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ORIGINAL ARTICLE

The role of volumetric modulated arc therapy (VMAT) in gynaecological radiation therapy: A dosimetric comparison of intensity modulated radiation therapy versus VMAT

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Abstract

Introduction: For gynaecological cancers, volumetric modulated arc therapy (VMAT) offers comparable plan quality with shorter treatment delivery times when compared to intensity modulated radiation therapy (IMRT). **Methods:** The clinical IMRT plans of twenty gynaecological cancer patients were compared with a retrospectively generated VMAT plan. Planning target volume (PTV) metrics compared were D95 > 99%, homogeneity index, and conformity index. Organs at risk (OAR) doses compared were bladder V45 < 35%, bowel V40 < 30%, femoral head and neck (FHN) V30 < 50%, V44 < 35% and V44 < 5%. Plan quality was also assessed by comparing the monitor units (MU), treatment time and the patient-specific quality assurance results. **Results:** VMAT and IMRT resulted in comparable PTV coverage with D95 values of 98.92% ± 0.69% and 98.91% ± 1.43% respectively, and homogeneity index values of 0.08 ± 0.02 (VMAT) and 0.08 ± 0.03 (IMRT). The conformity index for VMAT was 0.93 ± 0.04 and IMRT 0.85 ± 0.06 (*P* < 0.001). For the bowel tolerance (40 Gy < 30%) VMAT resulted in 22.39% ± 12.5% compared to 28.8% ± 16.78% for IMRT, with bladder and FHN VMAT doses also lower. VMAT MU were 694.35 ± 126.56 compared to 606.8 ± 96.16 for IMRT (*P* < 0.01). Treatment times of 6.6 ± 0.82 min and 2.47 ± 0.35 min were achieved for IMRT and VMAT respectively. **Conclusion:** VMAT showed improvements in sparing OAR compared to IMRT. Target volume coverage with VMAT was equivalent or better than that of IMRT. These results in conjunction with the confirmed shorter treatment delivery time, have led to the development and implementation of a clinical protocol.

Introduction

Radiation therapy is routinely used in the role of primary and adjuvant therapy for gynaecological malignancies.[1–5] Commonly, the clinical target volume (CTV) for gynaecological malignancies include structures such as the gross tumour volume (GTV), cervix, uterus, parametria, vagina and regional lymph nodes.[6] Depending on disease staging, radiotherapy is used not only to treat the primary site of disease but also the pelvic lymph nodes at various levels. As a result, gastrointestinal and genitourinary tracts are often included in the irradiated volume.[7] The need to reduce dose to normal tissue and decrease the level of toxicity and morbidity while allowing dose escalation to the tumour volume, has motivated the implementation of modulated radiation therapy techniques for gynaecological cancers.[8]

Intensity modulated radiation therapy (IMRT) has been explored as a means to decrease doses to the organs at risk (OAR) while maintaining dose to the CTV. A number of retrospective dosimetric studies comparing IMRT to 3-dimensional conformal radiation therapy –

whole pelvic radiation therapy (3DCRT-WPRT) have shown significant reductions in the volume of small bowel, rectum, bladder and bone marrow receiving the prescribed dose.[9,10] However, a higher number of monitor units (MU) are delivered for IMRT compared to 3DCRT-WPRT, increasing treatment delivery times. Volumetric modulated arc therapy (VMAT) may be another approach to investigate improvement in these parameters.

VMAT, considered to be similar to IMRT was first described by Yu et al. in 1995.[11] It is capable of delivering radiation therapy with a multi-leaf collimator (MLC) which dynamically alters the shape of the treatment field while the gantry rotates around the patient. Step-and-shoot IMRT maintains a constant dose rate throughout the treatment; while VMAT has the potential to vary the dose rate enabling it to change the beam's intensity. As described by Bortfeld and Webb,[12] VMAT possesses the unique feature of delivering the whole treatment with only one rotation of the gantry and is therefore potentially faster than IMRT. Many authors have concluded that VMAT has an improved efficiency of delivery for equivalent dosimetric quality using fewer MU compared to 3DCRT and IMRT treatments.[13–15]

Whether VMAT with one single rotation is comparable to fixed field IMRT in the treatment of complex-shaped gynaecological target volumes is discussed in the literature. Stieler et al.[16] showed that VMAT provided treatment plans with high conformity and homogeneity compared to step-and-shoot-IMRT when treating complex mono-concave treatment volumes for anal cancers. As the planning target volume (PTV) for gynaecological malignancies is similar to that for anal malignancies it is beneficial to investigate whether VMAT could have a positive impact in their treatment. Cozzi et al.[7] conducted a planning study comparing VMAT with five field fixed IMRT in patients with cervical cancer. Their results showed similarities in coverage to the target volume, with VMAT plans producing improved conformity and homogeneity. The doses to OAR improved and there was a reduction in the integral dose by an average of 12% compared with IMRT.

