoxon matched-pairs and the Friedman test (nonparametric repeated measures ANOVA). A paired test was chosen as the same datasets were used for each treatment option. To be statistically different, the values needed to be significant at the 95% level.

Results

An example dose distribution produced using IMRT, VMAT-1A, and VMAT-2A for a single dataset is displayed in Figure 1. The planning guidelines were able to be achieved for all 20 datasets for both the IMRT and VMAT-2A techniques. For the VMAT-1A technique, the planning guidelines were achieved for only eight datasets. The 12 VMAT-1A cases that did not meet guidelines failed because of the dose range across the PTV being beyond the minimum 90% and maximum 107% constraints.

When the PTV DVH is compared for a single dataset, the trend is for the IMRT plan to have the steepest dose gradient

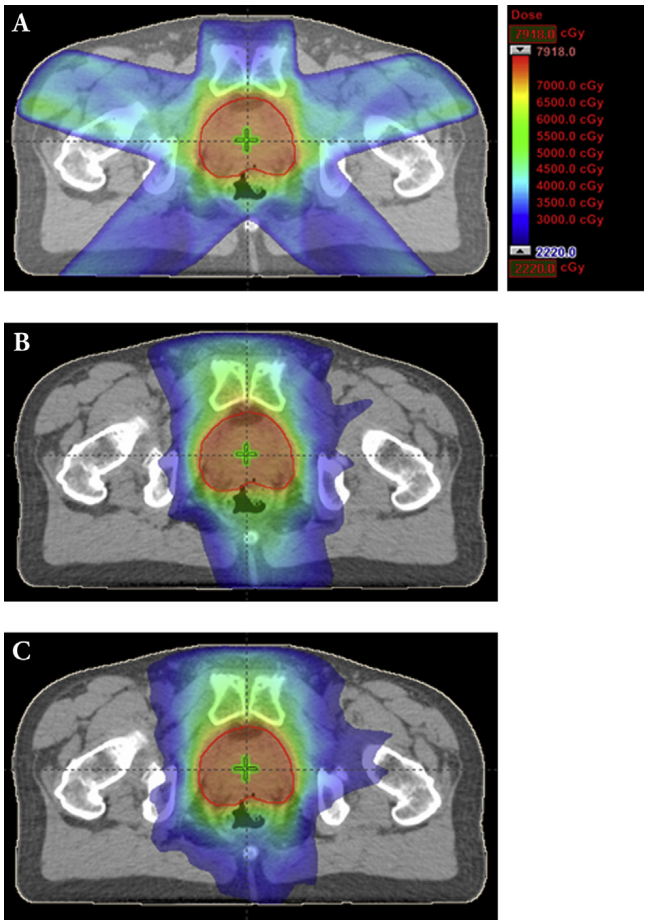

Figure 1. Example of dose distribution achieved using (A) intensity-modulated radiation therapy, (B) single-arc volumetric-modulated arc therapy (VMAT), and (C) double-arc VMAT beam arrangement for a single dataset. A 107%–30% isodose range is displayed.

across the PTV, followed by the VMAT-2A technique, then for the VMAT-1A plan (Figure 2). This trend is observed in all dataset DVHs and indicates that dose uniformity across the PTV is best for the IMRT plan, followed by the VMAT-2A and, finally, the VMAT-1A plan.

The results for HI, CN, planning time, treatment time, and number of MUs are presented Table 3.

As with the dose uniformity observed in the DVHs, the median HI is best for IMRT planning which is significantly

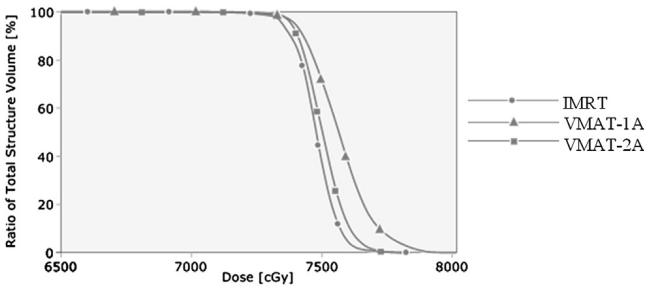

Figure 2. The planning target volume (PTV) dose volume histograms for intensity-modulated radiation therapy (IMRT), volumetric-modulated arc therapy using a single arc (VMAT-1A), and using a VMAT double arc (VMAT-2A) beam arrangement for a single computed tomography dataset.

better than VMAT-2A, which in turn is significantly better than the VMAT-1A plans.

