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# Dosimetric dependence on the collimator angle in prostate volumetric modulated arc therapy

**Muhammad Isa[1,2], Jalil ur Rehman[1,3], Muhammad Afzal[1], James C L Chow[2,4]**

[1]*Department of Physics, The Islamia University of Bahawalpur, Bahawalpur, Pakistan*
[2]*Radiation Medicine Program, Princess Margaret Cancer Center, Toronto, Canada*
[3]*Department of Radiation Physics, UT MD Anderson Cancer Center, Houston, USA*
[4]*Department of Radiation Oncology, University of Toronto, Toronto, Canada*

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## Abstract

**Purpose:** The purpose of this study is to investigate the dose-volume variations of planning target volume (PTV) and organs-at-risk (OARs) in prostate volumetric modulated arc therapy (VMAT) when varying collimator angle. The collimator has the largest impact and is worth considering, so, its awareness is essential for a planner to produce an optimal prostate VMAT plan in a reasonable time frame. **Methods**: Single-arc VMAT plans at different collimator angles (0°, 15°, 30°, 45°, 60°, 75° and were created systematically using a Harold heterogeneous pelvis phantom. The conformity index (CI), homogeneity index (HI), gradient index (GI), machine monitor units (MUs), dose-volume histogram and mean and maximum dose of the PTV were calculated and analyzed. On the other hand, the dose-volume histogram and mean and maximum doses of the OARs such as the bladder, rectum and femoral heads for different collimator angles were determined from the plans. **Results:** There was no significant difference, based on the planned dose-volume evaluation criteria, found in the VMAT optimizations for all studied collimator angles. A higher CI (0.53) and lower HI (0.064) were found in the 45° collimator angle. In addition, the 15° angle provided a lower value of HI similar to the 45° collimator angle. Collimator angles of 75° and 90° were found to be good rectum sparing, and collimator angles of 75° and 30° were found to be good for sparing of right and left femur, respectively. The PTV dose coverage for each plan was comparatively independent of the collimator angle. **Conclusion:** Our study indicates that the dosimetric results provide support and guidance to allow the clinical radiation physicists to make careful decisions in implementing suitable collimator angles to improve the PTV coverage and OARs sparing in prostate VMAT.

**Keywords:** VMAT; Dose-Volume Histogram; Collimator Angle; Organs-At-Risk

## Introduction

Volumetric modulated arc therapy (VMAT) has become a standard delivery option in the field of prostate radiotherapy, due to its shortened delivery time and the smaller monitor units (MUs), as compare to step-and-shoot intensity modulated radiotherapy (IMRT).[1-6] Patient dosimetry between prostate VMAT and IMRT has been extensively studied, which reveals that prostate VMAT can produce comparable or even improved target coverage and normal tissue (bladder, rectum and femoral heads) sparing.[7-11]

VMAT encloses more dose delivery parameters such as dynamic multileaf collimator movement, dose rate, and gantry speed with single or multiple photon arcs in the treatment,[12-15] which requires a more powerful machine, patient quality assurance procedures, dose calculation algorithm, and dosimetric evaluation for the treatment.[16-19]

Until the availability of the Elekta linear accelerator VMAT in 2008[20], the only commercially available treatment planning system (TPS) was ERGO++ (3D Line Medical Systems/ Elekta Ltd, Crawley, UK), which needed an initial definition of sub-arcs and had manual version of the multileaf collimator (MLC) before automatic weight optimization and was not considered a full inverse planning system.[11, 21 ,22] In December 2009, two manufacturers introduced a new system of VMAT delivery that employed a VMAT treatment planning tool, implemented in Oncentra with Master-plan v3.3 (Nucletron BV, Veenendal, The Netherlands) with VMAT application on a Synergy linac (Elekta Ltd, Crawley, UK). Initially, the Synergy linac was used for a limited number of patients.[8, 23]

RapidArc (Varian Medical Systems, Palo Alto, CA) is a VMAT technique delivering radiation dose over one or several continuous arcs with the simultaneous adjustment of

Corresponding author: James C L Chow; Department of Radiation Oncology, University of Toronto, Toronto, Canada.