Step-and-shoot IMRT for gynaecological cancers was implemented at Radiation Oncology Princess Alexandra Hospital – Raymond Terrace (ROPART) in 2011. With the clinical use of VMAT increasing in the department the implications of implementing VMAT for gynaecological cancers with respect to effective and efficient treatment strategies needed to be investigated. The aim of this study was to evaluate the dosimetric performance of VMAT for gynaecological cancers compared to step-and-shoot IMRT plans generated using the ROPART IMRT protocol. Specific aims of the study

were to determine if VMAT (1) improves healthy tissue sparing and doses to organs at risk; (2) maintains or improves the degree of PTV coverage; (3) significantly reduces the beam on time (treatment time) per fraction.

Method

Patient selection

Institutional ethics approval was granted to conduct a retrospective dosimetric comparison of IMRT and VMAT for twenty patients who had received curative treatment for gynaecological cancer using IMRT. Patients treated between 2011 and 2014 were included, specifically five for carcinoma of the cervix, thirteen for endometrial carcinoma and two with carcinoma of the uterus. All patients had undergone computed tomography (CT) simulation using a Somatom Sensation Open 20-slice scanner (Siemens Medical Solutions, Forchheim, Germany). Patients were positioned supine with indexed knee and feet stabilisation devices. Scans were acquired with 3 mm slice thickness covering the region from L3 to the proximal half of the femur's diaphysis. Patients were scanned following the departmental protocol for bladder and bowel preparation of a full bladder and empty rectum. CTVs were defined following the Radiation Therapy Oncology Group (RTOG) guidelines (Table 1) and a uniform 7 mm expansion margin used to create the PTV.[17] Planning was carried out using the department's IMRT protocol in the Pinnacle[3] version 9.4 (Philips Healthcare, Fitchburg, WI, USA) treatment planning system. All patients were treated on Clinac iX (Varian Medical Systems, Palo Alto, USA) linear accelerators.

Planning techniques

IMRT

The step-and-shoot IMRT optimisation was performed using the direct machine parameter optimization (DMPO) algorithm in Pinnacle[3]. For each plan, 8 coplanar beams were used at gantry angles of 155, 100, 60, 20, 340, 300, 260 and 205°. Collimator angle was set at 0°. A maximum number of segments of 144 (18 per beam), minimum segment area of 6 cm^2 and a minimum of 5MU per segment was applied to each plan. The collapsed cone algorithm with a dose grid of $0.25 \times 0.25 \times 0.25$ mm was used for dose calculation. The prescribed dose was 50.4 Gy in 28 fractions or 45 Gy in 25 fractions. All plans were for a single volume PTV. The planning goals as per the department's gynaecological IMRT protocol (see Table 2) were applied initially and

Table 1. RTOG consensus clinical target volume for adjuvant (postoperative) radiotherapy for cervical and endometrial cancer.

Target Site	Definition
Common iliac lymph nodes	From 7 mm below L4–L5 interspace to level of bifurcation of common iliac arteries into external and internal iliac arteries
External iliac lymph nodes	From level of bifurcation of common iliac artery into external artery to level of superior aspect of femoral head where it becomes femoral artery
Internal iliac lymph nodes	From level of bifurcation of common iliac artery into internal artery, along its branches (obturator, hypogastric) terminating in paravaginal tissues at level of vaginal cuff
Upper vagina	Vaginal cuff and 3 cm of vagina inferior to cuff
Parametrial/ paravaginal tissue	From vaginal cuff to medial edge of internal obturator muscle/ischial ramus on each side
Presacral lymph nodes[1]	Lymph node region anterior to S1 and S2

[1]If patient has cervical cancer or endometrial cancer with cervical stromal invasion.

priorities adjusted during optimisation to achieve desired clinical outcomes specific to each patient.[18] Note for the OARs, critical structure constraints follow RTOG 1203 guidelines (See Table 3).[17]

