Original Article

Variation of PTV dose distribution on patient size in prostate VMAT and IMRT: a dosimetric evaluation using the PTV dose–volume factor

James C. L. Chow[1,2], Runqing Jiang[3,4], Daniel Markel[1]

[1]Radiation Medicine Program, Princess Margaret Cancer Center, University Health Network, Toronto, Canada, [2]Department of Radiation Oncology, University of Toronto, Toronto, Canada, [3]Medical Physics Department, Grand River Regional Cancer Centre, Grand River Hospital, Kitchener, Canada, [4]Department of Physics, University of Waterloo, Waterloo, Canada

Abstract

Background: We propose to use the PTV dose–volume factor (PDVF) to evaluate treatment plans of prostate volumetric modulated arc therapy (VMAT) and intensity modulated radiotherapy (IMRT).

Purpose: PDVF was used to compare the variation of planning target volume (PTV) coverage between VMAT and IMRT because of weight loss of patient.

Materials and methods: VMAT and IMRT plans of five patients (prostate volume = 32–86·5 cm^3) using the 6 MV photon beams were created with the external contour reduced by depths of 0·5–2 cm to reflect the weight loss. Moreover, integral doses (volume integral of the patient dose) and prostate tumour control probability (TCP) were calculated.

Results: We found that reduced depth resulted in PDVF decreasing $0·03 \pm 4·7 \times 10^{-4}$ (VMAT) and $0·04 \pm 9·7 \times 10^{-3}$ (IMRT) per cm for patients. The decrease of PDVF or degradation of PTV coverage was found more significant in IMRT plans than VMAT with patient size reduction. The integral dose did not change significantly between VMAT and IMRT, while the prostate TCP increased with an increase of reduced depth.

Conclusion: We concluded that PDVF can be successfully used to evaluate the variation of PTV coverage because of weight loss of patient in prostate VMAT and IMRT. Degradation of PTV coverage in prostate VMAT is less significant than IMRT regarding patient size reduction.

Correspondence to: Dr James Chow, Radiation Medicine Program, Princess Margaret Cancer Center, University Health Network, Toronto, ON, Canada M5G 2M9. Tel: +416 946 4501. Fax: +416 946 6566. E-mail: james.chow@rmp.uhn.on.ca

INTRODUCTION

Volumetric modulated arc therapy (VMAT) has been developed as an alternative technique for intensity modulated radiotherapy (IMRT) to

treat prostate cancer.[1–4] In VMAT, since both the multi-leaf collimator (MLC) aperture and dose rate can simultaneously be adjusted in a photon arc, a fraction of VMAT can be delivered with less treatment time than IMRT.[5,6] In addition, some studies have proved that prostate VMAT, with improved rectal, bladder and femoral head sparing, is a good alternative to IMRT.[7–11] These made VMAT a popular technique in prostate radiotherapy.

Weight loss of patient because of side effects of dehydration and loss of appetite sometimes occurs in prostate radiotherapy.[12] The contraction of external body contour because of reduced depth from weight loss affects the dose coverage of planning target volume (PTV). Since prostate VMAT and IMRT are complicated techniques with monitor unit (MU) varying with the MLC aperture, dose rate and gantry angle, it is very difficult to rescale the MU per beam based only on the dose ratios (e.g., tissue-phantom or tissue-maximum ratio) as in the case of 3D conformal radiotherapy (3DCRT) such as the four–field box technique.[13] It is also difficult to predict the PTV coverage in prostate VMAT and IMRT plans with patient size changing without a computed tomography (CT) rescan for replan, as a large number of irregular beamlets were used in the treatment. Therefore, a comprehensive evaluation of the PTV dose distribution according to a simple model is needed to guide the radiation staff if a CT rescan and treatment replan are needed.

