Peer Reviewed **Original Article**

VALIDATION OF THE FIRST VMAT IMPLEMENTATION IN EAST AND CENTRAL AFRICA USING AAPM TG 119 DATASETS

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https://doi.org/10.54450/saradio.2021.59.2.#605

ABSTRACT

Background. VMAT is considered a complex radiotherapy modality due to the higher number of variables than classical modalities that need to be controlled for the delivered treatment to be a close reproduction of the treatment plan. For this reason, preclinical validation of new VMAT implementations, following established recommendations, is a vital part of the system's commissioning.

Aim. This study aimed to validate the commissioning of a radiotherapy system upgraded to be VMAT capable and to establish initial local confidence limits.

Method. VMAT treatment plans were created on TG-119 structure sets registered to a homogenous RW3 phantom. Dosimetric verification was performed using a calibrated ionisation chamber in absolute dose mode, a detector array, and an independent dose calculation software. Dose-difference ratios between measured and planned 'point doses' in the phantom and the associated confidence limits were derived. Gamma assessment of planned versus measured and independently-calculated dose distributions was evaluated against criteria of 3%/3mm, 3%/2mm, and 2%/2mm at 10% threshold.

Results. The point dose-difference averaged over measurement locations in high-dose regions was 0.019 (0.015) for a confidence limit of 0.048. In the low dose regions, the average dose-difference was 0.012 (0.011) and confidence limit (0.034). The combined 2D gamma passing rates for the MatriXX for 3%/3mm, 3%/2mm, and 2%/2mm criteria were 99.6% (0.24), 98.4% (0.82), and 95.3% (2.01), with confidence limits 0.8, 3.2, and 8.6, respectively. Combined 3D global gamma passing rates for the independent calculation software were 99.9% (0.08), 99.8% (0.25), and 98.3% (2.20). The confidence limits were 0.2, 0.7, and 6.0, respectively.

Conclusion. Dosimetric evaluation yielded passing rates and confidence limits comparable or superior to those of TG 119 and reports of similar studies available in the literature. The dose-difference ratios were also within tolerance limits recommended by TG 218. As such, the commissioning of our VMAT system was validated, and initial local confidence limits were established.

Keywords: IMRT, QA, gamma evaluation

LAY ABSTRACT

A study was done to check acceptable performance in an upgraded radiotherapy system.

INTRODUCTION

Intensity-modulated radiation therapy (IMRT), as an external beam treatment delivery technique, has been proven to improve target dose conformity and to spare organs-at-risk, resulting in better treatment outcomes coupled with lower morbidity.[1-4] Both fixed-gantry IMRT and its rotational variant volumetric modulated arc therapy (VMAT) are offered as standard techniques in most clinics in high-income countries, while some centres in developing countries are now transitioning from 2D and 3D-CRT to IMRT.[5] IMRT is inherently a complex technique requiring rigorous commissioning and acceptance testing before clinical deployment. In addition, after successful implementation, it is recommended that pretreatment verification be performed on every plan before delivery.[6,7] There are recorded fatal incidents attributed to improper implementations and clinical application of the technique.[8,9] A 2008 survey by the Radiological Physics Centre (now Imaging and Radiation Oncology Core, IROC) reported that out of 250 irradiations of a head and neck phantom by centres participating in the RPC credentialing exercise, 28% failed to meet relatively liberal passing criteria of 7% for dose in a low gradient region and 4mm distance-to-agreement in high dose gradient regions.[10] This finding suggested that some IMRT systems had not been adequately commissioned even after the centres had sufficient confidence in their implementations to participate in the survey. Credentialing by the RPC was a requirement for centres wishing to participate in clinical trials run by the Radiation Therapy Oncology Group (RTOG). A review of at least 13000 patient-specific IMRT QA data be-

tween the years 2005 to 2011 from 13 treatment sites concluded that there existed a non-trivial failure rate,[11] further emphasising the importance of accurate commissioning and preclinical validation.

