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

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Original Article

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 200820, 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.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, Veendendal, 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
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. 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 cm³. The bladder, rectum, and femoral heads have contoured volumes of 59.83 cm³, 36.26 cm³ and 166 cm³, respectively.

VMAT plan and treatment delivery

For planning the data, a Synergy 6° 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, USA) with AC-QSimSTM 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 D50%, D95%, D90%, maximum dose (Dmax), mean dose (Dmean), 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).
GI is defined as the ratio of volume covered by at least a given percentage of the prescription dose. Mathematically, GI in this study is expressed in (2) as:

\[ GI = \frac{V_{50}}{V_{100}} \]  \hspace{1cm} (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\(^\circ\) collimator angle is closer to unity than any other studied collimator angles. A collimator angle of 0\(^\circ\) requires fewer MUs while 75\(^\circ\) and 90\(^\circ\) collimator angles require the most MUs. The highest HI values were established for a 60\(^\circ\) collimator angle whereas we found lower values for 45\(^\circ\) and 15\(^\circ\) angles. It was found that a 30\(^\circ\) collimator angle showed as lower GI value of GI that was closer to unity while higher values were found at 0\(^\circ\) collimator angle. Figure 1 shows Dose distribution at collimator 90.

| Table 1: Dosimetric results for PTV for all collimator angles. |
|-------------------|-------|-------|-------|-------|-------|-------|-------|
| Collimator angles | 0\(^\circ\) | 15\(^\circ\) | 30\(^\circ\) | 45\(^\circ\) | 60\(^\circ\) | 75\(^\circ\) | 90\(^\circ\) |
| \( D_{99\%} \) (Gy) | 72.41 | 72.59 | 72.40 | 72.60 | 72.40 | 72.61 | 72.73 |
| \( D_{95\%} \) (Gy) | 78.44 | 78.44 | 78.79 | 78.55 | 78.96 | 78.86 | 78.40 |
| \( D_{90\%} \) (Gy) | 73.47 | 73.50 | 73.38 | 73.63 | 73.34 | 73.71 | 73.58 |
| \( D_{\text{max}} \) (Gy) | 79.40 | 79.24 | 79.89 | 79.87 | 79.62 | 80.41 | 79.40 |
| \( D_{\text{mean}} \) (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.
Average accumulated DVHs of the PTV, rectum, bladder and femoral heads are shown in \textbf{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_{5\%} doses are shown in \textbf{Table 2}. V_{30\%} and V_{38\%} were chosen since they have been used as physics quality assurance evaluation criteria at the Princess Margaret cancer center. V_{14\%} and V_{22\%} were calculated for rectum as well as for bladder and are shown in \textbf{Table 2}. The dose to the femoral heads was found to be within the acceptable range; their mean, maximum, D_{3\%}, V_{14\%} and V_{22\%} are calculated and shown in \textbf{Table 2}.

