Original Article

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A Comparison Study of Volumetric Modulated Arc Therapy Quality Assurances Using Portal Dosimetry and MapCHECK 2

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A Varian Portal Dosimetry system was compared to an isocentrically mounted MapCHECK 2 diode array for volumetric modulated arc therapy (VMAT) QA. A Varian TrueBeam STx with an aS-1000 digital imaging panel was used to acquire VMAT QA images for 13 plans using four photon energies (6, 8, 10 and 15 MV). The EPID-based QA images were compared to the Portal Dose Image Prediction calculated in the Varian Eclipse treatment planning system (TPS). An isocentrically mounted Sun Nuclear MapCHECK 2 diode array with 5 cm water-equivalent buildup was also used for the VMAT QAs and the measurements were compared to a composite dose plane from the Eclipse TPS. A γ test was implemented in the Sun Nuclear Patient software with 10% threshold and absolute comparison at 1%/1 mm (dose difference/distance-to-agreement), 2%/2 mm, and 3%/3 mm criteria for both QA methods. The two-tailed paired Student's t-test was employed to analyze the statistical significance at 95% confidence level. The average γ passing rates were greater than 95% at 3%/3 mm using both methods for all four energies. The differences in the average passing rates between the two methods were within 1.7% and 1.6% of each other when analyzed at 2%/2 mm and 3%/3 mm, respectively. The EPID passing rates were somewhat better than the MapCHECK 2 when analyzed at 1%/1 mm; the difference was lower for 8 MV and 10 MV. However, the differences were not statistically significant for all criteria and energies (p-values >0.05). The EPID-based QA showed large off-axis over-response and dependence of γ passing rate on energy, while the MapCHECK 2 was susceptible to the MLC tongue-and-groove effect. The two fluence-based QA techniques can be an alternative tool of VMAT QA to each other, if the limitations of each QA method (mechanical sag, detector response, and detector alignment) are carefully considered.

Key Words: Pretreatment QA, VMAT, EPID, Portal dosimetry, MapCHECK 2

Introduction

Volumetric modulated arc therapy (VMAT) can deliver highly conformal dose distributions with better monitor unit (MU) efficiency and shorter treatment time. However, a patient-specific VMAT quality assurance (QA) is more challenging than conventional intensity modulated radiation therapy (IMRT) due to increased complexity such as variations in gantry speed and dose rate with complicated leaf sequencing.

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Electronic portal imaging device (EPID) is attractive for the IMRT and VMAT QA using portal imaging and dosimetry due to high resolution of imaging and simple set-up of the detector. Bakhiari et al.[1] used a 38% isointensity line of cine EPID images to verify multileaf collimator (MLC) leaf positions during VMAT delivery. Sharma et al.[2] tested the EPID portal dosimetry for IMRT QA using 181 intensity modulated fields that was compared to a two-dimensional (2D) ion chamber array (MatriXX, IBA, Louvain-la-Neuve, Belgium), and concluded that both fluence verification methods produced comparable QA results. Clemente et al.[3] reported that the portal dosimetry was a useful QA tool for dynamic and static IMRT delivery. Applicability and limitations of the portal dosimetry for VMAT QA have been also investigated.[4-10] Baily et al.[4] compared two commercially available EPID-based systems

for IMRT and VMAT delivery: Varian (Palo Alto, CA, U.S.A.) Portal Dosimetry and Sun Nuclear Cooperation (SNC; Melbourne, FL, U.S.A) EPIDose. They concluded that the two systems yielded similar QA results for most of clinical IMRT cases; however, the EPIDose allowed more accurate analysis for off-axis, asymmetric fields and VMAT QA.