The American Association of Physicists in Medicine (AAPM) Task Group 119 was formed to produce quantitative universal confidence limits against which users may assess their systems' dosimetric commissioning adequacy.[12] To this end, seven different institutions that offered static-beam IMRT treatment planning and delivery on platforms from various manufacturers participated in the task group. Each centre had passed the RPC IMRT credentialing test. The centres were provided with pre-contoured DICOM RT image sets representing clinical head-and-neck (HN), prostate, and a structure set consisting of three cylindrical targets arranged consecutively in the superior-inferior direction (Multitarget), as well as a generalised concave-shaped (CShape) target around a cylindrical avoidance structure. The CShape structure had two different plan goals: an easy objective (CShape (Easy)) was expected to be achieved, while the more challenging objective (CShape (Hard)) was not expected to be achieved and was meant to push an optimisation engine. All centres created IMRT treatment plans using identical planning objectives and constraints and geometric parameters. Verification plans were created, and measurements of point doses and dose distributions at specific locations and planes were done using small-volume ionisation chambers, film, detector arrays, and electronic portal imaging devices, depending on institutes' inventories. Analysis was performed using the gamma index,[13] with the passing rate for criteria of 3%/3mm recorded for composite beam deliveries. From these results, confidence limits were established using the approach by Venselaar and Palta,[14,15] where the confidence limit *CL* is given by $CL = |100-mean|+1.96\sigma$. In this expression, "*mean*" is the average passing rate in an IMRT verification plan for specific passing criteria, and σ is the associated standard deviation. By this approach, if a centre's confidence limit is CL_1, the gamma passing rate is expected to be at least (100 - CL_1) % 95% of the time. Thus, the CLs were used as baseline expectation values for assessing IMRT commissioning: centres wishing to validate their IMRT commissioning would repeat this exercise and determine their local confidence limits. If they fell within the TG 119 baseline values, their commissioning may be considered validated. Otherwise, further investigation could be warranted. Task Group report 218,[16] published in 2018 and considered an update to report 119, provided other recommendations and guidance on patient-specific IMRT QA, considering new developments in treatment delivery methods, verification tools and analysis methodologies. In particular, the report recommends gamma passing rates of ≥ 95%, 3%/2mm, 10% and ≥ 90%, 3%/2mm, 10% for tolerance and action levels, respectively. The use of perpendicular composite (PC) measurements is discouraged in favour of true composite (TC) or perpendicular field by field (PFF) where TC is not possible.

In this study, a dosimetric validation of a VMAT implementation is reported. To the author's knowledge, this implementation was the first in East and Central Africa.

AIM

This study aimed to perform end-to-end validation of an implementation of a RapidArc® treatment planning and delivery system at The Nairobi Hospital in Kenya following recommendations in the TG 119 and TG 218 reports and to establish initial confidence limits. RapidArc is an implementation of VMAT by Varian Medical Systems (Varian) (Varian Medical Systems, Palo Alto, CA, USA).

MATERIALS AND METHODS

Two phantoms were used. The first was a square phantom made from several slabs of RW3 measuring 30cm × 30cm × 15cm. The centre slab was machined to precisely fit a CC13 ionisation chamber (serial number 2323) from IBA Dosimetry (IBA Dosimetry, Schwarzenbruck, Germany) and align its cavity centre with the phantom centre. Four different CT scans were made. First with the ion chamber positioned at a depth of 8.0cm – set as the isocentre, then subsequently at depths of 5.5cm, 10.5cm, and 12.0cm corresponding to TG 119 requirements for ion chamber measurements at positions 2.5cm anterior and 2.5cm, 4.0cm posterior to the isocentre. The scans were performed on a Philips Brilliance 16 (Philips Medical Systems, Eindhoven, Netherlands) using a slice thickness of 3.0mm. The second phantom was an IBA Dosimetry Miniphantom (serial number 21288) with an IBA Dosimetry MatriXX (serial number 18414) ionisation chamber array. This phantom arrangement was scanned on a Toshiba Acquilion One CT scanner (Canon Medical Systems, Otawara, Tochigi, Japan) using a slice thickness of 3mm. The CT image sets were uploaded to the Varian Eclipse v15.6 treatment planning system. Structure sets supplied with TG 119 were transferred to the RW3 phantom via image registration. RapidArc treatment plans, each with a 2-arc arrangement and energy 6MV, were created for all structure sets. Fluence optimisation was performed using Photon Optimizer v15.6.4 according to the plan objectives provided in TG 119. Post optimisation 3D dose calculation was performed with Varian's Anisotropic Analytical Algorithm v15.6.4 using the default grid size of 2.5mm.