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dose rate, gantry rotation speed, and multi-leaf collimator (MLC) field aperture. RapidArc has gained enormous interest because of its potential in delivering quality dose distribution with significantly shortened treatment time and lower number of MU. Several recent studies have reported the use of arc-based radiation dose delivery methods in prostate cancer.[5, 7, 11, 24-26]

Multileaf collimators (MLC) are the best tool for beam shaping, and an important way to minimize the absorbed dose to healthy tissue and critical organs. They have moveable leaves arranged in pairs that can block a certain part of beam. Owing to its ability to control leaf position and with a large number of controlled leaves, it can be used to shape any desired field.[27] Its manufacturers have established the necessary mechanisms for precision, control and reliability, together with reduction of leakage and transmission of radiation between and through the leaves. Moreover, it provides precise dose delivery to any part or the treated volume, accurately.[28] Otto has stated[3] and later on approved[29] that a 45° collimator angle is feasible dosimetrically in most cases. While, Bortfield *et al.*[29] found that the superiority of the above collimator angle (45°) was ambiguous. Furthermore, Bortfield and Webb did their work with a 0° collimator angle for a 2D model.[30]

Treutwein *et al.*[31] concluded that the approximation was still effective for 4° gantry spacing and same passing rates were found for IMRT. The work of Feygelman *et al.*[32] and Bzdusek *et al.*[4] revealed that good dosimetric results were found with minimum calculation time for 4° gantry spacing. So, for the best maximum dose to the PTV and for good dosimetric results 4° gantry spacing was used in this study.

For this collimator angle analysis, in addition to dosimetry (dose-volume criteria, mean and maximum dose), CI, HI, GI and MU, comparison among different collimator angles such as 0°, 15°, 30°, 45°, 60°, 75° and 90° for smart-arc VMAT have been scrutinized. The aim of this study is to find the best collimator angle for coverage of the PTV and sparing of OARs. The results of this study will help to inform planners in choosing the appropriate collimator angle.

# Methods and Materials

## Planning schemes

This study was established in order to compare dose distribution among different collimator angles (0°, 15°, 30°, 45°, 60°, 75° and 90°) focusing on the PTV and OARs. For each change of collimator angle, a new plan was re-optimized for that angle. The prescription dose was 78 Gy per 39 fractions. The treatment plan was not changed for each angle, only repeated by changing the collimator angles. The prostate Harold phantom developed by Chiarot *et al.*[33] was used for this study. Computed tomography (CT) images (2 mm slice thickness and slice interval) were taken from the Toshiba scanner (Aquilion ONE TSX-301A; Toshiba medical systems, USA) containing 512 × 512 pixels in each slice. The Harold phantom was irradiated by a 120 kV photon beam with 300 mA current perpendicular to the phantom surface. After the CT simulation, digital imaging and communication in medicine (DICOM) CT images were transferred to the Pinnacle treatment planning system (TPS) for contouring and planning preparation.

The rectum, bladder, PTV, and femoral heads were contoured on the TPS. The whole prostate was assigned as gross tumor volume (GTV). The PTV was drawn by expanding 1 cm around the CTV in all directions uniformly except in the posterior direction, where an expansion of 0.7 mm was performed for a total contoured volume of 85.89 $cm^3$. The bladder, rectum, and femoral heads have contoured volumes of 59.83 $cm^3$, 36.26 $cm^3$ and 166 $cm^3$, respectively.

## VMAT plan and treatment delivery

For planning the data, a Synergy S® linear accelerator with energy of 6 MV, equipped with beam modulator head, an iViewGT electronic portal imaging device, and on board cone beam CT XVI was used for VMAT delivery. There were no moveable jaws and the maximum field size was 16 cm × 21 cm. Maximum variable dose rate for each VMAT plan was 600MU/min and the gantry was rotated from 180 to 179.9 in the clockwise direction with 91 control points.

Smart-arc prostate VMAT plans were generated on Pinnacle (Philips, Version 9.2.0, Fitchburg, WI, U.S.A) with AC-QSim3™ and were optimized with the direct machine parameter optimization (DMPO) algorithm. The isocenter was positioned at the center of the CTV and plans were set up in 39 fractions for 78 Gy minimum doses to the CTV. All calculations were performed using adaptive convolve (AC) having a calculation grid spacing of 0.25 cm. In order to make fair comparisons, no modification was done throughout the optimization to the dose-volume constraints and weighting.

## Dosimetric evaluation

The dosimetric comparison was carried out using the following parameters such as $D_{99\%}$, $D_{95\%}$, $D_{5\%}$, maximum dose ($D_{max}$), mean dose ($D_{mean}$), Conformity Index (CI), Homogeneity Index (HI), Gradient index (GI) and MUs for the PTV for collimator angle as shown in Table 1.