VMAT

The same CTV, prescription and planning goals used for the clinical IMRT plan were used to generate the VMAT plans in Pinnacle[3]. In order to achieve the desired level of modulation, a beam model was enabled to continuously vary the dose rate as well as the gantry rotational speed. Maximum gantry rotation speed was set at 4.8° per sec. The maximum jaw speed was set at 2 cm/sec and the maximum MLC speed was set to 2.25 cm/sec. The VMAT plans were calculated with the collapsed cone convolution dose engine and a dose grid resolution of $0.25 \times 0.25 \times 0.25$ mm. Dose rate and gantry speed were set to variable 0–600 MU/min and 0.5–4.8° per sec. MU constraints were set with a maximum gantry MU delivery of 20 MU per °, minimum gantry MU delivery

Table 2. Planning goals for the IMRT gynaecological protocol.

Region of interest	Dose
Bowel (may include small ± large)	V40 < 30%
Rectum	V40 < 80%
Bladder	V45 < 35%
Femoral heads and necks	V30 < 50%
	V40 < 35%
	V44 < 5%
Kidneys if required (individually reported)	V18 < 2/3

Table 3. RTOG 1203 organ at risk constraint guidelines.

Organ at risk	Avoidance doses
Bowel	Per protocol: Up to 30% receives 40 Gy
Rectum/rectal wall	Per protocol: Up to 80% receives 40 Gy
Bladder	Per protocol: Up to 35% receives 45 Gy
Femoral heads and necks	No more than 50% above 30 Gy
	No more than 35% above 40 Gy
	No more than 5% above 44 Gy

of 0.2 MU per ° and minimum MLC MU delivery set at 0 MU per cm.

To determine a class solution for comparing with the IMRT plans, three separate trials were conducted on each patient's dataset; single arc with gantry rotation from 184 to 176°, dual arcs (DA) with gantry rotation from 184 to 176° and 176 to 184° or twin arcs (TA) with gantry rotation from 184 to 176° and 176 to 184°. A DA is where one beam is created prior to optimisation and a second arc created during optimisation. A TA is where two beams are created prior to optimisation. All arcs were optimised with a gantry spacing of 4°. To reduce the contribution of tongue and groove effect during the arc rotation and to maximise possible leaf trajectories non-coplanar to the patient's axis, the collimator rotation remains fixed to a value different from zero. Varying collimator angles of 10, 15, 20 and 35° were trialled and evaluated for plan conformity and with respect to MLC leaf travel constraints.

Dosimetric comparison

For the PTV the volume receiving 95% of the prescribed dose (V95%) was compared for the IMRT and VMAT plans. The degree of conformality of the plans was measured using a conformity index, $CI_{95\%}$, represents the product of two ratios- the ratio of V95 to the PTV volume and the ratio of V95 to the volume enclosed by the 95% isodose (see eq. 1).[19] The ideal value for the conformity index is equal to 1 where the 95% isodose is exactly equal to the PTV in shape, volume and position.

$$CI_{95\%} = \frac{TV_{RI}}{TV} \times \frac{TV_{RI}}{V_{RI}} \qquad (1)$$

TV = target volume

TVRI = target volume covered by the reference isodose (RI) which is 95% of the prescription dose