The treatment plans were exported to Varian Mobius3D, an independent dose verification software. Our installation had been commissioned following the manufacturer's guidelines. The software uses an independent collapsed cone convolution (CCC) algorithm to recalculate 3D dose distribution on DICOM-RT data sets from the treatment planning system (TPS) and performs 3D gamma analysis per user-specified parameters of passing criteria, calculation grid size and dose threshold. For this study, 3D global gamma analysis was performed for 3%/3mm, 3%/2mm and 2%/2mm passing criteria and dose threshold of 10% of dose maximum. Verification plans were created and calculated on all the square phantom arrangements and the Miniphantom-MatriXX setup. The plans were delivered on

a C-2300CD Linac (Varian Medical Systems, Palo Alto, CA, USA) equipped with the Millenium-120 Multi-leaf Collimator. RapidArc capability was added to this Linac during an upgrade in 2019 after initial commissioning in 2013. Point dose measurements were taken in phantom with the calibrated 0.125cc CC13 ionisation chamber volume connected to an IBA Dosimetry DOSE 1 electrometer (Serial number 17255) in absolute dose mode. For this mode, the detector's $N_{D,w}$, k_Q, and k_S factors had been uploaded and stored on the electrometer using Dose 1 Admin software. Temperature and pressure readings were obtained from an IBA Dosimetry type L36040 thermometer and an OPUS20 THIP (Lufft, Fellbach, Germany) weather station (serial number 030.0919.0802.34), respectively and captured on the electrometer for k_{TP} correction. Before each point-dose measurement, the Linac output was verified to be within 1%.

Planar dose measurements were measured on the Miniphantom-MatriXX arrangement controlled from IBA Dosimetry Omnipro I'MRT v1.6. For comparison purposes, dose planes calculated on the Miniphantom were exported from the TPS with a spatial resolution of 0.762cm to match the detector array. Gamma index analysis was performed using DoseLab Pro v7.0.0. The passing rates for 3%/3mm, 3%/2mm and 2%/2mm criteria within a dose threshold of 10% of the global maximum dose.

RESULTS AND DISCUSSION

Planning

As shown in Table 1, all treatment plans were normalised to meet the TG 119 goals for 100% isodose coverage to at least 95% of the target volume. Figures 1 to 5 show the dose-volume histograms for all the VMAT plans, while Table 2 shows the plan conformity index (CI) and homogeneity index (HI). In this report, the definitions of CI and HI adopted are:

$$CI = \frac{V_{95}}{V_{PTV}} \quad (1)$$

$$HI = \frac{D_5 - D_{95} \times 100\%}{D_{presc}} \quad (2)$$

D_{presc} is the prescribed dose.

TG 119 plan goals were achieved in all plans, except for Core(D_{99}) of the CShape plans. Even the TG 119 average for this dose-volume point was higher than the plan objective by more than 1SD.

Table 1. Treatment planning results achieved at specific dose-volume points for the reference TG 119 and this study

