

Validation of the RapidArc Delivery System Using a Volumetric Phantom as Per Task Group Report 119 of the American Association of Physicists in Medicine

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Abstract

Aim: This study validated the RapidArc (RA) delivery using a volumetric ArcCHECK phantom as per the guidelines proposed in Task Group Report 119 from the American Association of Physicists in Medicine Task group 119 (AAPM TG 119). This study also investigated the impact of the Acuros XB (AXB) algorithm in comparison to analytical anisotropic algorithm (AAA) on the RA dose calculations in the homogeneous medium of the ArcCHECK phantom. **Materials and Methods:** A volumetric ArcCHECK phantom along with AAPM TG 119 tests was used to evaluate the RA plans and verify the dose delivery for photon beam of 6 MV energy. **Results:** The RA planning results were comparable and satisfied the planning criteria stated in the TG 119 report for all test cases. The average percentage gamma passing rates for the AAA-calculated plans were 98.5 (standard deviation [SD]: 0.6), 98.5 (SD: 1.3), and 98.1 (SD: 2.0) and for the AXB-calculated plans were 95.1 (SD: 1.8), 96.1 (SD: 1.3), and 94.0 (SD: 0.9) for the Clinac-iX (6 MV) and TrueBeam (TB)-STx (6 MV_filtered beam [FB] and 6 MV_flattening filter-free beam [FFFB]), respectively. For ion chamber measurements, the average percentage dose differences for the AAA-calculated plans were 1.5 (SD: 2.5), 2.7 (SD: 1.4), and 1.4(SD: 2.7) and for AXB-calculated plans were 2.3 (SD: 1.6), 3.2 (SD: 1.5), and 2.3 (SD: 2.0) for Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 MV_FFFB), respectively. **Conclusion:** Thus, the ArcCHECK can successfully be utilized for the validation of the RA delivery. The AXB has potential to perform dose calculations comparable to those of the AAA for RA plans in the homogeneous medium of the ArcCHECK phantom.

Keywords: American Association of Physicists in Medicine Task group 119, Acuros XB, ArcCHECK, RapidArc

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INTRODUCTION

Volumetric modulated arc therapy (VMAT) is a novel technique proposed by Otto.^[1] The concept of rotational therapy was initially explored by Brahme *et al.*^[2] Later in 1995, Yu^[3] proposed the clinical use of intensity modulated arc therapy (IMAT) with field shape modulated per gantry angle on the linear accelerator to produce conformal dose distribution. VMAT is the extension of the IMAT principle.

RapidArc (RA) radiation therapy is one of the most sophisticated technologies available in radiotherapy (RT) departments worldwide. It more precisely targets a cancerous tumor while sparing the healthy surrounding tissues. It also significantly reduces patient treatment times and radiation exposure. In the RA technique, the optimal dose distribution

with efficient treatment delivery can be achieved with the interplay of various modulation parameters such as dose rate, gantry rotation speed, multileaf collimator (MLC) movement, and the number of control points.^[1,4] However, owing to the physical limitations of hardware operation and misalignment between the dosimetric and mechanical components of the linear accelerator, dose discrepancies can occur in the radiation

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beam delivery.^[5,6] Thus, it is desirable to employ appropriate and extensive quality assurance (QA) at the RA planning and delivery level, as errors at these stages may alter the treatment outcomes. However, it is tedious and laborious to perform RA QA at an individual level because of the various complex parameters involved.

Task group (TG) 119 of the American Association of Physicists in Medicine (AAPM) has proposed a guideline for IMRT commissioning and QA.^[7] The goal of this report was to quantify the overall performance of the IMRT systems. The concept of the TG 119 has also been successfully utilized to quantify the overall performance of VMAT or RA delivery by Wen *et al.*,^[8] Mynampati *et al.*,^[9] and Nithya *et al.*^[10]

The present study validated RA delivery using a volumetric ArcCHECK phantom as per the guidelines proposed in TG 119 report. This study also investigated the impact of the Acuros XB (AXB) algorithm on RA plan dose calculations in the homogeneous medium of the ArcCHECK phantom.

MATERIALS AND METHODS

The ArcCHECK (Model 1220, Sun Nuclear Corporation, Melbourne, Florida) is a three-dimensional (3D) beam dosimetry QA system intended for the measurement of RT dose distributions that are delivered as defined by a planning system and compared to the dose distribution as calculated by the planning system.^[11] It is a cylindrical water-equivalent phantom with a 3D array of 1386 diode detectors arranged in a spiral pattern with 10-mm sensor spacing. The active area of each detector is 0.8 mm × 0.8 mm, and the sensitivity is 0.4 nC/Gy. There are no time or dose limits for measurements using the ArcCHECK phantom. A temperature sensor measures the ambient temperature of the detector area. Dose measurements from each sensor are updated every 50 milli seconds. The ArcCHECK is also equipped with two inclinometers, to help measuring the angle of rotation about the cylinder axis as well as the tilt of the axis. The center of the phantom (15 cm diameter) is designed to accommodate various accessories such as a solid homogeneous core, a dosimetric core with ion chamber(s) or diode arrays, an imaging QA core, and a core with heterogeneous materials for dose studies.^[12]

For point dose verification, a CC 13S (IBA Dosimetry, Germany) ion chamber with a Dose 1 (IBA Dosimetry, Germany) electrometer was used for absolute point dose measurements in conjunction with the ArcCHECK. The ion chamber was placed in the central core of the ArcCHECK at the isocenter of the linear accelerator. Diodes were kept 2.9 cm below the surface of the ArcCHECK; this thickness of the buildup material is equivalent to 3.3 cm of water. Dose fluence maps were acquired at 89.6 cm, i.e., the diode level, and measured in cumulative mode. Dose fluence maps and absolute point dose measurements were performed simultaneously. The ion chamber readings were corrected for temperature and pressure variation. SNC patient software version 6.2 (Sun

Nuclear Corporation, Melbourne, Florida) was used to compare the calculated and measured doses.

