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Evaluation of Patient-Specific Quality Assurance for RapidArc Treatment Delivery Using Dose Volume Histogram

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Abstract

This study aims to evaluate the application of dose volume histogram (DVH) metrics within the patient-specific quality assurance (PSQA) protocol in various sites for RapidArc treatment delivery. Forty patients were included in this study, of which twenty each Head and Neck (H&N) and Pelvis Rapid Arc plans were evaluated. Octavius 4D 1500 detector array with vented parallel plate ion chambers was used for this study, which reconstruct the pre-treatment measured doses into three-dimensional (3D) during pre-treatment quality assurance. The verisoft DVH application was utilized to estimate the dose administered to the patient's volume, explicitly focusing on the errors associated in the DVH. The measured data were compared with the treatment planning system created verification plan. Three-dimensional local and global gamma were evaluated using different gamma criteria of 3 mm/3%, 3 mm/2%, 2 mm/3% and 2 mm/2%, respectively. In addition, the agreement score was analysed for axial, coronal, and sagittal planes in addition to the volumetric analysis. All plans meet the action level requirement of >95% with 3%/3 mm gamma acceptance criteria. In addition, the DVH demonstrated that the doses administered to the target volumes and organs at risk remained within the specified dose tolerances for all cases. The DVH analysis will be applied to identify the instances where patient dose errors surpass the predetermined established action threshold. The gamma index did not initially identify these and may have utility in determining the reason for failed plans. Further, it enables identifying and managing dose errors associated with the patient's anatomy. Finally, this study has showcased the incorporation of DVH metrics into RapidArc PSQA protocol may deliver clinically meaningful outcomes in close proximity to the gamma index.

Keywords: DVH, PSQA, Radiotherapy, Action Level, RapidArc

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INTRODUCTION

The accuracy of radiation delivery in radiotherapy is affected by uncertainties in both planning and delivery, including the modulation of the multi-leaf collimators (MLC). The radiotherapy treatment generated in planning systems utilizes a complex motion of the MLCs, dose rate, and gantry speed, necessitates a comprehensive quality assurance workflow to independently verify the accuracy of the dose distribution generated in the treatment planning system (TPS) and delivery system in treatment machines [1].

The technical fusion of Intensity Modulated Radiation Therapy (IMRT) and Arc modalities resulted in the Rapid Arc® (Varian Medical

Systems) technique achieving comparable or better dosimetric dose distribution parameters than IMRT alone [2]. RapidArc planning incorporates concomitant continuous motion of the gantry, dynamic motion of the MLC s and a continuous variation in the dose rate. Therefore, the continuous motion of the gantry around the target during planning amplifies the risk of uncertainty in the planned dose delivery. Hence to ensure patient safety and delivery accuracy, a Patient-Specific Quality Assurance (PSQA) was widely used before the actual plan execution in a patient for the RapidArc treatment delivery plan [3]. Further, conventional PSQA is usually done by measuring the proposed plan in a standard phantom, followed by comparing the measured and calculated two-dimensional(2D) or three-dimensional (3D) dose distribution. The gamma index is popularly used to calculate the percentage of matching by using the percentage dose difference(DD) and distance to the agreement(DTA) criteria for each pixel with different gamma criteria [4].

A recent study proposed that the gamma index method is insensitive to MLC errors and detects clinically relevant dose errors [5]. Furthermore, gamma analysis based on analysis using different detectors does not provide any correlation that indicates any clinically relevant metrics, such as the estimated deviations in dose-volume histograms. In addition, it was observed that decreasing the gamma passing rate cannot predict any direct clinical impact; also, it has a bound accuracy for regions with very steep dose gradients [6]. For instance, assuming a specific plan has a gamma passing rate of 95%, it does not assure a higher level of safety for the patient during delivery compared to another plan with a pass rate of 85%. Therefore, the sizes and positions of these dose errors are significant in inpatient treatment [7].

The emergence of advanced software with the potential to estimate the patient's administered dose leads to a significant major shift in PSQA, with the potential utilization of the gamma index method. In radiotherapy delivery, the utilization of the gamma index for PSQA may be insufficient, and a method to assess the administered dose to the patient is required. So, combining dose volume histogram (DVH) information within the patient-specific quality assurance and adding gamma passing rates is the current requirement to provide comprehensive patient-specific quality assurance [8].

