

# Composite QA for intensity-modulated radiation therapy using individual volume-based 3D gamma indices

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## ABSTRACT

The aim of this study was to investigate the feasibility and sensitivity of using individual volume-based 3D gamma indices for composite dose-volume histogram (DVH)-based intensity-modulated radiation therapy (IMRT) quality assurance (QA). Composite IMRT QA for 15 cervical cancer patients was performed with ArcCHECK. The percentage dosimetric errors (%DEs) of DVH metrics when comparing treatment planning system and QA-reconstructed dose distribution, percentage gamma passing rates (%GPs) with different criteria for individual volumes and global gamma indices were evaluated, as well as their correlations. Receiver operating characteristic (ROC) curves were applied in order to study the sensitivities of the global and individual volume gamma indices. Most %DEs of the DVH metrics were within 3%. The  $\gamma_{PTV}$  and  $\gamma_{rectum}$  were <80% at 2%/2 mm; apart from these two individual volume indices, all other individual volume gamma indices and global indices had acceptable %GPs. For the criteria of 2%/2 mm, 3%/3 mm and 4%/4 mm, individual volume-based %GPs and global %GPs were correlated in 11, 1 and 12 out of 24 %DE metrics, and in 5, 4 and 5 out of 24 %DE metrics, respectively. Individual volume-based %GPs had a higher percentage of correlation with DVH metrics (%DEs) compared with global %GPs in composite IMRT QA. The areas under the curve (AUCs) of individual volume %GPs were higher than those of global %GPs. In conclusion, individual volume-based %GPs had a higher correlation with %DEs of metrics and a higher sensitivity presented by ROC analysis compared with global %GPs for composite IMRT QA. Thus, use of individual volume-based 3D gamma indices was found to be feasible and sensitive for composite IMRT QA.

**Keywords:** intensity-modulated radiation therapy; quality assurance; dose-volume histogram metrics; gamma index; percentage dosimetric errors

## INTRODUCTION

Due to its dose-painting ability, intensity-modulated radiation therapy (IMRT) has become a routinely employed radiotherapy technique in the management of many cancers. The inverse-planning feature and high degree of modulation in IMRT plans, which result in complex dose distributions with sharp gradients, necessitate patient-specific quality assurance (QA) for each treatment plan. Conventional IMRT QA is usually performed by comparing a measured and calculated per-beam fluence distribution on a phantom

with simple geometry [1]. A gamma index that combines percentage dose difference and distance to agreement (DTA) is applied to compare the measured and calculated dose in the phantom. A 2D gamma passing rate is then calculated for assessment of the QA result [2].

However, to date few published studies have demonstrated a strong correlation between gamma passing rates and clinically relevant dose differences for per-beam IMRT QA. Instead, recent experimental studies have revealed limited sensitivity of gamma

analysis to patient dose deviation under various IMRT errors [3, 4]. In fact, a recent study demonstrated that per-beam planar gamma passing rates do not predict clinical impact on the patient in terms of changes in the dose–volume histogram (DVH) values for the clinical target volume (CTV) and organs at risk (OARs), which calls into question the feasibility of gamma passing rate–based IMRT QA [5]. As a result, new approaches based on 3D dose reconstruction and DVH metrics have recently been developed and tested [6–8].

The advantage of DVH metrics–based dose verification is that it provides greater insight into the dose delivered to a patient’s specific organs, enabling a treatment plan to be accepted or rejected based on clinically relevant dose differences. However, DVH-based IMRT QA increases the clinical workload and introduces inefficiencies into busy clinics, because physicists have to evaluate the differences between (i) the planned patient dose and DVH and (ii) the QA system–reconstructed patient dose and DVH, rather than using a single gamma index. Evaluation of these critical DVH indicators can become numerous and complex (compared with when using a simple passing-rate metric). It can also be impractical in some extreme cases, as a physician might decide to review the patient dose and DVHs twice—once upon completion of the treatment planning and again after the pre-treatment dose QA.

However, studies have demonstrated that the 3D global gamma passing rate for the whole dose grid is weakly correlated with errors in the DVH-based metrics for pretreatment IMRT [6, 9]. The purpose of this study was to investigate the feasibility and sensitivity of using the individual volume–based 3D gamma passing rate for composite IMRT QA.

