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Physics Investigation

Application of TG-218 action limits to SRS and SBRT pre-treatment patient specific QA

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ABSTRACT

AAPM TG-218 provides recommendations for standard IMRT pre-treatment QA without giving specifics for stereotactic radiosurgery (SRS) and stereotactic body radiotherapy (SBRT). In light of this, our purpose is to report our experience with applying TG-218 recommendations to a large multicenter clinical SRS and SBRT program for a range of diverse clinical pre-treatment QA systems. Pre-treatment QA systems included Delta4 (Scandidos), Portal Dosimetry (Varian Medical Systems), ArcCHECK (SunNuclear), and SRS MapCHECK (SunNuclear). Plans were stratified by technique for each QA system, and included intracranial and extracranial IMRT and VMAT (total QA cases n=275). Gamma analysis was re-analyzed with spatial/dose criteria combinations ranging from 1 to 3 mm and 1% to 4%, and action and tolerance limits were calculated per plan type and compared to the "universal" TG-218 action limit of 90%. The analysis indicated that spatial tolerance criteria could be tightened to 1 mm while still maintaining an in-control QA process for all QA systems evaluated.

Keywords: SRS, SBRT, IMRT&VMAT QA, Gamma analyses

INTRODUCTION

Intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) are complex treatment delivery modes that utilize dynamic MLC motion, dose rate modulation, and in the case of VMAT, gantry rotation speed modulation to achieve the desired dose distribution.[1] Due to the complex nature of these techniques, patient-specific quality assurance techniques have been developed to ensure that the intended dose is correctly delivered[2]. In addition, accurate Treatment Planning System (TPS) beam modeling is necessary to reduce uncertainty errors during the TPS planning process; the ability of the TPS to accurately model patient specific IMRT and VMAT treatment plans is verified partly through pre-treatment Quality assurance (QA).[3] Thus, patient specific pre-treatment QA for IMRT and VMAT have become a routine step in the treatment process.

Stereotactic radiosurgery (SRS) is a non-surgical radiation therapy technique used to treat functional abnormalities and small tumors of the brain with a high dose in a single or few fractions[4]; similarly, stereotactic

body radiotherapy (SBRT) refers to this same concept applied extracranially. Given the increased dose, high dose modulation, and tight margins, patient specific pre-treatment QA is of increased importance for SRS and SBRT[5], with professional organizations recommending it be part of an effective QA program [3,6,7].

A common strategy for patient-specific pre-treatment QA is to compare TPS dose calculations with some form of 2D or 3D dose measurements[8], with common analysis metrics including dose difference, distance to agreement and Gamma Index [9,10]. Dosimetric measurement technology, analysis metrics, and action criteria vary between institutions [3,11], and questions remain about effectiveness of commonly used criteria [12,13]. AAPM task group 218 (TG-218) recently published guidelines for pre-treatment QA which summarizes published data, compares QA criteria among institutions, and gives recommendations on tolerance and action limits. This included a universal action limit of 3% / 2mm with 10% threshold and 90% passing rate, as well as a general strategy for defining action limits that are specific to the institution, treatment technique, and/or treatment site. However, these TG-218 recommendations apply to standard IMRT and VMAT, whereas for SRS and SBRT cases, they state that tighter tolerances may be warranted without giving any specifics. In light of this, the purpose of this work is to report our experience in applying the TG-218 recommendations to the suite of QA devices available in our clinic for SRS and SBRT cases.

MATERIALS AND METHODS

For this study we re-analyzed the pre-treatment QA from 4 different QA devices with respect to the TG-218 recommendations, for a total of 275 plan and 1214 field QA deliveries. All the cases used in this study were clinically treated, and the QA results that were reanalyzed for this study were the original clinical QA delivery, with the exception of the SRS mapCHECK which was recently commissioned for SRS QA. For the SRS mapCHECK, the QA delivery was performed retrospectively for previously treated clinical plans. A Gamma Index based analysis was performed with 6 spatial/dose criteria combinations: 4%/1mm, 3%/3mm, 3%/2mm, 3%/1mm, 2%/1mm, 1%/1mm for a total of 6198 Gamma Index analyses. For each specific combination of treatment technique and treatment site, we calculated the action limit and tolerance limit and compared to the "universal" TG-218 action limit of 90% with a Gamma <1. Finally, correlation of the Gamma Index results with respect to treatment plan characteristics were examined.