For analysis purposes, the gamma criteria of 3 mm distance to agreement and 3% dose difference (DD) were used for the evaluation of the RA plans, with a threshold value 10%. A gamma passing rate of 90% and above was considered acceptable.^[13] A tolerance limit of ± 5% was considered acceptable for ion chamber measurements in comparison to the treatment planning system (TPS) calculations.

The AAPM TG 119 computed tomography (CT) and radiotherapy (RT) structure sets are available at <http://www.aapm.org/pubs/tg119/default.asp>. The RT structures were imported into Eclipse TPS. Thereafter, these DICOM RT structures were fused and registered on the CT images of a homogeneous ArcCHECK phantom provided by Sun Nuclear. In this study, the following test cases were used for planning and delivery verification: multi-target, prostate, head and neck, C-shape (easy), and C-shape (hard). Full descriptions of these structures are available in the AAPM TG 119 report.

Varian linacs, namely, TrueBeam (TB)-STx (60 leaf pairs high-definition [HD] MLC: inner 32 leaf pairs 0.25 cm and outer 28 leaf pairs 0.5 cm resolution at isocenter) and a Clinac-iX (2300CD) (60 leaf pairs millennium MLC: inner 40 leaf pairs 0.5 cm and outer 20 leaf pairs 1.0 cm resolution at isocenter) were used for this study. Eclipse TPS version 11 (Varian Medical System, Palo Alto, USA) was used for RA planning. Aria version 11 (Varian Medical System, Palo Alto, USA) was used for the record and verification system. A filtered beam (FB) of 6 MV from the Clinac-iX linac machine and FB and flattening filter-free beam (FFF) 6 MV from the TB-STx were used for planning purposes. The dose rates were 600 MU (6 MV_FB) and 1200 MU (6 MV_FFF) per minute, respectively. Linac calibration was performed under the reference conditions prescribed by Technical Series Report no. 398 recommended by the International Atomic Energy Agency.^[14] The linac was calibrated at 1 cGy per MU for a reference source-to-skin distance of 100 cm at the d_{max} depth for their respective photon beams (Clinac-iX: 6 MV and TB: 6 MV_FB and 6 MV_FFF).

RA planning was performed for all mentioned test sites as prescribed in the AAPM TG 119 report. All treatment plans and dose calculations were performed with Eclipse TPS version 11 for both linacs. The RA plans were optimized using the progressive resolution optimizer 3 algorithm (PRO3, second generation), and the concept of PRO was described by Otto.^[1] In this algorithm, the full arc is progressively optimized at 178 control points in four phases. At every iteration level, it optimizes the MLC position and monitor unit (MU) weight within the limitations (MLC speed, gantry speed, dose rate, and mechanical limits) of the delivery unit.^[15] During optimization, dose calculation is performed with a simplified multi-resolution dose calculation algorithm. To mitigate leakage due to the tongue and groove effect, the collimator was rotated to 30° from the nominal angle. The

final dose calculations were carried out using the analytical anisotropic algorithm (AAA) with a dose grid resolution of $1.5 \text{ mm} \times 1.5 \text{ mm} \times 1.5 \text{ mm}$. Keeping the number of MUs the same, the plans were also recalculated using the AXB algorithm for comparison with the AAA-calculated results. The ArcCHECK phantom was assigned as poly (methyl methacrylate) (PMMA) material with mass density of 1.160 g/cm^3 and assigned CT value was 231 Hounsfield unit (HU).

Evaluation parameters

Each RA plan was evaluated with respect to the AAPM TG 119 planning criteria. Apart from the AAPM TG 119 criteria, for intercomparison, these results were also evaluated with respect to MLC type, beam type, and dose calculation algorithm type. The conformity index (CI) was calculated as the ratio between the volume covered by the prescribed isodose and the target volume.^[16] The prescription doses (PD) for the C-shape, head and neck, multi-target, and prostate test cases were 50, 50, 50, and 76 Gy, respectively. Similarly, the homogeneity index (HI) was calculated as the DD normalized to the dose prescribed between doses covering 5% (D_5) and 95% (D_{95}) of the target.^[16]

Further, the dose-spillage volumes were computed to assess the normal tissue sparing outside the target volume. The following virtual structures were assessed for the different dose spillage volumes: (a) high-dose spillage volume (V_{HS}) taking into account of normal tissue receiving the >90% of the PD, (b) intermediate-dose spillage volume (V_{IS}) taking into account of normal tissue receiving >50% of the PD, (c) low-dose spillage volume (V_{LS}) taking into account of normal tissue receiving >25% of the PD. Finally, the treatment efficiency of each RA plan was calculated as a ratio of the cumulative sum of MUs per fraction to the dose per fraction. A two-sample paired *t*-test was performed to find the statistical significance of these results. A *P*-value < 0.05 was considered statistically significant with 95% confidence limit.

RESULTS

Treatment planning benchmarking is necessary for RT institutes to investigate their planning ability and to facilitate a review of the accuracy of TPSs under local relevant conditions. Table 1 shows the planning results for all test cases: C-shape (easy), C-shape (hard), head and neck, multi-target, and prostate, with planning goals and their respective results reported in the AAPM TG 119 report. The RA plan results were comparable to those of the AAPM TG 119 report and satisfied or exceeded all planning criteria stated in the AAPM TG 119 for all test cases. RA plans were optimized using couch modeling, a set of HUs valid for low and high energy, and the entire couch length was used as couch surface HU: -300 and couch interior HU: -1000. Figure 1 presents the test structures on an ArcCHECK phantom with the planned dose for the RA plans.