CN values indicate the conformity of the VMAT-1A plans is best, being significantly better than both the VMAT-2A and IMRT plans. The VMAT-2A plans demonstrate significantly improved CN compared to the IMRT plans.

IMRT plans were generated in a median time of 10.10 minutes. VMAT-1A plans took significantly longer time to generate (30.57 minutes), whereas VMAT-2A plans took significantly longer time still (45.85 minutes).

The times presented here to produce an IMRT, VMAT-1A, or VMAT-2A plan represents the time needed to generate a dose distribution with only one optimization and a single calculation. It does not include the time required to run multiple optimizations and calculations in order to meet the FVC guidelines. If the planning guidelines were not achieved after the first optimization and calculation, further attempts were made to meet these guidelines. However, the additional planning time required beyond the first optimization and calculation was not recorded.

The planning guidelines were met at the first attempt in all cases using IMRT. Using VMAT-1A, 18 cases required more than one attempt to achieve the planning guidelines and still the guidelines were not achieved in all cases. For the VMAT-2A technique, eight of the 20 datasets required more than one attempt to achieve the planning criteria.

VMAT-1A treatments were delivered significantly faster than both IMRT and VMAT-2A. Median values report VMAT-1A could be delivered in 1.3 minutes. IMRT and VMAT-2A treatments required 3.2 minutes and 3.3 minutes, respectively. There was no significant difference in the time needed to treat using IMRT or VMAT-2A.

The VMAT-1A technique required the lowest median number of MUs (512) to deliver a single 200-cGY treatment. The VMAT-2A method required the next lowest median number of MUs (566). There was not a statistically significant difference between the number of MUs used in both VMAT planning techniques. IMRT required significantly more MUs (614, median) than both VMAT-1A and VMAT-2A to deliver a single fraction.

The dose delivered to the OAR from each planning technique is reported in Table 4. IMRT delivers significantly less dose to the rectum than both VMAT methods at V_{20} and V_{30}. VMAT delivers a significantly lower dose than IMRT to the bladder and heads of femur in the V_{60}–V_{70} and V_{30}–V_{40} ranges, respectively.

Discussion

For each of the 20 datasets, both the IMRT and VMAT-2A techniques were able to produce plans that meet the defined guidelines. When using the VMAT-1A technique, the same planning guidelines were able to be achieved for only eight of the 20 datasets.

The IMRT technique demonstrated a better coverage and a more homogeneous dose across the PTV compared to both

Table 3
Summary data representing the planning time, treatment time, monitor units required, homogeneity index and conformity number for the IMRT, VMAT-1A and VMAT-2A plans

	IMRT (N = 20)		VMAT-1A (N = 8)		VMAT-2A (N = 20)		P values		
	Median	95% Confidence Interval	Median	95% Confidence Interval	Median	95% Confidence Interval	IMRT Vs VMAT-1A (N = 8)	IMRT Vs VMAT-2A (N = 20)	VMAT-1A Vs VMAT-2A (N = 8)
Planning Time (min)	10.1	9.23 – 10.71	30.57	28.82 – 32.05	45.85	43.4 – 48.93	<0.0001	< 0.0001	< 0.0001
Treatment Time (min)	3.23	3.16 – 3.32	1.34	1.33 – 1.35	3.29	3.28 – 3.30	0.008	*0.25*	0.008
Monitor Units	613.5	590.11 – 647.1	511.5	485.5 – 575.0	565.5	526.9 – 597.7	0.016	0.006	*0.19*
Homogeneity Index	0.0375	0.032 – 0.049	0.0655	0.058 – 0.071	0.0435	0.038 – 0.050	0.004	0.003	0.008
Conformity Number	0.793	0.779 – 0.802	0.826	0.811 – 0.848	0.812	0.786 – 0.827	<0.001	0.004	0.028

* Italic values indicate a significant difference was NOT observed.

VMAT methods. Similarly, VMAT-2A plans had a significantly improved HI than VMAT-1A. The poor homogeneity observed for the VMAT-1A plans contributes to this method failing to achieve the FVC planning guidelines in 12 of the datasets.

Other prostate planning studies have reported lower HI in VMAT plans when compared to IMRT [10, 17, 18]. Unlike this study, in the previous publications, all VMAT plans were able to produce plans adequate for treatment. This is likely due to the planning guidelines for the PTV and OAR reported in the other studies differing to those adhered to here.

