Nuclear Engineering and Technology 53 (2021) 4098–4105

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Calculation of Jaws-only IMRT (JO-IMRT) dose distributions based on the AAPM TG-119 test cases using Monte Carlo simulation and Prowess Panther treatment planning system

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ARTICLE INFO

Article history:
Received 8 July 2020
Received in revised form
18 June 2021
Accepted 4 July 2021
Available online 6 July 2021

Keywords:
JO-IMRT plan
AAPM TG-119
Monte Carlo simulation
DOSCTP

ABSTRACT

The aim of this study is to calculate the JO-IMRT dose distributions based on the AAPM TG-119 using Monte Carlo (MC) simulation and Prowess Panther treatment planning system (TPS) (Panther, Prowess Inc., Chico, CA). JO-IMRT dose distributions of AAPM TG-119 were calculated by the TPS and were recalculated by MC simulation. The DVHs and 3D gamma index using global methods implemented in the PTW-VeriSoft with 3%/3 mm were used for evaluation. JO-IMRT dose distributions calculated by TPS and MC were matched the TG-119 goals. The gamma index passing rates with 3%/3 mm were 98.7% for multi-target, 96.0% for mock prostate, 95.4% for mock head-and-neck, and 96.6% for C-shape. The dose in the planning target volumes (PTV) for TPS was larger than that for the MC. The relative dose differences in D99 between TPS and MC for multi-target are 1.52%, 0.17% and 1.40%, for the center, superior and inferior, respectively. The differences in D95 are 0.16% for C-shape; and 0.06% for mock prostate. Mock head-and-neck difference is 0.40% in D99. In contrast, the organ curve for TPS tended to be smaller than MC values. JO-IMRT dose distributions for the AAPM TG-119 calculated by the TPS agreed well with the MC.

1. Introduction

In radiotherapy, intensity-modulated radiation therapy (IMRT) is developed to overcome the limitations of the 3D-CRT technique [1,2]. IMRT provides the radiation doses more suitable to the tumor by dividing the fields into multiple irregular beam segments [3]. Jaws-only IMRT (JO-IMRT) is an alternative technique that could be applied in a LINAC without the multileaf collimator (MLC) to deliver the IMRT plan, which technique requires more complexity than conventional MLC-IMRT, and the possibility of large errors in the dose distribution [4,5]. Furthermore, the JO-IMRT plan is composed of many small beam segments. Therefore, quality assurance (QA) for the JO-IMRT plan before treatment is one of the important steps, requires a lot of technical skill, experience as well as equipment, and also an indispensable step in the treatment process [6]. QA for JO-IMRT plans can be carried out using a variety of dosimetric devices, methods, and so forth to verify the accuracy of JO-IMRT dose distributions. In our previous works [7–11], we performed QA for the JO-IMRT plans using both experimental dosimetry and MC simulation for the head-and-neck cancer cases. In 2009, a set of test cases included multi-target, mock prostate, mock head-and-neck, and C-shape has been developed by the (American Association of Physicists in Medicine) Task Group 119 (TG-119) to estimate the overall accuracy of planning and delivery of IMRT treatments [12].

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https://doi.org/10.1016/j.net.2021.07.005

Since TG-119 has been published until now, researchers have shown an increased interest in not only IMRT but also volumetric modulated arc therapy (VMAT). Dinesh et al. (2012) [13] compared VMAT and IMRT plans using AAPM TG-119 test cases. Their IMRT and VMAT planning results matched TG-119 goals. Nithya et al. (2015) [14] created the TG-119 test plans for IMRT and VMAT using Monaco treatment planning system (TPS), and compared their results with the reports of Ezzell et al. [12] and Dinesh et al. [13]. They also achieved the goals mentioned in AAPM TG-119 using the Monaco TPS. Ashokkumar et al. (2017) [15] validated the commissioning of upgraded 6 MV FFF beam dosimetrically using AAPM TG-119 benchmark plans for VMAT and to compare with IMRT plans for both FF and FFF photon beams. Nainggolan et al. (2019) [16] evaluated VMAT and IMRT in Eclipse TPS using the TG-119. It can be seen that most of the above studies only calculated the dose distributions in TPS and did not include results from MC simulations. MC simulation is proposed as an appropriate dose verification for treatment plans instead of experimental evaluations measured by ionization chambers, film or two-dimensional (2D) array detectors and so on [6,17,18]. In 2018, Onizuka et al. [19] performed MC simulation to verify VMAT dose distributions of TPS using the AAPM TG-119 structure sets. Their results pointed out that the MC simulation and 3D gamma analysis is useful to verify the dose distributions. Hence, the aim of this study is to verify the JO- IMRT dose distributions from Prowess Panther TPS (***evaluated***) by comparing the plan dosimetry with MC simulation (***reference***) using the AAPM TG-119 test cases, which is not found anywhere.

2. Materials and methods

2.1. JO-IMRT plan in Prowess Panther TPS

Computed tomography (CT) images of four structure sets were downloaded directly from the AAPM website (www.aapm.org) and imported into Prowess Panther TPS. Fig. 1 shows the structures of Multi-Target (a), Mock Prostate (b), Mock Head-and-Neck (c), and C-shape (d). The JO-IMRT dose distributions of these cases were calculated by the collapsed-cone convolution (CCC) algorithm using the 6 MV photon beam generated by a Siemens Primus LINAC (Siemens Medical Solutions, Concord, CA). All the JO-IMRT beam parameters, dose prescriptions, and planning objectives followed the TG-119 guidelines [12].