Analytical anisotropic algorithm-calculated plans

For the C-shape test cases in Table 1, the PTV D_{95} and PTV D_{10} for the Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 MV_FFFB) were comparable to the AAPM TG 119 results.

The core D_{10} results were not achieved in the C-shape (hard) test cases. However, these results were comparable to the AAPM TG 119, which also reported higher values. Figures 2 and 3 show the dose-volume histogram (DVH) comparison for C-shape (easy) and C-shape (hard) test cases from RA plans calculated using the AAA and AXB algorithms for the Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 MV_FFFB), respectively.

For the head-and-neck test case, the target coverage PTV D_{90} was comparable to the AAPM TG 119 for all plans. Cord (d_{max}) and parotid D_{50} also satisfied the planning criteria stated in the AAPM TG 119 report for all RA plans. Figure 4 presents the DVH comparison for the head-and-neck test case from the RA plans calculated using the AAA and AXB algorithm for the Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 MV_FFFB), respectively.

For the multi-target test case in Table 1, all plans achieved the planning goals and were comparable to the AAPM TG 119 except for the central D_{99} , which was slightly lower than the AAPM TG 119 but comparable to the standard deviation (SD) in TG 119 results (1.62 Gy). Figure 5 shows the DVH comparison for the multi-target test case from RA plans calculated using the AAA and AXB algorithms for the Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 MV_FFFB), respectively.

For the prostate case in Table 1, the target coverage was comparable to those of the AAPM TG 119 results for all plans. Bladder dose (D_{30} and D_{10}) and rectum dose (D_{30}) were lower than those of the AAPM TG 119. The rectum dose D_{10} was comparable to that of the AAPM TG 119. Figure 6 shows the DVH comparison for the prostate test case from the RA plans calculated using AAA and AXB algorithm for the Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 MV_FFFB), respectively.

Acuros XB-calculated plans

This study also investigated the impact of the AXB dose calculation algorithm in RA treatment delivery. The results calculated with the AXB algorithm are shown in Table 1 in comparison to the AAA-calculated results. The AXB showed a lower dose to target structures by average percentage DDs of 1.05 (SD: 0.83), 1.89 (SD: 1.32), and 2.33 (SD: 1.02) for the Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 MV_FFFB), respectively. Similarly, the AXB showed a lower dose to the organ-at-risk (OARs) structures by average percentage DDs of 0.39 (SD: 2.28), 4.79 (SD: 2.05), and 5.26 (SD: 2.55) for the Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 FFFB), respectively.

Tables 2 and 3 show the average CI and HI for RA plans calculated using the AAA and AXB algorithms, respectively. The average CIs were 1.010 (SD: 0.055), 1.011 (SD: 0.057), and 1.013 (SD: 0.058), and the average HIs were 0.061 (SD: 0.011), 0.052 (SD: 0.010), and 0.056 (SD: 0.011) using the AAA calculation for the Clinac-iX (6 MV) and TB-STx (6

Table 1: RapidArc planning on an ArcCHECK phantom for all structures in comparison to the American Association of Physicists in Medicine task group 119 report for the Clinac-iX (6 MV) and TB-STx (6 MV_filtered beam and 6 MV flattening filter-free beam), respectively

Parameters	Plan goal (cGy)	Clinac-iX		TB-STx				TG 119
		6MV FB		6MV FB		6 MV FFFB		6 MV
		AAA	AXB	AAA	AXB	AAA	AXB	Mean±SD
C Shape (easier)								
PTV D ₉₅	5000	5001.4	4951.8	5003.8	4939.3	5005.1	4895.5	5010±17
PTV D ₁₀	<5500	5299.2	5260.5	5243.9	5170.5	5241.1	5132.7	5440±52
CORE D ₁₀	<1000	2271.1	2229.1	2088.6	1932.2	2131.2	1963.9	2200±314
C Shape (hard)								
PTV D ₉₅	5000	5003.2	4950.7	5000.5	4939.7	5000.5	4907.1	5011±16.5
PTV D ₁₀	<5500	5362.3	5326.1	5310.9	5237.7	5310.0	5212.2	5702±220
CORE D ₁₀	<1000	1715.3	1648.7	1418.3	1322.6	1447.9	1300.5	1630±307
H and N								
PTV D ₉₀	5000	5001.8	4963.2	5001.4	4915.7	5003.3	4895.0	5028±58
PTV D ₉₉	>4650	4846.7	4786.5	4849.6	4780.3	4854.2	4761.9	4704±52
PTV D ₂₀	<5500	5143.5	5096.5	5143.2	5053.9	5150.2	5041.5	5299±93
Cord (dmax)	<4000	3408.3	3359.4	3417.2	3250.8	3487.6	3297.1	5741±250
Rt Parotid D ₅₀	<2000	1769.6	1754.3	1744.9	1638.1	1749.8	1655.1	1798±184
Lt Parotid D ₅₀	<2000	1860.9	1819.8	1723.4	1612.2	1715.9	1613.3	1798±184
Multi-target								
Central D ₉₉	>5000	4897.9	4759.2	4977.9	4852.1	4979.3	4808.6	4955±162
Central D ₁₀	<5300	5296.3	5303.1	5287.7	5285.7	5296.1	5239.4	5455±173
Superior D ₉₉	>2500	2573.3	2570.1	2598.9	2530.2	2591.5	2497.8	2516±85
Superior D ₁₀	<3500	2910.5	2892.1	2935.1	2867.9	2912.6	2869.3	3412±304
Inferior D ₉₉	>1250	1320.7	1286.5	1295.5	1218.9	1312.7	1252.7	1407±185
Inferior D ₁₀	<2500	1680.1	1649.9	1666.4	1620.8	1669.4	1606.1	2418±272
Prostate								
Prostate D ₉₅	>7560	7628.3	7531.9	7584.1	7508.8	7571.9	7467.8	7566±21
Prostate D ₅	<8300	8107.5	8086.1	7993.9	7905.3	7982.3	7861.4	8143±156
Rectum D ₃₀	<7000	4890.3	4810.8	4661.8	4509.6	4738.5	4572.1	6536±297
Rectum D ₁₀	<7500	7437.7	7247.3	7383.9	7244.5	7375.2	7207.9	7303±150
Bladder D ₃₀	<7000	2944.9	2880.1	2760.3	2646.3	2781.3	2669.2	4304±878
Bladder D ₁₀	<7500	5096.4	5045.5	4857.3	4751.8	4685.1	4563.1	6269±815