QA Devices

Four QA devices were used in this study: Delta4 (ScandiDos AB, Uppsala, Sweden), Portal Dosimetry (Varian Medical Systems, Palo Alto CA), ArcCHECK (Sun Nuclear, Melbourne, FL)), and SRS MapCHECK (Sun Nuclear, Melboume, FL).

The first QA device included in this study is the Delta4 (ScandiDos AB, Uppsala, Sweden); at our institution this device is utilized for pre-treatment QA of all VMAT cases as well as IMRT fields that use Flattening Filter Free (FFF) photons for a True Composite QA measurement with all couch rotations overridden and set to zero. The Delta4 system consists of 1069 p-type diodes on two near-orthogonal planes embedded in a cylindrical PMMA phantom with 22cm diameter.[14] The Delta4 interpolates dose to points without detectors to reconstruct 3D dose for comparison with the calculated dose matrix.

The second device included is the Varian portal dosimetry (Varian Medical Systems, Palo Alto, CA) system. This is used at our institution for pre-treatment QA of IMRT plans with flattened beams for a Perpendicular Field by Field QA measurement with all gantry and couch rotations overridden and set to zero, by comparing the delivered fluence taken with the Electronic Portal Imaging Device (EPID)[15] (aSi-500) to a prediction made using Varian's Portal Dosimetry Image Prediction (PDIP) algorithm.[16]

A third device, ArcCHECK (ArcCHECK, Sun Nuclear, Melbourne, FL), is used at a satellite of our institution for pre-treatment VMAT SRS and SBRT QA (in cases where Delta4 device would be used at the main center). We use True Composite QA measurement for ArcCHECK with all couch rotations overridden and set to zero. ArcCHECK is a cylindrical (21cm diameter) water-equivalent phantom with a three-dimensional array of 1386 diode detectors (0.8 x 0.8 mm^2 active area per detector) at 10 mm spacing.[17]

The final device included in the study is the SRS MapCHECK; This device was recently acquired at our institution for use with VMAT SRS cases. SRS MapCHECK is inserted horizontally into the StereoPHAN phantom and provides a true composite measurement that included rotation of the gantry and couch. The SRS MapCHECK is a High-density diode array for stereotactic patient QA measurements. It includes a 77 x 77mm^2 array of 1013 detectors, each with a 0.48 x 0.48mm^2 active area.[18] For each QA delivery the horizontal plane was aligned to be at the center of at least one radiosurgery target so as to measure the high dose region.

Criteria analysis

Gamma Index is a widely used comparison metric for pre-treatment QA, proposed in 1998 by Low

et al.[19]Six combinations of dose difference criteria (DD) and distance to agreement criteria (DTA) for the Gamma Index were used to analyze QA results, stratified by QA device, treatment technique, and treatment site. The threshold pixels criterion (TH) in terms of percentage of the maximum dose for action limit (AL) and tolerance limit (TL) are set to the universal value of 10% recommended by TG-218.[3] The pass rates for both AL and TL are based on the percentage of detectors with a Gamma Index <1.

Patient case selection

A number of linear accelerators were utilized across two centers within the same institution, on a range of Varian machine models (Novalis Tx, TrueBeam, TrueBeam STx) of linear accelerator (Varian Medical Systems, Palo Alto, CA) at two cancer centers (Duke University Medical Center and Duke Raleigh Hospital). All SRS cases were treated on linear accelerators with High Definition MLC (Novalis Tx and TrueBeam STx, 0.25mm MLC width for central ±4cm), while SBRT cases also included linear accelerators with standard MLC. All linear accelerators of the same model are beam matched, and further analysis evaluating differences between results from separate linear accelerators and MLC models indicated no significant difference. For the Delta4, 49 VMAT SRS cases (single intracranial target and multiple intracranial targets), 66 VMAT SBRT cases (lung, liver and spine) and 23 IMRT FFF cases (various extracranial targets) were re-analyzed. For Portal Dosimetry, 25 IMRT Brain cases and 18 IMRT non FFF photons cases (various extracranial targets) were re-analyzed. For ArcCHECK, we re-analyzed 74 VMAT SRS plans (single intracranial targets and multiple intracranial targets). For SRS MapCHECK, 20 VMAT SRS (multiple intracranial targets) were re-delivered and re-analyzed. We analyzed Hypofractionated Image Guided Radiation Therapy (HIGRT) (which includes 6-10 fractions) and SBRT (1 to 5 fractions) jointly in this study. For IMRT using FFF photons, since we have not commissioned the capability of using portal dosimetry, we used the Delta4 device as per historical practice. The ArcCHECK is used at the satellite location in place of the Delta4 device. Pre-treatment QA measurements were re-analyzed, after which plan specific action and tolerance limits were calculated. The number of cases for each combination of device and site are given in Table 1 along with the analysis criteria. For two

Table 1. Summary of Sterotactic Radiosurgery (SRS) and Sterotactic Body Radiation Therapy (SBRT) cases included in the study, along with Gamma Analysis dose difference (DD) and distance to agreement (DTA) criteria.