2.2. Monte Carlo simulation

2.2.1. Modeling of Siemens Primus head configuration using the BEAMnrc

The head configuration of the Siemens Primus M5497 LINAC at the Dong Nai General hospital was modeled by the EGSnrc-based BEAMnrc code for 6 MV photon beam. All material components, dimensions of the accelerator consisting of a target, primary collimator, flattening filter, internal ionization chamber, mirror, and secondary collimator were provided by the vendor and detailed in the published works [20,21]. The percentage depth dose (PDD) and dose profiles for a field size of 2×2, 5×5, and 10×10 cm^2 were calculated using the DOSXYZnrc code. The measurements were performed using ionization chamber CC13, with a cavity volume of 0.13 cm^3 with a length of 5.8 mm and a radius of 3 mm (IBA Dosimetry, Germany), in a water phantom with dimension of $50 \times 50 \times 30$ cm^3. The ionization chamber was controlled by the Omni Pro-accept V7.4c through the CU500E block (IBA Dosimetry, Germany), which was responsible for providing ± 300 V for the chamber, and controlling the chamber to the correct position to measure. The PDD and dose profiles at SSD = 100 cm for field sizes of 2×2, 5×5, and 10×10 cm^2 were measured to compare the results from MC simulations.

2.2.2. Calculation of JO-IMRT dose distributions as per TG-119 test cases

After the JO-IMRT dose distributions of the four tests was calculated by Prowess Panther TPS, All parameters of isocenter, field size, SSD, gantry angles, and DICOM plan files were imported into the DOSCTP [22,23], which was used for the calculation of 3D dose distribution using MC simulation. The calculation grid size was set at $0.3 \times 0.3 \times 0.3$ cm^3. Source number 8 in the library of DOSXYZnrc codes [11] was used with MC parameters. The electron and the photon cut-off energies were: ECUT = 0.70 MeV and PCUT = 0.01 MeV, respectively. The number of history was equal to 2×10^9.

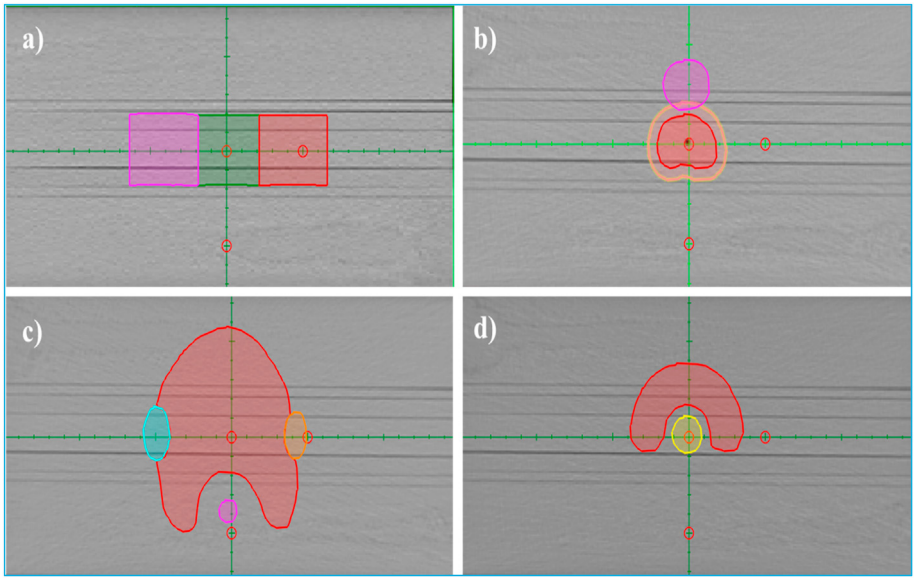

Fig. 1. AAPM TG-119 structure sets [12].

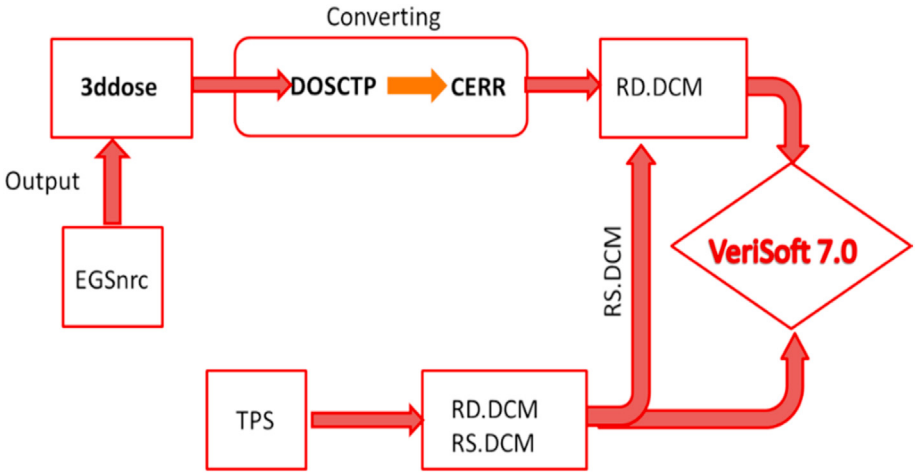

Fig. 2. Flowchart showing the main process for comparing the MC and TPS dosimetry using the gamma index.