There is a deficiency of harmony in the methods and analysis for PSQA of highly conformal treatments such as RapidArc. Hence, the current study aims to evaluate the clinical experience of the DVH metrics as a comprehensive patient-specific pre-treatment QA for RapidArc treatment delivery in two different clinical sites. This will open a path for the evaluation of the plan regarding DVHs to assist in deciding to finalize a treatment plan for the treatment delivery [9].

MATERIAL AND METHODS

PSQA results comprising percentage gamma passing rate with different gamma criterion was analysed for forty patients' Head and Neck (HN)(n=20) and Pelvis(n=20). The selected patients had different prescription doses and fractionation schedules that depended on the treatment site and stage; however, none of the patients in the current cohort received stereotactic radiotherapy or radiosurgery. In addition, patients with extreme circumstances, such as unusual physiological conditions or prosthetic implants, were excluded from this study.

All plans were planned with two full arcs. In the first arc, the rotation was given in the CCW direction with a starting gantry angle of 178° and collimator angle of 350°, and in the second arc was in the CW direction with a starting angle of 182° and collimator angle of 10°. For each plan, an isotropic grid size of 2.5 mm was given and computed with an analytical anisotropic (AAA) dose calculation algorithm in Eclipse v15.6 (Varian Medical Systems, Palo Alto, CA, USA). All plans were delivered with a 6 MV flattening filtered photon beam in a linear accelerator (Truebeam, Varian Medical Systems, Palo Alto, CA, USA) equipped with a millennium 120 multi-leaf collimator.

Patient-specific quality assurance plans were created in a virtual CT scan of Octavius 4D phantom (PTW, Freiburg, Germany) made of acrylic with a density of 1.05 g/cm^3, shown in Figure 1. The

measured doses were compared with the planned dose using conventional gamma analysis. The detector array comprises 1500 vented parallel plate ion chambers, sized at (4.4 × 4.4 × 3) mm^3, whose centres are separated two by two by 7.07 mm. The matrix, therefore, has 27 rows of 27 chambers. It can reconstruct three-dimensional (3D) doses for all quality assurance pre-treatment data measured.

The calculated dose administered to the patient was determined using Verisoft (v7.2, PTW, Freiburg, Germany), in addition to reconstructing the delivered DVH by scaling the measurements onto the patient CT set. The necessary inputs are as follows: DICOM radiation therapy (RT) files for the patient plan (RT plan, RT Dose, RT Structures, CT Images) and phantom plan (RT plan, RT dose).

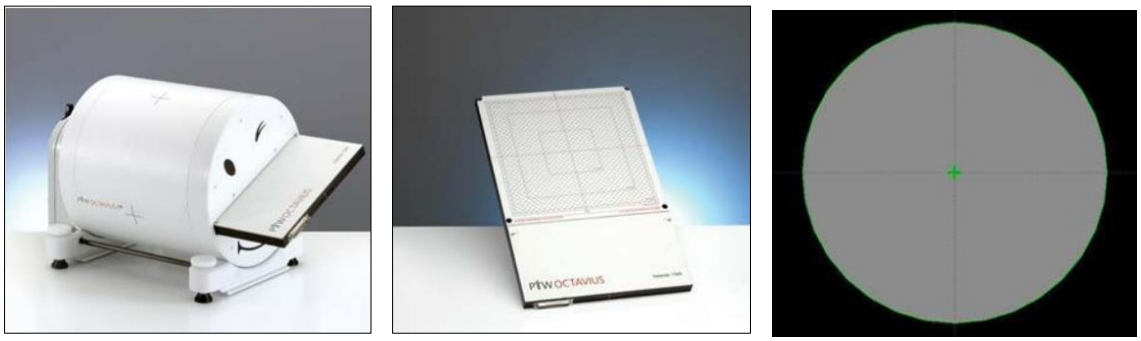

Figure 1. Representation of (a) Octavius Phantom, (b) 2D-Detector Array, (c) Virtual CT slice of Octavius Phantom.

GAMMA ANALYSIS

The gamma index method evaluated the agreement between each point's calculated and measured dose distribution. The global and local gamma index was calculated concerning the maximum dose and reference point. The gamma passing rate parameter was used as an acceptance criterion of the given analysis. *Two gamma criteria were used to test the data, distance-to-agreement (DTA)/dose difference.* The agreement score was analysed for axial, coronal, and sagittal planes. Three-dimensional gamma was evaluated using different criteria of 3 mm/3%, 3 mm/2%, 2 mm/3% and 2 mm/2%, respectively, with a lower % dose threshold of 10% for global and local normalisation.