By definition, RTOG CI (98) is the volume of the target receiving > 98% of the prescribe dose divided by the volume of the PTV which has optimal value of 1. HI is defined as the dose received by 5% of the PTV minus the dose received by 95% of the PTV divided by the mean dose (its optimal value is 0) as shown in Equation (1).[34]

$$HI = \frac{D_{5\%} - D_{95\%}}{D_{mean}} \quad \ldots\ldots\ldots\ (1)$$

GI is defined as the ratio of volume covered by at least a given percentage of the prescription dose.[35] Mathematically, GI in this study is expressed in (2) as:

$$GI = \frac{V_{50}}{V_{100}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

where, $V_{50}$ is the volume covered by the at least 50% of the prescription dose. A value closer to unity embodies a faster dose fall-off in normal tissue, which may indicate a lower dose to critical structure.

### Dose-volume histogram (DVH) evaluation

Dose-volume histogram plots were used to provide quantitative comparisons among the VMAT plans using the different collimator angles. Considerable attention should be placed on ensuring an unbiased comparison for successive computation of numerous indices. The DVHs data for each collimator angle was gathered from Pinnacle with a bin size of 0.01 Gy. PTV and organ specific individual DVHs for each collimator angles were calculated.

## Results

This study has been carried out on a Harold phantom and clinically acceptable VMAT plans satisfying a minimum of 99% prescribed coverage to PTV were achieved. Mean doses for all collimator angles were found between 75.96 (Gy) and 76.42 (Gy). The values of CI for all collimator angles are summarized in **Table 1** revealing that a 45° collimator angle is closer to unity than any other studied collimator angles. A collimator angle of 0° requires fewer MUs while 75° and 90° collimator angles require the most MUs. The highest HI values were established for a 60° collimator angle whereas we found lower values for 45° and 15° angles. It was found that a 30° collimator angle showed as lower GI value of GI that was closer to unity while higher values were found at 0° collimator angle. Figure 1 showes Dose distribution at collimator 90.

**TABLE 1:** Dosimetric results for PTV for all collimator angles.

| Collimator angles | 0° | 15° | 30° | 45° | 60° | 75° | 90° |
|---|---|---|---|---|---|---|---|
| $D_{99\%}$ (Gy) | 72.41 | 72.59 | 72.40 | 72.60 | 72.40 | 72.61 | 72.73 |
| $D_{5\%}$ (Gy) | 78.44 | 78.44 | 78.79 | 78.55 | 78.96 | 78.86 | 78.40 |
| $D_{95\%}$ (Gy) | 73.47 | 73.50 | 73.38 | 73.63 | 73.34 | 73.71 | 73.58 |
| $D_{max}$ (Gy) | 79.40 | 79.24 | 79.89 | 79.87 | 79.62 | 80.41 | 79.40 |
| $D_{mean}$ (Gy) | 76.20 | 76.25 | 76.28 | 76.38 | 76.24 | 76.42 | 75.96 |
| CI | 0.49 | 0.51 | 0.51 | 0.53 | 0.48 | 0.52 | 0.37 |
| HI | 0.06 | 0.064 | 0.07 | 0.064 | 0.073 | 0.065 | 0.066 |
| GI | 7.9 | 7.6 | 4.97 | 5.5 | 5.7 | 5.4 | 9.4 |
| MUs | 351 | 352 | 365 | 356 | 362 | 364 | 366 |