Structure	Parameter	TG 119 Goal (Gy)	TG 119 Result (Gy)	TG 119 SD	RapidArc (Gy)
Mock Prostate					
PTV	D_{95}	75.60	75.66	0.21	75.60
	D_5	83.00	81.40	1.56	82.66
Rectum	D_{30}	70.00	65.36	2.97	59.55
	D_{10}	75.00	73.03	1.50	70.84
Bladder	D_{30}	70.00	43.94	8.78	37.70
	D_{10}	75.00	62.69	8.15	56.96
Mock HN					
	D_{90}	50.00	50.28	0.58	50.00
	D_{99}	46.50	47.04	0.52	47.50
	D_{20}	55.00	52.99	0.93	52.23
	Max	40.00	37.41	2.50	33.65
	D_{50}	20.00	17.98	1.84	15.17
Multitarget					
Central target	D_{99}	50.00	49.55	1.62	50.00
	D_{10}	53.00	54.55	1.73	53.61
Superior target	D_{99}	25.00	25.16	0.85	24.66
	D_{10}	35.00	34.12	3.04	26.78
Inferior target	D_{99}	12.50	14.07	1.85	12.12
	D_{10}	25.00	24.18	2.72	15.18
CShape easier					
PTV	D_{95}	50.00	50.10	0.17	50.00
	D_{10}	55.00	54.44	0.17	53.58
Core	D_{99}	25.00	22.00	3.14	26.78
CShape harder					
PTV	D_{95}	50.00	50.11	0.17	50.00
	D_{10}	55.00	57.02	2.20	54.28
Core	D_{99}	10.00	16.30	3.07	15.50

Table 2. Measures of plan quality

	Prostate	HN	Multitarget	CShape easier	CShape harder
Conformity index	1.24	1.18	1.41	1.28	1.30
Homogeneity index	9.3%	7.4%	7.7%	7.7%	9.2%
MU	592	727	469	811	895

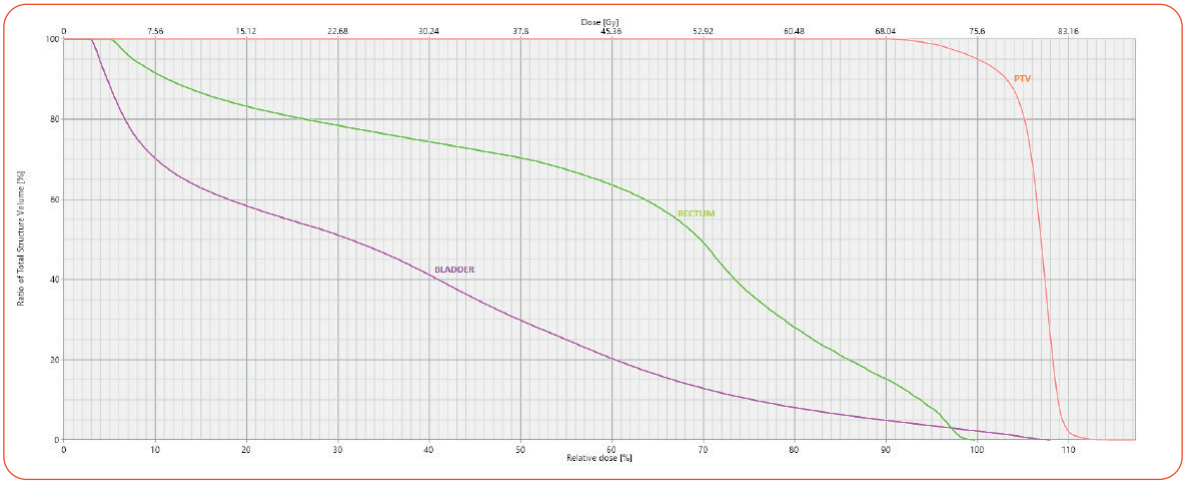

Figure 1. Dose-volume histograms for mock prostate plan.

