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EVALUATION OF PATIENT-SPECIFIC QUALITY ASSURANCE (PSQA) USING OCTAVIUS 4D IN IMRT PLANNING FOR NASOPHARYNGEAL CANCER CASES

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ABSTRACT

Patient-Specific Quality Assurance (PSQA) is an important procedure for verifying the accuracy of dose planning before administering radiation therapy to patients. This study investigated the effects of progressively stricter OAR constraints on fluence complexity and Patient-Specific Quality Assurance (PSQA) performance in nasopharyngeal cancer IMRT as a preliminary case-based investigation. Three IMRT plan variations were created for two patients (tumor volumes: 56.16 cm³ and 75.35 cm³) using TPS Monaco: Plan0 (no OAR constraints), Plan1 (moderate constraints), and Plan2 (strict constraints) for the parotid glands, brainstem, and spinal cord. PSQA was performed using the PTW Octavius 4D phantom with gamma index criteria of 3%/3 mm, 3%/2 mm, and 2%/2 mm, in accordance with the AAPM TG-218. All plans achieved GPR values above the 95% tolerance limit for the 3%/2 mm criterion (95.5-99.8%) and above 90% for the 2%/2 mm criterion, confirming clinically acceptable deliverability across all optimization levels. Notably, the GPR in the patient with a larger tumor volume (ID2, 75.35 cm³) did not decrease with stricter constraints. The Plan2 GPR (99.5%) exceeded the Plan1 GPR (98.5%), whereas the patient with a smaller tumor volume (ID1, 56.16 cm³), whose GPR declined consistently from Plan0 to Plan2. This divergence reveals that the relationship between OAR constraint stringency and plan deliverability is patient-specific and governed by the geometric interaction between the tumor volume and surrounding OARs; larger targets afford the TPS greater dosimetric flexibility, thereby reducing the need for narrow MLC segments even under strict constraints. These findings suggest that Octavius 4D-based PSQA serves not only as a routine delivery verification tool but also as a patient-specific plan selection tool, and that the 3%/2 mm criterion is recommended as the primary clinical evaluation parameter for nasopharyngeal IMRT.

Keywords: Gamma Index; IMRT; Nasopharyngeal Cancer; Octavius 4D; PSQA

INTRODUCTION

External beam radiation therapy (EBRT) is widely used for the treatment of head and neck cancers. With technological advancements, three-dimensional conformal radiation therapy (3D-CRT)

using a linear accelerator equipped with a multi-leaf collimator (MLC) has begun to replace conventional techniques because it can shape the radiation beam according to the contour of the target, thereby providing a better dose distribution than previous techniques [1]. However, although 3D-CRT can improve dose delivery quality, this technique still has limitations in handling the anatomical complexity of the head and neck region and its proximity to critical structures. The MLC plays a crucial role in shaping the radiation beam by independently opening or closing leaf pairs over specific portions of the photon field, allowing the irradiation field to conform precisely to the target tumor [2]. These developments led to the emergence of intensity-modulated radiation therapy (IMRT), which has since become the standard of care for radiotherapy in head and neck cancer.

In IMRT, radiation is delivered from multiple gantry angles, and the radiation intensity is modulated through dynamic MLC movement so that enabling the radiation fluence to be adjusted in a complex manner according to the required dose distribution [3]. However, this complexity causes the dose gradient to become extremely steep, making treatment delivery more sensitive to mechanical deviations. Small discrepancies between dose distribution calculations in the TPS and actual dose delivery may result in mechanical instability in the linac, MLC position errors, variable dose output, or excessively low monitor unit (MU) values in certain segments. Therefore, every radiation plan must undergo dosimetric verification before clinical implementation using PSQA. Various studies have also shown that PSQA results are influenced by the verification methods and devices used, making the selection of an appropriate measurement system a key factor in the successful implementation of IMRT-based radiotherapy [4].