## MATERIALS AND METHODS

### Patients and treatment planning

Fifteen consecutive patients with cervical cancer who had undergone 7-field IMRT after hysterectomy were enrolled in this study. Detailed target delineation and treatment planning had been reported [10]. Briefly, the CTV was contoured according to the consensus guideline of the Radiation Therapy Oncology Group (RTOG) 0418 and its atlas on the RTOG website, which comprises a central vaginal CTV and a regional nodal CTV [11]. The former included the proximal vagina and paravaginal tissues and the latter consisted of the common iliac, external and internal iliac, and presacral lymph nodes. The planning target volume (PTV) was generated by using 7 mm uniform expansion of the CTV. OARs were contoured on the full bladder scan using the RTOG guideline and including bladder, bowel cavity, rectum, femoral heads, and other normal tissues. All plans were generated by a senior dosimetrist. Seven equally spaced coplanar fields were used for the IMRT plans. The gantry angles were as follows: 0, 51, 102, 153, 204, 255 and 306.

The prescription dose was 45 Gy for the PTV at 1.8 Gy per fraction. The planning goal for IMRT was to obtain 95% of the prescribed dose over 98% of the PTV and not to exceed 110% maximum dose. For the OARs (rectum, bladder and small bowel), the dose received by 2% of the tissue volume ( $D_2$ ) was limited to 45 Gy. The complementary constraints of  $V_{40}$  (Gy) were <40% for

the rectum, <50% for the bladder, <25% for the small bowel and <5% for the femoral heads. The IMRT plans were generated with a treatment planning system (TPS) (Monaco 5.1.1; Elekta, Crawley, UK) for a 6-MV photon beam on an Elekta Synergy linac (Elekta Ltd, Crawley, UK) equipped with an 80-leaf multileaf collimator (MLCi2<sup>TM</sup>, Elekta Ltd, Crawley, UK).

### Composite IMRT QA

Composite 3D IMRT QA was performed with a 3D diode array ArcCHECK (Model 1220) and SNC Patient (v.6.2.1; Sun Nuclear Corporation). A strict calibration of the whole system was performed in advance according to the manufacturer’s standards. An ArcCHECK movie (ACML) file generated by the SNC Patient software during the phantom dosimetric verification, which contains calculated gantry angles as a function of time, together with the RT Plan [digital imaging and communications in medicine (DICOM) file containing all the information about the plan’s parameters] and RTDose (DICOM file containing all the information about the dose distribution) exported from TPS were exported into the 3DVH program. A 3D dose deposition on the patients’ CT dataset was reconstructed without measurement using a CCC/S algorithm based on the commissioned fluence model and the dose engine to provide an independent dose verification for TPS calculation [12]. The delivered 3D dose distribution in the phantom was reconstructed with the planned dose perturbation (PDP) algorithm and compared with the dose distribution in TPS [13].

### DVH-based metrics dose evaluation and 3D gamma analysis

Percentage dosimetric errors (%DEs) of DVH metrics when comparing the TPS and the ArcCHECK QA–reconstructed dose distribution were recorded and compared. The %DEs for each of the metrics was defined as  $[(D_{\text{ArcCHECK}} - D_{\text{TPS}})/D_{\text{TPS}}] \times 100$ . For target coverage, the  $D_{\text{mean}}$ ,  $D_2$  and  $D_{98}$  (mean dose and dose to 2% and 98% of the volume, respectively) and the  $V_{95}$  (percentage of the volume irradiated by 95% of the prescription dose) of the PTV and the CTV were calculated and compared. For the OARs, the  $D_{\text{mean}}$ ,  $V_{45}$  and  $V_{40}$  of the bladder,  $D_{\text{mean}}$ ,  $V_{45}$ , and  $V_{40}$  of the rectum,  $D_{\text{mean}}$ ,  $D_3$  (dose delivered to 3% of the volume),  $V_{50}$  and  $V_{30}$  of the left and right femoral heads, and  $D_{\text{mean}}$ ,  $V_{30}$ ,  $V_{40}$  and  $V_{45}$  of the small bowel were calculated. All plans were calculated with a dose grid of 2 mm  $\times$  2 mm  $\times$  2 mm.

Relative %GPs for individual target and OAR volumes, defined as individual volume–based gamma indices (e.g.  $\gamma_{\text{PTV}}$ ,  $\gamma_{\text{bladder}}$  etc.) were calculated with three different acceptance criteria: 4%/4 mm, 3%/3 mm and 2%/2 mm, respectively, with a 10% lower dose threshold (TH). Global %GPs, defined as the gamma passing rates for the whole patient during QA analysis were also calculated with three different acceptance criteria: 4%/4 mm, 3%/3 mm and 2%/2 mm, respectively, with a 10% lower dose TH.