ANALYSIS OF DVH METRICES

DVH matrices from the target volumes (Clinical Target Volume (CTV) and Planning Target Volume (PTV)) and nearby organs at risk structures were evaluated in DVH by comparing the measured dose from the system and compared with planned dose values of the same structures from the TPS. Furthermore, the maximum dose (D_{max}) and mean dose (D_{mean}) differences were evaluated for reporting the dose to the PTV, CTV and OAR DVHs. In addition, the percentage dose difference was calculated using the following equation:

$$\%D_{difference} = \left(\frac{D_{reconstruction} - D_{TPS}}{D_{TPS}}\right) \times 100$$

Statistical analysis was performed for gamma passing rate with Statistical Package for the Social Sciences (version 22; IBM Corp., Armonk, NY, USA) regarding the mean, standard deviation and median with range.

RESULTS

The mean gamma passing rate for 20 H&N and 20 Pelvis patients was > 95% for 3%/3 mm global gamma criteria, the detailed analysis of mean with standard deviation and median with range tabulated in Table 1. However, for both sites with 2%/3 mm and 2 mm/3% gamma criteria, the mean

passing rate decreased by>90% in all planes and with volume analysis. Furthermore, to determine the sensitivity to locate the errors in the patient plan, stringent 2%/2 mm acceptance criteria were used. In addition, the volume analysis showed the mean passing rate for all patients was (91.99 ± 2.80)% and (95.11 ± 3.31)% for the H&N, and Pelvis sites, respectively. Out of all planes, the transverse plane has a maximum passing rate for all gamma criteria in both sites.

With the addition of local gamma criteria, passing rates decreased more rapidly than global gamma. The mean passing rate with 2%/3 mm was (94.19 ± 3.43)% and (95.62 ± 3.31)% for the transverse plane. Only 3%/3 mm and 2%/3 mm gamma criteria achieved a>90% gamma passing rate for both sites.

The difference in dose was computed in percentage by comparing the DVH matrices from TPS and calculating the same patient in the Verisoft system. Figure 2a and Figure 3a show the box plot of the maximum dose (D_{max})difference for the structures (Target and OARs) drawn in the pelvis and H&N site.

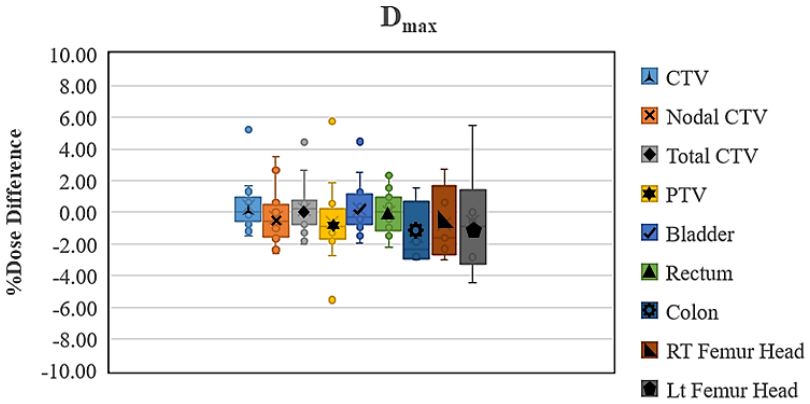

Figure 2. (a) Variation of Maximum Dose (Dmax) difference for Target and OARs of Pelvis Group (n=20).

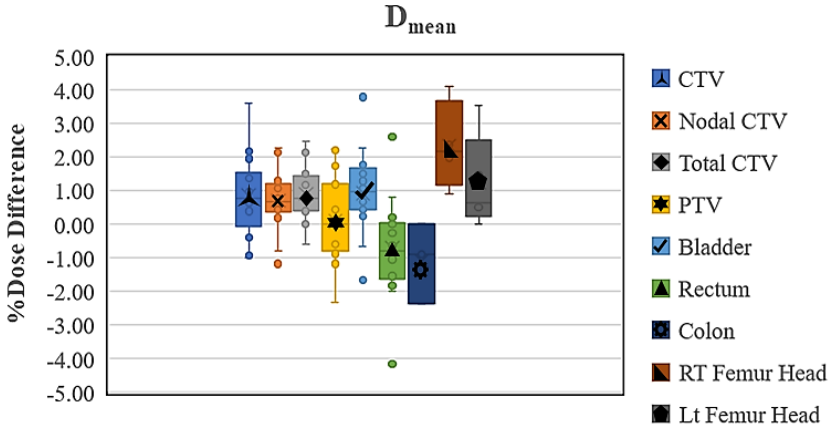

Figure 2. (b) Variation of Mean Dose (Dmean) difference for Target and OARs of Pelvis Group (n=20).