Patient-specific quality assurance (PSQA) is an important aspect of radiotherapy quality assurance that ensures that the dose prescribed by the treatment planning system (TPS) matches the dose delivered by a linear accelerator (linac) to the patient. PSQA is performed before irradiation to verify the consistency between TPS-calculated and delivered dose distributions [5].

According to the AAPM TG-218 recommendations, the tolerance and action limits for the gamma passing rate (GPR) measurement results are set at ≥ 95% for a gamma index variation of 3%/2 mm with a threshold of 10% [6]. Values below this threshold may be caused by the complexity of the treatment plan, tissue heterogeneity, overlapping target geometries between the tumor and organs at risk, or mechanical instability in the MLC and linac [7].

The gamma index (GI) is a widely used parameter for comparing two radiation dose distributions, which is measured and calculated as a standard of conformity. The gamma passing rate (GPR) indicates the system's response to error detection. With a low GPR value, the GI measurement system is sensitive to errors [8]. This method is based on the Dose Difference (DD) and Distance to Agreement (DTA) criteria, which define the relative tolerance for spatial and dosimetric deviations under a pass-fail framework, as recommended in AAPM TG-119, based on clinical standards of 3% DD and 3 mm DTA that are acceptable for photon beams with a 90% pass rate [9]. To evaluate the GPR, the criteria used were 2% DD and 2 mm DTA [10]. In this study, Octavius 4D was selected as the verification system because it can perform real-time three-dimensional fluence measurements during gantry rotation. This is suitable for multi-field IMRT plans compared with EPID systems or dosimetry films, which only provide two-dimensional evaluations [11].

Several studies have investigated PSQA performance in IMRT using various detector systems. Shen et al. (2021) evaluated the gamma passing rates in nasopharyngeal carcinoma and head and neck IMRT and found that anatomical features, such as air cavities and bony structures, significantly influenced the GPR outcomes [12]. Bin et al. (2023) demonstrated that plan complexity metrics derived from 269 IMRT plans, including 50 nasopharyngeal cases, are strong predictors of GPR in dosimetric verification [13]. Similarly, Chiavassa et al. (2019) reviewed a broad range of complexity metrics and concluded that increased fluence modulation consistently reduces the agreement between the measured and planned doses [14]. However, these studies focused primarily on correlating complexity metrics or anatomical features with GPR, without systematically investigating how deliberate variations in OAR dose constraints, which are applied at the treatment planning level, propagate into changes in fluence complexity, and ultimately affect PSQA deliverability. Specifically, no study has yet examined, in the context of nasopharyngeal carcinoma IMRT, whether progressively stricter OAR constraints for structures such as the parotid glands, brainstem, and spinal cord can still produce clinically deliverable plans, as verified by the Octavius 4D system. This represents a clinically relevant gap, given that planners routinely face a trade-off between tightening OAR protection and maintaining plan deliverability. Therefore, this study aimed to investigate the relationship between OAR optimization levels, fluence complexity, and PSQA performance in nasopharyngeal IMRT planning using the Octavius 4D system. This study should be considered a preliminary investigation to evaluate the relationship between optimization constraints and PSQA performance in complex IMRT plans.

In this study, three IMRT plan variations were created based on differences in organ-at-risk (OAR) optimization in the Treatment Planning System (TPS). Plan0 was designed as the basic plan without additional OAR constraints, Plan1 used moderate constraints, and Plan2 used stricter constraints for the parotid gland, brainstem, and spinal cord based on Dmean and Dmax parameters. These organs were prioritized because they are critical structures associated with radiation side effects in nasopharyngeal cancer radiotherapy, such as xerostomia and neurological complications. Increasing OAR protection can improve healthy tissue safety; however, it may also produce more complex fluence patterns and increase the sensitivity of MLC movements during irradiation. Therefore, PSQA evaluation is important to determine whether highly optimized IMRT plans can be delivered accurately and consistently using a linac system.

