

Original Article

Dosimetric comparison between the prostate intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc therapy (VMAT) plans using the planning target volume (PTV) dose–volume factor

James C. L. Chow^{1,2}, Runqing Jiang^{3,4}, Alexander Kiciak⁴, Daniel Markel⁵

¹Radiation Medicine Program, Princess Margaret Cancer Centre, University Health Network, Toronto, ON,

²Department of Radiation Oncology, University of Toronto, Toronto, ON, ³Medical Physics Department, Grand River Regional Cancer Center, Grand River Hospital, Kitchener, ON, ⁴Department of Physics and Astronomy, University of Waterloo, Waterloo, ON, ⁵Medical Physics Unit, University of McGill, Montreal, QC, Canada

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Abstract

Background: We demonstrated that our proposed planning target volume (PTV) dose–volume factor (PDVF) can be used to evaluate the PTV dose coverage between the intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc therapy (VMAT) plans based on 90 prostate patients.

Purpose: PDVF were determined from the prostate IMRT and VMAT plans to compare their variation of PTV dose coverage. Comparisons of the PDVF with other plan evaluation parameters such as $D_{5\%}$, $D_{95\%}$, $D_{99\%}$, D_{mean} , conformity index (CI), homogeneity index (HI), gradient index (GI) and prostate tumour control probability (TCP) were carried out.

Methods and materials: Prostate IMRT and VMAT plans using the 6 MV photon beams were created from 40 and 50 patients, respectively. Dosimetric indices (CI, HI and GI), dose–volume points ($D_{5\%}$, $D_{95\%}$, $D_{99\%}$ and D_{mean}) and prostate TCP were calculated according to the PTV dose–volume histograms (DVHs) of the plans. All PTV DVH curves were fitted using the Gaussian error function (GEF) model. The PDVF were calculated based on the GEF parameters.

Results: From the PTV DVHs of the prostate IMRT and VMAT plans, the average $D_{99\%}$ of the PTV for IMRT and VMAT were 74.1 and 74.5 Gy, respectively. The average prostate TCP were 0.956 and 0.958 for the IMRT and VMAT plans, respectively. The average PDVF of the IMRT and VMAT plans were 0.970 and 0.983, respectively. Although both the IMRT and VMAT plans showed very similar prostate TCP, the dosimetric and radiobiological results of the VMAT technique were slightly better than IMRT.

Conclusion: The calculated PDVF for the prostate IMRT and VMAT plans agreed well with other dosimetric and radiobiological parameters in this study. PDVF was verified as an alternative of evaluation parameter in the quality assurance of prostate treatment planning.

Keywords: Dose–volume histogram; Gaussian error function; prostate IMRT; prostate VMAT; treatment plan evaluation

Correspondence to: Dr James Chow, Radiation Medicine Program, Princess Margaret Cancer Center, University Health Network, 610 University Avenue, Toronto, ON, Canada M5G 2M9. Tel: 416 946 4501. Fax: 416 946 6566. E-mail: james.chow@rmp.uhn.on.ca

INTRODUCTION

Contemporary external beam radiation treatment modalities such as intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc therapy (VMAT) provide steep 3D dose gradients by complex treatment plans using many beam segments.^{1–4} These steep dose gradients associated with the target are generated by either delivering the segments through static photon beams (e.g., step-and-shoot IMRT),⁵ or through the VMAT technique interplaying the multileaf collimator (MLC) field, dose rate and gantry speed in a single or multiple arcs.⁶ In prostate radiotherapy, the relatively new VMAT technique was proved to deliver comparable dose coverage at the planning target volume (PTV) with similar organs-at-risk (OARs) sparing compared with IMRT.^{7–9} In addition, generally VMAT consumes less monitor unit per treatment and hence requires less treatment time.^{10,11} This results in an enhancement of patient throughput and a reduction of the MLC loading. However, VMAT is a more complex delivery technique involving the rotation of gantry and variation of dose rate. A more complicated monitor unit calculation and patient-specific quality assurance are therefore needed compared with IMRT.^{12,13}