For both sites, the dose difference for the target was <5%, except for two patients in the pelvis site is going beyond 5% in PTV (-5.53% and 5.75%). The maximum difference in OAR was observed in the pelvis site for femur heads, with a maximum difference of 5.51%. For the H&N site, the maximum dose difference was observed for left parotid (-6.95 to 8.35)%, right parotid (-6.86 to 6.81)% and mandible (-8.45 to 5.04)%. Figure 2b and Figure 3b show the box plot of the mean dose (D_{mean}) difference in the structures (Target and OARs) drawn in the Pelvis and H&N sites.

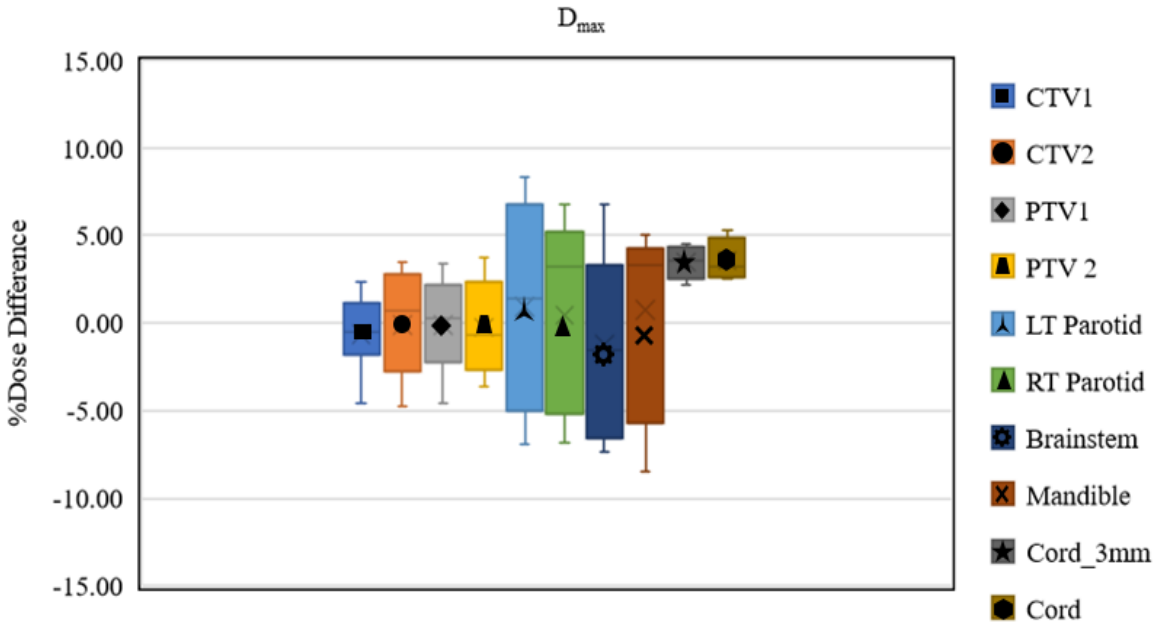

Figure 3. (a) Variation of Maximum Dose difference (Dmax) for Target and OARs of Head and Neck Group (n=20).