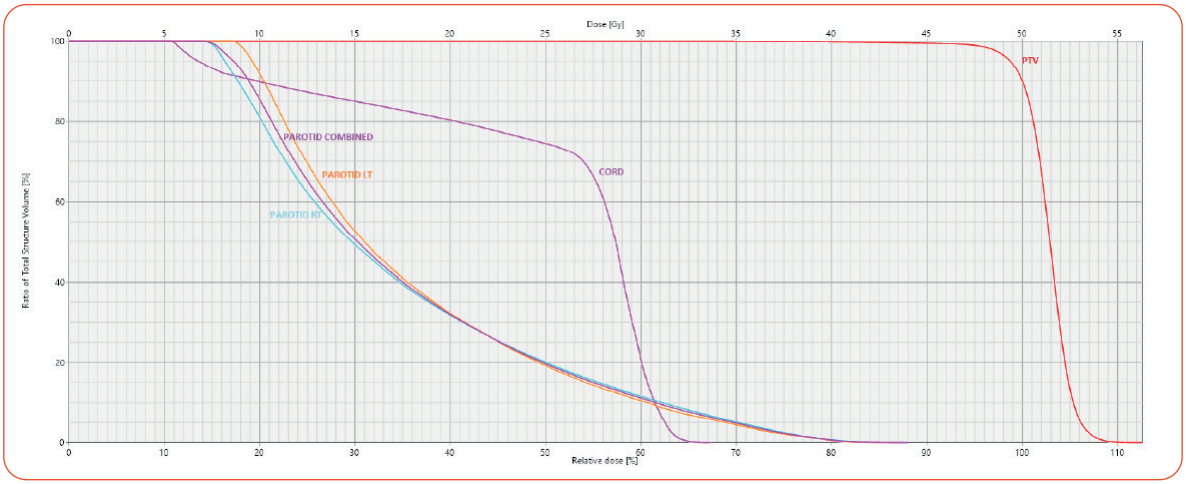

Figure 2. Dose-volume histograms for the H&N plan.

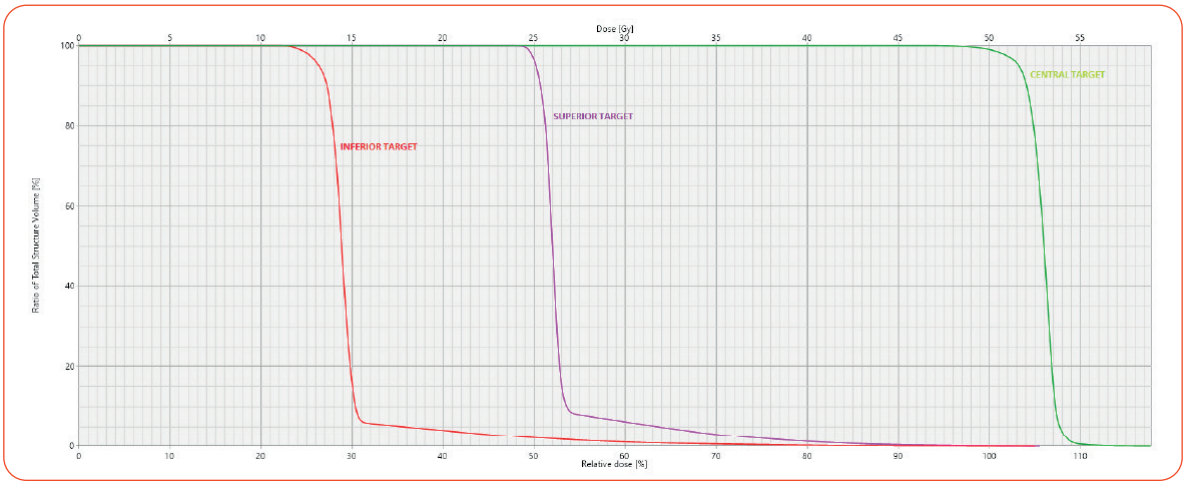

Figure 3. Dose-volume histograms for the multitarget plan.