VRI = volume of reference isodose

The homogeneity of treatment was expressed in terms of the difference between the dose covering the 2 and 98% of the PTV (D2% – D98%). It is divided by the dose received by 50% of the PTV in order to determine
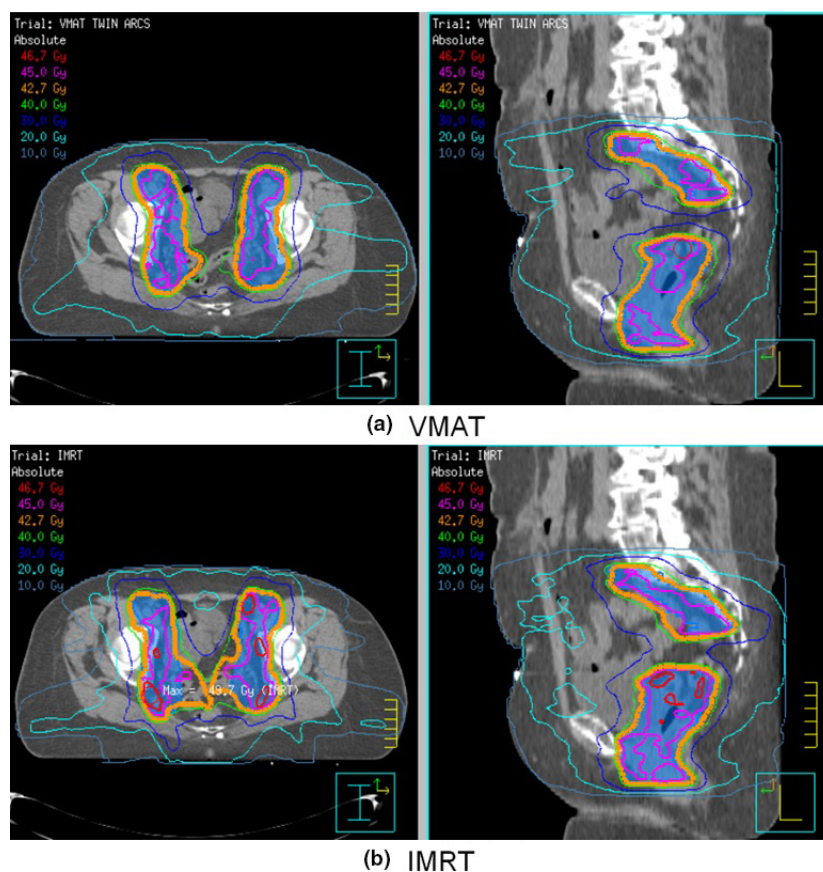
Figure 1. Dose distribution in a typical transverse and sagittal slice for VMAT compared to IMRT. (A) IMRT (B) VMAT PTV45 is shown by the light blue shaded area; the 95% isodose curve is shown by the thick orange line. The purple and red lines represent 100% of the reference dose and Dmax dose respectively. Dmax, maximum dose.

the homogeneity value (see eq. 2). An ideal value of 0 represents complete homogeneity within the PTV.

$$HI = \frac{PTV\ D2\% - PTV\ D98\%}{PTV\ D50\%} \quad (2)$$

Plan quality was assessed by comparing the means of variables generated from the IMRT and VMAT plans. A Shapiro-Wilk test was performed for each variable for the IMRT and VMAT to test the assumption of normality. If a variable was normally distributed for both the IMRT and VMAT data, then a paired *t*-test was chosen to compare the means, otherwise a Wilcoxon signed-rank test was chosen. Additionally, three radiation oncologists also reviewed the VMAT plans alongside the IMRT plans, with respect to clinical acceptability.

Evaluation of plan delivery

Treatment delivery times were measured in the quality assurance mode of the MOSAIQ Oncology Information System (Elekta, Stockholm, Sweden) where treatment fields were scheduled in the automatic field sequencer. The doses delivered were measured using the EPIQA EPIdos, Bratislava, Slovakia) dosimetry system. The system allows a dosimetric image acquired by an EPID to be converted into a dose map and then compared with the reference dose distribution for patient-specific QA.

Results

Dosimetric comparison

It became evident in the early stages of the study that the single arc dosimetry was significantly inferior to the conventional 8 field step-and-shoot IMRT plans. The decision was therefore made to cease dose calculations and eliminate these results from the study. It was found that the DA optimisation approach increased the level of modulation during optimisation. However, one of the arcs will give a greater MU to dose ratio compared to

**Table 4.** IMRT versus VMAT dosimetric comparison.

	Tolerance	IMRT	VMAT	*P*-value
PTV 95% reference Dose coverage	–	98.91% ± 1.43%	98.92% ± 0.69%	0.950
Conformity index	–	0.85 ± 0.06	0.93 ± 0.04	<0.001
Homogeneity index[1]	–	0.08 ± 0.03	0.081 ± 0.02	0.575
Integral dose	V30[1]	1743.51 ± 591.90 cc	1300.07 ± 454.10 cc	<0.001
	V20[1]	5074.04 ± 1424.45 cc	4548.8 ± 1072.15 cc	0.003
	V10[1]	9208.91 ± 2263.86 cc	9384.59 ± 2381.71 cc	0.155
Treatment delivery time	–	6.6 ± 0.82 min	2.47 ± 0.04 min	<0.001
Monitor units[1]	–	606.8 ± 96.16	694.35 ± 126.56	0.009
Bowel	V40 < 30%	28.8% ± 16.78%	22.39% ± 12.50%	0.057
	V30[1]	47.27% ± 16.25%	37.66% ± 15.98%	<0.001
	V20	77.91% ± 12.74%	71.96% ± 14.38%	<0.001
Rectum	V45 < 60%[1]	44.9% ± 29.65%	40.67% ± 26.12%	0.064
Bladder	V45 < 35%[1]	50.11% ± 25.82%	46.96% ± 24.85%	0.090
Left femoral head and neck	V30 < 50%	11.62% ± 7.56%	7.47% ± 5.17%	0.011
Right femoral head and neck	V30 < 50%	10.38% ± 6.74%	6.66% ± 4.35%	0.010