This study proposes that for prostate VMAT and IMRT plan evaluation, the PTV dose–volume factor (PDVF) can be used to examine the PTV coverage because of change of dose distribution in the treatment. The PDVF is based on the dose–volume data set of the PTV, and is calculated using the Gaussian error function,[14–16] which has been used to model the cumulative dose–volume histograms (cDVH) of target and critical organ in radiotherapy. PDVF = 1 represents an ideal PTV coverage of 100% volume acquired 100% prescribed dose, while in a realistic plan, PDVF is used to be slightly smaller than 1. In this study, PDVF was used to compare the change of PTV dose distribution because of weight loss of patient between prostate VMAT and IMRT. In addition, changes of integral dose and prostate tumour

control probability (TCP) in patients because of weight loss between VMAT and IMRT were compared.

MATERIALS AND METHODS

Patient and treatment planning

In a group of 30 prostate patients with prostate volumes ranging from 32 to 86·5 cm^3 in the Grand River Hospital, Kitchener, Canada, five patients with prostate volumes of maximum (86·5 cm^3), middle between maximum and median (65·7 cm^3), median (48·4 cm^3), middle between median and minimum (40·6 cm^3) and minimum (32 cm^3) were selected to provide a representative subgroup. Both prostate VMAT and IMRT plan were created for each patient based on the same set of dose–volume constraints for the inverse planning and RapidArc optimisation (Varian Medical Systems, Palo Alto, CA, USA) from our previous work.[14] The prescription dose was 78 Gy with 2 Gy per fraction at the PTV with no lymph nodes and semi–vesicle targeted. For prostate VMAT plan, a single 360° photon arc of 6 MV was used with MU for each treatment equal to 400–500, and beam-on time equal to about 2 minutes. For prostate IMRT plan, seven beams of 6 MV with angles equal to 40°, 80°, 110°, 250°, 280°, 310°, 355° were used.

The VMAT and IMRT plan of each patient were repeated with reduced depths of 0.5, 1, 1.5 and 2 cm. The prescription dose, beam parameters and beam geometry were kept the same. Since we found that the patient's body contour mostly reduced in the anterior and both lateral directions, the replan was done by contracting the body contour with corresponding depth in these directions.[12] The normal tissue outside the body contour was then replaced by air, and the relative electron density of normal tissue was overridden by that of air in the replan. Figure 1 shows how the contracted body contour was made in the CT image of axial view for the patient with the medium size prostate. This method of body contour reduction is currently used in the Grand River Hospital to estimate dosimetric changes of the target and critical organs in prostate radiotherapy, when there is a weight loss or patient size change. cDVH of

Figure 1. Computed tomographic image of the axial view for the patient with medium size prostate ($48\cdot4\,cm^3$). The external body contour was reduced by $1\,cm$ depth (anterior, left and right direction) with the excluded patient body (normal tissue) substituted by air.
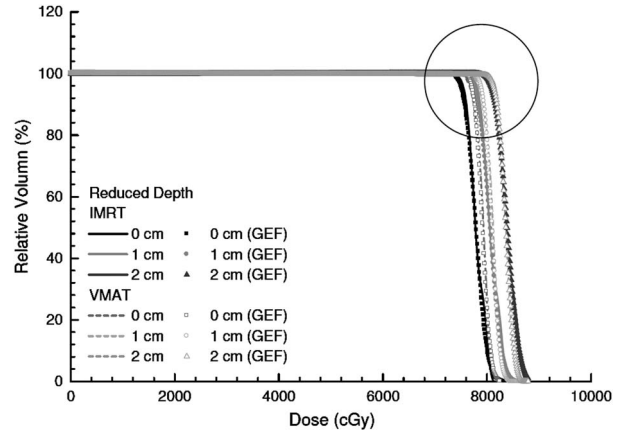

Figure 2. Dose–volume histograms (DVHs) of planning target volume in prostate volumetric modulated arc therapy and intensity modulated radiotherapy plans for the patient with medium size prostate ($48\cdot4\,cm^3$). Depths of the external body contours were reduced by 0, 1 and 2 cm. Corresponding DVHs fitted using the Gaussian error function are also shown. The circle shows the region with the 'curved edge' that is related to the parameter c_1.