2.2.3. Data analysis method

The DVH and gamma index (3%/3 mm) were used to compare the MC and TPS results. The DVH was determined using the CERR program [24] and the gamma index was implemented in the Verisoft (PTW) program. Fig. 2 shows the flowchart of the main process of the MC and TPS comparison using the gamma index.

In the first step, The RS.dcm and RD.dcm files were exported by TPS and then imported into the Verisoft. *In the second step*, the.*3ddose file from the MC simulation using the EGSnrc code was converted to RD.*dcm by combining between the DOSCTP and CERR. The RD.*dcm files from simulation associated with RS.*dcm file were also used as an input in the Verisoft-PTW to perform an evaluation of the 2D and 3D global gamma criteria of 3% dose difference (DD) and 3 mm distance to agreement (DTA) [12].

The confidence limit (CL) was calculated based on the results from the 3D gamma analysis by equation (1):

$$CL = (100 - \text{mean}) + 1.96\sigma \quad (1)$$

where mean is the mean percentage of points passing gamma criteria and σ is the standard deviation.

The relative percentage dose difference between MC and TPS was calculated according to equation (2) [25]:

$$\Delta D(\%) = 100 \times \frac{(|D_{MC} - D_{TPS}|)}{D_{\text{Pres}}} \quad (2)$$

In Eq. (2), ΔD: relative percentage dose difference of MC with TPS, D_{MC}: the absolute dose of Monte Carlo, D_{TPS}: the absolute dose of TPS, D_{Pres}: the prescription dose

We also calculated the conformity index (CI) [26] and homogeneity index (HI) [27] for all tests using equation (3):

$$CI = \frac{PTV_{ref}}{PTV} \times \frac{PTV_{ref}}{Vref} \quad (3)$$

In Eq. (3), V_{ref} is the volume of the organ which is outlined by the prescription isodose-line. PTV_{ref} is the volume of PTV which is outlined by the prescription isodose-line.

$$HI = \frac{D_{2\%} - D_{98\%}}{D_P} \quad (4)$$

In Eq. (4), $D_{2\%}$ and $D_{98\%}$ represent doses received at 98% and 2% of the volume coverage, respectively. D_p demonstrates the prescription dose.

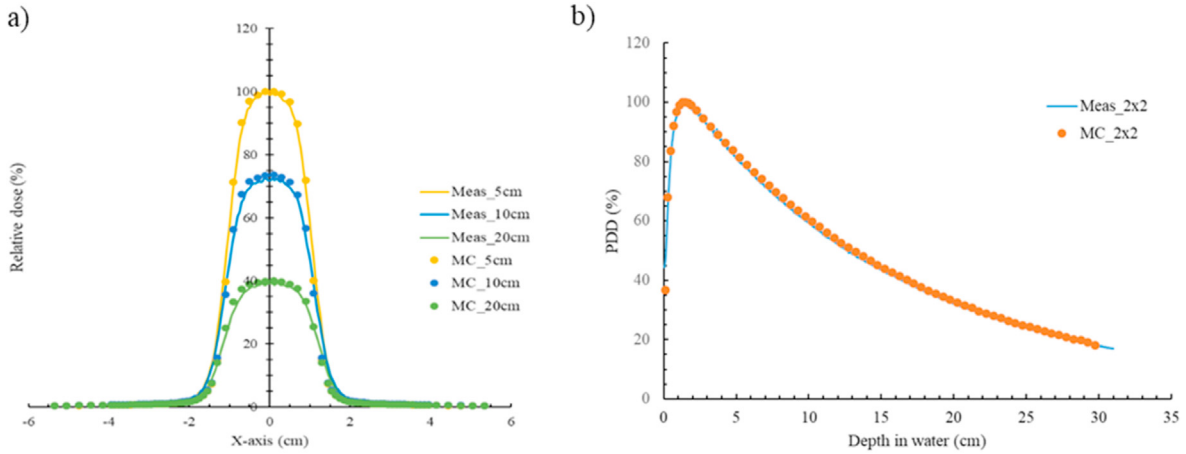

Fig. 3. Comparison of measured (solid lines) and MC - calculated (dots) dose profiles (a) and PDDs (b) of a 2 × 2 cm^2 field.