### Correlation and sensitivity analysis

Statistical correlations between 3D %GPs of individual volumes and %DEs, as well as correlations between global %GPs and %DEs were investigated using Pearson’s correlation coefficient ( $r$ ) with SPSS

**Table 1. Dosimetric comparison between treatment planning system- and 3DVH program-reconstructed dose distributions**

DVH metrics	TPS	3DVH	Percentage dose difference (%)	P
<b>PTV</b>				
D <sub>mean</sub> (Gy)	48.18 ± 0.52	47.49 ± 0.34	1.45 ± 0.82	<0.001
D <sub>2</sub> (Gy)	50.65 ± 1.65	49.05 ± 1.22	3.25 ± 1.20	0.005
D <sub>98</sub> (Gy)	46.02 ± 1.43	45.95 ± 0.89	0.15 ± 1.24	0.86
V <sub>95</sub> (%)	94.04 ± 10.81	87.74 ± 21.00	11.71 ± 21.48	0.31
<b>CTV</b>				
D <sub>mean</sub> (Gy)	48.83 ± 0.43	47.82 ± 0.54	1.21 ± 0.34	0.34
D <sub>2</sub> (Gy)	50.73 ± 1.34	49.31 ± 1.27	2.65 ± 1.11	0.88
D <sub>98</sub> (Gy)	46.34 ± 1.25	46.76 ± 0.87	0.16 ± 1.64	0.92
V <sub>95</sub> (%)	98.85 ± 9.34	94.45 ± 15.22	9.09 ± 16.32	0.08
<b>Bladder</b>				
D <sub>mean</sub> (Gy)	36.05 ± 1.32	35.94 ± 1.35	0.31 ± 0.72	0.82
V <sub>45</sub> (%)	25.52 ± 4.65	22.00 ± 4.53	6.64 ± 8.34	0.045
V <sub>40</sub> (%)	40.68 ± 4.98	39.48 ± 5.26	3.17 ± 2.77	0.53
<b>Rectum</b>				
D <sub>mean</sub> (Gy)	35.33 ± 4.95	35.65 ± 5.14	-0.77 ± 1.42	0.86
V <sub>45</sub> (%)	29.03 ± 5.62	25.46 ± 5.69	14.89 ± 8.32	0.09
V <sub>40</sub> (%)	44.26 ± 5.18	44.57 ± 5.04	-0.69 ± 3.05	0.87
<b>Left femoral head</b>				
D <sub>mean</sub> (Gy)	27.86 ± 3.25	28.55 ± 3.16	-2.48 ± 2.41	0.56
D <sub>3</sub> (Gy)	41.93 ± 4.61	41.92 ± 3.88	-0.12 ± 3.06	0.99
V <sub>30</sub> (%)	35.73 ± 16.89	38.78 ± 16.35	-12.07 ± 18.05	0.62
<b>Right femoral head</b>				
D <sub>mean</sub> (Gy)	29.29 ± 3.84	27.77 ± 3.46	5.42 ± 3.24	0.26
D <sub>3</sub> (Gy)	45.39 ± 3.93	41.86 ± 3.71	8.58 ± 5.93	0.02
V <sub>30</sub> (%)	41.12 ± 16.77	35.63 ± 16.47	20.43 ± 19.81	0.37
<b>Small bowel</b>				
D <sub>mean</sub> (Gy)	14.21 ± 4.74	14.03 ± 4.58	1.09 ± 1.00	0.92
V <sub>30</sub> (%)	22.07 ± 9.51	21.69 ± 9.24	1.80 ± 3.79	0.91
V <sub>45</sub> (%)	14.55 ± 7.75	13.83 ± 7.29	4.68 ± 3.79	0.80
V <sub>40</sub> (%)	7.95 ± 4.34	6.66 ± 3.35	8.45 ± 15.53	0.37

**Table 2. The %GPs of global and individual volume-based gamma indices with criteria of 2%/2 mm, 3%/3 mm and 4%/4 mm for cervical cancer patients who have undergone IMRT**