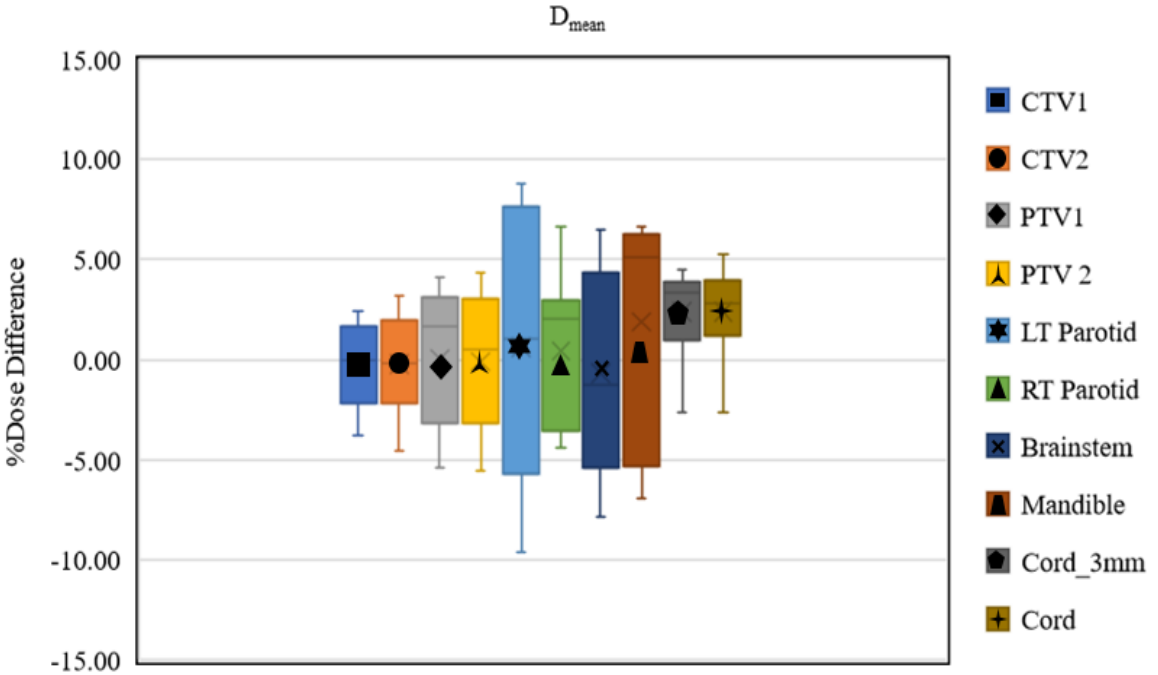

Figure 3. (b) Variation of Mean Dose (Dmean) for Target and OARs of Head and Neck Group (n=20).

The target dose difference for both sites was <5%, except for one patient in the H&N site having a dose difference of -5.38%. A considerable variation was observed in the femoral heads for the pelvis site, and one patient with a 4.16% variation was observed in the rectum. However, all the variation was within 5%.

In the head and neck, maximum variation was observed in the left parotid (-9.58 to 8.76)%, right parotid (-4.38 to 6.63)%, brainstem (-7.87 to 6.63)% and mandible (-6.94 to 6.61)%. However, the dose difference in the mean dose for OARs was within 10%.

Table 1. Variation of gamma passing rate for Head and Neck, and Pelvis site showed in Mean and standard deviation on the left side and median (range) on the right side for 3D (Coronal, sagittal and transverse plane) and volumetric gamma index (local and global).