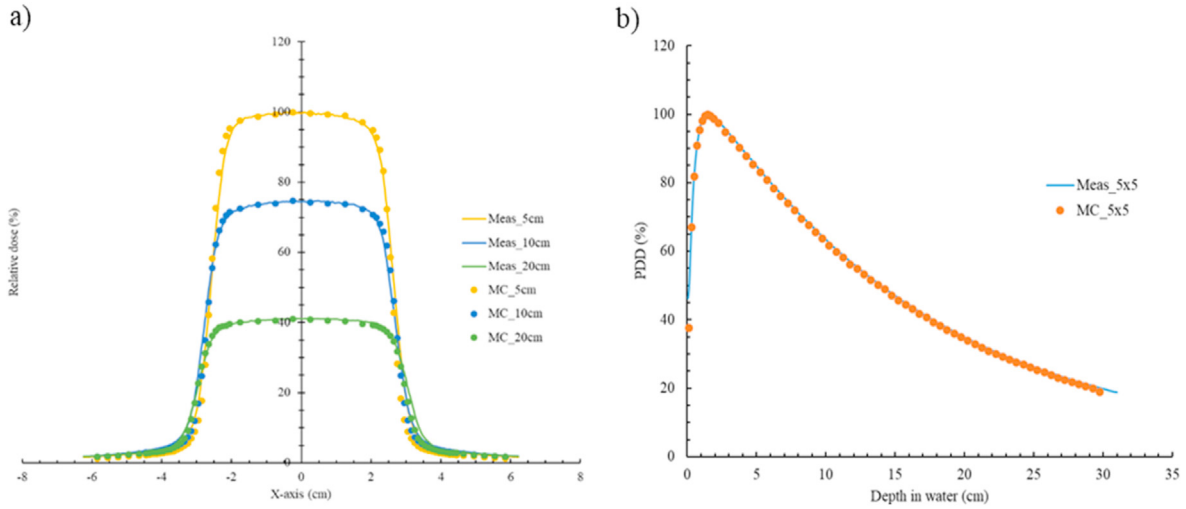

Fig. 4. Comparison of measured (solid lines) and MC - calculated (dots) dose profiles (a) and PDDs (b) of a 5 × 5 cm^2 field.

3. Results

3.1. Modeling of Siemens Primus head configuration using the BEAMnrc

The PDD was normalized at a depth of 1.5 cm and the dose profiles were calculated and measured at depths of 5, 10 and 20 cm. Figs. 3, 4 and 5 illustrate a comparison of the measured and MC-calculated PDDs and dose profiles at 2 × 2, 5 × 5, and 10 × 10 cm^2 photon fields, respectively. The measured and calculated MC PDDs agreed within 2% up to a depth of 30 cm, except at the build-up region (3.9% of maximum dose difference). Similarly, dose profiles also agreed within 2%, except in the penumbral regions at depths of 5, 10, and 20 cm (2.6% of maximum dose difference). The Siemens Primus head configuration was therefore well modeled by the BEAMnrc.

3.2. Calculation of JO-IMRT dose distributions based on the TG-119 test cases

3.2.1. The dose-volume histograms (DVH)

Fig. 6 shows a comparison of DVH calculated by TPS and MC using the TG-119 structural sets. It can be observed that the DVH calculated by the TPS agreed well with the MC.

The results from the DVH are summarized in Table 1. The relative dose differences between TPS and MC were 1.52%, 0.17%, and 1.40% in D99 at the center, superior, and inferior, respectively for multi-target, 0.06% in D95 for mock prostate, 0.40% in D99 for mock head-and- neck, and 0.16% in D95 for C-shape.

Fig. 7 represents a minimum, 25%, 50%, 75%, and maximum values in order, and the dot inside the box is the mean value in each parallel bar of the box plot. As one can see from Fig. 7, the CI, HI of TPS and MC were similar. The average CI and HI were 0.70 and 0.74, 0.21 and 0.17 for TPS and MC, respectively.

3.2.2. Gamma evaluation

We calculated the 2D and 3D gamma indices by comparing TPS and MC calculated dose distributions. The 2D analysis was conducted by considering each transversal, coronal and sagittal planes. The 3D analysis evaluated the total volume. Generally, the gamma index passing rate with 3%/3 mm criteria for the head-and-neck cases is the lowest among the TG-119 test cases. This is a complex case due to the left and right parotids and spinal cord located very near the PTV. Otherwise, the multi-target case is the easiest cases with the highest gamma index passing rate of 98.7%.

Fig. 8 illustrates a comparison of 2D gamma distributions with 3%/3 mm criteria in transversal (Fig. 8a), coronal (Fig. 8b), and sagittal (Fig. 8c) planes for the multi-target case. The 2D gamma

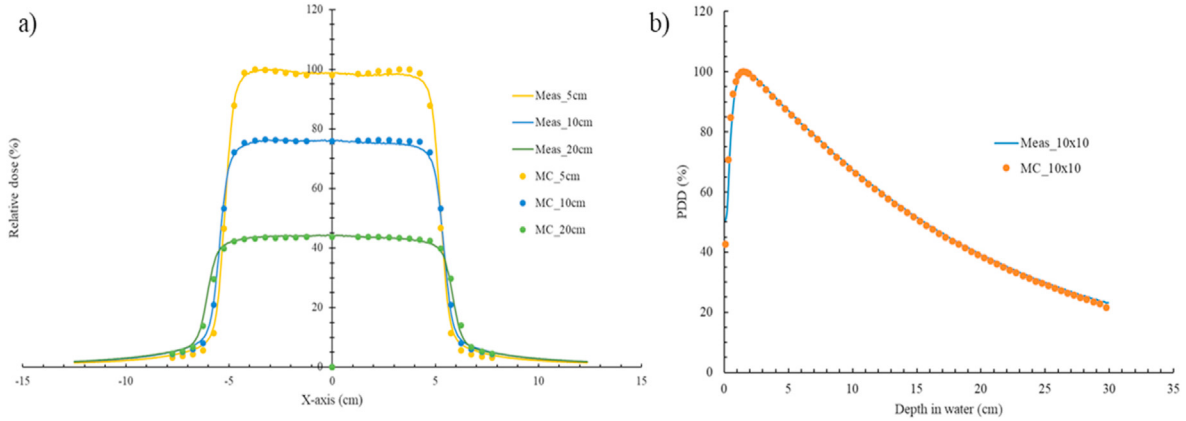

Fig. 5. Comparison of measured (solid lines) and MC - calculated (dots) dose profiles (a) and PDDs (b) of a 10 × 10 cm^2 field.