Clinical implementation of 2D diode array detectors (SNC MapCHECK/MapCHCK 2) has been reported for patient-specific verification of VMAT plans.[4,8,11-14] The 2D detector arrays have received considerable attention for verification of IMRT/VMAT plans due to compact diode size (0.8×0.8 mm^2), dose linearity, real-time measurement, reproducibility, and high sensitivity. However, large angular response variation of diode makes MapCHECK/MapCHECK 2 undesirable for VMAT QA.[12] Baily et al.[4] showed close agreement between the EPIDdose system and isocentrically mounted MapCHECK for 6 MV VMAT QA.

Four different photon beam energies (6 MV, 8 MV, 10 MV, and 15 MV) are available for Varian VMAT (RapidArc) plan delivery using our Varian TrueBeam STx. In this study, a Varian Portal Dosimetry system commissioned for the four energies is compared to the isocentrically mounted MapCHECK 2 diode array for VMAT QAs as a function of photon beam energy.

Materials and Methods

1. VMAT plans

Varian VMAT treatment plans for 13 patients involving different disease sites (two brains, one chest, three head and necks (H&Ns), one lung, one pancreas, two prostates, one rectum, and two stomachs) were retrospectively selected in this study. For the same patient, the VMAT plans were re-generated at 6 MV, 8 MV, 10 MV and 15 MV energies using the same 1 or 2 arcs (gantry rotation of 360^o except for one brain (120^o and 90^o) and one chest (210^o)) with collimator rotation of 30^o or 45^o in the Varian Eclipse treatment planning system (TPS; version 11.0). Anisotropic analytical algorithm (AAA) with calculation grid size of 2.0 mm was used to calculate dose. The Varian TrueBeam STx with high definition 120 multileaf collimator (HD 120 MLC; 2.5 mm central 32 leaf pairs spanning 8 cm and 5.0 mm leaf pairs in the periphery) commissioned at the four energies was employed to deliver the VMAT treatment plans.

2. VMAT QAs using Portal Dosimetry and MapCHECK 2

The Varian Portal Dosimetry system (version 11.0) consists of three main components: (1) the portal dose image prediction (PDIP) module in the Eclipse TPS, (2) the portal imager to measure the image, and (3) the ARIA portal dosimetry review workspace to evaluate the IMRT QA test. The Varian TrueBeam PortalVision imager (aS1000 amorphous silicon) has an imaging area of 40×30 cm^2 at a source-to-detector distance (SDD) of 100 cm and an array of 1024×768 pixels. The EPID images were calibrated with dark field and flood field and scaled to have 1 CU (Calibrated Unit; arbitrary EPID image unit related to monitor units (MU) and dose) corresponding to 100 MU with 10×10 cm^2 field at 100 cm SDD for daily measurement at the four energies. A profile correction using a diagonal beam profile measured at the dmax in water using 40×40 cm^2 field was applied for the calibration of the EPID detector following the vender's instruction.[15] The PDIP algorithm in the Eclipse created the comparison images for portal dosimetry VMAT QA.[16]

The MapCHECK 2 diode array on an isocentric mounting fixture (IMF) was also used for pretreatment QAs of the same VMAT plans. MapCHECK 2 has 1527 n-type diode detectors covering 26×32 cm^2 at 7.07 mm uniform spacing across the entire area. MapCHECK 2 with 5 cm water equivalent buildup (including 2 cm inherent buildup) was scanned with a CT scanner (General Electric Healthcare, Little Chalfont, United Kingdom) and transferred to the Eclipse TPS for verification planning. A composite dose plane of the VMAT plans (gantry angle set to 0^o) was taken from the Eclipse TPS for comparison to measurements. Prior to daily QA delivery, MapCHECK 2 was calibrated using 10×10 cm^2 field at the four energies instructed by the manufacturer to minimize day-to-day machine variation. The device was mounted on IMF with a 3 cm solid water block where the beam always impinged orthogonally on the surface, and planned collimator angles were used for QA measurements.

