Technical Note

Setting the Tolerance and Action Limit for Patient-specific Quality Assurance of Craniospinal Irradiation Volumetric Modulated Arc Therapy: Based on AAPM TG-218 Report

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Abstract

Purpose: The purpose of this study was to investigate the tolerance limits (TL) and action limits (AL) in gamma passing rate for craniospinal irradiation volumetric modulated arc therapy (VMAT) treatment plans. **Materials and Methods:** Twenty-eight patients were planned using the VMAT technique; plans were delivered on an Elekta Versa HD. The delivered fluence was recorded by PTW 2D array, and the gamma passing rate (%GP) was analyzed using PTW VeriSoft. The universal TL and AL from TG 218 were applied to analyze the %GP for each plan. As per AAPM TG 218, a statistical process control of %GP was performed to set the TL and AL. **Results:** The average %GP for the brain, upper spine, and lower spine was 98.4%, 98.8%, and 98.4%, respectively. The TL and AL for the brain, upper spine, and lower spine were TL: 95.1%, 95.1% and 94.8%, and AL: 89.7%, 89.3%, and 86.7%, respectively. The analysis of variance test showed that the *P* value in %GP among the brain, upper spine, and lower spine was >0.1679. The %GP rate between the sites was not statistically significant. **Conclusion:** AAPM TG 218 guidelines are more suitable for establishing TL and AL for craniospinal irradiation (CSI) VMAT plans. This study suggests that a single value of TL and AL for CSI plans, rather than site-specific values, could be suitable for monitoring CSI patient-specific quality assurance trends and the same can be utilized.

Keywords: AAPM TG218, action limits, gamma analysis, patient-specific quality assurance, tolerance limits

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Introduction

Medulloblastoma is the most common malignant brain tumor in childhood, with a lower incidence in adults. Long-term survival rates for low-and moderate-risk patients have exceeded 80% due to advances in treatment.[1] Seidel *et al.* reported that radiotherapy has evolved into a curative approach for low- to standard-risk patients, incorporating technically advanced, dose-reduced craniospinal irradiation (CSI) combined with tumor bed boosts and polychemotherapy.[1] Achieving therapeutic goals in radiotherapy requires rigorous verification of treatment plans and measured doses. Verifying a patient's plan before delivery helps identify potential errors that could lead to incorrect treatment.[2,3] These plan verifications, often referred to as patient-specific quality assurance (PSQA), are quantified using the gamma passing rate (%GP).[4,5] The %GP is the number of measured points agreeing with calculated points by given gamma criteria and this can be expressed as percentage. The %GP typically requires tolerance and action limits (AL) to evaluate the suitability of a treatment plan.[6,7] American Association of Physicists in Medicine (AAPM) Task Group (TG) 218 provides comprehensive guidelines for setting tolerance limits (TL) and AL for intensity-modulated radiotherapy and volumetric modulated arc therapy (VMAT) PSQA.[8] While Task Group (TG) 218 recommends universal TL and AL values, these may not be applicable to every clinic globally. The choice of limits depends on factors such as delivery modality, site-specific characteristics, plan complexity, and the quality assurance (QA) devices used. TG 218 further suggests establishing local TL and AL through a statistical control process, enabling clinics to compare universal and local limits.[8] Many studies have reported

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TL and AL for individual sites, such as the head and neck, thorax, pelvis, and prostate.[9-12] However, no studies have addressed TL and AL for VMAT CSI plans, which involve three distinct regions (cranial [brain], thorax [upper spine], and pelvis [lower spine]) in a single treatment plan. Since TL and AL for each site may vary, it is essential to determine site-specific values.[8,9] This raises the question: are three separate sets of TL and AL necessary for CSI, or would a single set suffice? In CSI, the brain field contributes to the upper spine, the upper spine field contributes to both the brain and lower spine, and the lower spine field contributes to the upper spine. This interdependence suggests that site-specific TL and AL may not be as critical as a single set of values for the entire CSI plan. In this study, we tested this hypothesis using statistical analysis, incorporating the recommendations of TG 218. Establishing a single set of TL and AL for CSI could simplify the QA process while providing valuable insights for the medical physics community. Given that the combination of radiotherapy and chemotherapy offers a curative approach for low- and moderate-risk medulloblastoma patients, it is crucial to perform PSQA and establish appropriate TL and AL for CSI planning techniques.