Metrics	2%/2 mm	3%/3 mm	4%/4 mm
Global passing rate	87.79 ± 0.79	96.33 ± 1.57	99.03 ± 0.57
$\gamma_{PTV}$	78.04 ± 2.20	91.08 ± 5.24	97.30 ± 1.92
$\gamma_{bladder}$	83.38 ± 3.72	94.95 ± 2.05	99.03 ± 0.65
$\gamma_{rectum}$	77.91 ± 3.85	91.93 ± 3.16	97.27 ± 1.70
$\gamma_{left\ femoral\ head}$	90.39 ± 3.87	98.81 ± 1.56	99.68 ± 0.38
$\gamma_{right\ femoral\ head}$	93.31 ± 3.39	98.81 ± 1.31	99.77 ± 0.42
$\gamma_{small\ bowel}$	86.18 ± 7.83	95.77 ± 3.55	99.27 ± 0.70

17.0 (spss Inc., Chicago, IL). The %DE was assumed to be correlated with a determined %GP when  $P < 0.05$ , which was obtained from  $r$ . In order to compare the sensitivities of 3D %GPs of individual volumes with global %GPs, the number of ‘false negative’ (FN) cases (cases where high QA passing rates implied large errors in DVH dose metrics) and ‘true positive’ (TP) cases (cases where low QA passing rates implied large errors in DVH dose metrics) were calculated. The sensitivity of this study is the true positive rate, that is  $TP/(TP + FN)$ , and the specificity of this study is the true negative rate. In particular, we considered all those structures ‘FN’ that had DVH metrics errors of  $>3\%$  among those patients with %GP  $> 95\%$ . We considered all the cases ‘TP’ that had DVH metrics errors of  $>3\%$  and %GP  $< 95\%$ . From the FN and TP rates, receiver operating characteristic (ROC) curves were generated to investigate the ability of individual volume %GPs and global %GPs to accurately identify a plan with dose errors  $>3\%$ .

## RESULTS

Table 1 shows the dosimetric comparison and %DEs of different DVH metrics between TPS- and 3DVH-reconstructed dose distributions. Most %DEs of the DVH metrics were within 3%. However, relatively higher dose differences were observed for the percentage volumes of certain isodose lines, such as  $V_{95}$  of the PTV and CTV,  $V_{45}$  of the bladder,  $V_{45}$  of the rectum,  $V_{30}$  of the left and right femoral heads, and  $V_{40}$  of the small bowel. Relatively higher dose differences were also seen for  $D_2$  of the PTV and  $D_3$  of the right femoral head. Table 2 shows the %GPs of global gamma indices and individual volume-based gamma indices with criteria of 2%/2 mm, 3%/3 mm and 4%/4 mm for cervical cancer patients who had undergone IMRT. Global %GPs were all acceptable for ArcCHECK QA.  $\gamma_{PTV}$  and  $\gamma_{rectum}$  were  $<80\%$  at 2%/2 mm; apart from these two individual volume indices, all other individual volume gamma indices had acceptable %GPs.

Table 3 shows the Pearson correlations and  $P$  values for global and individual volume-based gamma indices, with %DEs of DVH metrics. For criteria of 2%/2 mm, 3%/3 mm and 4%/4 mm, individual volume %GPs were correlated with 11, 11 and 12 out of 24 %

DE metrics, and global %GPs were correlated with 5, 4 and 5 out of 24 %DE metrics, respectively. Figure 1 presents the ROC curves comparing individual volume %GPs with global %GPs for 3%/3 mm criteria with respect to some DVH metrics for cervical cancer patients. The areas under the curve (AUCs) of individual volume %GPs were higher than those of global %GPs.

## DISCUSSION

In this work, individual volume %GPs and global %GPs, as well as their correlations with %DEs of DVH metrics between TPS- and QA-reconstructed dose were investigated for composite IMRT QA. Individual volume %GPs had a higher correlation with %DEs of DVH metrics compared with global %GPs for composite cervical cancer IMRT QA. ROC analysis also demonstrated that individual volume %GPs were more sensitive than those of global %GPs for IMRT patients.