A γ test[17] was implemented for both EPID and MapCHECK 2 QAs in SNC Patient software (version 6.0) with 10% threshold (dose points less than the threshold were ex-

cluded from the analysis) and absolute comparison (normalized to the maximal value of the predicted dose (global)) to have the same QA environment as shown in Fig. 1. The EPID-based QA measurements and PDIP images were exported via DICOM format and imported in the Patient software using a DICOM EPID filter. The portal dosimetry QA was analyzed for each arc because only one composite dosimetric image could be created for each arc. An average γ passing rate of multiple arcs for a patient was used for the QA analysis. The γ passing rates between portal dosimetry and MapCHECK 2 QAs with dose difference/distance-to-agreement (DTA) criteria of 1%/1 mm, 2%/2 mm, and 3%/3 mm were compared by the two-tailed paired Student's t-test at the 95% confidence level. Inter-energy variations using the same QA device were also examined.

Results

The average γ passing rates were greater than 95% at 3%/3 mm criteria using both QA methods for all four energies as shown in Table 1, which was clinically acceptable according to Stock et al.[18] The γ passing rates of EPID-based QA were

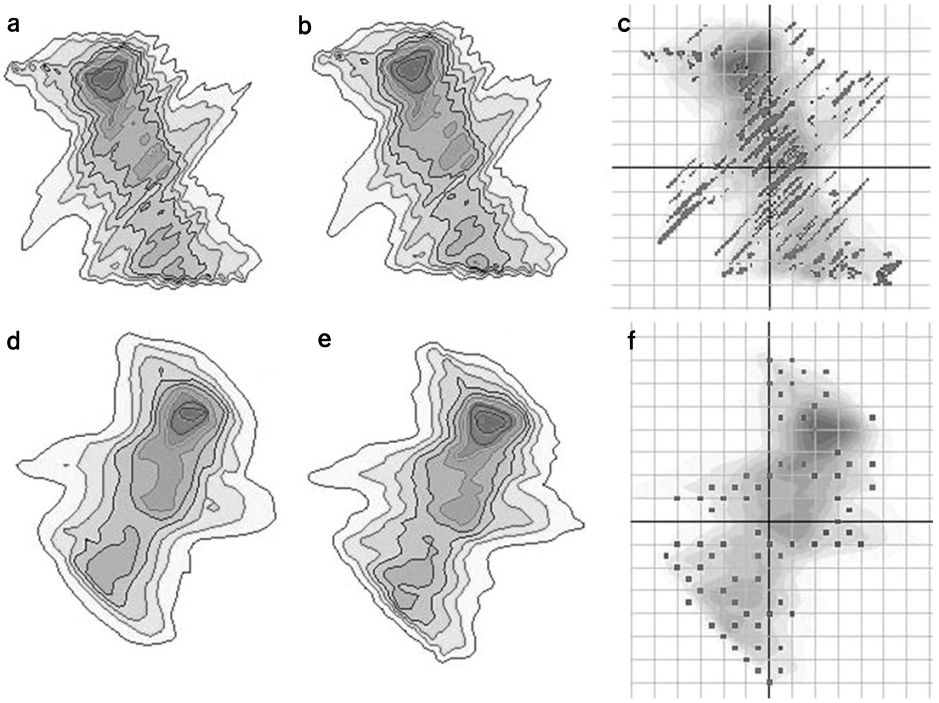

Fig. 1. Gamma analysis of a 6 MV VMAT QA plan at 1%/1 mm using the SNC Patient software. (a) EPID-based measurement, (b) Portal Dose Image Prediction, (c) failed gamma points for EPID-based QA, (d) MapCHECK 2 measurement, (e) calculated dose for MapCHECK 2, and (f) failed gamma points for MapCHECK 2 QA.

Table 1. The γ passing rates (%) of EPID portal dosimetry (E) and MapCHECK 2 (M) QAs.