METHOD

Patient Selection

Two male patients with nasopharyngeal cancer, aged 55 and 73 years, with tumor volumes of 56.16 cm^3 and 75.35 cm^3, respectively, were included in this study. The tumor was located adjacent to the parotid glands and in proximity to both the brainstem and spinal cord, with a prescribed dose of 70 Gy/33 fractions being administered. Three IMRT radiation plans (Plan0, Plan1, and Plan2) were created with variations in the optimization constraints for the OARs. Plan0 did not include optimization constraints other than prioritizing the PTV. Plan1 applied moderate dose constraints

to the parotid glands, brainstem, and spinal cord, whereas Plan2 applied high-dose constraints to the same organs. The purpose of these variations was to observe the effect of increasing the number of organ constraints on the delivery of the IMRT plan. The dose constraints for each plan are listed in Table 1.

Table 1. Dose constraints for organs at risk of each plan for ID1 and ID2

Organs	Parameter	Plan0 (cGy)		Plan1 (cGy)		Plan2 (cGy)	
		ID1	ID2	ID1	ID2	ID1	ID2
Parotid glands	Dmean	≤ 2600	≤ 2600	≤ 2500	≤ 2500	≤ 2451	≤ 2400
Brainstem	Dmax	≤ 5400	≤ 5400	≤ 4100	≤ 4300	≤ 4100	≤ 4300
Spinal cord	Dmax	≤ 4500	≤ 4500	≤ 3400	≤ 3500	≤ 4000	≤ 3400

All plans were created using TPS Monaco with the Monte Carlo calculation algorithm. Gamma analysis was performed using the 3%/3 mm, 3%/2 mm, and 2%/2 mm criteria, with a tolerance threshold of 10% of the maximum dose, according to the AAPM TG-218 recommendation. This study focused only on evaluating PSQA using the gamma index. DVH-based analyses for the PTV and OAR were not performed because the purpose of the study was to assess fluence deliverability and dose delivery consistency, not to evaluate the quality of the plan. DVH analysis was considered a limitation of this study.

PTW Octavius 4D Calibration

The Octavius 4D phantom was calibrated using a dose of 200MU with a field area of 10 × 10 cm^2 for all photon energies. This calibration was performed to ensure a linear response of the detector to dose variations under standard conditions.