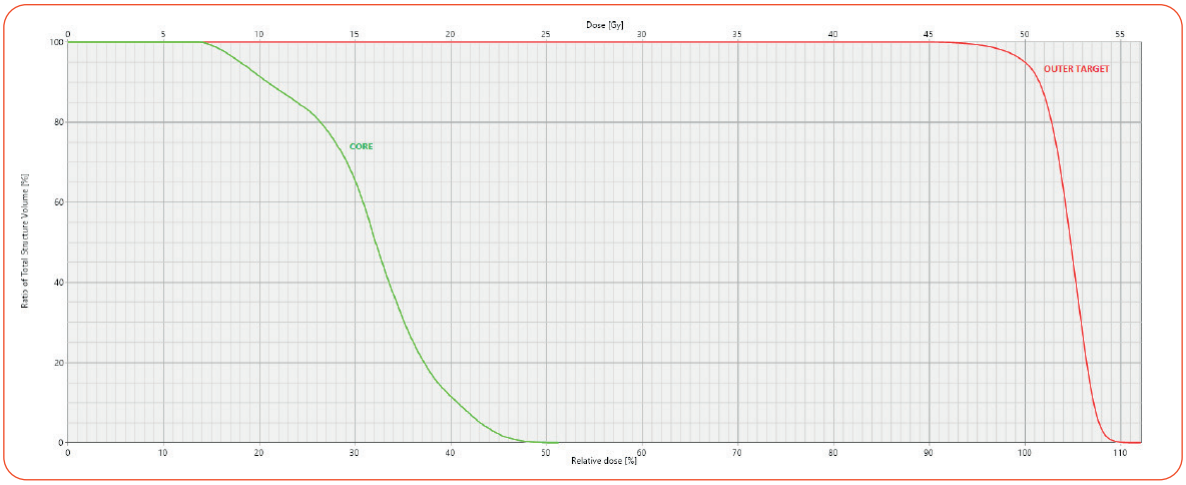

Figure 4. Dose-volume histograms for CShape(Easy) plan.

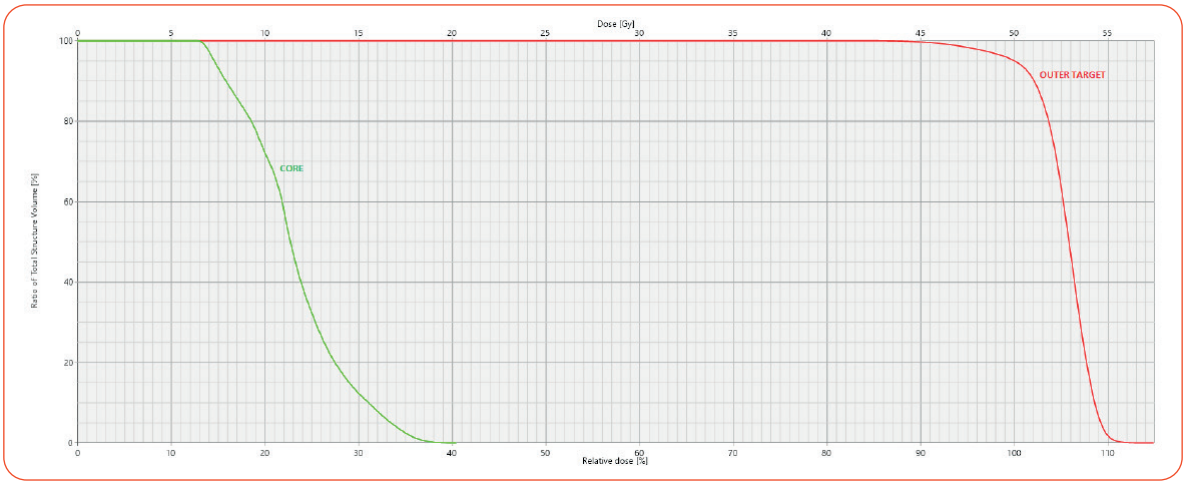

Figure 5. Dose-volume histograms for CShape(Hard) plan.

Table 3. 2D (MatriXX) and 3D (Mobius3D) gamma passing rates for the true composite setup

Test case	MatriXX			Mobius3D		
	3%/3mm	3%/2mm	2%/2mm	3%/3mm	3%/2mm	2%/2mm
Multitarget	99.8	98.8	97.9	100	100	99.9
Prostate	99.9	99.6	96.4	100	100	99.9
H&N	99.7	98.3	95.8	99.8	99.4	94.6
CShape (easier)	99.3	97.6	93.4	99.9	99.9	98.4
CShape (harder)	99.5	97.7	93.2	99.9	99.9	98.6
Overall combined	99.6 (0.24)	98.4 (0.82)	95.3 (2.01)	99.9 (0.08)	99.8 (0.25)	98.3 (2.17)
Confidence limit	0.8	3.2	8.6	0.2	0.7	6.0