Beam energy / Gamma criteria		6 MV			8 MV			10 MV			15 MV		
		1%/ 1 mm	2%/ 2 mm	3%/ 3 mm	1%/ 1 mm	2%/ 2 mm	3%/ 3 mm	1%/ 1 mm	2%/ 2 mm	3%/ 3 mm	1%/ 1 mm	2%/ 2 mm	3%/ 3 mm
EPID-based	Mean	70.8	93.6	98.3	60.4	88.7	96.2	66.4	91.5	97.3	65.9	92.2	98.0
QA (E)	S.D.	16.4	9.1	2.9	18.5	13.4	5.7	20.3	12.5	4.9	16.2	9.8	3.7
MapCHECK2	Mean	61.4	91.9	98.2	57.1	90.2	97.8	63.3	93.2	98.5	59.2	90.5	98.2
QA (M)	S.D.	6.8	4.3	1.8	7.2	5.5	2.5	6.9	3.4	1.6	8.0	5.3	2.2
Difference	Mean	9.4	1.7	0.1	3.4	-1.5	-1.6	3.1	-1.7	-1.2	6.7	1.7	-0.2
(E-M)	S.D.	17.2	11.0	3.7	21.0	16.2	6.8	22.4	13.7	5.6	18.7	11.6	4.2
p-value (E vs. M)		0.07	0.60	0.90	0.56	0.72	0.35	0.62	0.66	0.44	0.22	0.62	0.87

better than those of MapCHECK 2 QA for all four energies when analyzed at 1%/1 mm (3.1% (10 MV) to 9.4% (6 MV) higher). However, the differences were not statistically significant ($p > 0.05$) for all criteria and energies as shown in Table 1.

Dependence of γ passing rate on field size was observed in the EPID-based QA as shown in Fig. 2. One of the stomach patients showed extremely low passing rates (from 79.7% for 8 MV to 89.0% for 6 MV at 3%/3 mm), whose equivalent-square field size by jaw setting (21.7 cm) was much larger than the other plans. Relatively low passing rates (less than 95%) for plans with small field size (less than 10 cm) were also observed for two brain patients at 8 MV and 10 MV (the same trend was observed at 1%/1 mm and 2%/2 mm). The MapCHECK 2 QA did not show any dependence of γ passing rate on field size; however, low passing rates for a H&N plan (less than 95% at 3%/3 mm) using four energies were found. None of the plans had the γ passing rates of less than 95% at 3%/3 mm using both QA methods.

The MapCHECK 2 QA did not show any statistically significant difference in γ passing rate using different energies at 3%/3 mm as shown in Table 2. However, the 6 MV EPID-based QAs showed better γ passing rates, while the 8 MV EPID-based QAs presented significantly lower γ passing rates than the other energies.

Discussion and Conclusions

The two QA methods based on portal dosimetry and MapCHECK 2 were effective tools for VMAT QA and produced clinically acceptable γ passing rates for most of cases. However, each QA method had several statistical outliers whose passing