PTV and integral dose of patient (body contour) were calculated for each patient with variations of reduced depths using the Eclipse treatment planning system (version 8.5, Varian Medical System, Palo Alto, CA). The integral dose is defined as the volume integral of the patient dose or the mean dose times the volume in the patient. In addition, the prostate TCP was calculated for all reduced depths of patients using our house-made MATLAB program.[17]

PDVF and integral dose

The dose–volume data of the PTV with variations of reduced depth were fitted using the Gaussian error function:[14]

$$\text{DVH}(V) = a_1\,erf\,[b_1(D - c_1)] + a_2\,erfc\,[b_2(D - c_2)], \qquad (1)$$

where a_1, b_1 and c_1 are parameters for the error function and a_2, b_2 and c_2 are parameters for the complimentary error function. D and V are the dose and volume, respectively. In Equation (1), it is found that parameters $a_{1,2}$, vary with the maximum relative volume of the cDVH curve in the modelling. The slope of the cDVH after the curve drop-off can be adjusted by $b_{1,2}$, while varying $c_{1,2}$ can change where the cDVH drop-off from the normalised volume is close to 1. For parameters $c_{1,2}$ in Equation (1), we found that the shape of the curved edge at the turning point (region inside the circle in Figure 2) in the cDVH is related to parameter c_1. Since such

'curved edge' is seen to be related to the PTV dose distribution, with 100% prescription dose at 100% of the PTV with a 90° edge, we can use c_1 to reflect the PTV dose distribution in a treatment plan. Based on the specific characteristic of c_1 in modelling the cDVH for the PTV of prostate, we defined the PDVF as:

$$\text{PDVF} = 1 - \left(\frac{|c_1 - c_0|}{c_0}\right), \qquad (2)$$

where c_0 is the prescription dose (78 Gy in this study). For an ideal cDVH of PTV with 100% prescribed dose in 100% target volume, the rectangular shaped cDVH of PTV results in c_1 the prescription dose. Therefore, an ideal PTV dose distribution reflects PDVF = 1 according to Equation (2). Since it is very difficult to create a prostate VMAT or IMRT plan with PDVF = 1 (due to patient's weight loss or intrafraction organ motion), a realistic plan usually has c_1 different from the prescription dose and hence PDVF slightly $<$1.

The integral dose of patient, based on definition using the volume integral, for each plan with reduced depth was calculated as a product of the mean dose multiplied by the volume of the external body contour.[18] The ratio of integral

dose of VMAT to that of IMRT was calculated for each patient with variation of reduced depth, in order to compare the integral dose dependence on patient size between prostate VMAT and IMRT.

Prostate TCP

The prostate TCP varying with the reduced depth in this study was calculated by the following equation:

$$TCP = \frac{\exp(a + bD)}{1 + \exp(a + bD)}, \qquad (3)$$

where D is the dose. a and b are related to the TCD_{50} and γ_{50}, which are the dose and normalised slope at the point of 50% probability control.[19] The control probability of the tumour-let with volume and dose, $TCP(v_i, D_i)$ can be inferred from the TCP for the whole volume by:

$$TCP(v_i, D_i) = TCP(D_i)^{v_i}, \qquad (4)$$

where (v_i, D_i) are the differential dose–volume histogram.

RESULTS AND DISCUSSION

Figure 2 shows the cDVHs of PTVs for the patient with medium size prostate and 0, 1 and 2 cm reduced depth. The solid (IMRT) and broken (VMAT) lines in the figure show the dose–volume data calculated by the treatment planning system, while the solid (IMRT) and open (VMAT) dots represent results modelled by the Gaussian error function using Equation (1). For both VMAT and IMRT plans, it is seen in Figure 2 that when the reduced depth increases, the drop-off region of the cDVH curve moves towards the higher dose. This is because of the increase of dose in the patient because of the contraction of body contour as per weight loss. The c_1 parameter obtained from Equation (1) in the cDVH fitting was used to calculate the PDVF using Equation (2).