AAA: Analytical anisotropic algorithm, AXB: Acuros XB, FFF: Flattening filter-free, SD: Standard deviation, TB: TrueBeam

Table 2: Conformity index for the task group 119 test cases from the analytical anisotropic algorithm and Acuros XB algorithm-calculated RapidArc plans for the Clinac-iX (6 MV) and TB-STx (6MV_filtered beam and 6MV_flattening filter-free beam), respectively

Structure	CI					
	Clinac-iX (6MV FB)		TB-STx (6MV FB)		TB-STx (6MV FFFB)	
	AAA	AXB	AAA	AXB	AAA	AXB
C Shape (easier)	1.037	0.970	1.035	0.953	1.033	0.785
C Shape (hard)	1.055	0.997	1.046	0.974	1.049	0.911
H and N	0.923	0.955	0.929	0.492	0.935	0.399
Multi-target	1.045	0.963	1.069	1.048	1.077	1.010
Prostate	0.989	0.943	0.977	0.923	0.971	0.851
Mean±SD	1.010±0.055	0.966±0.020	1.011±0.057	0.878±0.221	1.013±0.058	0.791±0.234

TB: TrueBeam, FB: Filtered beam, FFFB: Flattening filter-free beam, CI: Conformity index, AAA: Analytical anisotropic algorithm, AXB: Acuros XB, SD: Standard deviation

MV_FB and 6 MV_FFFB), respectively. The average CIs were 0.966 (SD: 0.020), 0.878 (SD: 0.221), and 0.791 (SD: 0.234) and the average HIs were 0.066 (SD: 0.013), 0.053 (SD: 0.008),

and 0.059 (SD: 0.013) using the AXB algorithm calculation for the Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 FFFB), respectively. The calculated *P*-values for CI and HI