Site (n= no. of sample)	Gamma Criteria			Coronal	Sagittal	Transverse	Volume Analysis
Head and Neck (n=20)	3D-Global	3%/3 mm	Mean ± SD	99.03 ± 0.60	98.99 ± 0.65	99.40 ± 0.82	98.81 ± 0.66
		2%/3 mm		97.30 ± 1.21	96.87 ± 1.57	98.40 ± 1.60	96.56 ± 1.50
		2 mm/3%		96.62 ± 1.51	97.04 ± 1.45	98.27 ± 1.78	96.79 ± 1.47
		2 mm/2%		92.90 ± 2.98	92.27 ± 3.16	95.12 ± 3.11	91.99 ± 2.80
Pelvis (n=20)		3%/3 mm		99.66 ± 0.35	99.41 ± 0.58	99.80 ± 0.32	99.65 ± 0.34
		2%/3 mm		98.46 ± 0.98	97.41 ± 2.38	98.52 ± 1.57	98.19 ± 1.56
		2 mm/3%		98.85 ± 0.89	98.08 ± 1.51	99.06 ± 0.90	98.79 ± 0.94
		2 mm/2%		95.93 ± 2.06	93.73 ± 4.13	95.61 ± 3.74	95.11 ± 3.31
Head and Neck (n=20)	3D-Local	3%/3 mm		95.00 ± 2.07	93.83 ± 2.84	95.65 ± 2.85	92.01 ± 2.98
		2%/3 mm		93.00 ± 2.60	91.90 ± 3.31	94.19 ± 3.43	90.31 ± 3.28
		2 mm/3%		86.19 ± 4.13	84.46 ± 4.80	87.58 ± 4.84	81.02 ± 5.17
		2 mm/2%		81.86 ± 4.71	80.21 ± 5.34	83.34 ± 5.88	76.78 ± 5.56
Pelvis (n=20)		3%/3 mm		97.52 ± 1.66	94.44 ± 3.43	97.37 ± 2.31	94.9 ± 3.76
		2%/3 mm		95.75 ± 2.36	92.88 ± 4.64	95.62 ± 3.31	92.74 ± 4.83
		2 mm/3%		93.39 ± 3.58	88.64 ± 5.98	92.43 ± 5.06	87.65 ± 7.05
		2 mm/2%		89.39 ± 4.63	83.17 ± 7.17	87.38 ± 6.88	82.57 ± 8.44
Head and Neck (n=20)	3D-Global	3%/3 mm	Median (Range)	99.2(97.6–99.9)	99.20(96.8–99.8)	99.8(96.60–100)	98.90(97.0–99.90)
		2%/3 mm		97.3(95.2–99.6)	97.10(91.9–99.3)	99.0(92.8–99.9)	96.70(92.6–99.30)
		2 mm/3%		96.8(93.3–98.8)	97.50(92.9–98.9)	98.8(91.2–99.8)	97.00(92.70–99.3)
		2 mm/2%		92.4(87.2–98.3)	93.40(82.9–96.6)	95.8(83.0–99.6)	92.15(84.4–97.2)
Pelvis (n=20)		3%/3 mm		99.8(98.6–100)	99.60(97.7–99.9)	99.9(98.5–100)	99.80(98.5–100)
		2%/3 mm		98.8(96.2–99.9)	98.15(90.0–99.6)	99.1(92.8–99.9)	98.65(93.4–99.7)
		2 mm/3%		99.2(96.0–99.7)	98.65(94.2–99.8)	99.4(96.3–100)	99.20(96.4–99.7)
		2 mm/2%		96.4(91.5–98.9)	94.90(82.6–98.2)	97.2(85.5–99.6)	96.25(86.8–98.7)
Head and Neck (n=20)	3D–Local	3%/3 mm		95.3(90.7–98.3)	94.30(84.5–97.6)	96.5(86.9–99.8)	92.00(84.4–97.2)
		2%/3 mm		93.7(87.7–97.8)	92.30(81.1–96.4)	94.9(83.9–99.7)	90.45(80.9–96.2)
		2 mm/3%		86.8(78.8–93.5)	84.90(69.7–91.2)	88.3(71.9–98.6)	81.40(68.9–90.8)
		2 mm/2%		82.3(73.9–90.7)	80.50(64.2–87.9)	83.6(65.3–97.1)	77.00(62.5–87.4)
Pelvis (n=20)		3%/3 mm		97.6(93.9–99.5)	96.70(86.8–98.9)	98.3(91.9–99.9)	95.90(86.1–99.1)
		2%/3 mm		96.2(90.9–99.1)	94.20(81.7–97.9)	96.4(87.4–99.4)	93.80(81.6–98.3)
		2 mm/3%		93.7(85.4–98.3)	90.80(75.9–95.9)	93.7(81.8–98.8)	89.70(73.0–96.0)
		2 mm/2%		90.2(79.1–96.7)	85.80(68.1–91.7)	88.5(73.5–96.4)	84.70(65.2–92.8)

DISSCUSSION

Pre-treatment patient-specific QA is essential for patient safety in advanced treatment planning and delivery. Furthermore, it plays a vital role in identifying and preventing errors associated with radiotherapy treatment's planning and delivery stages. The conventional method used for PSQA using gamma passing rates provides a good agreement scale but has minimal clinical significance. AAPM Task Group 218 have examined numerous aspects of PSQA(6); it stated a universal tolerance level for gamma pass rate set at a minimum of 95% for optimal clinical results with gamma criteria of 3%/2 mm for a threshold dose of 10%; further, the pass rate that surpasses 90% is considered the universally accepted threshold for action. However, the same gamma criteria were surveyed by Anetai et al., and they found that the proposed criteria are well accepted [10]. The current study used our

clinical experience of an Octavius 4D with a two-dimensional detector array and a Verisoft tool as a comprehensive patient-specific pre-treatment QA analysis tool.