[1]Normally distributed.

the other. The TA optimisation approach on the other hand was found to generally result in two arcs with a similar MU to dose ratio and produce similar segments around the arc. The isodose distribution shown in Figure 1 provides a visual comparison of the DA and TA techniques. Comparable results were acquired for all data sets used in the trial. For the 20 patient data sets used all plans, DA and TA, passed dosimetric review by the same three oncologists specialising in gynaecological cancer. For the basis of this study all results shown are for the TA technique. This technique has a 35° collimator angle which provided the most consistent

dosimetric results when taking into consideration the large nodal volumes, the beam shaping required to achieve small bowel dose objectives and the MLC leaf travel constraints.

The results of the dosimetric comparison between IMRT and TA with 35° collimator angle VMAT techniques are shown in Table 4 and in Figures 2–7. There was no significant difference in the mean D95% and HI values for PTV between the two techniques ($P = 0.2176$) however the CI was significantly higher for the VMAT plans ($P < 0.001$). On average the doses to all of the OARs were lower for the VMAT plans.
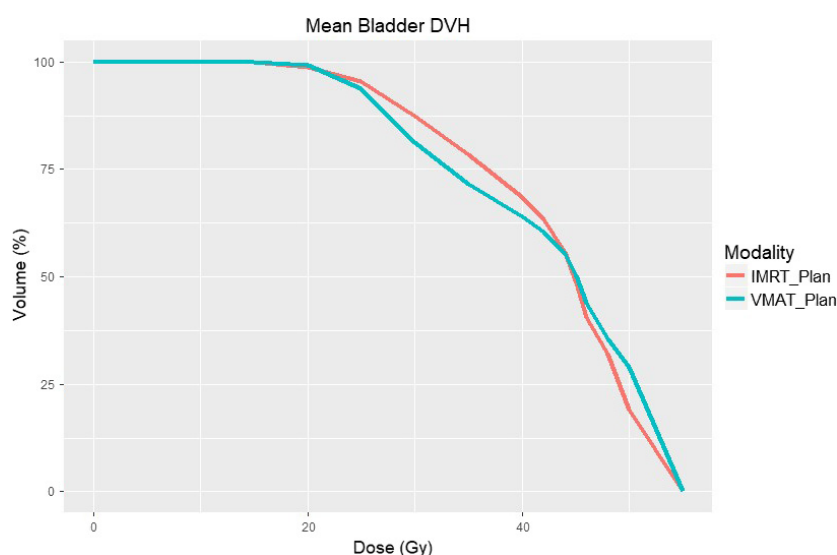
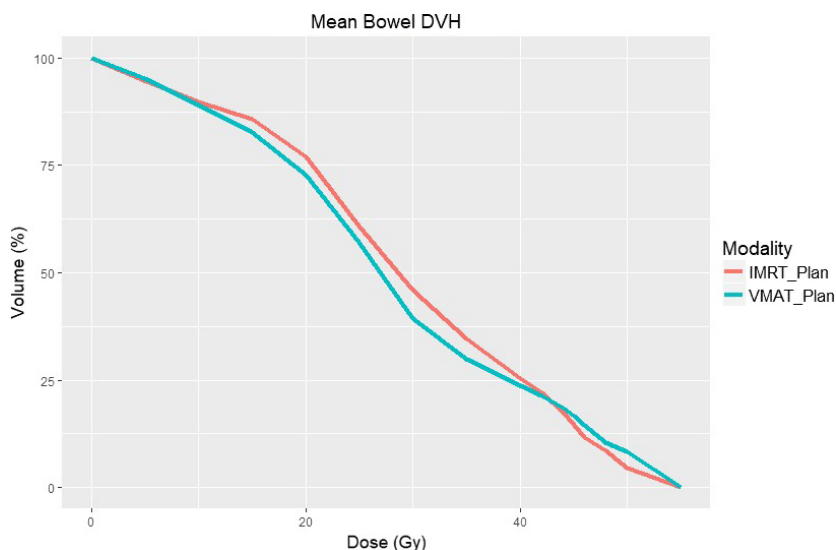**Figure 2.** Mean bladder DVH comparison between IMRT and VMAT.