Although both spatial information and dose differences for a 2D or 3D volume were included in the gamma index, we lacked dose difference information regarding patients’ specific structures, which made it difficult to extrapolate %GPs to clinical implications [14]. Reconstructed 3D DVH metrics-based analysis provided important information, such as the dose deviations, the pass rates and the locations of the dose deviations in the patients’ target volumes and organs, as well as identification of the error origins [15, 16]. Table 1 indicated that most %DEs of the DVH metrics for composite IMRT QA were within 3%. However, in areas with a sharp dose gradient and in metrics with small volumes, relative high dose differences were observed, such as percentage volume of certain isodose lines and point dose ( $D_2$ ). These large %DEs might have resulted from insufficient spatial resolution of our measurement devices. This is consistent with previous dose difference analysis for IMRT and volumetric-modulated arc therapy (VMAT) QA in nasopharyngeal cancer, esophageal cancer and prostate cancer patients [12, 17, 18].

In pretreatment IMRT QA, a 3% dose difference and 3 mm DTA criteria is most commonly used by physicists with a proposed %GP of 90% for per-beam planar analysis and 88–90% for composite IMRT QA [19]. However, there is still no generally accepted criteria for the 3D gamma index in composite IMRT QA based on reconstructed 3D dose distribution [20]. Additional gamma pass criteria of 2%/2 mm (stricter), 4%/4 mm (less strict) were applied in this study for better evaluation. Both global and individual volume-based %GPs with different acceptance criteria are presented in Table 2 for correlation analysis. Currently, in addition to the ArcCHECK and 3DVH system used in this study [18], several other QA methods are also available for 3D dose reconstruction for DVH metrics based on IMRT QA, such as LINAC on-board detectors [21], diode array [7], EPID panels [22] and LINAC control system log files [23]. However, pre-treatment IMRT dosimetric evaluation with 3D gamma indices has demonstrated that there is a lack of correlation between 3D %GPs and %DEs [12]. Consistent with this, our results here also indicated that global 3D %GPs were correlated with %DEs, weakly. As shown in Table 3, the global %GPs were correlated with 5, 4 and 5 out of 24 %DE metrics for %GP criteria of 2%/2 mm, 3%/3 mm and 4%/4 mm, respectively.

**Table 3. The Pearson correlation and *P* values for global and individual volume-based gamma indices with %DEs of DVH metrics**