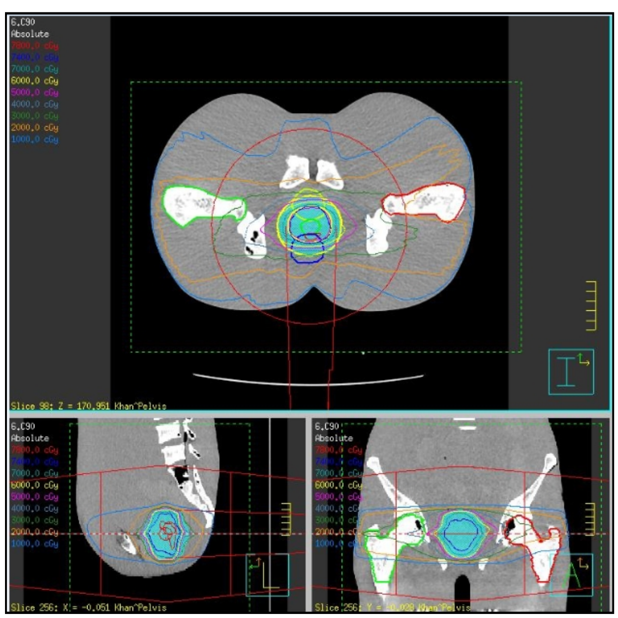

**FIG. 1:** Dose distribution at collimator 90.

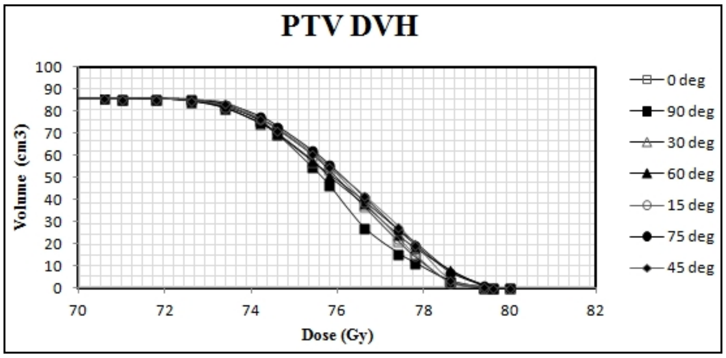


**FIG. 2:** Average dose-volume histogram of the PTV.

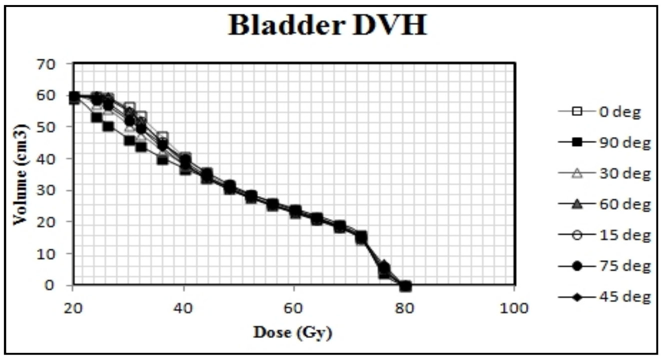


**FIG. 3(a):** Average dose-volume histogram of the bladder.

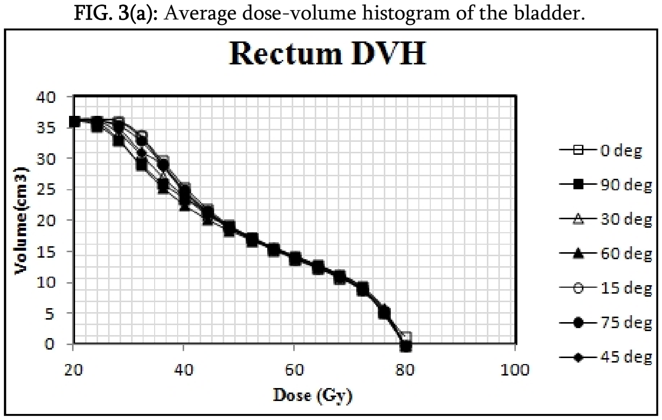


**FIG. 3(b):** Average dose-volume histogram of the rectum.

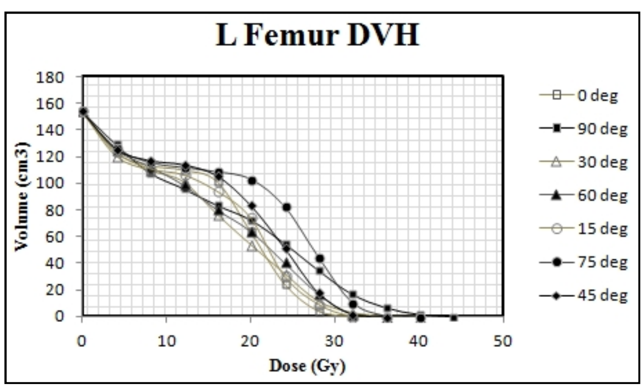


**FIG.4(a):** Average dose-volume histogram of the Left femur.

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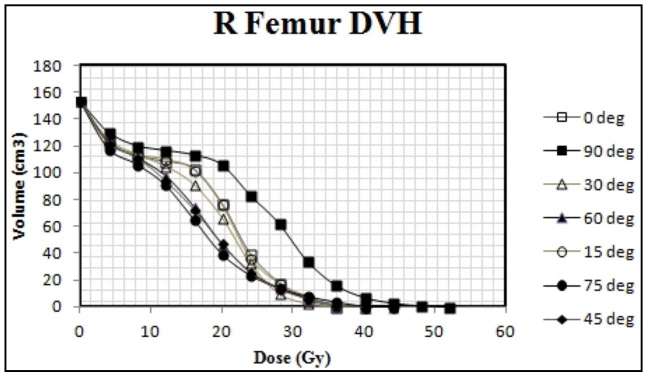