In quality assurance of the prostate treatment plan, evaluating the PTV dose coverage is important. It is because nowadays prescription dose to the prostate in radiotherapy is getting higher and higher,^{14,15} taking advantage of a very deep dose gradient achievable around the target using the IMRT or VMAT technique. Such deep dose gradients from the prostate can spare OARs such as bladder and rectum. Some dose–volume parameters such as $D_{99\%}$, D_{mean} , conformity index (CI), homogeneity index (HI) and gradient index (GI) are defined, and help to justify the merit of PTV dose coverage.¹⁶ These parameters have their specific dosimetric meanings regarding their corresponding characteristics at the target dose coverage. For example, $D_{99\%}$ determines the dose in the PTV dose–volume histogram (DVH) with 99% of volume, whereas CI is the volume of target receiving >98% of the prescribed dose divided by the PTV. It is seen that the evaluation of target dose coverage is a

process to justify a group of dose–volume points and parameters. In addition, radiobiological parameter such as prostate tumour control probability (TCP) should be considered in the plan evaluation. In general, the more the plan evaluation parameters with various dimensions of diversity are considered, the more accurate and thorough is the evaluation result.

Recently, big data in radiation treatment planning becomes a timely and hot topic.^{17,18} Solution in big data storage is desirable because more and more complex treatment plans are generated in pace with the advancement of dose delivery technology. Our suggested Gaussian error function (GEF) model can simplify the cumulative DVH curves of target and OARs in simple mathematical parameters that greatly save the storage space of treatment plans.^{19–21} Our PTV dose–volume factor (PDVF), calculated as per the GEF parameter, reflects the phenomenal characterisation of the PTV DVH curve, and was proposed to evaluate the PTV dose coverage in the prostate treatment plan.²² In this study, the PDVF were calculated for 90 prostate patients (40 IMRT and 50 VMAT). Through comparison with other dose–volume and radiobiological parameters, the validity of PDVF was justified by comparing the prostate IMRT and VMAT plans.

MATERIALS AND METHODS

Patient and treatment planning

In this study, 40 prostate IMRT and 50 prostate VMAT patients were selected in the Grand River Hospital, Canada. The information of maximum volume (V_{max}), minimum volume (V_{min}), mean volume (V_{mean}), median volume (V_{median}) and standard deviation for the target and OARs (rectum, bladder, left femur and right femur) of the prostate IMRT and VMAT patients are shown in Table 1. The prostate IMRT and VMAT plans were created using the Pinnacle³ (version 7.4, Philips Medical System, Andover, MA, USA) or Eclipse treatment planning system (version 8.5, Varian Medical System, Palo Alto, CA, USA) under the same dose prescription (78 Gy/39 fractions) and dose–volume criteria (Table 2) in the inverse planning

Table 1. Information of the V_{max} , V_{min} , V_{mean} , V_{median} and standard deviation for the planning target volume (PTV), rectum, bladder, left and right femur of the intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc therapy (VMAT) prostate patients

	IMRT (n = 40)					VMAT (n = 50)				
	PTV	Rectum	Bladder	Left femur	Right femur	PTV	Rectum	Bladder	Left femur	Right femur
V_{max} (cm ³)	355.1	180.5	913.2	283.1	261.7	308.5	142.1	635.9	246.3	240.3
V_{min} (cm ³)	77.8	35.9	109	150.6	158.8	149	30.1	61.4	121.7	123.5
V_{mean} (cm ³)	180.0	76.8	305.6	202.1	208.4	194.2	70.2	309.2	183.0	183.6
V_{median} (cm ³)	177.6	70.3	227.6	199.3	207.4	187.5	63.8	299.7	179.9	182.5
SD	54.5	30.1	198.2	31.7	31.7	49.1	28.1	133.6	25.9	25.9

Table 2. Dose–volume criteria for the volumes of interest in the intensity-modulated radiotherapy and volumetric-modulated arc therapy inverse planning optimisation