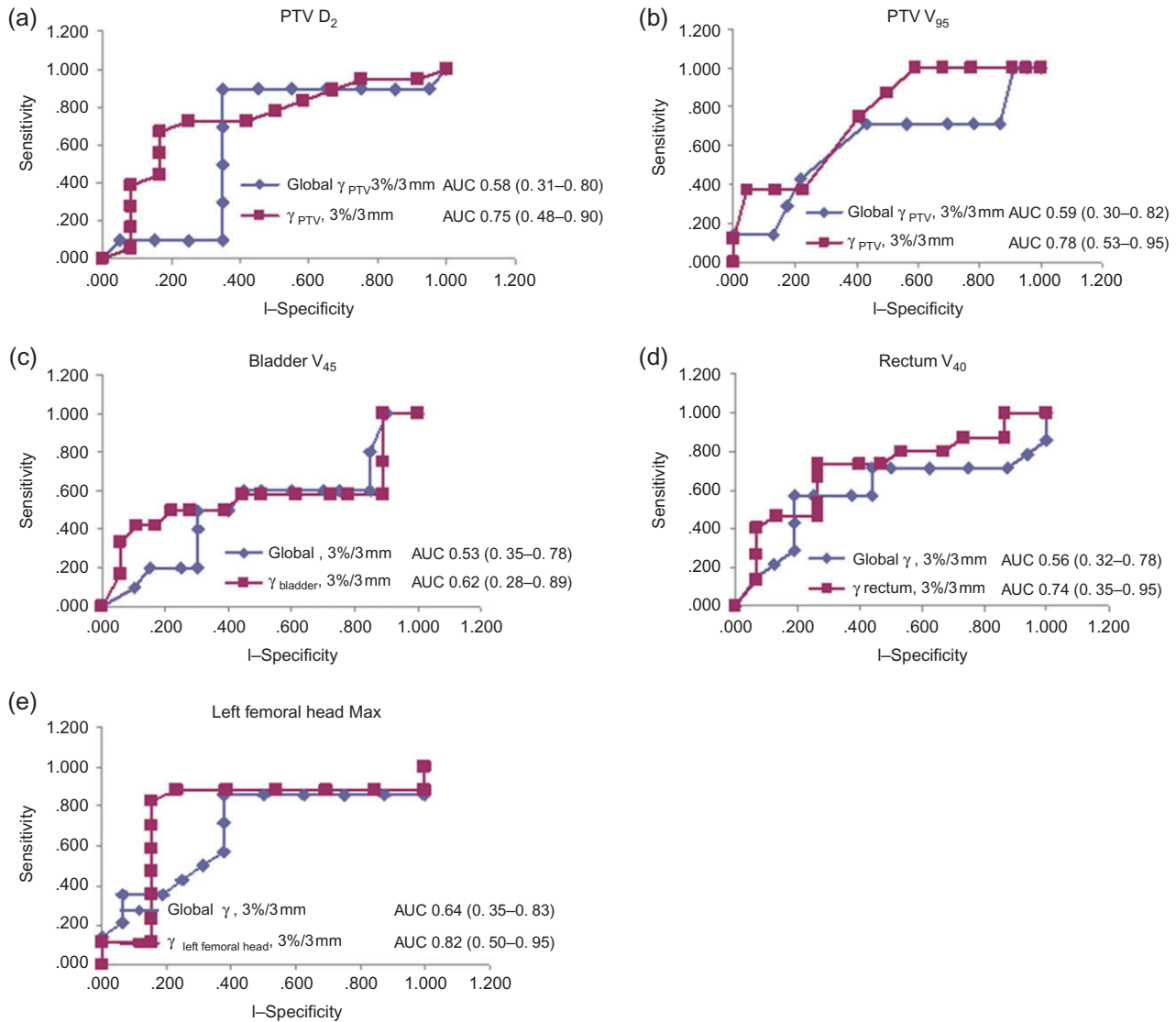
GP%	Individual volume 2%/2 mm		Individual volume 3%/3 mm		Individual volume 4%/4 mm		Global 2%/2 mm		Global 3%/3 mm		Global 4%/4 mm	
	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>
PTV												
D <sub>mean</sub>	-0.77	<0.001	-0.76	<0.001	-0.77	<0.001	-0.75	<0.001	-0.74	<0.001	-0.73	0.002
D <sub>2</sub>	-0.63	<0.001	-0.71	<0.001	-0.77	<0.001	-0.23	0.41	-0.20	0.47	-0.24	0.39
D <sub>98</sub>	-0.78	<0.001	-0.82	<0.001	-0.81	<0.001	-0.67	<0.001	-0.69	0.004	-0.66	0.01
V <sub>95</sub>	-0.40	0.21	-0.52	0.11	0.63	0.01	-0.30	0.28	-0.29	0.29	-0.33	0.23
CTV												
D <sub>mean</sub>	-0.72	<0.001	-0.71	<0.001	-0.74	<0.001	-0.73	<0.001	-0.71	<0.001	-0.70	0.003
D <sub>2</sub>	-0.57	<0.001	-0.69	<0.001	-0.75	<0.001	-0.33	0.45	-0.24	0.55	-0.31	0.44
D <sub>98</sub>	-0.72	<0.001	-0.80	<0.001	-0.79	<0.001	-0.65	<0.001	-0.65	0.01	-0.61	0.02
V <sub>95</sub>	-0.38	0.32	-0.48	0.21	0.56	0.02	-0.34	0.35	-0.39	0.39	-0.37	0.28
Bladder												
D <sub>mean</sub>	-0.61	0.01	-0.60	0.01	-0.60	0.01	-0.41	0.13	-0.50	0.06	-0.63	0.01
V <sub>45</sub>	-0.41	0.13	-0.38	0.16	-0.34	0.21	-0.34	0.22	-0.35	0.21	-0.39	0.15
V <sub>40</sub>	-0.44	0.10	-0.53	0.02	-0.71	<0.001	-0.24	0.38	-0.30	0.28	-0.40	0.15
Rectum												
D <sub>mean</sub>	0.10	0.72	0.03	0.92	-0.12	0.67	-0.23	0.42	0.19	0.49	-0.15	0.58
V <sub>45</sub>	-0.05	0.87	-0.13	0.66	-0.16	0.57	-0.10	0.73	-0.11	0.71	-0.12	0.67
V <sub>40</sub>	0.21	0.45	-0.14	0.62	-0.12	0.68	-0.07	0.81	0.07	0.81	-0.02	0.95
Left femoral head												
D <sub>mean</sub>	-0.62	0.01	-0.63	0.01	-0.52	0.04	-0.37	0.17	-0.40	0.14	-0.39	0.16
D <sub>3</sub>	-0.66	0.01	-0.54	0.03	-0.46	0.09	-0.38	0.16	-0.52	0.04	-0.44	0.10
V <sub>30</sub>	-0.49	0.07	-0.43	0.11	-0.37	0.18	-0.26	0.34	-0.30	0.28	-0.31	0.27