In this study, IMRT plans were produced significantly faster than both VMAT techniques. On average, IMRT plans were generated three times faster when compared to VMAT-1A plans and five times faster than VMAT-2A plans. Similar trends have been previously reported [5, 14, 19, 20]. In reality, the results presented here are flattering to VMAT techniques as they assume the planning guidelines are met at the first attempt. This was indeed the case for the IMRT plans generated with a clinically proven template. However, all but two of the VMAT-1A plans required several attempts and still did not guarantee the planning guidelines were achieved. There was no indication as to which datasets the VMAT-1A technique would successfully achieve the planning guidelines versus those that would fail. The VMAT-2A technique proved more successful with only eight of the 20 datasets requiring more than one attempt to achieve the planning criteria.

It is important to recognize the impact increased planning time may potentially have on a radiotherapy department.

Table 4
The dose to the rectum, bladder and heads of femur represented as the percentage volume (V) of the organ receiving n dose (V_n)

	IMRT (N = 20)		VMAT-1A (N = 8)		VMAT-2A (N = 20)		P values		
	Median	95% Confidence Interval	Median	95% Confidence Interval	Median	95% Confidence Interval	IMRT Vs VMAT-1A (N = 8)	IMRT Vs VMAT-2A (N = 20)	VMAT-1A Vs VMAT-2A (N = 8)
Rectum									
V_{15}	78.2	71.7 – 83.8	83.4	73.4 – 88.8	78.5	71.4 – 83.7	> 0.05	> 0.05	> 0.05
V_{20}	69.7	63.9 – 77.0	80.0	70.0 – 85.8	74.0	67.67 – 79.7	< *0.01*	*0.008*	> 0.05
V_{30}	60.5	54.0 – 66.5	71.0	62.1 – 79.1	63.7	57.9 – 70.2	< *0.01*	*0.023*	> 0.05
V_{40}	47.2	40.1 – 51.3	58.8	51.1 – 66.2	47.0	42.2 – 53.6	< *0.001*	0.0609	< *0.01*
V_{50}	31.3	27.3 – 36.8	36.0	31.6 – 45.1	30.5	27.5 – 37.2	< *0.001*	0.52	< *0.01*
V_{60}	22.2	18.7 – 27.3	22.7	18.6 – 32.0	21.5	18.1 – 26.7	> 0.05	> 0.05	> 0.05
V_{70}	12.6	10.4 – 16.7	12.9	9.4 – 19.7	12.6	10.3 – 17.2	> 0.05	0.048	> 0.05
Bladder									
V_{15}	47.2	41.4 – 65.3	42.8	26.8 – 84.2	45.8	40.0 – 64.1	> 0.05	> 0.05	> 0.05
V_{20}	43.6	38.1 – 61.6	36.7	23.3 – 80.2	41.4	36.5 – 60.2	> 0.05	> 0.05	> 0.05
V_{40}	24.2	22.2 – 39.7	23.9	13.3 – 57.7	25.7	22.8 – 41.3	> 0.05	0.27	> 0.05
V_{50}	19.3	17.9 – 32.7	18.1	9.9 – 43.9	19.5	17.5 – 32.3	> 0.05	0.50	> 0.05
V_{60}	15.3	14.3 – 26.5	12.3	6.8 – 33.7	14.6	13.4 – 25.3	< *0.01*	*0.0006*	> 0.05
V_{65}	13.2	12.4 – 23.1	10.1	5.6 – 29.2	12.4	11.6 – 22.2	< *0.001*	*0.0005*	> 0.05
V_{70}	10.5	10.0 – 18.9	8.0	4.5 – 24.5	10.2	9.6 – 18.7	< *0.01*	0.14	> 0.05
V_{75}	2.7	1.9 – 5.1	3.3	0.7 – 13.3	5.0	4.4 – 10.0	< *0.05*	*0.008*	> 0.05
LT Femur									
V_{30}	25.1	20.5 – 32.5	0.3	-0.3 – 4.8	5.8	3.9 – 19.3	< *0.001*	*0.0002*	> 0.05
V_{40}	6.9	4.4 – 11.2	0.1	-0.1 – 0.2	0.002	-0.3 – 4.6	< *0.01*	*0.0003*	> 0.05
RT Femur									
V_{30}	30.2	23.7 – 36.5	0.5	-0.3 – 3.7	1.7	2.0 – 10.5	< *0.001*	< *0.0001*	> 0.05
V_{40}	10.2	7.6 – 16.9	0	-0.03 – 0.2	0	-0.3 – 1.6	< *0.01*	< *0.0001*	> 0.05

* Italic values indicate a significant difference was observed.