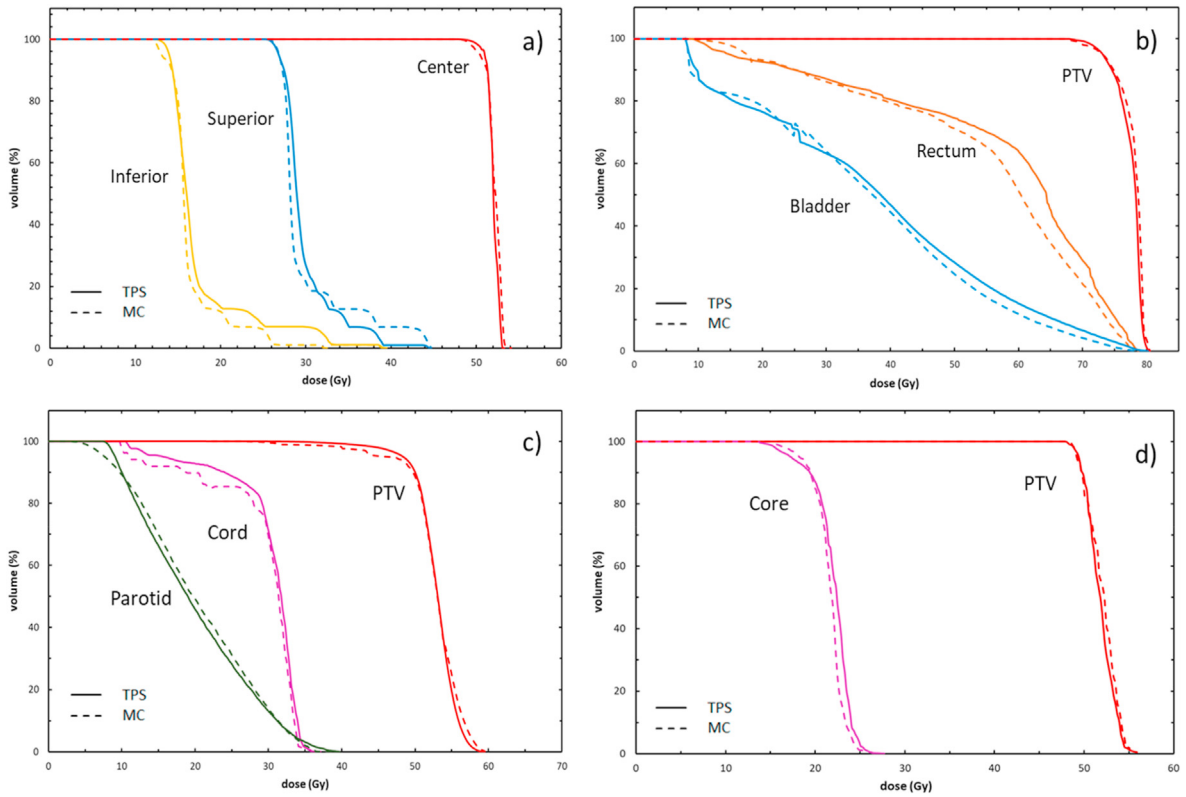

Fig. 6. DVH comparisons of the TPS and MC for Multi-target (a), Prostate (b), Head-and-Neck (c), C-Shape (d).

Table 1
Dosimetric difference indices between MC and TPS.

Structure	Parameter	Goal (cGy)	Our work (cGy)			Onizuka et al. (2018) (cGy)			Ezzell et al. (2009) (cGy)
			TPS	MC	$\Delta D(\%)$	TPS	MC	$\Delta D(\%)$	
Multi − Target									
Central	D99	>5000	4973	4894	1.52	5130	5060	1.35	4955
	D10	<5300	5284	5298	0.27	5280	5310	0.58	5455
Superior	D99	>2500	2608	2617	0.17	2600	2480	2.31	2516
	D10	<3500	3449	3770	6.17	3300	3600	5.77	3412
Inferior	D99	>1250	1324	1251	1.40	1350	1260	1.73	1407
	D10	<2500	2393	2054	6.52	2320	2300	0.38	2418
Mock Prostate									
PTV	D95	>7560	7316	7311	0.06	7580	7460	1.54	7566
	D5	<8300	7952	7977	0.32	7920	7990	0.90	8143
Rectum	D30	<7000	6971	6755	2.77	6610	6680	0.90	6536
	D10	<7500	7498	7473	0.32	7540	7520	0.26	7303
Bladder	D30	<7000	4894	4692	2.59	4180	4390	2.69	4394
	D10	<7500	6572	6177	5.06	7140	7140	0.00	6269
Mock Head/Neck									
PTV	D90	>5000	4999	4978	0.40	5140	5070	1.35	5028
	D99	>4650	4112	4076	0.69	4850	4710	2.69	4704
	D20	<5500	5493	5500	0.85	5260	5390	2.50	5299
Cord	Dmax	<4000	3714	3664	0.96	3920	4050	2.50	3741
Parotid	D50	<2000	1898	1972	1.42	1900	2040	2.69	1798
C-Shape									
PTV	D95	>5000	5011	5003	0.16	5080	5030	1.00	5010
	D10	<5500	5478	5491	0.26	5500	5580	1.60	5440
Core	D5	<2500	2498	2357	2.82	2380	2500	2.40	2200