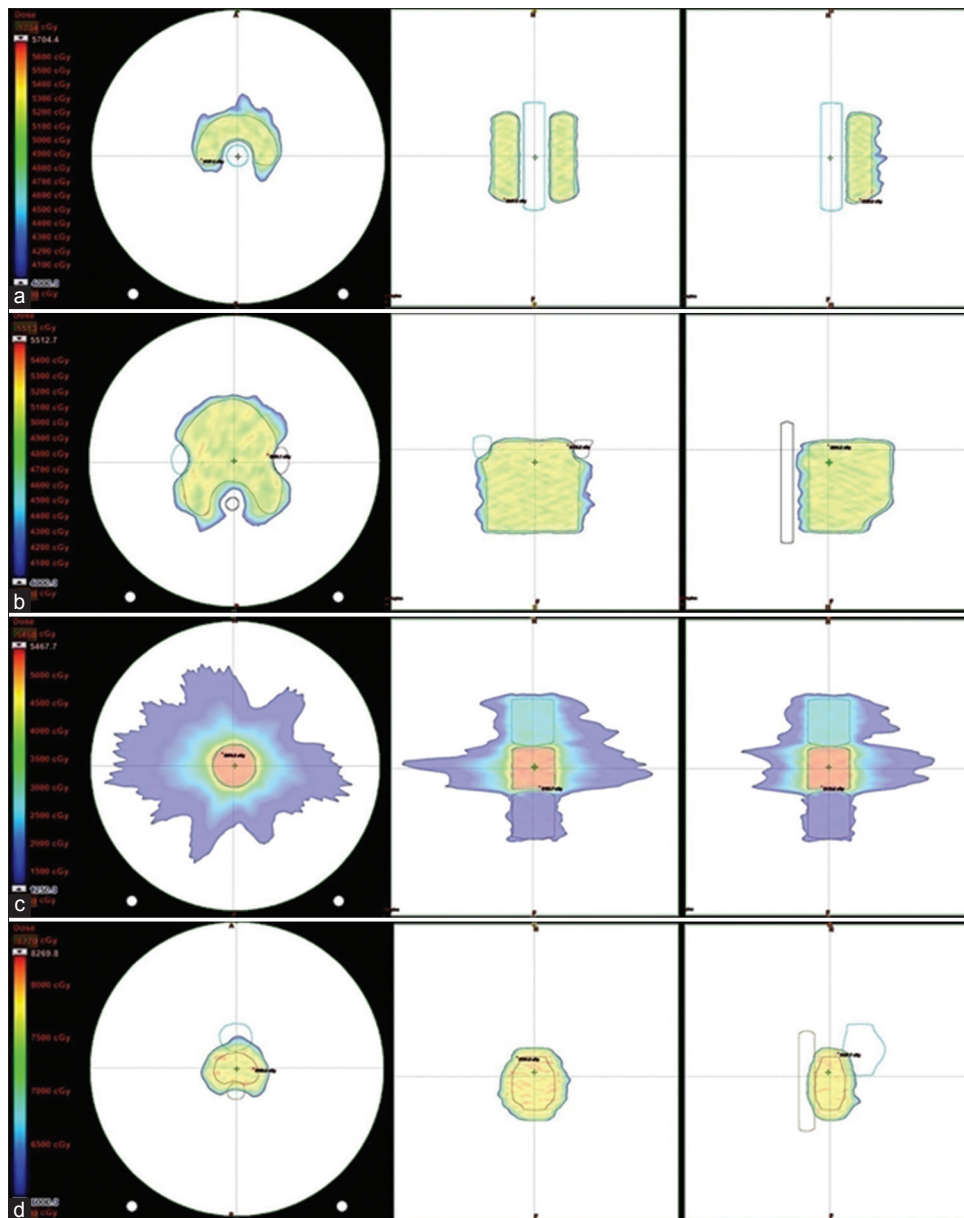


Figure 1: Structures (a) C-shape, (b) head and neck, (c) multi-target, and (d) prostate on an ArcCHECK phantom with planned doses for RapidArc planning in transverse, frontal, and sagittal planes

were > 0.05 for the AAA and AXB-calculated plans, which were not statistically significant.

Millennium versus high-definition multileaf collimator analysis

This study also investigated the impact of the different type of multileaf collimator (MLC) used in RA planning for photon beams of 6 MV energy generated using Clinac-iX and TB-STx, respectively. The results for these MLC systems are shown in Table 1 for AAA and AXB calculation. For AAA calculations, the average percentage DDs found in target coverage were 0.22 (SD: 0.94) and for OARs DD was 5.58 (SD: 5.30) between millennium and HD-MLC, respectively. Similarly, for AXB calculations, the average percentage DDs found in target coverage was 1.07 (SD: 1.54) and for OARs DD was 8.29 (SD:

5.85) between millennium and HD-MLC, respectively. There was no significant difference ($P > 0.05$) found in CI for RA planning using millennium and HD-MLC systems for AAA and AXB dose calculation algorithms, respectively. However, there was significant difference ($P < 0.05$) found in HI for RA planning using millennium and HD-MLC systems for AAA and AXB dose calculation algorithms, respectively. In overall, HD-MLC produces comparable CI and superior HI in comparison to millennium MLC system.

Filtered beam versus flattening filter-free beam analysis

In addition, this study investigated the impact of the different type of photon beams of 6 MV energy generated using TB-STx in flattening filter and flattening filter-free mode, respectively. The results for these different beam types are shown in Table 1

for AAA and AXB calculation. For AAA calculations, the average percentage DDs found in target coverage was 0.04 (SD: 0.43) and for OARs DD was 0.53 (SD: 1.82) between FB and FFFB, respectively. Similarly, for AXB calculations, the average percentage DDs found in target coverage was 0.40 (SD: 0.94)

and for OARs DD was 0.03 (SD: 1.85) between FB and FFFB, respectively. There was no significant difference ($P > 0.05$) found in CI and HI using FB and FFFB of 6 MV energy for AAA and AXB dose calculation algorithms, respectively, except CI ($P < 0.05$) for AXB calculation.

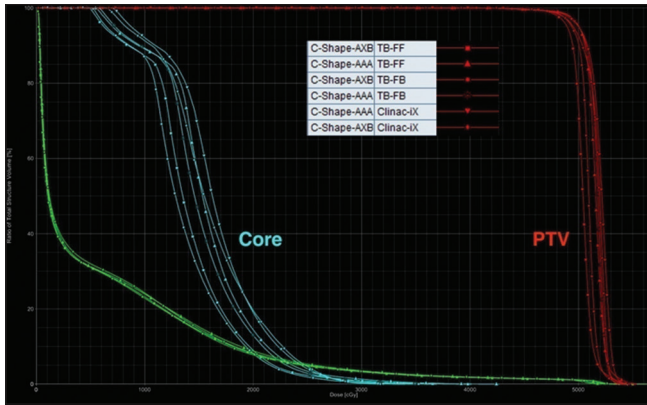


Figure 2: Dose-volume histogram comparisons of the C-shape (easy) case from RapidArc plans calculated using the analytical anisotropic algorithm and Acuros XB algorithm for the Clinac-iX (6 MV) and TrueBeam-STx (6 MV filtered beam and 6 MV flattening filter-free beam), respectively

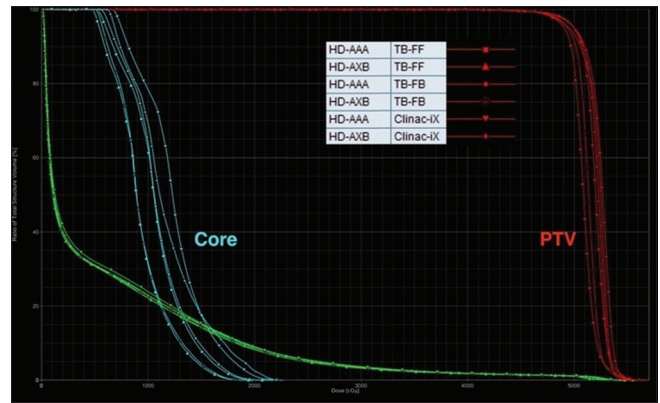


Figure 3: Dose-volume histogram comparisons of the C-shape (hard) case from RapidArc plans calculated using the analytical anisotropic algorithm and Acuros XB algorithm for the Clinac-iX (6 MV) and TrueBeam-STx (6 MV filtered beam and 6 MV flattening filter-free beam), respectively