\begin{table}[h]
\centering
\caption{Mean dose-volume criteria, average mean and maximum doses of the critical organs for VMAT plans at different collimator angles. V_{30\%}, V_{38\%}, V_{14\%}, and V_{22\%} are percentage volume receiving at least 30 Gy, 38 Gy, 14 Gy, and 22 Gy, respectively. D_{5\%}, D_{3\%}, D_{0\%} are the doses given to 5\%, 3\% and 5\% of the volumes, respectively.}
\label{tab:mean_dose_volume_criteria}
\begin{tabular}{lcccccc}
\hline
Collimator angles & 0\textdegree & 15\textdegree & 30\textdegree & 45\textdegree & 60\textdegree & 75\textdegree & 90\textdegree \\
\hline
\hline
Rectum & & & & & & & \\
D_{\text{max}} (Gy) & 53.69 & 53.56 & 52.59 & 53.62 & 52.05 & 53.61 & 52.29 \\
D_{\text{avg}} (Gy) & 79.13 & 79.09 & 79.77 & 79.87 & 79.62 & 79.92 & 79.12 \\
D_{5\%} (Gy) & 50.29 & 50.09 & 49.66 & 49.97 & 50.07 & 50.17 & 50.35 \\
D_{3\%} (Gy) & 68.33 & 68.39 & 68.07 & 69.14 & 68.93 & 68.66 & 69.25 \\
V_{30\%} (%) & 36.26 & 36.26 & 36.22 & 36.26 & 36.19 & 36.26 & 35.64 \\
V_{38\%} (%) & 35.43 & 35.96 & 33.07 & 35.3 & 31.69 & 34.76 & 31.67 \\
\hline
Bladder & & & & & & & \\
D_{\text{max}} (Gy) & 53.08 & 52.47 & 51.59 & 49.66 & 49.17 & 50.07 & 50.00 \\
D_{\text{avg}} (Gy) & 78.73 & 78.58 & 79.36 & 78.24 & 79.47 & 78.96 & 78.63 \\
D_{5\%} (Gy) & 50.40 & 49.33 & 49.31 & 48.92 & 48.69 & 49.17 & 50.59 \\
D_{3\%} (Gy) & 69.02 & 68.74 & 68.93 & 69.15 & 68.41 & 69.46 & 70.16 \\
V_{30\%} (%) & 59.84 & 59.69 & 58.12 & 59.53 & 59.84 & 57.31 & 54.40 \\
V_{38\%} (%) & 54.24 & 55.48 & 51.22 & 59.53 & 54.76 & 50.51 & 44.43 \\
\hline
Left Femur & & & & & & & \\
D_{\text{max}} (Gy) & 16.06 & 16.20 & 15.19 & 18.06 & 16.12 & 20.34 & 17.75 \\
D_{\text{avg}} (Gy) & 31.63 & 32.42 & 37.46 & 34.42 & 35.17 & 32.50 & 35.45 \\
D_{5\%} (Gy) & 27.13 & 28.32 & 29.27 & 29.86 & 30.05 & 32.50 & 35.54 \\
V_{14\%} (%) & 105.66 & 108.19 & 105.07 & 104.8 & 102.69 & 112.8 & 99.5 \\
V_{22\%} (%) & 95.65 & 91.40 & 69.20 & 100.98 & 75.18 & 107.64 & 90.02 \\
\hline
Right Femur & & & & & & & \\
D_{\text{max}} (Gy) & 17.32 & 17.34 & 16.33 & 14.92 & 15.14 & 14.33 & 22.73 \\
D_{\text{avg}} (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_{14\%} (%) & 108.68 & 111.12 & 107.56 & 102.69 & 95.87 & 117.4 & 87.23 \\
V_{22\%} (%) & 98.96 & 98.16 & 87.20 & 65.57 & 67.53 & 56.94 & 111.7 \\
\hline
\end{tabular}
\end{table}

\section*{Discussion}

\subsection*{Dose-volume indices}

An investigation of the collimator angles reveals that a 45\textdegree 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\textsuperscript{29} a 45\textdegree collimator angle is preferred to 0\textdegree 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\textsuperscript{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 versus 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. 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. 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: D99% of PTV ≥ 74.1 Gy, D95% of rectum and bladder ≤ 70 Gy, D50% of rectum and bladder ≤ 53 Gy, D50% of femoral heads ≤ 53 Gy. For the mean D99% and D80% of the rectum and bladder, all the collimator angles satisfy the corresponding dose-volume criteria. The mean D99% and D80% 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 D99% and D80% 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 D99% which was on average 0.23% and 0.9% higher than the other collimator angles, respectively. For percentage bladder and rectum volume receiving at least the given dose, lower V30%, V38%, 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 V14Gy, V22Gy 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. V30Gy and V38Gy) are constantly lower for a 75° collimator angle. This shows that collimator angle of 75° is good for bladder sparing with V38Gy value is 40.51. It is apparent in the Figure 3(b) that the percentage volume receiving our choosen doses (e.g. V30Gy and V38Gy) are always lower for a 90° collimator angle. This shows that 90° collimator angle results in better rectum sparing and its V38Gy value is 31.97. It can be seen that V14Gy and V22Gy are persistently lower for 75° collimator angle. This shows that 75° collimator angle is good for sparing of the right femur and its V22Gy value is 56.94. It can be realized in Figure 4(b) that percentage volume receiving doses (e.g. V14Gy and V22Gy) are persistently lower for the 30° collimator angle. This shows that 30° collimator angle is suitable for left femur sparing (its V22Gy value is 69.20).

For non-single arc prostate VMAT, Rana et al. 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 penil bulb when compared to the single arc technique. On the other hand, Sze et al. 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.

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