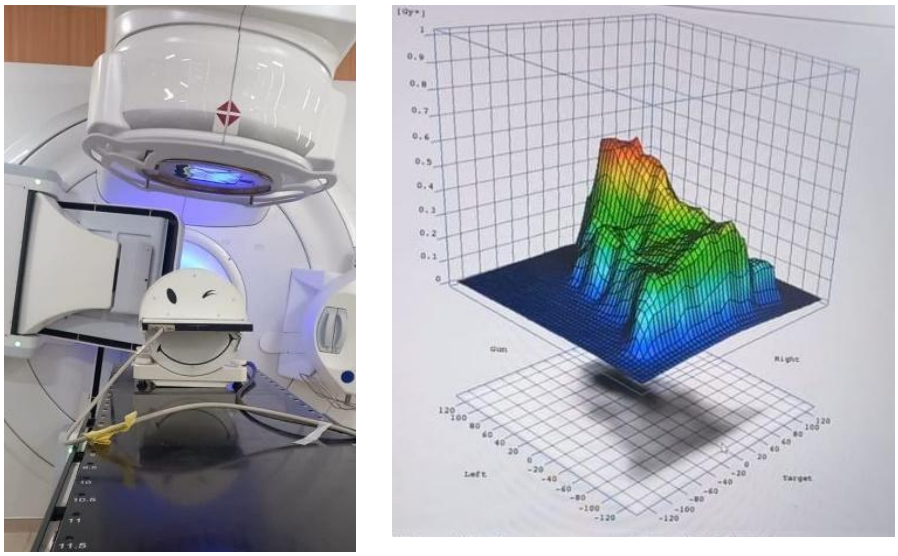
PSQA Measurement

Each plan (Plan0, Plan1, and Plan2) was sent to the Elekta Versa HD Linac using a 6MV photon beam. Measurements were performed using Octavius 4D, a PTW Octavius 1500 array detector, and Verisoft software. The detector comprises 1,405 ionization chambers arranged in a checkerboard pattern, each measuring 4.4 × 4.4 × 3 mm (0.06 cm^3) and covering an active area of 27 × 27 cm [11]. The inclinometer setting was used to synchronize the gantry rotation with the gantry angle of the linac. The beam direction was perpendicular to the detector array to minimize the beam direction correction factor. All measurements were performed at a source-to-surface distance (SSD) of 100 cm using a 9-field IMRT configuration with gantry angles ranging from 0° to 320°.

RESULTS AND DISCUSSION

The Octavius 4D phantom is a rotating polystyrene cylinder. Dose measurement using Octavius 4D with gamma index analysis is the primary method for pre-treatment radiotherapy Quality

Assurance (QA). This method compares the fluence from the dose distribution measured by Octavius with that predicted by the treatment planning system (TPS). The fluence used is spatial fluence, in which photons strike the detector on a two-dimensional (2D) surface. The Octavius phantom setup mounted on the linac and the dose profile displayed on the Verisoft software are shown in Figure 1.



(a) (b)

Figure 1. Pre-treatment using Octavius. (a) Octavius 4D IMRT phantom.(b) Dose profile displayed using the Verisoft software.

Figures 2 (ID1) and 3 (ID2) show a comparison of the fluence maps between the TPS and the measurement results using Octavius 4D for the three irradiation plans (Plan0, Plan1, and Plan2). Overall, the measured fluence maintained the planned TPS fluence distribution structure in the target area, indicating that the linac could reproduce the radiation intensity modulation according to TPS specifications without significant deviation from the target.

The differences between the plans are shown in the modulation levels at the target edges. In Plan0, the irradiation pattern was relatively easy to implement because the radiation intensity settings were uncomplicated. The MLC aperture was not divided into many small segments; therefore, the MLC movement was more stable during the irradiation. This makes Plan0 easier to reproduce by the linac and produces a high GPR. In Plan1, the dose constraints for the parotid glands, brainstem, and spinal cord were stricter than those in Plan0; therefore, the TPS must adjust the radiation intensity in a more complex manner to ensure that the target receives an adequate dose while protecting the organs at risk. This makes the irradiation pattern more varied and increases the number of small sections resulting from the MLC opening, making irradiation more sensitive to small changes when performed using linear accelerators. In Plan2, the dose constraints for the organs at risk were more stringent. To meet these constraints, TPS reduces the dose to the organs at risk while maintaining the dose to target organs. This process causes the fluence at the target edge to change dynamically because it must balance two objectives: maintaining target coverage

while protecting OARs. Consequently, the fluence modulation pattern at the target edge became more diverse, and the MLC formed smaller segments in several fields (particularly in fields 4, 6, and 8). This increase in the number of small segments physically complicates the plan delivery and makes accurate reproduction by the linac challenging.