Materials and Methods

Treatment planning and delivery

Table 1 shows the demographic details of 28 patients. All CSI VMAT plans were created using the Monaco treatment planning system (TPS) version 6.1. CSI planning techniques have been widely discussed in the literature;[13-16] in this study, the overlap technique was adopted. Each plan used multiple iso centers, determined by the patient's height: two iso centers were used for patients under 55 cm, and three iso centers were used for patients taller than 55 cm. Each region – the brain, upper spine, and lower spine – was assigned an individual iso center for planning purposes. During planning, the calculation grid size was set to 0.3 cm, with an arc increment of 20°, a minimum segment width of 0.6 cm, 180 control points per arc, and a statistical uncertainty of 1% per plan. The jaw was fixed, with an overlap of at least 4–6 cm at each iso center to minimize junction errors. A full arc was used for the brain, whereas the spine was treated with two posterior partial arcs on each side (left and right), each with a 70° arc length, Figure 1 shows the beam arrangement for one of the three iso-center plan. All approved plans were delivered using the Elekta Versa HD linear accelerator (linac) with a 6 MV photon beam. The plans were optimized to achieve adequate target coverage, with 95% of the planning target volume receiving at least 95% of the prescribed dose, while sparing critical organs such as the heart, kidneys, and lungs. Each site was irradiated individually by shifting the couch longitudinally; lateral and vertical shifts were set to zero for all patients to minimize errors when transitioning between the iso centers.

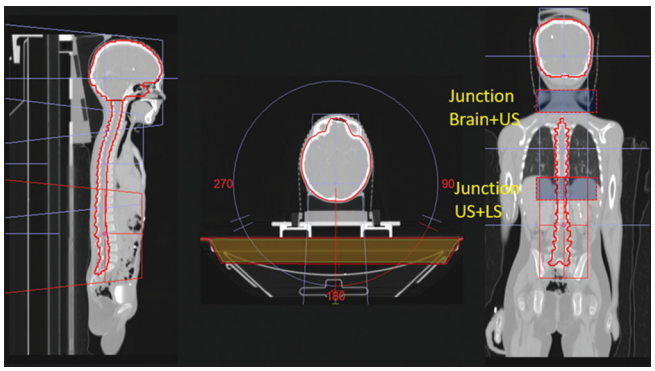

Figure 1: Beam arrangement for craniospinal irradiation volumetric modulated arc therapy plan. US: Upper spine, LS: Lower spine

Patient-specific quality assurance process

Figure 2 shows the PSQA setup in the linac bunker. For each CSI plan, QA plans were created independently for each treatment site. All QA plans used a two-dimensional (2D) array embedded in a slab phantom, positioned at a depth of 5 cm and with a source-to-surface distance of 95 cm. In this study, the PTW 2D array 1500 was used as the QA device. This array covers a maximum field size of 27 cm × 27 cm and consists of 1405 ionization chambers, each separated by 7.1 mm.

The QA plans were then exported to the PTW VeriSoft platform, where gamma analysis was performed. The actual treatment plans were delivered on the linear accelerator in

Table 1: Patient's demographic details

Patient	Sex	Pathology	Age (years)	PTV length (cm)
1	Male	Medulloblastoma	8	51.72
2	Female	Medulloblastoma	9	52.33
3	Male	Medulloblastoma	11	62.21
4	Male	Medulloblastoma	7	54.5
5	Female	Medulloblastoma	19	70.01
6	Female	Medulloblastoma	7	46.87
7	Male	Medulloblastoma	9	64.62
8	Female	Medulloblastoma	8	55.64
9	Male	Medulloblastoma	11	66.96
10	Male	Medulloblastoma	12	55.57
11	Female	Medulloblastoma	10	62.53
12	Male	Medulloblastoma	6	51.72
13	Female	Medulloblastoma	6	44.82
14	Female	Medulloblastoma	7	55.27
15	Male	Medulloblastoma	16	74.19
16	Male	Medulloblastoma	15	65.86
17	Female	Medulloblastoma	7	44.61
18	Male	Medulloblastoma	7	48.56
19	Male	Medulloblastoma	13	67.04
20	Female	Medulloblastoma	14	52.44
21	Male	Medulloblastoma	17	71.43
22	Male	Medulloblastoma	12	57.03
23	Male	Medulloblastoma	10	57.54
24	Male	Medulloblastoma	7	55.55
25	Male	Medulloblastoma	9	49.57
26	Female	Medulloblastoma	9	51.81
27	Female	Medulloblastoma	14	52.72
28	Male	Medulloblastoma	15	61.68