Volumes of interest	Dose–volume criteria (Gy)
CTV	$D_{99\%} \geq 78$
PTV	$D_{99\%} \geq 74.1$
PTV	Maximum dose to 1 cm ³ ≤ 81.9
Rectum	$D_{50\%} \leq 60$ $D_{35\%} \leq 65$ $D_{25\%} \leq 70$
Bladder	$D_{15\%} \leq 75$ $D_{50\%} \leq 65$ $D_{35\%} \leq 70$ $D_{25\%} \leq 75$
Left and right femur	$D_{15\%} \leq 80$ $D_{5\%} \leq 54.3$

Abbreviation: CTV, clinical target volume; PTV, planning target volume.

optimisation.²³ The seven-beam technique was used in the prostate IMRT plans with the 6 MV photon beams at the 40, 80, 110, 250, 280, 310 and 355° beam angles, whereas the single-photon arc technique was used for the VMAT plans.²⁴ The 6 MV photon beams were produced by a Varian 21 EX linear accelerator equipped with a 120-leaf MLC (Varian Medical System). Dosimetry of all treatment plans were verified using the MapCHECK[®] or ArcCHECK[®] patient-specific QA system (Sun Nuclear, Melbourne, FL, USA).²⁵ For all IMRT and VMAT plans, the PTV DVHs were determined to calculate the dose–volume points ($D_{5\%}$, $D_{95\%}$, $D_{99\%}$ and D_{mean}), radiobiological parameter (prostate TCP) and PDVF for comparison.

Calculations of the CI, HI and GI

The CI is defined as the volume of the target receiving >98% of the prescribed dose divided by

the PTV,²⁶ and has an optimal value of 1. The HI is defined by the following equation:²⁷

$$HI = \frac{D_{5\%} - D_{95\%}}{D_{mean}}, \tag{1}$$

where $D_{5\%}$ is the dose received by 5% of the PTV, $D_{95\%}$ the dose received by 95% of the PTV and D_{mean} the mean dose. In Equation (1), the optimal value of HI is equal to 0 (i.e., $D_{5\%} = D_{95\%}$). The GI is defined as:²⁸

$$GI = \frac{V_{50\%}}{V_{100\%}}, \tag{2}$$

where $V_{50\%}$ and $V_{100\%}$ are the volumes covered by at least 50 and 100% of the prescribed dose, respectively. A GI value closer to 1 embodies a faster dose fall-off in normal tissue, which may indicate a lower dose to the critical structure.

Calculation of the prostate TCP

The prostate TCP is determined using the following equation:

$$TCP = \frac{\exp(p + qD)}{1 + \exp(p + qD)}, \tag{3}$$

where p and q are related to the D_{50} and the normalised slope at the point of 20% control probability, γ_{50} , and D is the dose. Information of D_{50} and γ_{50} can be found from Okunieff et al.²⁹ summarised related clinical data for various tumours and reported parameters. The control probability for the tumourlet, TCP (v_i, D_i) with volume v_i and dose D_i , can be inferred from the TCP in Equation (3) for the whole volume using the following equation:

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

In Equation (4) (v_i, D_i) represents the differential DVH. In this study, the cumulative DVH acquired

Table 3. Average dose–volume histogram curve fitting parameters for the intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc therapy (VMAT) plans using the Gaussian error function model

	IMRT	VMAT
a_1	-1.14	100
a_2	49.43	50.35
b_1	0.0067	-0.0048
b_2	0.0042	-0.0064
c_1	7,465	7,835
c_2	7,875	7,765

from the prostate treatment plan was converted to the differential one using our home-made computer routine on the MATLAB platform.²⁴

Calculation of the PDVF

All PTV DVHs for the prostate IMRT and VMAT plans were modelled using the GEF in this study. The GEF can be written as:^{19–21}

$$DVH(V) = a_1 erf[b_1 \times (D - c_1)] + a_2 erfc[b_2 \times (D - c_2)], \tag{5}$$

where *erf* and *erfc* are the Gaussian error and complementary error function, respectively. a_1 , b_1 and c_1 are parameters in the *erf* and a_2 , b_2 and c_2 are parameters in the *erfc*. D and V are the dose and volume of the PTV, respectively. In Equation (5), it is found that parameters a_1 and a_2 are related to the maximum relative volume of the cumulative DVH curve in the modelling, whereas b_1 and b_2 are related to the slope of the DVH curve after the curve drop-off. Parameters c_1 and c_2 , however, are related to the variation of DVH drop-off position where the normalised volume is close to 1. It is found that c_1 is related to the shape of the curved edge at the turning point in the DVH. Results of the average parameters ($a_{1,2}$, $b_{1,2}$ and $c_{1,2}$) in Equation (5) for the prostate IMRT and VMAT plans are shown in Table 3.