Octavius's 3%/2mm gamma criteria fluence map for ID1 and ID2

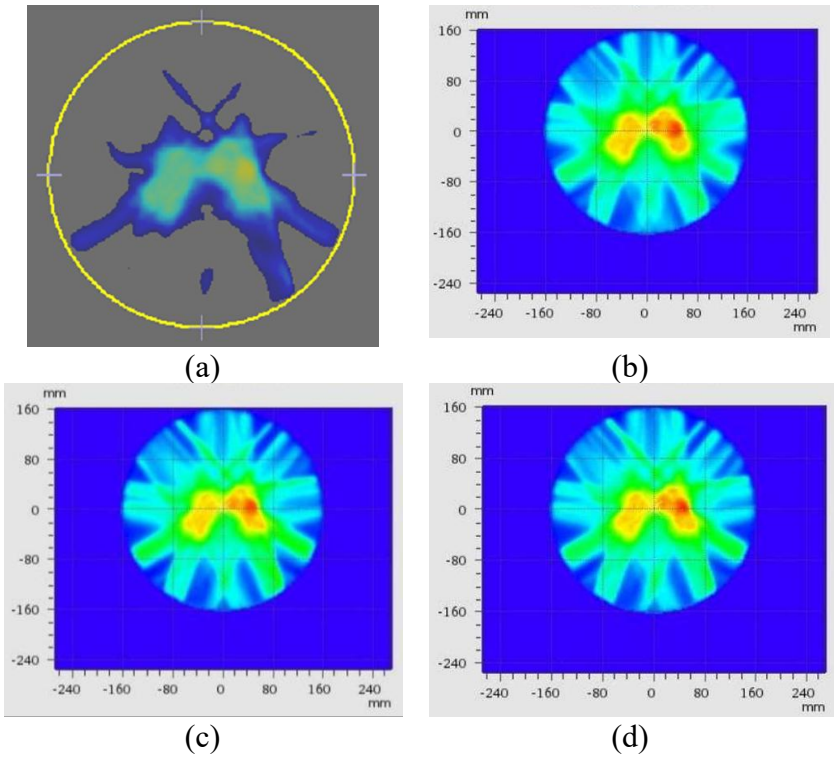
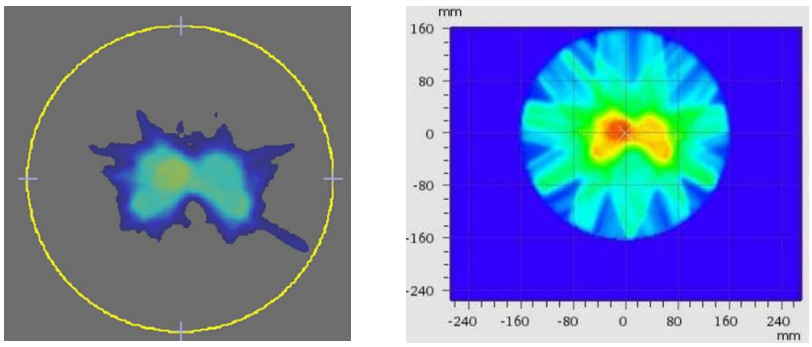


Figure 2. Comparison of TPS calculated and measured fluence maps for ID1. (a) Fluence map on TPS. (b) Fluence map on Plan0. (c) Fluence map on Plan1. (d) Fluence map on Plan2.

More complex fluence modulation increases the sensitivity of dose delivery to small mechanical variations in MLC positioning and gantry motion. Consequently, plans with higher modulation complexities may produce lower GPR values while remaining within clinically acceptable limits.



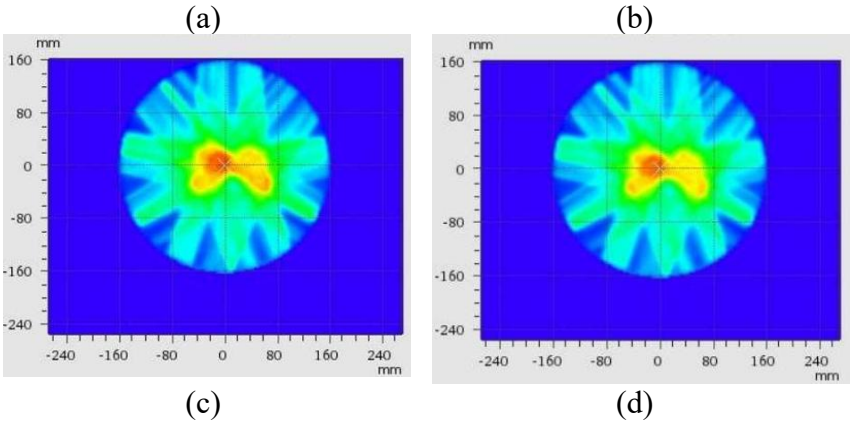


Figure 3. Comparison of TPS-calculated and measured fluence maps for ID2. (a) Fluence map on the TPS. (b) Fluence map on Plan0. (c) Fluence map on Plan1. (d) Fluence map on Plan2.