PTV: Planning target volume

QA mode, with each treatment site delivered separately, and the delivered fluence captured independently by the PTW 2D array. If any field extended onto the electronic edge of the 2D array, the array was adjusted by shifting it in the longitudinal direction, with the shift recorded. This shift was accounted for during gamma analysis only for plans where the 2D array had been adjusted.

Gamma analysis

At our institute, TL and AL recommended by AAPM TG 218 have been applied to all VMAT cases, regardless of the treatment site, since 2019. In this study, all CSI VMAT plans followed the AAPM TG 218 gamma criteria, which specify a 3% dose difference (DD) and 2 mm distance-to-agreement (DTA) (3%/2 mm) for gamma analysis. Here, DD represents the DD between measured and calculated dose distributions, whereas DTA is the distance between a point in one dose distribution and the corresponding dose level in a second distribution. Gamma analysis was performed with global normalization and a low-dose threshold of 10%.

Tolerance and action limit calculation

The calculation of TL and AL was adapted from AAPM TG 218. In this study, 28 patient plans were randomly selected retrospectively (from 2022 to 2024) and included in the PSQA process. From the PSQA measurements, the %GP values were obtained for the 3%/2 mm criteria, which were used for the calculation of TL and AL. The control chart (I-chart) is the core concept of the statistical control process; the I-chart indicates when the PSQA monitoring process is out of control. The I-chart includes the upper control limit (UCL) and lower control limit (LCL), with any variation beyond these limits indicating that the process is out of control.[8,12] In the I-chart, the spread of the data should closely follow the centerline (CL) as much as possible.

The calculation requires the following parameters: CL, moving range (mR), variance (σ^2), UCL, and LCL, all of which are calculated using the following equations:[8]

$$CL = \frac{1}{n}\sum_{1}^{n} x \quad (1)$$

$$\overline{mR} = \frac{1}{n-1}\sum_{i=2}^{n} |x_i - x_{i-1}| \quad (2)$$

$$UCL = CL + 2.66\ X\ \overline{mR} \quad (3)$$

$$LCL = CL - 2.66\ X\ \overline{mR} \quad (4)$$

$$AL = 100\% - \beta\sqrt{\sigma^2 + (\overline{x}_i - T)^2 / 2} \quad (5)$$

where x_i is the mean %GP, n is the number of patients ($n = 28$), T can be considered a 100% (since maximum %GP is 100%). β is a constant and its value can be 6 as per AAPM TG 218.[8]

To evaluate the impact of increasing plan complexity on %GP an approximate modulation scaling factor (MSF) was used, it is defined as ratio of monitor unit and dose per fraction (MSF = MU/Dose per fraction).

Statistical treatment

All the data were analyzed using the *F*-test (analysis of variance [ANOVA]), including Tukey's honest significant difference (HSD) test. The *F*-test determines whether there is an overall difference between the sample means (among the brain, upper spine, and lower spine). Tukey's HSD test indicates the significance between pairs of data (brain vs. upper spine, brain vs. lower spine, and upper spine vs. lower spine). $P < 0.05$ is considered statistically significant in both tests.