Figure 3. Mean bowel DVH comparison between IMRT and VMAT.

Figures 2–7 illustrate the dosimetric differences between IMRT and VMAT for the mean doses of the PTVs and OARs. Comparison of the means of the volume of the 20 and 30 Gy isodose lines showed they were significantly smaller for the VMAT plans, $P = 0.003$ and $P < 0.001$ respectively. However, the volume of the 10 Gy isodose line was smaller for the IMRT plans ($P = 0.155$). There was no significant difference in the MU ($P = 0.093$), however VMAT treatment delivery times were significantly faster ($P < 0.001$).

Evaluation of plan delivery

Absolute dosimetric measurements for 5 of the 20 patient datasets were analysed using a gamma pass rate of 90% or greater for 3%/3 mm as the benchmark. From the results in Table 5 it can be observed that for VMAT arcs (TA), the average pass rate was consistently above 98%. IMRT results showed each patient plan had an average pass rate of greater than 97%. Although the IMRT plans showed higher pass rates in relation to the tolerance level of 90%, it is evident that VMAT can
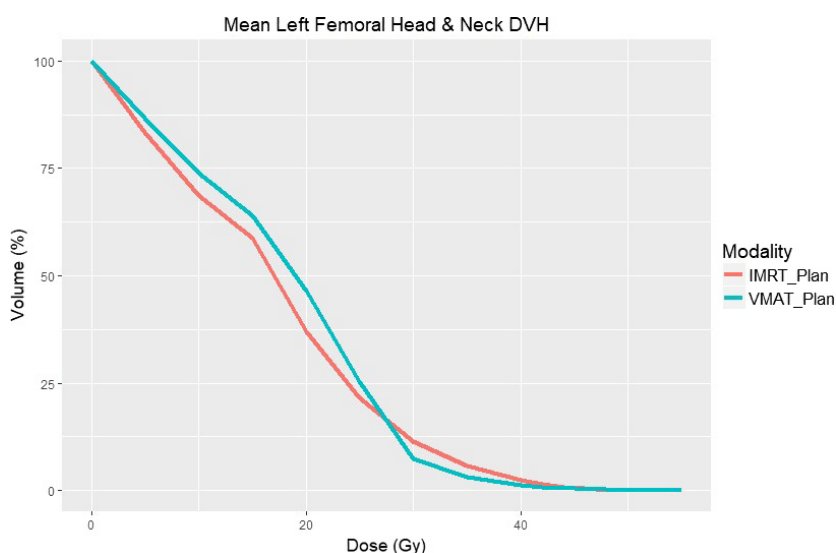

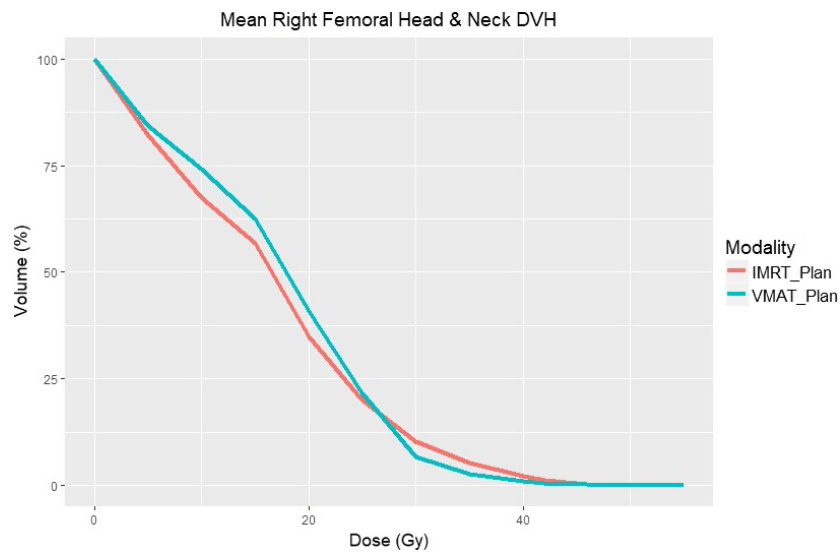**Figure 4.** Mean left femoral head and neck DVH comparison between IMRT and VMAT.