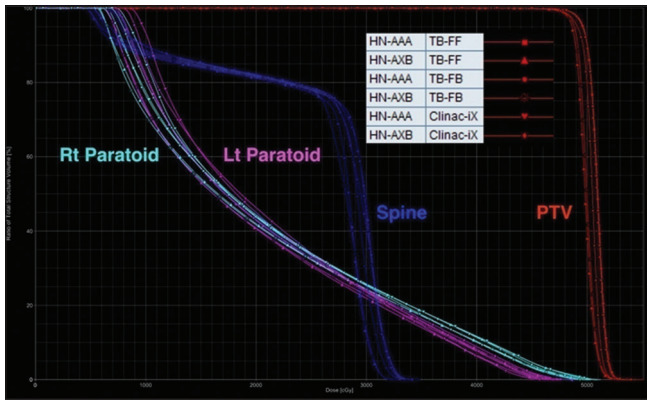


Figure 4: Dose-volume histogram comparisons of the head-and-neck case from RapidArc plans calculated using analytical anisotropic algorithm and Acuros XB algorithm for the Clinac-iX (6 MV) and TrueBeam-STx (6 MV filtered beam and 6 MV flattening filter-free beam), respectively

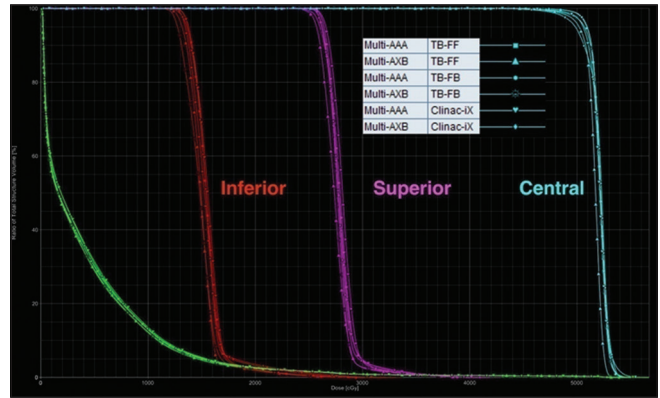


Figure 5: Dose-volume histogram comparisons of the multi-target case from RapidArc plans calculated using analytical anisotropic algorithm and Acuros XB algorithm for the Clinac-iX (6 MV) and TrueBeam-STx (6 MV filtered beam and 6 MV flattening filter-free beam), respectively

Table 3: Homogeneity index for task group 119 test cases from the analytical anisotropic algorithm and Acuros XB algorithm-calculated RapidArc plans for the Clinac-iX (6 MV) and TB-STx (6 MV filtered beam and 6 MV flattening filter-free beam), respectively

Structure	HI					
	Clinac-iX (6MV FB)		TB-STx (6MV FB)		TB-STx (6MV FFFB)	
	AAA	AXB	AAA	AXB	AAA	AXB
C shape (easier)	0.064	0.065	0.052	0.052	0.054	0.057
C shape (hard)	0.076	0.079	0.067	0.067	0.070	0.072
H and N	0.046	0.046	0.042	0.046	0.047	0.048
Multi-target	0.055	0.069	0.044	0.047	0.045	0.047
Prostate	0.063	0.073	0.053	0.052	0.063	0.073
Mean±SD	0.061±0.011	0.066±0.013	0.052±0.010	0.053±0.008	0.056±0.011	0.059±0.013

HI: Homogeneity index, TB: TrueBeam, FB: Filtered beam, FFFB: Flattening filter-free beam, AAA: Analytical anisotropic algorithm, AXB: Acuros XB, SD: Standard deviation

Dose spillage volume analysis

Dose spillage volumes normalized to target volume are shown in Table 4, along with their *P* values comparing for different MLC and beam type using AAA, AXB calculation for Clinac-iX (6 MV), and TB-STx (6 FB and 6 FFFB), respectively. There was significant difference ($P < 0.05$) found in V_{HS} , V_{IS} , and V_{LS} for the millennium and HD-MLC system using AAA and AXB calculation, respectively. For AAA calculations, there was no significant difference ($P > 0.05$) found in dose spillage volume V_{HS} and V_{IS} , except V_{LS} ($P < 0.05$) between millennium and HD-MLC system for 6 MV photon beam. For AXB calculations, there was significant difference ($P < 0.05$) found in dose-spillage volume V_{HS} , V_{IS} , and V_{LS} between millennium and HD-MLC system for 6 MV photon beam. There was no significant difference ($P > 0.05$) found in dose spillage volume V_{HS} , V_{IS} , and V_{LS} between FB and FFFB for both algorithm calculations.

Treatment efficiency

For the evaluation of the treatment efficiency of RA plans for filtered and flattening filter-free photon beams of 6MV using millennium and HD-MLC system, the numbers of MUs per dose fraction were also studied. The MUs were 4.30 ± 1.54 , 4.32 ± 1.62 , and 5.00 ± 1.90 for Clinac-iX (Millennium, 6 MV) and TB-STx (HD, 6 MV_FB and 6 MV_FFFB), respectively. There was no significant difference found in MU per dose fraction for FB of 6 MV energy generated using Clinac-iX (Millennium) and TB-STx (HD), respectively. On the other side, there was a significant increase in MU per dose

fraction for FFFB of 6 MV energy over FB of 6 MV energy generated using TB-STx (HD), respectively.