Results

Figure 3 shows the measured and TPS fluence for one of the patients, by comparing this fluence %GP can be obtained. The average %GP for the brain, upper spine, and lower spine fields was 98.4%, 98.8%, and 98.4%, respectively. The TL for the brain, upper spine, and lower spine were 95.1%, 95.1%, and 94.8%, whereas the AL were 89.7%, 89.3%, and 86.7%, respectively. Across all three sites (averaged %GP for the brain, upper spine, and lower spine), the overall %GP was

Figure 2: The patient-specific quality assurance setup in the linac bunker

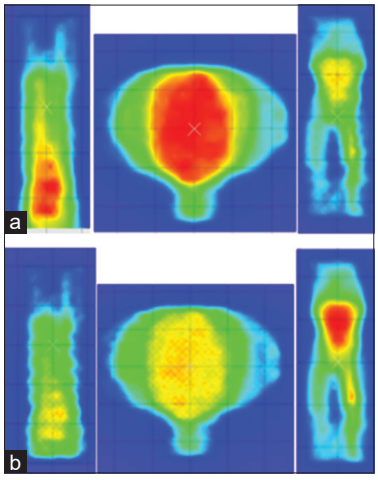

Figure 3: Treatment planning system calculated (a) and two-dimensional array (b) measured fluence

98.5%, with average TL and AL values of 95.3% and 89.2%, respectively.

Plan complexity was measured as MF for each plan, with average MF values of 3.1 ± 1.1 for the brain, 2.5 ± 0.5 for the upper spine, and 2.2 ± 0.4 for the lower spine. The highest observed correlation between %GP and MF was 0.34. Statistical analysis was performed on the %GP data for the brain, upper spine, and lower spine to evaluate significance. The overall *P* value from the *F*-test (ANOVA) was > 0.05, indicating no statistically significant differences in %GP between the brain, upper spine, and lower spine. Pairwise comparisons using Tukey's HSD test also showed no significant differences between any of the sites, with the following *P* values: brain versus upper spine (0.2231), brain versus lower spine (0.2516), and upper spine versus lower spine (0.997). Figure 4 presents the calculated parameters of the statistical control process in terms of whisker box plot.

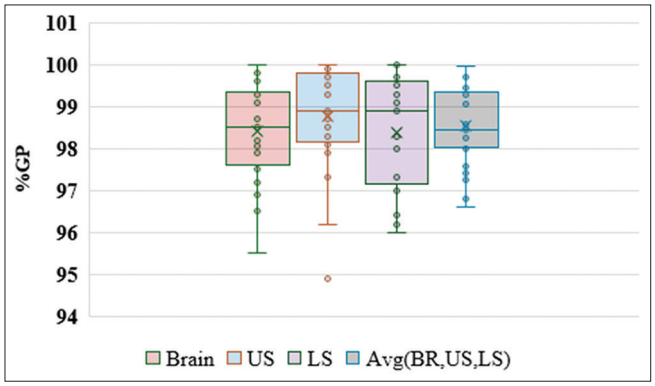

Figure 4: Statistical control process parameters in whisker box plot (from left: brain, upper spine, lower spine and average data). BR: Brain, US: Upper spine, LS: Lower spine

The shorter box length of avg (Brain, Upper spine and lower spine) shows that the data points were in good agreement with each other. The tallest box length of lower spine shows slightly dispersed data compared to other sites; the dispersion data were not statistically significant. There was only one point as an outlier in the give plot for upper spine [Figure 4] shows that the maximum number of pints was closer to mean value.

Discussion

For lower- and moderate-risk patients, who are expected to have good survival rates, it is essential to deliver radiotherapy with the highest levels of accuracy and precision. PSQA is a critical component of the radiotherapy process, enabling the identification of dose delivery errors through gamma analysis. Establishing TL and AL for such patients plays a vital role in ensuring treatment quality. In this study, we aimed to determine the TL and AL in PSQA for CSI-VMAT plans using the PTW 2D array. The literature emphasizes the need for site- and modality-specific TL and AL, accounting for both high and low plan complexities. Xia *et al*. established TL and AL for SRS and compared their findings to TG 218, suggesting that spatial tolerance criteria could be tightened to 1 mm while maintaining QA control across various systems.[17] Similarly, Price *et al*. used TG 218 guidelines to establish TL and AL for SBRT, concluding that stricter gamma criteria do not necessarily predict clinically meaningful delivery errors.[18] Fusella *et al*. highlighted the importance of adjusting TL and AL frequently as the number of cases grows or when new technologies are introduced.[10]

The use of I-charts is critical for monitoring and adjusting TL and AL over time. In this study, I-charts were employed to monitor PSQA data for the brain, upper spine, and lower spine independently. Figure 5 also shows the I-charts for these sites,