The PDVF is therefore defined as:²²

$$PDVF = 1 \left(\frac{|c_1 - c_0|}{c_0} \right), \tag{6}$$

where c_0 is the prescription dose of 78 Gy for the prostate IMRT and VMAT plans in this study. When 100% of prescribed dose covers 100% of target volume, the rectangular shaped PTV DVH results in c_1 equal to the prescription dose. Therefore, $PDVF = 1$ reflects an ideal

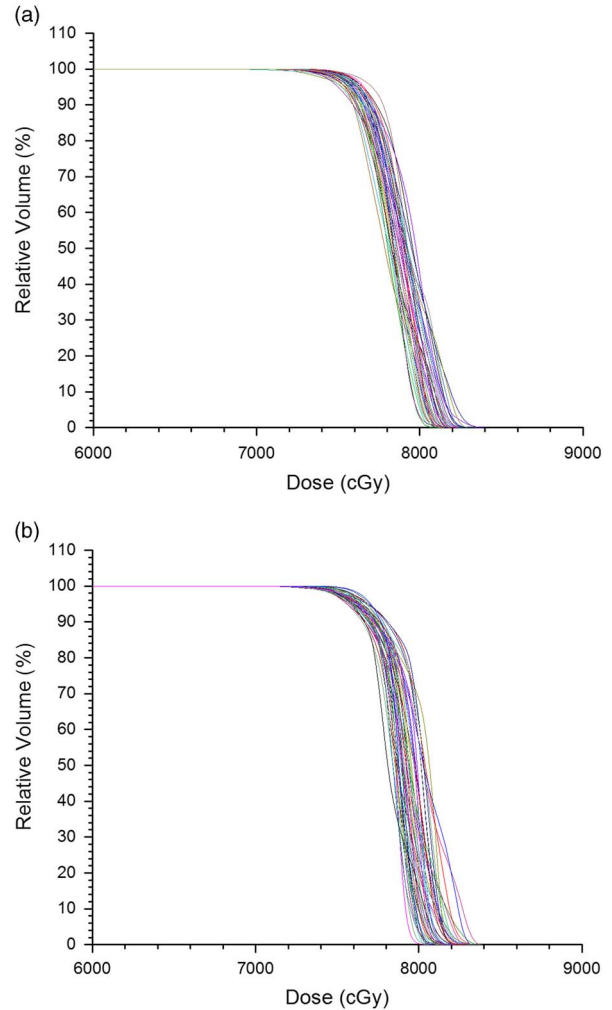


Figure 1. Dose–volume histograms of planning target volume for all (a) intensity-modulated radiotherapy and (b) volumetric-modulated arc therapy prostate plans.

PTV dose coverage in Equation (6). However, due to OAR sparing, shape of the external contour and tissue heterogeneity, the realistic value of PDVF should be slightly lower than the optimal value of 1.

RESULTS AND DISCUSSION

Figures 1a and 1b show the PTV DVHs of all prostate IMRT and VMAT plans, respectively. The dose in the x-axis of Figure 1 starts from 60 Gy instead of 0 to zoom out the drop-off portions of the DVH curves. Relative volume is shown in the y-axis for convenience to determine the dose–volume points. The average $D_{5\%}$, $D_{95\%}$ and $D_{99\%}$ were determined from Figure 1 for the