Figure 5. Mean right femoral head and neck DVH comparison between IMRT and VMAT.

Discussion

This study found that PTV coverage and homogeneity was similar for IMRT and VMAT while plan conformity, bowel dose and treatment delivery times were significantly improved with the TA VMAT plans. Literature shows there a limited dosimetric studies comparing fixed field IMRT to VMAT in gynaecological malignancies. Cozzi et al.[7] concluded that DA VMAT is better than IMRT for gynaecological malignancies. In comparison to IMRT, which has been proven to be superior to conventional 3DCRT,[20–24] VMAT displayed a reduction to dose to bladder, bowel and rectum and achieved better PTV coverage with improved conformity and homogeneity.[7] Deng et al.[25] showed no significant differences between OAR doses but better dose conformity, slightly less MU and shorter delivery times with VMAT. Guy et al.[26] showed VMAT results with shorter treatment delivery times, and reduced MU, while maintaining a conformity index similar to that of IMRT.
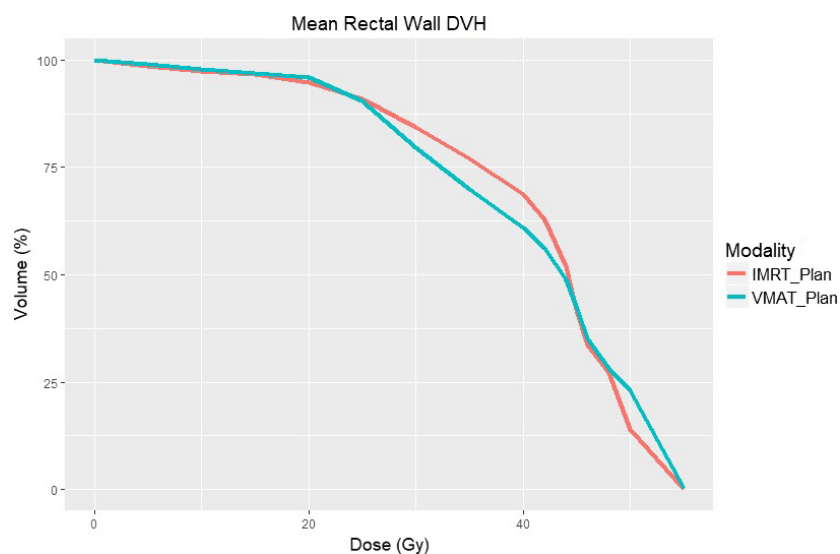
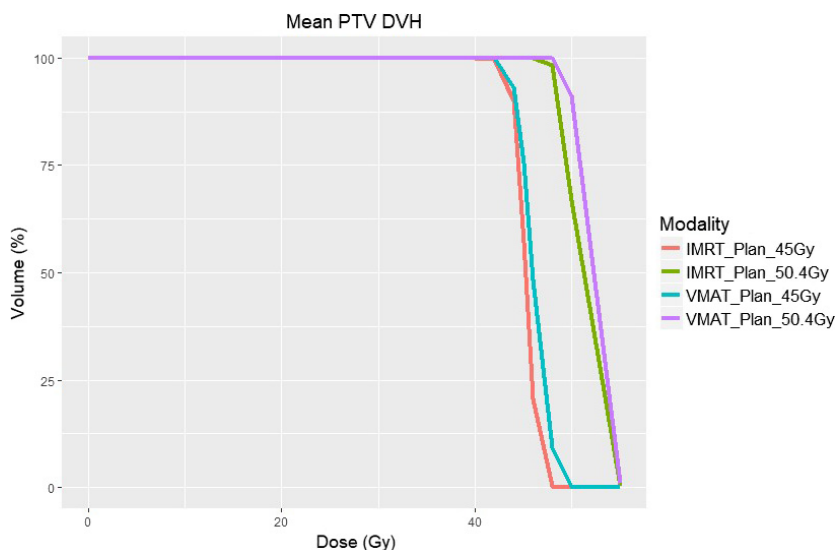**Figure 6.** Mean rectal wall DVH comparison between IMRT and VMAT.