**FIG. 4(b):** Average dose-volume histogram of the right femur.

**TABLE 2:** Mean dose-volume criteria, average mean and maximum doses of the critical organs for VMAT plans at different collimator angles. $V_{30Gy}$, $V_{38Gy}$, $V_{14Gy}$, and $V_{22Gy}$ are percentage volume receiving at least 30 Gy, 38 Gy, 14 Gy, and 22 Gy, respectively. $D_{50\%}$, $D_{30\%}$, $D_{5\%}$ are the doses given to 50%, 30% and 5% of the volumes, respectively.

| Collimator angles | 0° | 15° | 30° | 45° | 60° | 75° | 90° |
|---|---|---|---|---|---|---|---|
| Rectum | | | | | | | |
| $D_{mean}$ (Gy) | 53.69 | 53.56 | 52.59 | 53.62 | 52.05 | 53.61 | 52.29 |
| $D_{max}$ (Gy) | 79.13 | 79.09 | 79.77 | 79.87 | 79.62 | 79.92 | 79.12 |
| $D_{50\%}$ (Gy) | 50.29 | 50.09 | 49.66 | 49.97 | 49.17 | 50.07 | 50.35 |
| $D_{30\%}$ (Gy) | 68.33 | 68.39 | 68.07 | 69.14 | 68.93 | 68.66 | 69.25 |
| $V_{30Gy}$ (%) | 36.26 | 36.26 | 36.22 | 36.26 | 36.19 | 36.26 | 35.64 |
| $V_{38Gy}$ (%) | 35.43 | 35.96 | 33.07 | 35.3 | 31.69 | 34.76 | 31.67 |
| Bladder | | | | | | | |
| $D_{mean}$ (Gy) | 53.08 | 52.47 | 51.59 | 51.99 | 52.37 | 52.49 | 50.69 |
| $D_{max}$ (Gy) | 78.73 | 78.58 | 79.36 | 78.24 | 79.47 | 78.96 | 78.63 |
| $D_{50\%}$ (Gy) | 50.40 | 49.33 | 49.31 | 48.92 | 48.69 | 50.59 | 50.00 |
| $D_{30\%}$ (Gy) | 69.02 | 68.74 | 68.93 | 69.15 | 68.41 | 69.46 | 70.16 |
| $V_{30Gy}$ (%) | 59.84 | 59.69 | 58.12 | 59.53 | 59.84 | 57.31 | 54.40 |
| $V_{38Gy}$ (%) | 54.24 | 55.48 | 51.22 | 50.43 | 52.56 | 40.51 | 44.43 |
| Left Femur | | | | | | | |
| $D_{mean}$ (Gy) | 16.06 | 16.20 | 15.19 | 18.06 | 16.12 | 20.34 | 17.75 |
| $D_{max}$ (Gy) | 31.63 | 32.42 | 37.46 | 34.42 | 35.17 | 37.32 | 45.89 |
| $D_{5\%}$ (Gy) | 27.13 | 28.32 | 29.27 | 29.86 | 30.05 | 32.50 | 35.54 |
| $V_{14Gy}$ (%) | 105.66 | 108.19 | 105.07 | 114.8 | 103.8 | 112.8 | 99.5 |
| $V_{22Gy}$ (%) | 95.65 | 91.40 | 69.20 | 100.98 | 75.18 | 107.64 | 80.02 |
| Right Femur | | | | | | | |
| $D_{mean}$ (Gy) | 17.32 | 17.34 | 16.33 | 14.92 | 15.14 | 14.33 | 22.73 |
| $D_{max}$ (Gy) | 37.06 | 39.05 | 40.62 | 40.08 | 40.80 | 43.55 | 54.14 |
| $D_{5\%}$ (Gy) | 31.04 | 32.14 | 28.88 | 31.17 | 31.31 | 32.27 | 39.74 |
| $V_{14Gy}$ (%) | 108.68 | 111.12 | 107.56 | 100.17 | 102.69 | 95.87 | 117.4 |
| $V_{22Gy}$ (%) | 98.96 | 98.16 | 87.20 | 65.57 | 67.53 | 56.94 | 111.7 |

Average accumulated DVHs of the PTV, rectum, bladder and femoral heads are shown in **Figures 2-4**, which are planned using VMAT with different collimator angles. The planning dose objectives of the rectum and bladder agree well with the prescribed dose; their mean, maximum, $D_{30\%}$ and $D_{50\%}$ doses are shown in **Table 2**. $V_{14\%}$ and $V_{38\%}$ were chosen since they have been used as physics quality assurance evaluation criteria at the Princess Margaret cancer center. $V_{30\%}$ and $V_{38\%}$ were calculated for rectum as well as for bladder and are shown in Table 2. The dose to the femoral heads was found to be within the acceptable range; their mean, maximum, $D_{5\%}$, $V14_{\%}$ and $V_{22\%}$ are calculated and shown in **Table 2**.