Figure 3 shows the dependence of prostate TCP on the reduced depth for the five patients using Equations (3) and (4). Figure 3 shows that the prostate TCP increases with an increase of reduced depth for both VMAT and IMRT technique. This result is obvious because patient
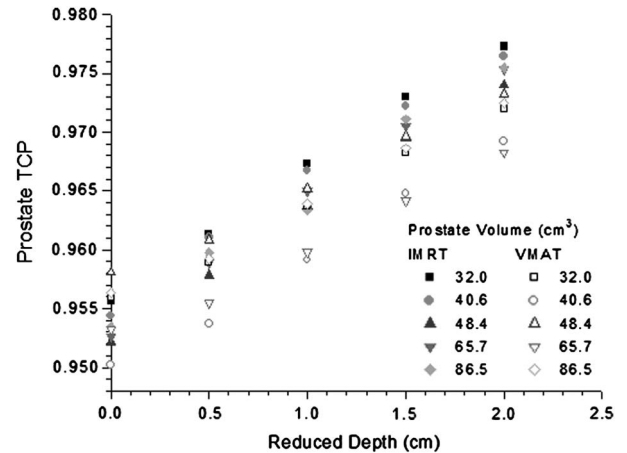

Figure 3. Relationship of the prostate tumour control probability and reduced depth for the five patients in volumetric modulated arc therapy and intensity modulated radiotherapy plans.

size reduction results in a decrease of photon beam attenuation, leading to a higher dose at the PTV. The prostate TCP therefore becomes higher as higher dose is deposited to the prostate. The results also agree with the increases of prostate $D_{99\%}$ and $D_{95\%}$ with a decrease of patient size as shown in Figure 2. It is also seen in Figure 3 that the variation of prostate TCP does not depend on the prostate volume in VMAT and IMRT plans. In Figure 3, it seems that patient size reduction can overdose the prostate and hence increases the prostate TCP in radiotherapy. However, this is equivalent to increase the prescription dose that would also affect the sparing of organ-at-risk. In addition, more dose–volume parameters such as PDVF should be considered for a thorough justification and comparison in treatment plan evaluation.

Figure 4 shows the relationship between the PDVF and reduced depth for all patients planned using the VMAT and IMRT technique. For both VMAT and IMRT plans with no patient size reduction, it can be seen in Figure 4 that PDVF varies between 0·98 and 1. This reflects the typical PDVF range for VMAT or IMRT plans that satisfied the dose–volume constraints in our prostate treatment.[15] Moreover, the PDVF is found to decrease more than 0·98 as the reduced depth increases. This shows that the dose distribution at the PTV becomes worse when the body contour starts to contract
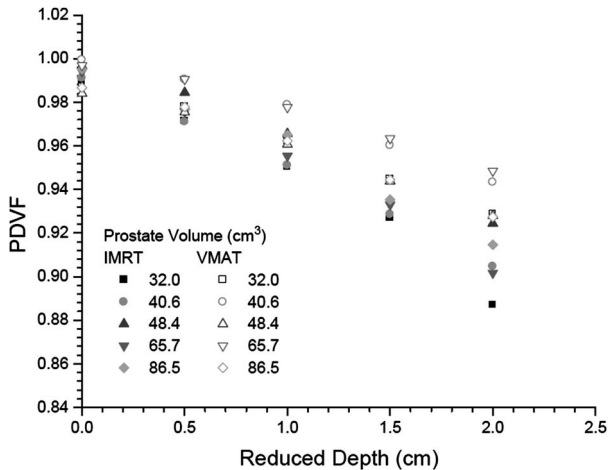
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Figure 4. Relationship of the PTV dose–volume factor and reduced depth for the five patients in volumetric modulated arc therapy and intensity modulated radiotherapy plans.
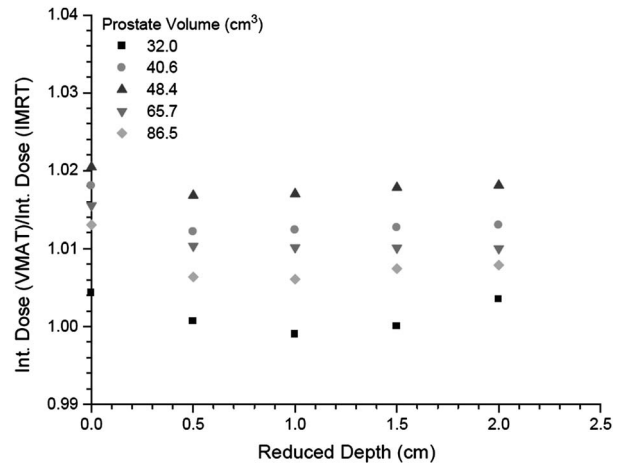