Continued

Table 3. Continued

GP%	Individual volume 2%/2 mm		Individual volume 3%/3 mm		Individual volume 4%/4 mm		Global 2%/2 mm		Global 3%/3 mm		Global 4%/4 mm	
	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>
Right femoral head												
D <sub>mean</sub>	-0.49	0.07	-0.42	0.12	-0.54	0.03	-0.10	0.72	-0.10	0.72	-0.16	0.56
D <sub>3</sub>	-0.54	0.04	-0.36	0.19	-0.41	0.13	-0.31	0.26	-0.30	0.28	-0.32	0.25
V <sub>30</sub>	-0.32	0.25	-0.11	0.69	-0.16	0.57	-0.14	0.61	-0.12	0.66	-0.15	0.60
Small bowel												
D <sub>mean</sub>	-0.56	0.03	-0.43	0.11	-0.57	0.02	-0.50	0.04	-0.38	0.16	-0.34	0.21
V <sub>30</sub>	-0.01	0.74	-0.01	0.80	-0.07	0.81	-0.04	0.90	-0.05	0.87	-0.06	0.83
V <sub>45</sub>	-0.33	0.23	-0.51	0.04	-0.36	0.20	-0.34	0.22	-0.27	0.33	-0.22	0.43
V <sub>40</sub>	-0.22	0.43	-0.20	0.48	-0.24	0.38	-0.17	0.56	-0.16	0.57	-0.14	0.62

Note: *r* is the Pearson correlation coefficient, which measures the linear correlation between two variables; *P* is the significance of this correlation.



**Fig. 1.** Comparative receiver operating characteristic (ROC) curves comparing individual volume percentage gamma passing rate (%GP) with global %GP at 3%/3 mm criteria for a range of DVH metrics for cervical cancer patients.

In this study, a higher percentage of correlation between individual volume %GPs and metrics %DEs was observed compared with global %GPs. This demonstrated the feasibility of utilizing direct prediction of the patient DVH and individual volume %GPs, rather than global %GPs, for pretreatment composite IMRT QA. Similarly, Wu *et al.* also concluded that it was feasible to use  $\gamma_{PTV}$  and  $\gamma_{10\%}$  as 3D  $\gamma$  analysis quantities for IMRT and VMAT QA based on EPID dose back-projection [20]. Individual volume gamma indices were better predictors compared with global gamma indices for two-arc VMAT of nasopharyngeal carcinoma patients, as shown by the ROC analysis [10]. The radiobiological gamma index had also been demonstrated to indicate correlation between gamma passing rates and clinical dose distribution [24].

One limitation of utilizing the gamma index is that it does not provide information about the anatomical location of where the failure occurs, or at which dose level it failed. DVH metrics-based QA

combined with a local gamma passing rate, the individual volume-based %GP calculated specifically for each ROI, provides a method for incorporating anatomical location into the gamma passing rate. One of the limitations of this study is that we were not able to determine which individual DVH metrics was the most sensitive index for composite IMRT QA. A more comprehensive review of the QA results beyond gamma analysis should be done, such as an additional representative point dose check, an isodose overlay check in three planes, DVH and dose statistics checks for all PTVs and critical structures.

## CONCLUSIONS

In this study, the feasibility and sensitivity of using individual volume-based 3D gamma indices for composite IMRT QA were investigated

and compared with those for using global gamma indices (in terms of %GPs) for cervical cancer patients who had undergone IMRT. Individual volume %GPs had a higher correlation with %DEs of DVH metrics and a higher sensitivity indicated by ROC analysis compared with global %GPs for composite IMRT QA.

### CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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### REFERENCES

- Ezzell GA, Galvin JM, Low D et al. Guidance document on delivery, treatment planning, and clinical implementation of IMRT: report of the IMRT Subcommittee of the AAPM Radiation Therapy Committee. *Med Phys* 2003;30:2089–115.
- Low DA, Harms WB, Mutic S et al. A technique for the quantitative evaluation of dose distributions. *Med Phys* 1998;25:656–61.
- Feygelman V, Zhang G, Stevens C et al. Evaluation of a new dose QA device, or: the X's and O's of 3D dosimetry arrays. *J Appl Clin Med Phys* 2011;12:3346–68.
- Kruse JJ. On the insensitivity of single field planar dosimetry to IMRT inaccuracies. *Med Phys* 2010;37:2516–24.
- Nelms BE, Zhen H, Tomé WA. Per-beam, planar IMRT QA passing rates do not predict clinically relevant patient dose errors. *Med Phys* 2011;38:1037–44.
- Zhen H, Nelms BE, Tome WA. Moving from gamma passing rates to patient DVH-based QA metrics in pretreatment dose QA. *Med Phys* 2011;38:5477–89.
- Olch AJ. Evaluation of the accuracy of 3DVH software estimates of dose to virtual ion chamber and film composite IMRT QA. *Med Phys* 2012;39:81–6.
- Nielsen M, Carlona M, Cruje C et al. Validation of plan dose perturbation software for use in patient specific IMRT quality assurance. *Med Phys* 2011;38:3582.
- Stasi M, Bresciani S, Miranti A et al. Pretreatment patient-specific IMRT quality assurance: a correlation study between gamma index and patient clinical dose volume histogram. *Med Phys* 2012;39:7626–34.
- Deng X, Han C, Chen S et al. Dosimetric benefits of intensity-modulated radiotherapy and volumetric-modulated arc therapy in the treatment of postoperative cervical cancer patients. *J Appl Clin Med Phys* 2017;18:25–31.
- Small WJ, Mell LK, Anderson P et al. Consensus guidelines for delineation of clinical target volume for intensity-modulated pelvic radiotherapy in postoperative treatment of endometrial and cervical cancer. *Int J Radiat Oncol Biol Phys* 2008;71:428–34.
- Jin X, Yan H, Han C et al. Correlation between gamma index passing rate and clinical dosimetric difference for pre-treatment 2D and 3D volumetric modulated arc therapy dosimetric verification. *Br J Radiol* 2015;88:20140577.
- Nelms BE, Opp D, Robinson J et al. VMAT QA: measurement-guided 4D dose reconstruction on a patient. *Med Phys* 2012;39:4228–38.
- Chan MF, Li J, Schupak K et al. Using a novel dose QA tool to quantify the impact of systematic errors otherwise undetected by conventional QA methods: clinical head and neck case studies. *Technol Cancer Res Treat* 2014;13:57–67.
- Boggula R, Jahnke L, Wertz H et al. Patient-specific 3D pretreatment and potential 3D online dose verification of Monte Carlo-calculated IMRT prostate treatment plans. *Int J Radiat Oncol Biol Phys* 2011;81:1168–75.
- McCurdy B, Mueller L, Backman E et al. Commissioning and validation of a novel measurement-based IMRT QA method, incorporating dose recalculation on patient CT data. *Med Phys* 2008;35:2760.
- Van Zijtveld M, Dirx MLP, de Boer HCJ et al. 3D dose reconstruction for clinical evaluation of IMRT pretreatment verification with an EPID. *Radiother Oncol* 2007;82:201–7.
- Yi J, Han C, Zheng X et al. Individual volume-based 3D gamma indices for pretreatment VMAT QA. *J Appl Clin Med Phys* 2017;18:28–36.
- Ezzell GA, Burmeister JW, Dogan N et al. IMRT commissioning: multiple institution planning and dosimetry comparisons, a report from AAPM Task Group 119. *Med Phys* 2009;36:5359–73.
- Wu C, Hosier KE, Beck KE et al. On using 3D  $\gamma$ -analysis for IMRT and VMAT pretreatment plan QA. *Med Phys* 2012;39:3051–9.
- Kapatoes JM, Olivera GH, Ruchala KJ et al. A feasible method for clinical delivery of verification and dose reconstruction in tomotherapy. *Med Phys* 2001;28:528–42.
- Wendling M, McDermott LN, Mans A et al. A simple back-projection algorithm for 3D *in vivo* EPID dosimetry of IMRT treatments. *Med Phys* 2009;36:3310–21.
- Qian J, Lee L, Liu W et al. Dose reconstruction for volumetric modulated arc therapy (VMAT) using cone-beam CT and dynamic log files. *Phys Med Biol* 2010;55:3597–610.
- Sumida I, Yamaguchi H, Kizaki H et al. Novel radiobiological gamma index for evaluation of 3-dimensional predicted dose distribution. *Int J Radiat Oncol Biol Phys* 2015;92:779–86.