# Discussion

## Dose-volume indices

An investigation of the collimator angles reveals that a 45° collimator angle has a 0.3% higher CI, 0.14% lower HI and 0.02% lower requires MUs than all other studied collimator angles. According to Bortifield[29] a 45° collimator angle is preferred to 0° collimator angle. He also clarified the hypothesis that the leaves of the MLC in a parallel opposed beam move in and orthogonal direction and consequently these beams are not terminated. Additionally, Otto[36] explained that only a single leaf pair can be used to modulate the intensity within a CT slice without collimator rotation and secondly that an 8% lower MU requirement can be found using a 45° collimator angle verses 0° angle. This also explains the fact that with a 45° collimator angle, one can irradiate the right and left side of the PTV as well add spare the rectum and bladder in a fashion that is not possible with a 0° angle. In our investigation, the number of MUs required are (0.02%) lower using a collimator angle of 45° than when using a collimator angle of 90°. Fogliata *et al.*[37] suggested that it might be surprising that higher MUs are not commonly suggested to improve the plan excellency. Obviously, additional MUs are not always exploited in smaller MLC apertures for better dose modulation. Verbakel *et al.*[38] clearly indicated that a 45° collimator angle permits satisfactory PTV dose distributions by switching on and off the beam from different directions.

### Dose-volume criteria, maximum and mean dose

Mean dose-volume criteria, maximum and mean dose are the important parameters for plan evaluation. **Table 1** shows the dosimetric results of the PTV and **Table 2** summarizes the mean dose-volume criteria of the bladder, rectum and femoral heads calculated by the treatment planning system. In this study the dose-volume evaluation criteria for the prostate VMAT plan are: $D_{99\%}$ of PTV ≥ 74.1Gy, $D_{30\%}$ of rectum and bladder ≤ 70Gy, $D_{50\%}$ of rectum and bladder ≤ 53 Gy, $D_{5\%}$ of femoral heads ≤ 53Gy. For the mean $D_{30\%}$ and $D_{50\%}$ of the rectum and bladder, all the collimator angles satisfy the corresponding dose-volume criteria. The mean $D_{50\%}$ and $D_{30\%}$ of bladder are found to be lower for the 60° collimator angle (on average 0.03% and 0.02%) than other studied collimator angles. However, the 90° collimator angle had a higher $D_{50\%}$ and $D_{30\%}$ for the rectum (on average 0.02% and 0.01%) than other studied collimator angles. For the left and right femoral head, the 90° collimator angle had a mean $D_{5\%}$ which was on average 0.23% and 0.9% higher more than the other collimator angles, respectively. For percentage bladder and rectum volume receiving at least the given dose, lower $V_{30\%}$, $V_{38\%}$, values were found using collimator angles of 90° and 60°, respectively. The percentage of the right and left femur volume receiving at least the given dose was lower for the $V_{14Gy}$, $V_{22Gy}$ criteria at collimator angles of 75° and 30°, respectively.

### Dose-volume histogram

**Figure 2** shows the average DVH of the PTV for all collimator angles planned using the VMAT technique. The dose range in **Figure 2** begins at 70 Gy rather than 0 Gy to focus on the drop-off region of the curve. No noticable difference has been found using all studied collimator angles as seen in **Figure 2**. It is obvious in **Figure 3(a)** that the percentage of volume receiving chosen doses (e.g. $V_{30Gy}$ and $V_{38Gy}$) are constantly lower for a 75° collimator angle. This shows that collimator angle of 75° is good for bladder sparing with $V_{38Gy}$ value is 40.51. It is apparent in the **Figure 3(b)** that the percentage volume receving our choosen doses (e.g. $V_{30Gy}$ and $V_{38Gy}$) are always lower for a 90° collimator angle. This shows that 90° collimator angle results in better rectum sparing and its $V_{38Gy}$ value is 31.97. It can be seen that$V_{14Gy}$ and $V_{22Gy}$ are persistently lower for 75° collimator angle. This shows that 75° collimator angle is good for sparing of the right femur and its $V_{22Gy}$ value is 56.94. It can be realized in **Figure 4(b)** that percentage volume receiving doses (e.g. $V_{14Gy}$ and $V_{22Gy}$) are persistently lower for the 30° collimator angle. This shows that 30° collimator angle is suitable for left femur sparing (its $V_{22Gy}$ value is 69.20).