Figure 7. Mean PTVs (50.4 Gy and 45 Gy) DVH comparison between IMRT and VMAT.

This study focused on the clinical performance of VMAT using Pinnacle[3] version 9.4 SmartArc, comparing 8 field step-and-shoot IMRT with single, DA and TA VMAT. The details regarding the planning algorithm have been described by Bzdusek et al.[27] Evidence showed in the early stages of this study that the single arc dosimetry was significantly inferior to the 8 field step-and-shoot IMRT. The decision was made to cease dose calculations and eliminate these results from the study. Initial study data included both dual and twin arcs with the first arc from 184 to 176° and the second arc counter clockwise from 176 to 184°, with gantry spacing set at 4°. While the gamma pass rates are very similar dosimetric quality assurance revealed differences between the two modalities. The DA technique revealed one of the arcs delivering a greater MU per Gy ratio to the PTV, while the TA technique produced a similar MU per Gy ratio. The use of two arcs revealed clinically comparable target volume coverage and improved dose sparing to all organs at risk. To allow maximum modulation per arc, no limitation on the beam delivery time was used during optimization. A further consequence of plan delivery evaluation was for clinical plans to have a final dose computation with gantry spacing of 2°. Continuous gantry motion, dose-rate variation and MLC motion were all used to obtain a better quality plan while using the highest degree of modulation.

The Varian Clinac iX (Varian Medical Systems, Palo Alto, USA) linear accelerators require a 0.5 mm leaf gap as per manufacturer recommended limits to prevent MLC collision. With the Pinnacle[3] machine model set at 0 mm leaf gap for 3DCRT and IMRT techniques, a separate VMAT machine model was established. Field size limitations to the EPIQA system that allows a dosimetric image acquired by an EPID to be converted into a dose map and then compared with the reference dose distribution for patient-specific QA meant maximum field sizes for the X and Y jaws needed to be considered. Due to these constraints maximum jaws sizes for Y jaws = 19 cm and X jaws = 14 cm or Y jaws = 14 cm and X jaws = 19 cm.

When comparing MU per fraction there was a statistically significant difference between the IMRT and VMAT plans ($P = 0.0093$). The mean MU for IMRT and VMAT were 606.8 ± 96.16 and 694.35 ± 126.56 respectively. Studies show that RapidArc users have reported very large reductions of more than 600 MU per fraction.[1, 9, 28, 29] However these differences in MU may be related to the different optimization algorithms and techniques used (sliding windows or step-and-shoot).[30]

Table 5. Absolute dosimetric measurement gamma pass rates for the different IMRT and VMAT plans.

Patient	Absolute dosimetric measurement		
	VMAT TA arc 01 (%)	VMAT TA arc 02 (%)	IMRT (All fields) (%)
1	99.97	99.88	98.8
2	99.85	99.83	100
3	99.71	99.34	99.93
4	99.51	99.75	97.5
5	98.88	99.2	99.25

TA, twin arcs.

Treatment delivery or beam on times were measured with the treatment fields scheduled in the QA mode of the record and verify system. VMAT possess the capabilities to deliver treatments in a much shorter time frame compared to that of IMRT. The actual beam on time of IMRT is significantly higher (6.6 ± 0.82 min) due to the 8 field beam arrangement, time taken to position the gantry and the mode up of the Clinac for each treatment beam. The reduction in treatment delivery/beam on time for VMAT 2 arcs (2.47 ± 0.035 min) is clinically relevant with regard to intra-fraction motion and patient compliance.

Conclusion

SmartArc produced VMAT plans, when compared to the clinically applied IMRT plans indicated equal or better PTV coverage and based on these results, provided more highly conformal treatment plans. While not all planning objective values for OAR resulted in significant reduction with VMAT, the results were still comparable between the two techniques. VMAT is able to reduce the amount of normal, healthy tissue receiving 30 and 20 Gy, while maintaining the volume receiving 10 Gy. These results in conjunction with the confirmed delivery efficiency in relation to reduced beam-on-time show VMAT plans are dosimetrically applicable when compared to step-and-shoot IMRT.

Acknowledgements

Conflict of Interest

The authors declare no conflict of interest.

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