Figure 5. Ratio of integral dose of patient in volumetric modulated arc therapy to intensity modulated radiotherapy versus the reduced depth for the five patients.

because of weight loss. For PDVF of both prostate VMAT and IMRT plans, it is found that the variation of PTV dose distribution with the reduced depth does not depend on the prostate volume. However, comparing PDVF of VMAT and IMRT plans, it is seen in Figure 4 that the PDVF decreases as $0{\cdot}03 \pm 4{\cdot}7 \times 10^{-4}$ (VMAT) and $0{\cdot}04 \pm 9{\cdot}7 \times 10^{-3}$ (IMRT) per cm for the patients. IMRT technique is found more sensitive than VMAT to the degradation of PTV coverage with patient size reduction. In addition, variation of PTV dose distribution with patient size seems not to be affected by the prostate volume for VMAT plan than IMRT. This is because the shape of prostate is typically rounded in the middle of the patient's pelvis (axial body contour also rounded). Photon beams in a 360° arc vary almost the same extent (e.g., decrease of attenuation) per the reduced depth in prostate VMAT, and result in a smaller degradation of PTV dose distribution compared with IMRT. It should be noted that though the patient data have represented five typical patients from a group of 30, more patients should be involved to achieve a better statistics. However, for this study mainly concerning the application of PDVF in plan evaluation, present patient data should be adequate for demonstration.

Figure 5 shows the ratio of integral dose of patient for VMAT to IMRT varying with the reduced depth. In Figure 5, the variation of

integral dose ratio with the reduced depth does not depend on the prostate volume. Moreover, integral doses of patients in VMAT are higher than those in IMRT. The dependence of integral dose on the patient size is found not significant. This is because for an increase of reduced depth, though the dose in the irradiated volume increases because of the decrease of photon beam attenuation, the patient's volume also decreases leading to less dose to be absorbed. The increase of mean dose and decrease of body volume result in the integral dose not varying significantly with patient size.

It should be noted that the present model for the change of abdomen anatomy because of patient's weight loss can be improved further by considering the depth change in the posterior direction, and the change of the prostate position relative to different thicknesses of the 'modified patient'. However, to only demonstrate the application of PDVF in the treatment plan evaluation, we believe our present model is adequate to provide a change of body contour for the dose variation in the PTV. Moreover, in future, it is worthwhile to study the dependence of prostate dosimetry on the patient size with variation of photon beam energy (e.g., 6 and 10 MV beam).

CONCLUSIONS

Variation of PTV dose distribution with patient size in prostate VMAT and IMRT was studied

using the suggested new parameter, PDVF, based on the dose–volume data set of PTV and Gaussian error function. Five patients with prostate volumes of 32–86·5 cm^3 were selected from a group of 30 for prostate VMAT and 7-beam IMRT plans with patient size reduction because of weight loss. For VMAT and IMRT plans using the 6 MV photon beams without patient size change, PDVF varied between 0·98 and 1 (ideal coverage). The PDVF was found to decrease more significantly in IMRT plan than VMAT with patient size reduction. Moreover, ratio of integral dose of VMAT to IMRT showed that variation of integral dose does not vary significantly with the reduced depth, and the prostate TCP increased with the patient size reduction in both techniques. The PDVF is introduced as an additional option to evaluate the PTV dose distribution in prostate VMAT and IMRT plans, and PDVF has potentials in the general prostate treatment plan evaluation.

Acknowledgements

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