Presumably, when using VMAT, it is preferable to treat with one arc to take advantage of the reported reduction in MUs and shortened treatment time [10]. However, from the results presented, it is unlikely that the FVC planning guidelines will be met on the first attempt, if at all, when planning with a single arc. The introduction of a second arc may be needed to successfully achieve the planning guidelines, but with a significant increase in planning time. Such uncertainty and exaggerated planning time for VMAT planning observed here may have significant impact on a radiotherapy departments planning resources, potentially reducing patient throughput and increasing waitlists. IMRT planning at FVC minimizes the uncertainty of achieving planning guidelines and reduces planning time significantly giving this technique a distinct advantage when comparing overall planning time.

The VMAT treatment planning systems are still in the early stages of development. The results presented here are obtained using Varian Medical Systems RapidArc v8.6, which uses aperture-based optimization. More recent versions of RapidArc use an optimizer that is both aperture- and fluence-based. Anecdotally, the primary author's early experience with this new optimization process in RapidArc version 10.0 (v10.0) is that the overall planning time for VMAT is reduced compared to v8.6. Further improvements in optimization, dose calculation, and computer processor speed will continue to reduce overall planning time [14, 19].

The discussion so far highlights an important consideration for VMAT planning. The quality of the plans produced using VMAT can depend greatly on the experience of the planner. It is critical that planers understand the optimization process in order to achieve the desired dose distribution in a timely manner [10]. Although this article shares our department's first experience with VMAT, inexperience is not likely accountable for the inability of the VMAT-1A technique to achieve departmental planning guidelines and the extended planning times using VMAT. One of the authors of this article has had previous experiences with VMAT planning [21]. Still the planning times using VMAT could not be shortened more than reported here and the planning guidelines were not always achieved with VMAT-1A.

In this study, VMAT did demonstrate some advantages over IMRT. The VMAT-1A plans were treated three times faster than IMRT. The observed reduction in treatment time using the VMAT-1A technique has the potential to increase the patient throughput of a radiation therapy department [5, 22]. Alternatively, the time saved by reducing the beam-on time could be used to implement online imaging without increasing a patient's total time in the treatment room [8, 22, 23]. Additionally, a shorter delivery time indicates improved patient comfort and a reduced probability of treatment errors caused by patient motion during a treatment [17, 18, 24]. Both improved target localization provided by online imaging and reduced patient motion during treatment has the potential to allow the size of the PTV to be reduced. A smaller PTV could mean less healthy tissue is irradiated ultimately reducing radiation-associated morbidities.

A shorter treatment time may also prove to be biologically advantageous. Evidence has shown that the radiation survival is not only a function of the total dose delivered but also depends on the duration that the radiation is delivered [25, 26]. There is a potential tumour cell killing benefit to deliver radiation doses in a shorter time [19].

Importantly, the time taken to deliver the VMAT-2A and IMRT treatments did not different significantly. Therefore, the time advantage VMAT offers for the treatment of prostate cancers is reduced when using more than one arc.

The results of this study upheld previous reports where VMAT treatments required significantly fewer MUs than IMRT [5, 8, 17–19, 22, 27]. As previously discussed, because VMAT uses fewer MUs to deliver a dose, the chances of secondary malignancies might be reduced. This is particularly relevant for patients with prostate cancer as they have a significant chance of long-term survival [27].

Dose conformity has been demonstrated to be better for the VMAT plans compared to IMRT. The improved conformity is inherent to arc delivery that delivers dose from 360°. As with any reduction in MUs, the improved conformity could reduce the risk of secondary cancers developing in the high-dose region when compared to IMRT [28]. Improved conformity also increases the opportunity of dose escalation that, in prostate treatments, has been demonstrated to improve local control [22]. Despite VMAT demonstrating improved conformity, dose escalation using VMAT may still be limited by the planning hotspots that have been reported to be greater for VMAT plans than for IMRT [10, 17].