For non-single arc prostate VMAT, Rana *et al.*[39] found that it is feasible to use a partial arc technique in a RapidArc prostate plan. They showed that for the same PTV coverage and plan optimization parameters, the partial arc technique delivered a higher dose to the femoral heads but lower doses to the rectum, bladder, and penile bulb when compared to the single arc technique. On the other hand, Sze *et al.*[40] reported that double arc technique could produce a better plan with improved PTV coverage and reduced treatment time compared to intensity modulated radiation therapy. They found that though the single arc technique resulted in a higher rectal dose, the technique had higher efficiency than the double arc. For a busy treatment unit demanding high patient throughput, single arc technique could be an acceptable option for simple prostate cases. However, for complex cases involving lymph doses, more than one single full arc may be required. It is worthwhile to study the collimator angle effect on different photon arc techniques in prostate VMAT. This is the future work in this study.

## Conclusion

This work explores the impact of different collimator angles on a dosimetric scoring function. Collimator angle selection could play vital role in improving the quality of treatment plans. It is concluded from the results that the dose variations with the change of collimator angle are significant. VMAT plans with said collimator angles do not play a substantial role in PTV coverage but for more accuracy, a 45° collimator angle provides superior PTV dose distribution than all other studied collimator angles as shown by a higher value of CI, lower value of HI and 1.4% higher value of MUs. It was observed that a 75° collimator angle appropriate for sparing of rectum and right femur. In our investigation, 90° and 30° collimator angles showed the highest sparing of the rectum and left femur, respectively. The results of our study set the groundwork for guiding the collimator angle selection with regards to PTV dose distribution and sparing of OARs in prostate VMAT planning. This work also can be extended to other treatment sites using VMAT.


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## Conflict of interest

The authors declare that they have no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

## References


1. Yu CX. Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomotherapy. *Phys Med Biol* 1995; 40:1435-49.
2. Webb S, McQuaid D. Some considerations concerning volume-modulated arc therapy: a stepping stone towards a general therapy. *Phys Med Biol* 2009; 54:4345-60.
3. Otto K. Volumetric modulated arc therapy: IMRT in a single gantry arc. *Med Phys* 2008; 35:310-7.
4. Bzdusek K, Friberger H, Eriksson K, et al. Development and evaluation of an efficient approach to volumetric arc therapy planning. *Med Phys* 2009; 36:2328-39.
5. Palma D, Vollans E, James K, et al. 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* 2008; 72:996-1001.
6. Hardcastle N, Tome WA, Foo K, et al. Comparison of prostate IMRT and VMAT biologically optimized treatment plans. *Med Dosim* 2011; 36:292-8.
7. Guckenberger M, Richter A, Krieger T, et al. Is a single arc sufficient in volumetric-modulated arc therapy (VMAT) for complex-shaped target volumes? *Radiother Oncol* 2009; 93:259-65.
8. Alvarez-Moret J, Pohl F, Koelbl O, Dobler B. Evaluation of volumetric modulated arc therapy (VMAT) with Oncentra Master Plan® for the treatment of head and neck cancer. *Radiat Oncol* 2010; 5:110.
9. Iori M, Cattaneo G, Cagni E, et al. Dose-volume and biological-model based comparison between helical tomotherapy and (inverse-planned) IMAT for prostate tumors. *Radiother Oncol* 2008; 88:34-45.
10. Zhang P, Happersett L, Hunt M, et al. Volumetric modulated arc therapy: planning and evaluation for prostate cancer cases. *Int J Radiat Oncol Biol Phys* 2010; 76:1456-62.
11. Wolff D, Stieler F, Welzel G, et al. Volumetric modulated arc therapy (VMAT) vs. serial tomotherapy, step-and-shoot IMRT and 3D-conformal RT for treatment of prostate cancer. *Radiother Oncol* 2009; 93:226-33.
12. Men C, Romeijn HE, Jia X, Jiang SB. Ultrafast treatment plan optimization for volumetric modulated arc therapy (VMAT). *Med Phys* 2010; 37:5787-91.
13. Rao M, Yang W, Chen F, *et al.* Comparison of Elekta VMAT with helical tomotherapy and fixed field IMRT: plan quality, delivery efficiency and accuracy. *Med Phys* 2010; 37:1350-9.
14. Cao D, Afghan MK, Ye J, et al. A generalized inverse planning tool for volumetric-modulated arc therapy. *Phys Med Biol* 2009; 54: 6725-38.
15. Shepard DM, Cao D, Afghan MK, Earl MA. An arc-sequencing algorithm for intensity modulated arc therapy. *Med Phys* 2007; 34:464-70.
16. Bedford JL, LeeYK, Wai P, et al. Evaluation of the Delta4 phantom for IMRT and VMAT verification. *Phys Med Biol* 2009; 54:N167-76.
17. Letourneau D, Publicover J, Kozelka J, et al. Novel dosimetric phantom for quality assurance of volumetric modulated arc therapy. *Med Phys* 2009; 36:1813-21.
18. Korreman S, Medin J, Kjaer-Kristoffersen F. Dosimetric verification of Rapid Arc treatment delivery. *Acta Oncol* 2009; 48:185-91.
19. Chow JC, Jiang R. Dosimetry estimation on variations of patient size in prostate volumetric-modulated arc therapy. *Med Dosim* 2013; 38: 42-7.
20. Haga A, Nakagawa K, Shiraishi K, et al. Quality assurance of volumetric modulated arc therapy using Elekta Synergy. *Acta Oncol* 2009; 48:1193-7.
21. Wolff D, Stieler F, Hermann B, et al. Clinical Implementation of Volumetric Intensity-Modulated Arc Therapy (VMAT) with ERGO++. *Strahlenther Onkol* 2010; 186:280-8.
22. Stieler F, Wolff D, Lohr F, et al. A fast radiotherapy paradigm for anal cancer with volumetric modulated arc therapy (VMAT). *Radiat Oncol* 2009; 4:48.
23. Dobler B, Weidner K, Koelbl O. Application of volumetric modulated arc therapy (VMAT) in a dual-vendor environment. *Radiat Oncol* 2010; 5:95.
24. Kjaer-Kristofferesen F, Ohlhues L, Medin J, Korreman S.RapidArc volumetric modulated therapy planning for prostate cancer patients. *Acta Oncol* 2009; 48:227-32.