passing rates with 3%/3 mm criteria were 98.7%, 96.7%, 94.5% at transversal, sagittal, and coronal planes, respectively.

Fig. 9 gives information about 2D gamma distributions of 3%/3 mm in the three planes (transversal (Fig. 9a), coronal (Fig. 9b),

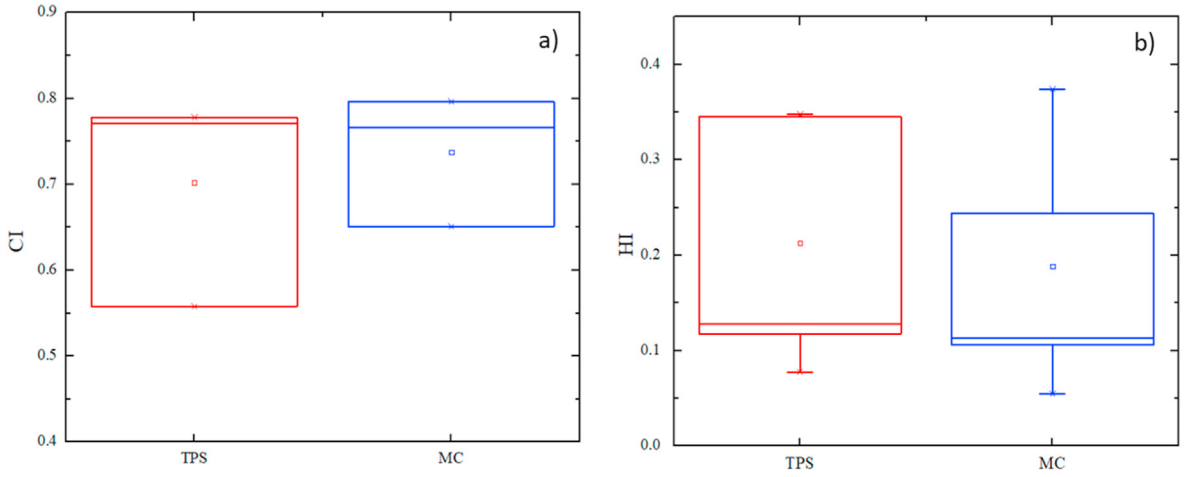

Fig. 7. A comparison of (a) CI and (b) HI between TPS and MC.

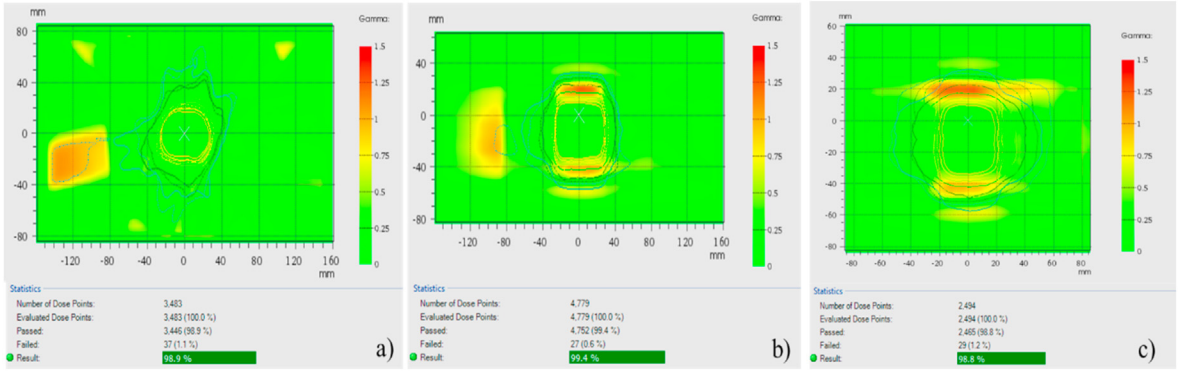

Fig. 8. Comparison of the 2D gamma between TPS and MC for multi-target case.