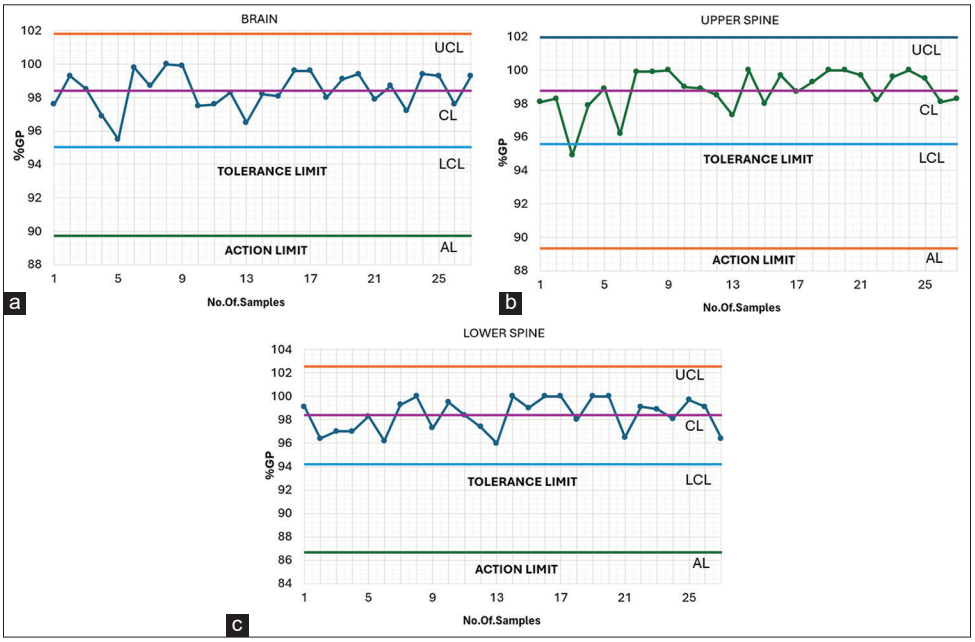

Figure 5: I chart for brain (a), upper spine(b), and lower spine(c). UCL: Upper control limit, CL: Centerline, LCL: Lower control limit, AL: Action limit

confirming that the QA process remained in control, with no data exceeding the UCL or LCL. Variations in %GP rates observed in this study may be attributed to uncertainties in delivery, dosimetry, and planning processes.[8] TG 218 highlights that TL can vary with plan complexity due to case-to-case variability. Plan complexity was assessed using approximate MF for each plan. Consistent with the findings of Xia *et al*., Price *et al*., and Fredh *et al*., this study found no significant correlation between %GP and plan complexity.[17-19] The statistical results showed that the there was no significant in TL and AL between brain, upper spine and lower spine. Similarly, the variations in %GP were also not statistically significant, supporting the conclusion that a single set of TL and AL can be used across all sites in CSI VMAT plans. For this study, the TL and AL values for all sites were averaged, resulting in a single TL of 95.3% and an AL of 89.2% for CSI VMAT plans. The AL observed in this study was 0.9% lower than the TG 218-recommended universal AL of 90%, indicating that TG 218's universal AL is slightly stringent to our institutional AL. Conversely, the TL in this study exceeded the TG 218 universal TL by 0.3%, suggesting that TG 218's universal TL (95%) is marginally lenient to our institutional TL. Nevertheless, the universal TL and AL recommended by TG 218 remain applicable for CSI VMAT plans involving three different treatment sites, ensuring a streamlined and effective QA process.

Conclusion

In this study, the universal TL and AL recommended by TG 218 were evaluated for CSI-VMAT plans. Given that CSI plans involve three different treatment sites, setting individual tolerances for each site was found to be redundant. The variations in TL and AL across the brain, upper spine, and lower spine were not statistically significant. Therefore, this study suggests that a single value of TL and AL, derived as the average TL and AL across all three sites, can be applied to the entire CSI plan. The maximum variation between the local (institutional) limits and the TG 218-recommended limits was 0.9%. This demonstrates that the universal TL and AL recommended by TG 218 remain valid for CSI VMAT plans. TG 218 thus serves as a valuable reference for establishing and standardizing these limits.

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Conflicts of interest

There are no conflicts of interest.

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