Table 4. Ion chamber measurements at specific in-phantom locations for RapidArc treatment. D_M, D_P, and D_{Pr} are the planned and prescribed doses respectively

Test case	Location	D_{Pr}	D_M	D_P	High dose $\frac{D_M - D_P}{D_{Pr}}$	Low dose $\frac{D_M - D_P}{D_{Pr}}$
Multitarget	Isocentre	2.0	2.107	2.089	0.009	
Prostate	Isocentre	2.1	2.299	2.304	-0.002	
	2.5cm posterior		1.544	1.551		-0.003
H&N	Isocentre	2.0	2.150	2.088	0.031	
	4.0cm posterior		1.166	1.122		0.022
CShape (easier)	Isocentre	2.0	0.533	0.500		0.017
	2.5cm anterior		2.146	2.098	0.024	
CShape (harder)	Isocentre	2.0	0.469	0.442		0.014
	2.5cm anterior		2.202	2.138	0.032	
				Mean	0.019	0.012
				Standard deviation	0.015	0.011
				Confidence limit	0.048	0.034

Planning results for the mock HN were either on par with or better than TG 119. For the mock prostate, the PTV(D_5) was higher than TG 119 by 1.26 Gy.

Composite measurements

Table 3 shows global 2D and 3D gamma evaluation results for passing criteria of 3%/3mm, 3%/2mm, and 2%/2mm, using a dose threshold of 10%. The Miniphantom was irradiated using patient geometry in a true composite setup, per TG 218 recommendation. However, due to the limitations of the Miniphantom, only the isocentric coronal plane could be evaluated. The passing rates for all plans were better than both TG 119 reference rates and results reported by Mynampati et al.[19] and Nainggolan et al.,[20] whose studies employed a MatriXX array. Although there are concerns about the suitability of the MatriXX device used in this geometric setup due to the angular dependence of its response,[21] it is accepted that this dependence is 'smeared out' when using VMAT delivery.[16] 3D gamma evaluation results are also reported for the software-based secondary verification tool Mobius3D. The average passing rates for all plans for all passing criteria were greater than 98%,

keeping with findings by Lee et al.[22] Although the development of universal guidelines on the implementation of software-based IMRT verification solutions is still a work in progress, studies suggest that such methods are superior in specificity and sensitivity to measurement-based solutions for detecting errors.[23,24]

Ionisation chamber measurements

For this study, nine out of the 11 recommended point dose measurements were done. Measurements at the multitarget plan's remaining superior and inferior position could not be done because our phantom did not allow placement of the ion chamber at positions superior or inferior to the isocentre. As shown in Table 4, in the high dose regions, the average absolute difference between planned and measured doses (normalised to prescribed dose) was higher than the TG 119 reference value (0.2%) but lower than the TG 218 recommended tolerance limit of ≤ 2%. Our confidence limit was 4.8% against 4.5% of TG 119. The mean IC dose difference was slightly higher in the low dose avoidance regions than the TG 119 reference (0.3%). The confidence limit was 3.4% for the low dose regions, better than the reference of 4.7%. These results compare well with those of Monti et al.[17] and Kumar et al.,[18] who performed similar studies, albeit on phantoms specially built for VMAT plan verification, as opposed to the square slab phantom in this study.

CONCLUSION

The commissioning of VMAT has been validated according to recommendations of the AAPM TG 119 and TG 218, and initial confidence limits have been established successfully for pretreatment verification using an ion chamber, a MatriXX detector array, and Mobius3D independent calculation software. The high gamma passing rates from Mobius3D evaluation using passing criteria of 3%/3mm, 3%/2mm, and 2%/2mm provide further confidence that our system was accurately commissioned. The results of this work could potentially contribute to the establishment of universal confidence limits for VMAT for measurement and software pretreatment evaluation tools.

COMPETING INTERESTS

The author declares that no competing interests exist.

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