Gamma and dose difference evaluation

Tables 5 and 6 show the results of the gamma evaluation and ion chamber measurement for all RA plans, respectively. The average percentage gamma passing rates for the AAA-calculated plans were 98.5 (SD: 0.6), 98.5 (SD: 1.3), and 98.1 (SD: 2.0) for the Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 MV_FFFB), respectively. The average percentage gamma passing rates for the AXB-calculated plans were 95.1 (SD: 1.8),

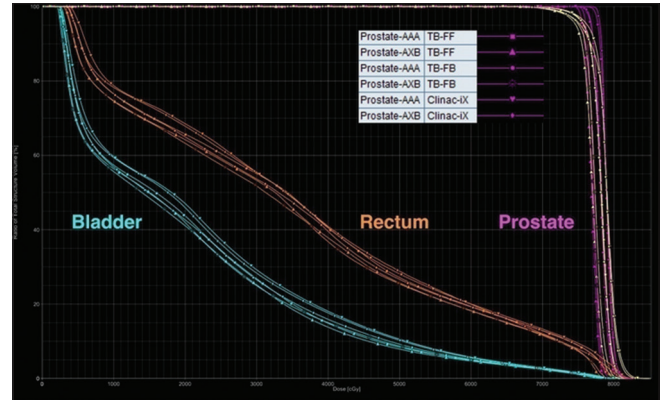


Figure 6: Dose-volume histogram comparisons of the prostate case from RapidArc plans calculated using analytical anisotropic algorithm and Acuros XB algorithm for the Clinac-iX (6MV) and TrueBeam-STx (6MV filtered beam and 6MV flattening filter-free beam), respectively

Table 4: Dose-spillage volumes normalized to target volume, along with their *P* values comparing for different multileaf collimator and beam type using analytical anisotropic algorithm, Acuros XB calculation for Clinac-iX (6 MV) and TB-STx (6MV filtered beam and 6MV flattening filter-free beam), respectively

Dose spillage volume	Millennium-120 (FB)		<i>P</i>	HD-120 (FB)		<i>P</i>	HD-120 (FFFB)		<i>P</i>	AAA <i>P</i>	AXB <i>P</i>	AAA <i>P</i>	AXB <i>P</i>
	AAA	AXB		AAA	AXB		AAA	AXB		Mill versus HD	Mill versus HD	FB versus FFFB	FB versus FFFB
V_{HS}	0.11±0.05	0.09±0.04	0.004	0.11±0.06	0.08±0.04	0.028	0.10±0.06	0.06±0.04	0.007	0.828	0.034	0.485	0.327
V_{IS}	2.54±1.03	2.44±0.99	0.005	2.46±1.09	2.27±0.99	0.010	2.44±1.08	2.22±0.98	0.011	0.171	0.021	0.653	0.357
V_{LS}	12.91±4.51	11.84±4.34	0.019	11.53±4.63	10.95±4.36	0.016	11.61±4.59	10.97±4.36	0.019	0.026	0.010	0.535	0.904

FB: Filtered beam, FFFB: Flattening filter-free beam, AAA: Analytical anisotropic algorithm, AXB: Acuros XB, HD: High definition

Table 5: Gamma analysis of the task group 119 test cases from the analytical anisotropic algorithm and Acuros XB algorithm-calculated RapidArc plans for the Clinac-iX (6 MV) and TB-STx (6MV filtered beam and 6MV flattening filter-free beam), respectively

Structure	Gamma (3%/3mm TH: 10%)					
	Clinac-iX (6MV FB)		TB-STx (6MV FB)		TB-STx (6MV FFFB)	
	AAA	AXB	AAA	AXB	AAA	AXB
C shape (easier)	98.1	93.9	98.1	95.1	98.6	93.2
C shape (hard)	98.5	96.6	98.7	96.4	99.2	95.3
H and N	99.1	93.5	99.9	98.3	99.5	94.4
Multi-target	97.7	94.1	96.6	95.4	94.6	93.5
Prostate	99.0	97.4	99.4	95.2	98.8	93.4
Mean±SD	98.5±0.6	95.1±1.8	98.5±1.3	96.1±1.3	98.1±2.0	94.0±0.9

TH: Threshold, FB: Filtered beam, FFF: Flattening filter free, AAA: Analytical anisotropic algorithm, AXB: Acuros XB, SD: Standard deviation

Table 6: Ion chamber measurements in comparison to the treatment planning system-calculated dose at the ArcCHECK isocenter for the task group 119 test cases from the analytical anisotropic algorithm and Acuros XB algorithm-calculated RapidArc plans for the Clinac-iX (6 MV) and TB-STx (6MV_filtered beam and 6MV_flattening filter-free beam), respectively

Structure	IC versus TPS calculation (% difference)					
	Clinac-iX (6MV FB)		TB-STx (6MV FB)		TB-STx (6MV FFFB)	
	AAA	AXB	AAA	AXB	AAA	AXB
C shape (easier)	3.4	4.7	4.1	4.6	4.4	4.9
C shape (hard)	-2.7	2.5	2.2	2.3	3.2	3.6
H and N	2.4	2.6	1.6	3.5	-0.7	1.7
Multitarget	1.4	1.2	1.3	1.1	-2.0	-0.3
Prostate	2.8	0.5	4.1	4.6	2.0	1.9
Mean±SD	1.5±2.5	2.3±1.6	2.7±1.4	3.2±1.5	1.4±2.7	2.3±2.0

TPS: Treatment planning system, IC: Ion Chamber, TB: TrueBeam, FFF: Flattening filter free, AAA: Analytical anisotropic algorithm, AXB: Acuros XB, SD: Standard deviation

96.1 (SD: 1.3), and 94.0 (SD: 0.9) for the Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 MV_FFFB), respectively. For ion chamber measurements, the average percentage DDs for the AAA-calculated plans were 1.5 (SD: 2.5), 2.7 (SD: 1.4), and 1.4(SD: 2.7) for the Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 MV_FFFB), respectively. The average percentage DDs for the AXB-calculated plans were 2.3 (SD: 1.6), 3.2 (SD: 1.5), and 2.3 (SD: 2.0) for the Clinac-iX (6 MV) and TB-STx (6 MV_FB and 6 MV_FFFB), respectively.