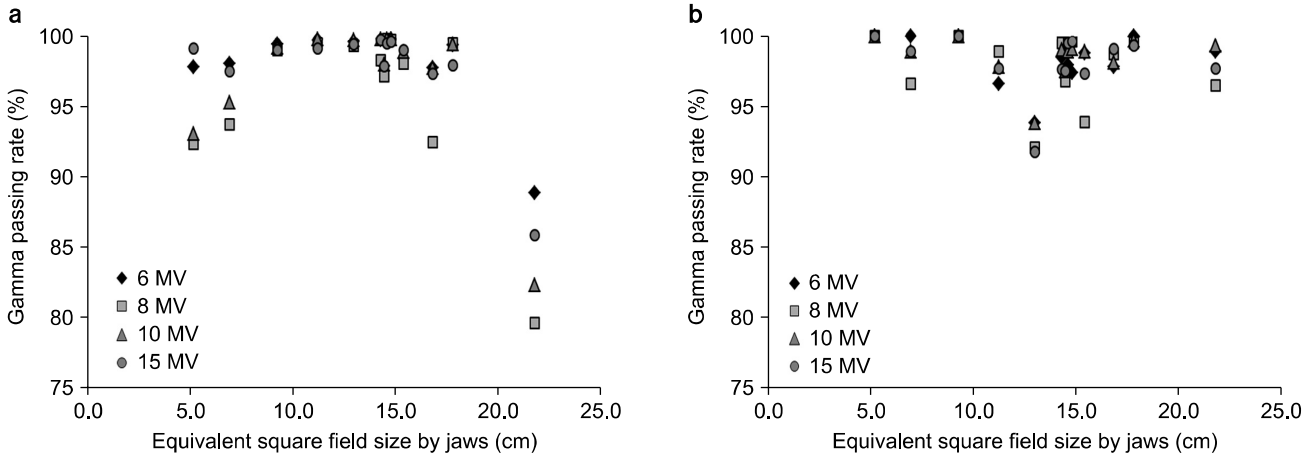

Fig. 2. Gamma passing rate of the 13 patients at 3%/3 mm: (a) EPID-based QA and (b) MapCHECK 2 QA. For plans with small (less than 10 cm) and large field size (greater than 20 cm), relatively low passing rates were observed for the EPID QA; however, the MapCHECK 2 QA did not show any particular dependence on field size.

Table 2. Statistical significance test (p-value) using Student's t-test between different energies.

γ criteria	6 MV vs. 8 MV			6 MV vs. 10 MV			6 MV vs. 15 MV		
	1%/ 1 mm	2%/ 2 mm	3%/ 3 mm	1%/ 1 mm	2%/ 2 mm	3%/ 3 mm	1%/ 1 mm	2%/ 2 mm	3%/ 3 mm
EPID-based QA	0.0003	0.01	0.02	0.04	0.07	0.13	0.02	0.07	0.19
MapCHECK 2 QA	0.02	0.11	0.53	0.14	0.06	0.12	0.11	0.18	0.88
	8 MV vs. 10 MV			8 MV vs. 15 MV			10 MV vs. 15 MV		
EPID-based QA	0.02	0.01	0.02	0.07	0.06	0.04	0.80	0.61	0.30
MapCHECK 2 QA	0.0002	0.01	0.16	0.13	0.71	0.39	0.02	0.01	0.17

rates were out of tolerance level. This originated from various contributing factors including mechanical sag and detector response.

Both QA measurements are affected by mechanical sag of detectors depending on gantry angle. Shifts in the center of the EPID images can be up to 5 mm reported by Bakhtiari et al.[1] This sag can be detected and corrected using two tungsten carbide ball bearings embedded in a 2 mm thick sold water slab detected by cine EPID imaging for arc delivery proposed by Rowshanfarzad et al.[10] Our machine has much less shifts in both cross-plane and in-plane profiles (up to 0.9 mm) and they were not further corrected in this study. The MapCHECK 2 on IMF has similar shifts by up to 2.6 mm for our system and it can be simulated by splitting beam angles for dose calculation in TPS.[19] Jin et al.[20] showed that the correction of the shift (~1.0 mm) would not make a statistically significant difference even if the γ passing rate would slightly improve.

Table 2 shows the γ passing rate using different energies did not consistently have statistical significance (or insignificance). First, it should be noted that the plans using four different energies for the same patient did not have the same leaf modulation and MUs due to different optimization using different energies even if the same objectives were used. Second, the QA results were a complex interplay of a variety of uncertainty sources such as mechanical accuracy including the sagging issue, dependence of detector on energy and dose rate, accuracy of commissioning a planning system (especially for the portal dosimetry), and intrinsic calibration and dosimetric uncertainty of detector. And thus a large variation in the γ passing rate was sometimes observed even though the same VMAT plan was delivered for the QA especially at 1%/1 mm criteria. Our portal dosimetry and MapCHECK 2 system showed a good agreement (less than 1.0% dosimetric error) between calculation and measurement in an acceptance test using static 10×10 cm^2 field for all four energies. However, due to complexity mentioned above, it was not an easy task to identify the exact reasons why there was no consistency in the γ passing rate in terms of energy. It requires a further in-depth study.