25. Yoo S, Wu QJ, Lee WR, et al. Radiotherapy treatment plans with RapidArc for prostate cancer involving seminal vesicles and lymph nodes. *Int J Radiat Oncol Biol Phys* 2010; 76:935-42.
26. Shaffer R, Morris WJ, Moiseenko V, et al. Volumetric modulated arc therapy and conventional intensity-modulated radiotherapy for simultaneous maximal intraprostatic boost: A planning comparison study. *Clin Oncol R Coll Radiol* 2009; 21: 401-7.
27. Boyer A, Biggs P, Galvin J, et al. Basic applications of Multileaf Collimators: report of the AAPM radiation therapy committee Task Group 50. *Med Phys* 2001.
28. Jeraj M, Robar V. Multileaf collimator in radiotherapy. *Radiol Oncol* 2004; 38:235-40.
29. Bortfeld T. The number of beams in IMRT-theoretical investigations and implications for single-arc IMRT. *Phys Med Biol* 2010; 55:83-97.
30. Bortfeld T, Webb S. Single-Arc IMRT. *Phys Med Biol* 2009; 54:N9-20.
31. Treutwein M, Hipp M, Koelbl O, et al. Searching standard parameters for volumetric modulated arc therapy (VMAT) of prostate cancer. *Radiat Oncol* 2012; 7:108.
32. Feygelman V, Zhang G, Stevens C. Initial dosimetric evaluation of Smart Arc a novel VMAT treatment planning module implemented in a multi-vendor delivery chain. *J Appl Clin Med Phys* 2010; 11:3169.
33. Chiarot CB, Siewerdsen JH, Haycocks T, et al. An innovative phantom for quantitative and qualitative investigation of advanced x-ray imaging technologies. *Phys Med Biol* 2005; 50:N287-97.
34. Forde E, Kneebone A, Bromley R, et al. Volumetric-modulated arc therapy inpostprostatectomy radiotherapy patients: A planning comparison study. *Medical Dosim* 2013; 38:262-7.
35. Paddick I, Lippitz B. A simple dose gradient measurement tool to complement the conformity index. *J Neurosurg* 2006; 105:194-201.
36. Otto K. Letter to the Editor on 'Single-Arc IMRT?' *Phys Med Biol* 2009; 54:L37-41.
37. Fogliata A, Nicolini G, Alber M, et al. IMRT for breast. A planning study. *Radiother Oncol* 2005; 76:300-10.
38. Verbakel WF, Senan S, Lagerwaard F, et al. Comments on 'Single-Arc IMRT? *Phys Med Biol* 2009; 54: L3.
39. Rana S, Cheng C. Feasibility of the partial-single arc technique in RapidArc planning for prostate cancer treatment. *Chin J Cancer* 2013; 32:546-52.
40. Sze HC, Lee MC, Hung WM, et al. RapidArc radiotherapy planning for prostate cancer: single-arc and double-arc techniques vs.intensity-modulated radiotherapy. *Med Dosim* 2012; 37:87-91.