In current study, both sites' plans crossed the action level of >95% with 3%/3 mm gamma acceptance criteria. In addition to stringent gamma criteria, 2%/2 mm failed to achieve the action level of >90% for both sites. On the computation of mean gamma pass rate with stringent criteria, 2%/2 mm significantly reduced for H&N than Pelvis sites, confirming the studies by other authors. However, it is anticipated that the approach will enhance the sensitivity of detecting dose errors by reducing the margin of error. Generally, for H&N treatment site required a higher modulation in small target volumes. Further, study suggested that 2%/2 mm criteria and an action level of >90% may lead to an increased number of false positive results. Hence, it is necessary to establish a suitable action level in this scenario.

A previous study by Urso et al. confirmed that three-dimensional and volumetric gamma index evaluation had a better agreement score than two-dimensional evaluation studied in Octavius 4D phantom. They also found that global gamma produces more homogeneous results and a higher passing rate because three-dimensional gamma gives slice-by-slice agreement considering all neighbouring, and volumetric gamma evaluation assesses the entire volume considering all planes in a time-resolved mode [11].

Also, studies showed that the transversal view of the patient's CT slice correlates well with the isodose distribution of the treatment plan. However, the detector resolution and computation algorithm significantly affected the gamma passing rate. However, a large amount of acquired data in RapidArc delivery with rotational arc acquisition allows better estimation of the dose distribution by the software [12]. In the current study, no action limits were chosen. However, it is observed that the dose to the target for both sites was within the 5% limit, which is similar to the result found by Low et al. [13]. Further, they found that the utilization of relative dose difference to assess DVHs may potentially lead to misleading results since this relative difference can be impacted by the dimension and position of the structure, particularly for OAR, which is generally located in the low-dose regions and obstructed by the MLCs. Coleman and Skourou et al. also observed that the proposed action levels based on DVH are excessively stringent, and challenges come when the anatomical entities present in close proximity to the target volume(PTV or CTV), such as target volume itself or OARs [5]. The PSQA results are affected mainly by the treatment delivery system, location of tumour sites, and complexity of treatment plans. Zhang et al. found that the action levels based on DVH (3% or 5%) are commonly employed in practice. However, it cannot apply to every structure due to different levels of complexity in the planning and delivery. Therefore, according to the actual situation, an appropriate setting and action level based on scientific DVH analysis are challenging [14]. However, determining a suitable action threshold for the gamma passing rate, which can differentiate between good and bad plans, remains challenging in PSQA. Furthermore, there is a potential for further incorporation of DVH. However, R Visser et al. studied DVH-based H&N IMRT QA with a strict action level of 2.5% and found two treatment plans that needed replanning; those were accepted based on gamma index evaluation [15]. Hence, they showed that using DVH information in the PSQA of IMRT treatment plans complements the standard gamma evaluation procedure and suggested setting dosimetric equipment-specific action limits for DVH.

In addition, for appropriate PSQA results, DVH-based evaluation includes the planning objectives to account for the minor systematic dose differences between the TPS and Quality Assurance systems. It is the responsibility of a clinically certified medical physicist to take action, when the measured dose exceeds the set tolerance limit. Generally, the initial state involves performing the phantom verification and detector positions, the patient's setup, and the treatment plan. After the correction, a second measurement should be performed if the error has been discovered. Suppose the tolerance signal is exceeded for several successive patients on the same day. In that case, this indicates a

problem with the linear accelerator output, and the machine output should be checked before treating other patients.

DVH-based treatment plan verification is a universal methodology as it is implementable for any radiotherapy treatment technique in any treatment site. However, some researchers made an effort to establish distinct action levels based on DVH criteria for various structures, including a 3% threshold for the target volume and a 5% for the OARs; this appears not applicable for all scenarios.

In the current study, DVH-based evaluation showed that the safety and effectiveness of radiotherapy rely on a critical parameter that is clinically relevant, and its use has significantly enhanced the correlation between patient-specific QA results and clinical. Hence, Octavius-based patient-specific QA with verisoft DVH evaluation and RadpidArc plan with AAA algorithm showed a good agreement. Further study can be done to set action limits based on the dosimetric equipment and different dose computation algorithm.

CONCLUSIONS

Gamma Index analysis is a very useful tool for routine RapidArc PSQA. However, the choice of gamma index varies on the degree of stringency required for the measurement. Hence, the current study demonstrated that integrating DVH matrices into a RapidArc protocol provides results of clinical significance that enhance the gamma index measurements. The DVH should be considered an investigation tool to identify the underlying cause of failed points due to its capability to detect dose-related structures directly linked to the treatment plan.

Acknowledgments

Not Applicable

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