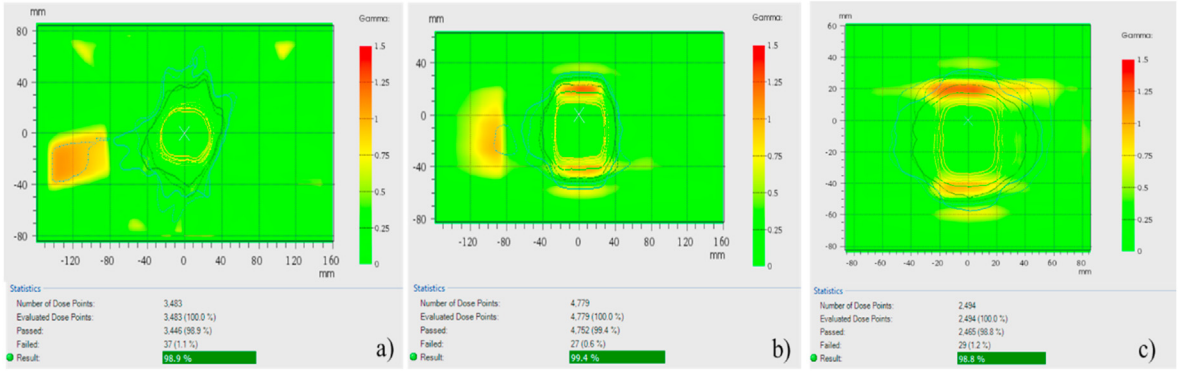

Fig. 9. Comparison of 2D gamma between TPS and MC for the mock prostate case.

sagittal (Fig. 9c)) for the mock prostate case stood at 98.9%, 99.4%, 98.8%, respectively. The maximum difference in gamma passing rates is as high as 5.2%. Positions that did not meet local gamma criteria are mainly at lower doses and low gradient areas.

A comparison of 2D gamma distributions with 3%/3 mm criteria in transversal, coronal, sagittal planes for the head-and-neck case is shown in Fig. 10. There was 97.4% gamma passing rate with criteria of 3%/3 mm in a transversal plane (Fig. 10a), 99.5% in sagittal (Fig. 10b) and 90.5% in coronal (Fig. 10c) plane. The 2D gamma in coronal plane demonstrated worse results than did the transversal and sagittal plane

Fig. 11 shows the comparison for the dose distributions of the MC with TPS in the C-Shape case using global gamma criteria of 3%/3 mm in the PTW-Verisoft.

The gamma passing rate for the C-Shape case was 98.5% for transversal (Fig. 11a), 100% for coronal (Fig. 11b), and 94.3% for sagittal (Fig. 11c). Figs. 8, 9, 10 and 11 illustrate the results of evaluating 2D gamma index on transversal, sagittal, and coronal planes of Multi-target, Prostate, Head-and-Neck and C-Shape case. It was highly consistent that the discrepancies occurred at the boundary

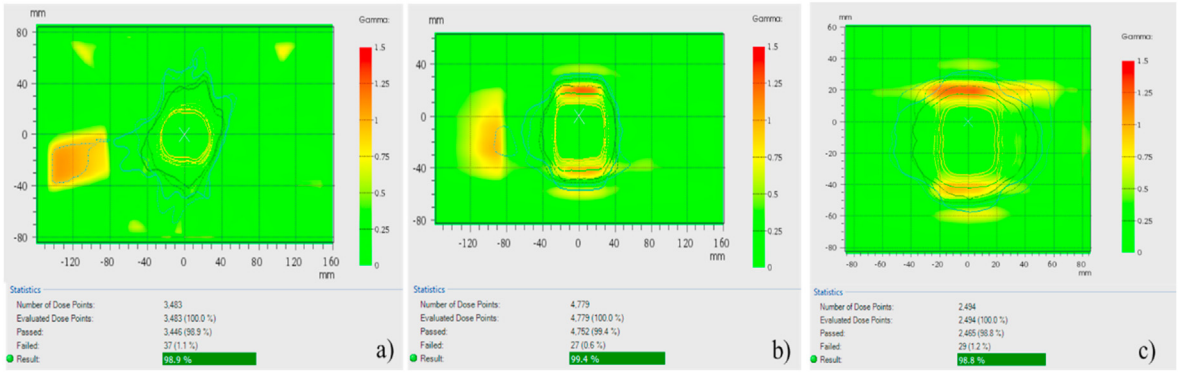

Fig. 10. Comparison of 2D gamma between TPS and MC for the head-and-neck case.

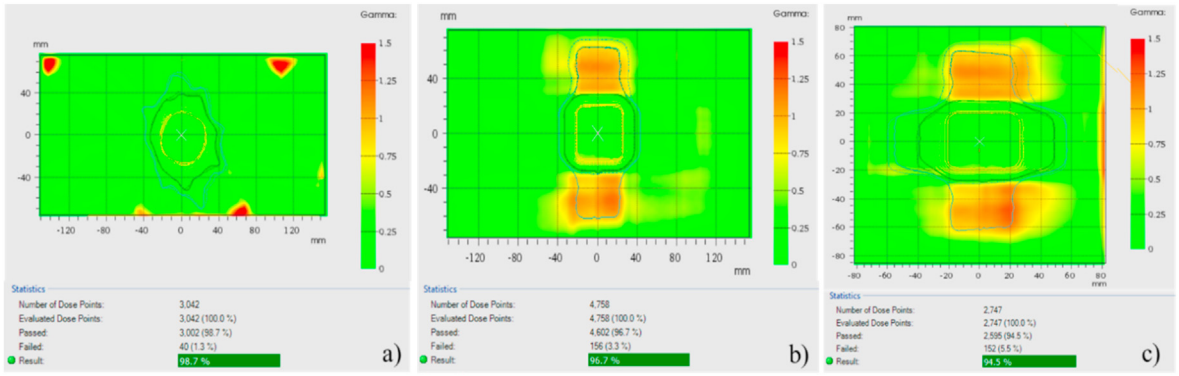

Fig. 11. Comparison of 2D gamma between TPS and MC for C-Shape case.