It has been reported that VMAT plans become less conformal in the low-dose range [14, 17, 18, 22]. This can be attributed to the dose being delivered from all directions. For IMRT plans, radiation dose is only deposited along the path of the fixed gantry angles. As a result, the volume of tissues receiving a low dose in VMAT is increased compared to IMRT. Therefore, the theoretical risk of secondary malignancies is not eliminated with VMAT [5]. For many sites, this may not be a concern. However, it may be problematic for some sites such as pediatric cancers [18].

VMAT plans were demonstrated to deliver lower dose to the bladder and heads of femur, and an increased dose to the rectum in the low-dose region when compared to IMRT. The results in the literature are conflicting regarding outcome for the dose delivered to the OAR. For example, it has been reported that sparing of the rectum, bladder, and femoral heads can be improved when using VMAT compared to IMRT [5, 10, 13, 17, 18, 28]. In contrast, to these reports, but in support of the present findings, others have reported that dose to the rectum is higher when using VMAT compared to IMRT [14, 20, 29]. The inconsistency across the studies is likely the result of the individual study characteristics. For example, variables such as PTV definition, OAR dose constraints, optimization values, and the number of treatment fields in IMRT or rotation arcs used in VMAT, could create inconsistencies between studies.

Conclusion

VMAT has been demonstrated to reduce the MUs and time required to treat prostate cancer compared to conventional IMRT. Despite these findings, our department is unlikely to adopt VMAT to treat the prostate primarily because of the uncertainty of achieving planning guidelines and increased planning time. This is not to rule out adopting VMAT for the treatment of prostate cancer in the future if improvements are made to plan optimization, dose calculation, and computer processor speed. The current version of VMAT may well yet prove to have an advantage for other sites being treated using IMRT at FVC such as head and neck cancers, and stereotactic body radiation therapy techniques.

References

[1] Nutting, C. (2003). Intensity-modulated radiotherapy (IMRT): the most important advance in radiotherapy since the linear accelerator? *Br J Radiol* 76, 673.

[2] Galvin, J. M., & De Neve, W. (2007). Intensity modulating and other radiation therapy devices for dose painting. *J Clin Oncol* 25, 924–930.

[3] Webb, S. (2003). The physical basis of IMRT and inverse planning. *Br J Radiol* 76, 678–689.

[4] Palma, D. A., Verbakel, W. F., Otto, K., & Senan, S. (2010). New developments in arc radiation therapy, A review. *Cancer Treat Res* 36, 393–399.

[5] Palma, D., Vollans, E., & James, K., et al. (2008). Volumetric modulated arc therapy for delivery of prostate radiotherapy: comparison with intensity-modulated radiotherapy and three-dimensional conformal radiotherapy. *Int J Radiat Oncol Biol Phys* 72, 996–1001.

[6] Hall, E. J., & Wuu, C. S. (2003). Radiation-induced second cancers: the impact of 3D-CRT and IMRT. *Int J Radiat Oncol Biol Phys* 56, 83–88.

[7] Elith, C., Dempsey, S. E., Findlay, N., & Warren-Forward, H. M. (2011). An introduction to the intensity-modulated radiation therapy (IMRT) techniques, tomotherapy, and VMAT. *J Med Imaging Radiat Sci* 42, 37–43.

[8] Otto, K. (2008). Volumetric modulated arc therapy: IMRT in a single gantry arc. *Med Phys* 35, 310–317.

[9] Varian Medical Systems Inc. Varian's new RapidArc radiotherapy technology. http://www.varian.com/us/oncology/treatments/treatment_techniques/rapidarc/resources.html.

[10] Jolly, D., Alahakone, D., & Meyer, J. (2011). A RapidArc planning strategy for prostate with simultaneous integrated boost. *J Appl Clin Med Phys* 12, 3320.

[11] Cozzi, L., Dinshaw, K. A., & Shrivastava, S. K., et al. (2008). A treatment planning study comparing volumetric arc modulation with RapidArc and fixed field IMRT for cervix uteri radiotherapy. *Radiother Oncol* 89, 180–191.

[12] Ling, C. C., Zhang, P., Archambault, Y., Bocanek, J., Tang, G., & Losasso, T. (2008). Commissioning and quality assurance of RapidArc radiotherapy delivery system. *Int J Radiat Oncol Biol Phys* 72, 575–581.