Gamma passing rate results

This study used gamma histograms recorded by Octavius with visualization of dose delivery accuracy and gamma evaluation displayed in Verisoft software, where gamma areas with values <1 were referred to as the gamma pass rates. Gamma areas with values >1 indicate a significant deviation between the measured and planned doses [15]. The GPR results are presented in Table 2.

Table 2. Gamma criteria 3%/3mm, 3%/2mm, dan 2%/2mm for ID1 and ID2

Plan	3%/3mm		3%/2mm		2%/2mm	
	ID1	ID2	ID1	ID2	ID1	ID2
Plan0	99.3%	100%	97.1%	99.8%	93.2%	98.4%
Plan1	99.1%	99.7%	96.1%	98.5%	92.3%	95.5%
Plan2	98.6%	99.9%	95.5%	99.5%	91.9%	97.3%

Table 2 shows that all IMRT plans (Plan0, Plan1, and Plan2) for both patients ID1 and ID2 produced high GPR values for all gamma criteria, indicating good agreement between the TPS calculations and measured dose distributions using Octavius 4D.

For the 3%/3 mm gamma criterion, all plans for ID1 and ID2 achieved GPR values above 98%, indicating that the dose delivery system and MLC movement functioned accurately during dose delivery.

In the stricter 3%/2 mm gamma criterion, a slight decrease in GPR was observed from Plan0 to Plan2 in ID1, with values of 97.1%, 96.1%, and 95.5%. This decrease indicates that increased optimization of at-risk organs tends to increase the complexity of the dose distribution and sensitivity to variations in distribution. However, all plans met the AAPM TG-218 tolerance limit of ≥95%. In ID2 for this gamma criterion, GPR values remained very high, ranging from 98.5%

to 99.8%, indicating that the plans could still be consistently reproduced despite higher optimization constraints.

For the most stringent gamma criterion (2 %/2 mm), the GPR values decreased further, particularly for ID1, where the GPR values ranged from 91.9% to 93.2%, whereas for ID2, the values ranged from 95.5% to 98.4%. Although the values in ID1 were below 95%, they were still above the minimum tolerance limit of 90% recommended by the AAPM TG-119 for complex IMRT plans. The progressive decrease in the GPR from Plan0 to Plan2 in ID1 suggests that stricter OAR constraints lead to more complex dose modulation and smaller MLC segment sizes. Smaller segments require more precise and rapid MLC movements, increasing the susceptibility of dose delivery to mechanical uncertainties. However, a lower GPR does not necessarily indicate linac failure or instability; it may reflect the increased complexity of the treatment plan generated during TPS optimization.

An interesting finding was observed in patient ID2, where GPR Plan2 scored higher than Plan1 on all gamma criteria, even though Plan2 applied stricter OAR constraints. For the 3%/2 mm criterion, the GPR for Plan1 in Patient ID2 was 98.5%, whereas Plan2 for Patient ID2 reached 99.5%—a 1.0% difference that contradicts the consistent pattern observed in Patient ID1. This anomaly cannot be explained by differences in optimization constraints alone but rather reflects the influence of distinct anatomical and tumor geometric characteristics between the two patients.

ID2 had a larger tumor volume (75.35 cm^3) than ID1 (56.16 cm^3), with the tumor located closer to the brainstem and spinal cord. These differences in volume and geometry can directly affect the dose distribution generated by TPS. For a larger tumor target, the TPS has more dosimetric regions to optimize the dose distribution: beams from various gantry angles can provide a more uniform dose contribution across the entire target volume, thereby eliminating the need for excessively narrow or discontinuous MLC modulation. Consequently, when the Plan2 constraints are tightened on ID2, the TPS does not need to create small MLC segments that are difficult for the linac to execute; instead, it simply redistributes the fluence intensity more smoothly among the existing segments. This is why the fluence complexity of Plan2 ID2 does not increase significantly compared to Plan1 ID2, and its GPR remains high or increases slightly.