Table 2
3D gamma passing rate with of 3%/3 mm criteria.

Test	% Gamma (3%/3 mm)
Multi - Target	98.7
Mock Prostate	96.0
Head-neck	95.4
C-shape easy	96.6
Mean	96.7
Standard deviation	1.44
CL = (100 - mean) + 1.96 σ	6.14

regions (i.e. high-dose dose areas) due to the effect of deterioration and scattering near the air, the surfaces indicate this difference. With a 3%/3 mm gamma criterion and a 10% threshold dose, the overall pass rate with local gamma (2D Gamma) is on average less than 3.8%. The maximum difference in the pass rate was as high as 9.5%, in the coronal plane for the head-and-neck case.

The radiotherapy practice requires 3D dose verification based on actual patient anatomies. The 3D gamma is an extension of the 2D gamma index into another dimension, allowing for consideration and evaluation of the entire volumetric patient dose distribution. The 3D gamma passing rate for the TG 119 test cases are summarized in Table 2.

The average 3D gamma index passing rates with 3%/3 mm of TPS with MC were 98.7%, 96.0%, 95.4%, and 96.6%, for Multi-target, Prostate, Head-and-Neck, and C-Shape, respectively. The CL obtained from the 3D gamma analysis for all cases were 6.14%. All these CLs were agreed well according to the TG 119 recommendation.

4. Discussion

AAPM TG-119 proposed 4 test for testing the accuracy of IMRT planning and delivery system. In this study, we applied the test based on the TG-119 to evaluate the accuracy of the JO-IMRT technique, implemented in Prowess Panther TPS on Siemens Primus LINAC using MC. To achieve this goal, the head of LINAC was simulated and the JO-IMRT dose distributions were determined using TPS and MC simulation.

By determinating the mean energy, full width at half maximum of the initial beam [20] together with the application of variance reduction techniques in MC simulation using the EGSnrc code [21], the PDDs and beam profiles in Figs. 3, 4 and 5 between MC and measurement for the 2×2, 5×5 and 10×10 cm^2 field size are in good agreement, which helps to increase the accuracy of calculating the JO-IMRT dose distribution.

The JO-IMRT dose distribution was calculated by TPS and MC. DVH plays an important role in evaluating the JO-IMRT plan, because the DVH values contain not only target volumes but also the critical organs. A comparison of DVHs calculated by TPS and MC for the TG-119 structural sets are shown in Fig. 6. In this study, It can be seen that in all 4 cases of the TG-119, the dose in the PTV for TPS tends to be greater than MC. In contrast, the dose in organs for TPS tends to be smaller than MC. This study produced results that corroborate the findings of a great deal of the previous work [19].

Table 1 presents the dosimetric indices difference between MC and TPS. The relative percentage dose differences between MC and TPS were 2.68%, 1.85%, 0.72%, and 1.08% for multi-target, mock prostate, mock head-and-neck, and C-shape. The average dose difference between MC and TPS was 1.96%. This also agrees with Onizuka et al. [19]. Additionally, the CI of TPS and MC were 0.56 and

0.65 for mock prostate, 0.78 and 0.77 for head-and-neck, 0.77 and 0.80 for C-shape. The HI of TPS and MC were 0.23 and 0.22 for multi-target, 0.13 and 0.11 for mock prostate, 0.35 and 0.24 for head-and-neck, 0.12 and 0.11 for C-shape. The average CI and HI were 0.70 and 0.74, 0.21 and 0.17 for TPS and MC, respectively. As one can see from Fig. 7, the CI and HI of TPS and MC were similar.

JO-IMRT dose distributions calculated by Prowess Panther TPS ("evaluated") and recalculated Monte Carlo ("reference") were compared using 2D and 3D gamma analysis with 3%/3 mm criteria. Tai et al. [7] performed quality assurance of the JO-IMRT plans for head-and-neck cancer by using MapCHECK 2 (2D gamma) and Octavius 4D 1500 (3D gamma). The average gamma index based on the 3%/3 mm criteria were 96.7%and 94.7%, for 2D, 3D gamma, respectively. The results of this study for head-and-neck case of the TG-119 indicate that the average 2D and 3D gamma was 97.4% and 95.4%, respectively. The results of the current study are consistent with Tai et al. [7,8]. Furthermore, the average 3D gamma index passing rates with 3%/3 mm of TPS with MC for all TG-119 test cases were 96.9%.

The AAPM TG-119 sets of the test cases are very helpful in evaluating the quality of the JO-IMRT plans and are imported into the Prowess Panther TPS to calculate the dose distributions compared with MC. The results of dose difference, DVH, gamma analysis showed good agreement between TPS and MC.

5. Conclusions

The Prowess Panther TPS-calculated JO-IMRT dose distributions in the study agreed well with Monte Carlo simulation based on the AAPM TG-119 test cases. The Prowess Panther TPS is capable of creating JO-IMRT plans not only for head-and-neck but also for models of multi-target, prostate, and C-shape according to the TG-119.

Financial disclosure

None declared.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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