The low γ passing rate for large-field EPID-based QA in Fig. 2 is attributed to off-axis EPID over-response. It was reported that off-axis EPID response is much higher than the dose measurement in water at the similar off-axis and greater than the central-axis response (up to 5% increase in response at 20 cm off-axis) for small MU irradiations.[21,22] This off-axis response can be corrected by a correction algorithm which used ratios of predicted dose and measured dose in order to modify the diagonal calibration profile and improved the agreement between prediction and measurement by up to 15% for fields near the detector edges.[6] This 1D correction algorithm is, however, limited by correcting only radially-symmetric EPID errors. A 2D matrix correction (ratio of normalized predicted response to normalized measured response at each pixel) was thus proposed, which improved the agreement by up to 10% than the 1D correction.[5] In our study, dependence of EPID response on energy was also observed. We found that the EPID response compared to PDIP using 8 MV and 10 MV was higher than 6 MV and 15 MV by up to 1% at the central area (using a field size of 10×10 cm^2) and up to 4.3% at 10 cm off-axis with the maximum MLC field size of 30×22 cm^2 (EPID/PDIP=1.056 (8 MV), 1.064 (10 MV), 1.047 (6 MV), and 1.021 (15 MV)). In addition, an inter-daily variation of EPID response (up to 1%) was observed. This resulted in the relatively low passing rates at 3%/3 mm for two plans of small field size (5.2 cm and 7.0 cm) in the EPID-based QA using 8 MV and 10 MV (Fig. 2), and can be improved by the 2D matrix correction. The 2D matrix correction requires an in-house independent comparison system and it is out of scope of our research which focused on commercially available, intact QA systems. It should be noted that the EPID response is linac-specific and depends on a number of beam parameters such as energy, scatter contribution, field size, response linearity, and dose rate.[7] It is thus required that readers should investigate their own EPID response using different energies before clinical use. It should also be noted that the Varian Portal Dosimetry system depends on the prediction of fluence and therefore does not account for errors in beam modeling or calculation algorithm.

The isocentrically mounted MapCHECK 2 is susceptible to the MLC tongue-and-groove effect (underdosage between two adjacent leaf pairs),[23] because diode detectors are aligned with MLC inter-leaf gaps and this usually decreases the γ passing rate.[20] It should be also noted that the tongue-and-groove effect is not an only source of uncertainty which makes the

passing rate different and the tongue-and-groove effect is differentially dependent upon a degree of MLC modulation. The H&N VMAT plan which showed the lowest passing rate (equivalent square field size=13.0 cm) in the MapCHECK 2 QA (Fig. 2b) was most affected by this effect. The tongue and groove effect is explained by rows of hot or cold diode spots under the tongues and grooves of MLCs along direction of MLC motion in the MapCHECK 2 QA and it was clearly shown in the H&N case especially at 1%/1 mm. It is believed that EPID-based QA showed better passing rates at 1%/1 mm for all energies than the MapCHECK 2 QA mainly due to the tongue-and-groove effect. In addition, the calibration field size of MapCHECK 2 different from the actual plan field size increases dosimetric uncertainty due to differential response of diode detector on scattered radiation,[24] and limited detector density in MapCHECK 2 should not be overlooked (the number of comparison points of the MapCHECK 2 QA was about 50 times less than that of the EPID-based QA).

In conclusion, both fluence-based QA methods should be employed with great care considering the limitations of each QA method. These two different QA techniques can serve as alternative QA tool to each other, if the VMAT QA using one of the QA tools does not meet the acceptable passing rate and the QA result is carefully analyzed with the limitations of each QA method.

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