DISCUSSION

This study evaluated the RA treatment delivery on a volumetric ArcCHECK phantom as per AAPM TG 119 recommendations and also investigated the impact of the AXB algorithm on RA plan calculations and delivery. The RA planning results for both algorithms satisfied the AAPM TG 119 criteria. Avgousti *et al.*^[17] also reported similar findings using a volumetric Delta4 phantom device for the evaluation of IMRT delivery as per AAPM TG 119. Ezzell *et al.*,^[7] Mynampati *et al.*,^[9] and Kaushik *et al.*^[18] also reported similar results based on the measurements on the rectangular slab geometries. The results showed that both algorithms were comparable in homogeneous medium of ArcCHECK phantom due to the same multiple source model used in the configuration phase of these algorithms. Hence, this substantiates the proper configuration and implementation of AXB in the TPS.^[19] This study reveals that the AXB plans had a lower dose to the target and OARs as compared to those of the AAA-calculated plans. Fogliata *et al.*^[20] reported that the AAA predicts an average 1.6% higher dose in the muscles for 6 MV in 3D-conformal planning as compared to the AXB. In another study, Fogliata *et al.*^[21] reported in soft tissues that the mean PTV dose was

lower for the AXB, with a range of $0.4\% \pm 0.6\%$ for IMRT and $1.3\% \pm 0.2\%$ for RA for a 6MV photon beam. Similar findings were also reported by Rana *et al.*^[22] This study also revealed that HD-MLC system spares more OARs and has lower spillage volumes outside the target comparing to the millennium-MLC system for similar target coverage. This is due to the difference in leaf width at isocenter, source to MLC distance, and leaf transmission-and-leakage. For an MLC system, leaf transmission-and-leakage also depends on leaf material, leaf height, and tongue-and-groove effect of MLC. Tanyi *et al.*^[23] had reported that HD-MLC spares the normal tissue and reduces the dose-spillage volumes outside the target in comparison to millennium-MLC system. This study reveals that flattening filter-free photon beam has significantly inferior treatment efficiency in terms of MUs comparing to filtered photon beam for similar target coverage. This is due to the forward peak nature of flattening filter-free photon beam, as the intensity of FFF beam abruptly decreases with off-axis distance for field sizes larger than and equal to $10 \text{ cm} \times 10 \text{ cm}$, which requires the off-axis distance-dependence intensity modulation of FFF photon beam. This necessitates large number of MUs to deliver uniform dose to the target.^[24,25]

This study showed that the AXB-calculated plans had lower gamma passing rates as compared to those of the AAA-calculated plans. Regarding the calculation algorithm, in a multicenter audit of VMAT planning and pretreatment verification, Jurado-Bruggeman *et al.*^[26] were unable to correlate the results of gamma passing rates with the algorithm itself or the software version. This could be influenced by various unidentified causes including the pre-measurement absolute dose calibration of ArcCHECK based on the TPS-calculated dose. Ion chamber measurements can also introduce bias, as the ion chamber was calibrated in a water medium, and measurements were made inside the PMMA cavity. Furthermore, there are differences in the dose computation approaches used in these algorithms. The AXB calculation is sensitive to medium composition and characterization as it calculates radiation transport in medium. In contrast, the AAA models the medium as water of different densities.

The AAPM TG 119 tests performed with a volumetric ArcCHECK phantom are useful for the validation of RA treatment planning and delivery. The TPS, the dose delivery system, and the dose measurement process are the main sources of deviation between the planned and measured doses. TPS is a major source of deviation, contributing approximately 50% of the total deviations between planned and measured results.^[7,27] McVicker *et al.*^[28] investigated the sensitivity of the TG 119 in finding the error involved in any stage of commissioning by creating an additional beam model in the TPS by introducing intentional errors in the original beam model. They concluded that the TG 119 commissioning criteria are effective in detecting errors. The European Society for Therapeutic Radiation Oncology guidelines^[29] on the verification of IMRT have recommended that “more information is urgently required about the accuracy of IMRT treatment delivery by conducting independent audit or inter-comparison programmes.” Similar

recommendation has been reported by other publications also.^[27,30-32] This may reveal unidentified errors in local treatment and delivery systems and hence lead to improved quality of treatment.

The limitation of the present study was that the ArcCHECK phantom is a homogeneous phantom; thus, the algorithm's ability to correctly model heterogeneities, which is more desirable for clinical environments, could not be assessed.

CONCLUSION

The AAPM TG 119 test cases were successfully applied on an ArcCHECK phantom. The ArcCHECK phantom has been proven as an easy, quick, and reliable system for RA delivery verification following the TG 119 recommendations. The AXB has potential to perform dose calculations comparable to those of the AAA for RA plans in the homogeneous medium of the ArcCHECK phantom. Therefore, the AAPM TG 119 report can be used as an effective tool for the quick evaluation of RA planning and delivery systems.

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Conflicts of interest

There are no conflicts of interest.

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