Conversely, in ID1, which had a smaller tumor volume (56.16 cm^3), the geometrically narrower distance between the target volume and OAR forced the TPS to create a sharper dose gradient at the target boundary. As the constraints were tightened from Plan1 to Plan2, the TPS had to form increasingly smaller and more precise MLC segments to maintain target coverage while reducing the dose to nearby OARs. This condition caused the GPR for ID1 to decrease consistently from Plan0 to Plan2. This pattern aligns with the findings of Shen et al. (2021), who reported that head-and-neck anatomical geometry, including the distance between the tumor and critical structures, significantly influenced GPR outcomes in IMRT for nasopharyngeal cancer [12]. Thus, the ID2 anomaly in Plan2 is not a system discrepancy but rather evidence that the complexity of fluence and GPR is determined not only by the strictness of optimization constraints but also by the interaction between the tumor's anatomical geometry and the surrounding OARs. This finding also constitutes a key contribution of this study, demonstrating that the relationship between the level of OAR optimization and plan deliverability is patient-specific and cannot be generalized without considering the individual anatomical factors.

From a clinical perspective, the results of this study provide practical guidance for radiation planners in selecting an appropriate optimization strategy. Plan1 (moderate constraints) demonstrated a good balance between OAR protection and treatment deliverability: GPR consistently remained above 95% for the 3%/2 mm criterion in both patients, indicating that this level of optimization is safe and can be accurately delivered by the linac. Plan2 (strict constraints) remained clinically acceptable as it fell within the AAPM TG-218 tolerance limits; however, the trade-off was an increased sensitivity to mechanical variations in the MLC, particularly in patients with smaller tumor volumes, such as ID1. Thus, the choice between Plan1 and Plan2 should consider the patient's individual risk profile: for patients with OARs adjacent to the tumor (small distance), such as ID1, the use of Plan2 should be accompanied by strict PSQA verification before clinical implementation, whereas for patients with larger tumor volumes, such as ID2, Plan2 can be applied with a lower risk of deliverability issues. Overall, the PSQA results of this study confirmed that increasing the OAR constraints does not necessarily compromise plan deliverability, provided that the TPS can optimize the fluence distribution without creating MLC segments that are excessively narrow. This is consistent with Das et al. (2022), who reported that GPR sensitivity to treatment plan complexity is nonlinear and strongly influenced by field geometry [7], and Deng et al. (2024), who demonstrated that more stringent optimization can yield clinically acceptable plans if adequately verified [16],[17]. The clinical implication is clear: Octavius 4D-based PSQA is not merely a routine verification procedure but also a treatment plan selection tool that can help planners determine whether a given level of OAR optimization can still be safely executed on the linac, particularly in patients with complex head and neck anatomy.

This study had several limitations. First, only two nasopharyngeal cancer cases were evaluated; therefore, the findings should be considered preliminary and cannot be generalized to broader clinical populations. Second, the PSQA evaluation focused only on gamma index analysis using Octavius 4D without additional complexity metrics such as modulation complexity score or DVH-based evaluation. Third, no formal statistical analysis was performed because of the small sample sizes. Future studies involving larger patient cohorts and broader dosimetric evaluation methods are required to strengthen and clinically validate the relationship between fluence complexity, OAR optimization, and PSQA performance.

CONCLUSION

This preliminary study demonstrated that all IMRT plans achieved clinically acceptable GPR values under the 3%/2 mm criterion, confirming that stricter OAR constraints do not necessarily compromise plan deliverability. The effect of OAR optimization on GPR was patient-specific and likely influenced by the tumor-OAR geometry and target volume. These findings suggest that the Octavius 4D-based PSQA may support not only delivery verification but also patient-specific plan selection during IMRT optimization. A 3%/2 mm criterion is recommended for clinical PSQA evaluation. Further studies with larger patient cohorts and additional dosimetric metrics are required to validate these findings.

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