[13] Weber, D. C., Wang, H., & Cozzi, L., et al. (2009). RapidArc, intensity modulated photon and proton techniques for recurrent prostate cancer in previously irradiated patients: a treatment planning comparison study. *Radiat Oncol* 4, 34.

[14] Yoo, S., Wu, Q. J., Lee, W. R., & Yin, F. F. (2010). Radiotherapy treatment plans with RapidArc for prostate cancer involving seminal vesicles and lymph nodes. *Int J Radiat Oncol Biol Phys* 76, 935–942.

[15] Feuvret, L., Noel, G., Mazeron, J. J., & Bey, P. (2006). Conformity index: a review. *Int J Radiat Oncol Biol Phys* 64, 333–342.

[16] van't Riet, A., Mak, A. C., Moerland, M. A., Elders, L. H., & van der Zee, W. (1997). A conformation number to quantify the degree of conformality in brachytherapy and external beam irradiation: application to the prostate. *Int J Radiat Oncol Biol Phys* 37, 731–736.

[17] Kjaer-Kristoffersen, F., Ohlhues, L., Medin, J., & Korreman, S. (2009). RapidArc volumetric modulated therapy planning for prostate cancer patients. *Acta Oncol* 48, 227–232.

[18] Zhang, P., Happersett, L., Hunt, M., Jackson, A., Zelefsky, M., & Mageras, G. (2010). Volumetric modulated arc therapy: planning and evaluation for prostate cancer cases. *Int J Radiat Oncol Biol Phys* 76, 1456–1462.

[19] Rao, M., Yang, W., & Chen, F., et al. (2010). Comparison of Elekta VMAT with helical tomotherapy and fixed field IMRT: plan quality, delivery efficiency and accuracy. *Med Phys* 37, 1350–1359.

[20] Kopp, R. W., Duff, M., Catalfamo, F., Shah, D., Rajecki, M., & Ahmad, K. (2011). VMAT vs. 7-field-IMRT: assessing the dosimetric parameters of prostate cancer treatment with a 292-patient sample. *Med Dosim* 36, 365–372.

[21] Hsu, F., Carolan, H., & Nichol, A., et al. (2010). Whole brain radiotherapy with hippocampal avoidance and simultaneous integrated boost for 1–3 brain metastases: a feasibility study using volumetric modulated arc therapy. *Int J Radiat Oncol Biol Phys* 76, 1480–1485.

[22] Wolff, D., Stieler, F., & Welzel, G., et al. (2009). Volumetric modulated arc therapy (VMAT) vs. serial tomotherapy, step-and-shoot IMRT and 3D-conformal RT for treatment of prostate cancer. *Radiother Oncol* 93, 226–233.

[23] Bedford, J. L. (2009). Treatment planning for volumetric modulated arc therapy. *Med Phys* 36, 5128–5138.

[24] Men, C., Romeijn, H. E., Jia, X., & Jiang, S. B. (2010). Ultrafast treatment plan optimization for volumetric modulated arc therapy (VMAT). *Med Phys* 37, 5787–5791.

[25] Bewes, J. M., Suchowerska, N., Jackson, M., Zhang, M., & McKenzie, D. R. (2008). The radiobiological effect of intra-fraction dose-rate modulation in intensity modulated radiation therapy (IMRT). *Phys Med Biol* 53, 3567–3578.

[26] Moiseenko, V., Duzenli, C., & Durand, R. E. (2007). In vitro study of cell survival following dynamic MLC intensity-modulated radiation therapy dose delivery. *Med Phys* 34, 1514–1520.

[27] Shaffer, R., Morris, W. J., & Moiseenko, V., et al. (2009). Volumetric modulated arc therapy and conventional intensity-modulated radiotherapy for simultaneous maximal intraprostatic boost: a planning comparison study. *Clin Oncol (R Coll Radiol)* 21, 401–407.

[28] Ost, P., Speleers, B., & De Meerleer, G., et al. (2011). Volumetric arc therapy and intensity-modulated radiotherapy for primary prostate radiotherapy with simultaneous integrated boost to intraprostatic lesion with 6 and 18 MV: a planning comparison study. *Int J Radiat Oncol Biol Phys* 79, 920–926.

[29] Sze, H. C. K., Lee, M. C. H., Hung, W., Yau, T., & Lee, A. W. M. (2012). RapidArc radiotherapy planning for prostate cancer: single-arc and double-arc techniques vs. intensity-modulated radiotherapy. *Med Dosim* 37, 87–91.