prostate IMRT and VMAT plans, and shown in Table 4. In addition, the mean doses, D_{mean} of PTV for the IMRT and VMAT plans were determined. It is seen that the prostate VMAT plans have slightly higher $D_{5\%}$, $D_{95\%}$, $D_{99\%}$ (81.5, 76.3 and 74.5 Gy) than IMRT plans ($D_{5\%} = 81.3$ Gy, $D_{95\%} = 75.6$ Gy, $D_{99\%} = 74.1$ Gy). Although both the IMRT and VMAT plans satisfied the dose–volume criteria of $D_{99\%} \geq 74.1$ Gy in Table 2, the VMAT plans have slightly higher average $D_{99\%}$ than IMRT. The degree of curve drop-off can be determined by evaluating the difference between $D_{5\%}$ and $D_{95\%}$, showing the slope of the drop-off portion in the DVH curve. In optimal case, $D_{95\%} = D_{5\%}$ shows a vertical drop-off of the DVH curve [i.e., HI = 0 according to Equation (1)]. From Table 4, the average $D_{5\%} - D_{95\%}$ for the prostate IMRT and VMAT plans are 7.2 and 5.2 Gy, respectively. This shows that the dose coverage of PTV for the prostate VMAT plans is slightly better than IMRT by considering the dose–volume points.

For the dosimetric indices in Table 4, the prostate IMRT plans have a lower average CI of 0.89 compared with VMAT (0.94). This shows that the VMAT plans produced better dose conformity to the PTV. For dose homogeneity, the average HI of prostate VMAT plans is 0.09, which is closer to 0 than that of the IMRT plans (HI = 0.12). The average GI of the IMRT plans is 1.5, which is higher than 1.2 for the VMAT plans. From the results of HI and GI comparisons, it is seen that the VMAT technique can provide better dose homogeneity and faster dose fall-off to the OAR at the PTV.

Table 4. Average dosimetric and radiobiological parameters for the intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc therapy (VMAT) prostate plans

	IMRT	VMAT
$D_{5\%}$ (Gy)	81.3	81.5
$D_{95\%}$ (Gy)	75.6	76.3
$D_{99\%}$ (Gy)	74.1	74.5
D_{mean} (Gy)	78.63	79.05
Conformity index	0.89	0.94
Homogeneity index	0.12	0.09
Gradient index	1.5	1.2
PDVF	0.970	0.983
TCP	0.956	0.958

Abbreviations: PDVF, planning target volume dose–volume factor; TCP, tumour control probability.

The prostate VMAT plans have a higher average PDVF (0.983) than IMRT (0.970) with 1 as the optimal value. This again shows that the VMAT plans have slightly better dose distribution (closer to the ideal case of a PTV DVH) at the PTV than the IMRT plans. Results of PDVF agree well with the dose–volume points and dosimetric indices. To determine the radiobiological effect, the average prostate TCP for the IMRT and VMAT plans were calculated as 0.956 and 0.958, respectively. Although the average prostate TCP of the VMAT plans is higher than the IMRT, the increase of TCP is only 0.2% regarding the slightly better PTV dose coverage in the VMAT plans. As acquisition of the PDVF only involves the parameter c_1 in the GEF model based on the cumulative DVH, calculation process is more efficient and simpler than other plan evaluation parameters, which require the whole set of dose–volume data and transformation of the cumulative DVH to differential. Moreover, dose–volume data can be stored in a much smaller space through the application of the GEF model.¹⁸

CONCLUSIONS

Dose coverage of the PTV in prostate radiotherapy was evaluated between the IMRT and VMAT techniques using dose–volume points, dosimetric indices, radiobiological parameter and PDVF based on the GEF model. From 90 prostate treatment plans, it is found that though the prostate VMAT plans have slightly better results on the dose–volume points, dosimetric indices and PDVF, the improvement of prostate TCP (0.2%) is not very significant. It is concluded that both the IMRT and VMAT technique can produce the required PTV dose coverage with the latter performing slightly better. The newly proposed PDVF were calculated from the IMRT and VMAT plans and agreed well with other plan evaluation parameters. As PDVF does not need the whole set of dose–volume data and DVH transformation in the calculation, it provides a more efficient alternative in the quality assurance of treatment planning.

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