					DD (%)						
					1	2	3	3	3	4	5
					DTA (mm)						
Device	**Technique**	**Site**	**Plan**	**Field**	**1**	**1**	**1**	**2**	**3**	**1**	**1**
Delta4	VMAT	Single intracranial target	24	71		×	×	×	×	×	×
	VMAT	Multiple intracranial targets	25	92		×	×	×	×	×	×
	VMAT	Liver	25	54		×	×	×	×	×	
	VMAT	Lung	16	36		×	×	×	×	×	
	VMAT	Spine	25	95		×	×	×	×	×	
	VMAT	Combined Liver, Lung, & Spine	66	185		×	×	×	×	×	
	IMRT (FFF)	Extracranial targets: liver (1), lung (11), spine (6), breast (5)	23	156		×	×	×	×	×	
Portal Dosimetry	IMRT (non-FFF photons)	Single intracranial target	25	163		×	×	×	×	×	
	IMRT (non-FFF photons)	Extracranial targets liver (3), lung(8), spine (3), other (4)	18	136		×	×	×	×	×	
ArcCHECK	VMAT	Single intracranial target	25	106		×	×	×	×	×	
	VMAT	Multiple intracranial targets	49	213		×	×	×	×	×	
SRS MapCHECK	VMAT	Multiple intracranial targets	20	92	×	×	×	×	×		

combinations (IMRT FFF and IMRT non-FFF), all extracranial targets are combined into a single analysis. This is because the total number of cases that fall into these specific combinations is small, so that there were not sufficient cases for analysis with different site. However, a joint analysis is warranted since all of these treatment plans are SBRT, and thus have relatively similar characteristics in dose falloff, PTV volume, and beam geometry.

Action and tolerance limit

Action and tolerance limits were calculated following TG-218 recommendations for each Gamma Index criteria combination for each QA device, treatment site, and treatment technique combination listed in Table 1. These combination specific action limits were then compared to the TG-218 "universal" action limit of 90%. Action limit is defined as "the amount the quality measures are allowed to deviate without risking harm to the patient as well as defining limit values for when clinical action is required".[3] If a QA result is outside the action limit, the plan may require further investigation.[4] Action limit for Gamma passing rates, as defined by TG-218, is given in equation (1), where Ais the difference between the upper and lower action limits, given in equation (2) and usually written as ±A/2:

$$A = 100 - \Delta A / 2 \tag{1}$$

$$\Delta A = \beta\sqrt{\sigma^2 + (\bar{x} - T)^2} \tag{2}$$

T is the process target value and σ^2 and $\bar{x}$ are the process variance and process mean, respectively. The constant β is a combination of process capability and balanced errors. The action limit under unspecified conditions is used to set the lowest level of process performance so that process performance exceeding the action limit may be negatively clinically affected. Hence if the QA is below the action limit, the plan may require further investigation.

Tolerance limits are defined as "the boundaries within which a process is considered to be operating normally, subject to only random errors"[3], using the following definitions:

$$Center\ line = \frac{1}{n}\sum\nolimits_1^n x \tag{3}$$

$$Upper\ control\ limit = Center\ line + 2.66 * \overline{MR} \tag{4}$$

$$Lower\ control\ limit = Center\ line - 2.66 * \overline{MR} \tag{5}$$

where x is an individual IMRT QA measurement, n is the total number of measurements, and moving range is:

$$\overline{MR} = \frac{1}{n-1}\sum_{i=2}^{n}\left|x_i - x_{i-1}\right| \tag{6}$$

With these defined, the tolerance limit is defined as:

$$T = x - 2.66 * \overline{MR} \tag{7}$$

Tolerance limit should be used as a warning that when exceeded, it indicates that the process is changing and needs attention. TG218 gives a universal tolerance limit standard of 95%. Hence if the QA is outside the tolerance limit, the QA device may require further investigation and may need to be recalibrated.[3]

Correlation analysis

Once the Gamma Index was recalculated for all cases, we evaluated correlation of the QA results with various factors related to the treatment plan, including plan complexity, distance of targets from isocenter, and PTV volume. Plan complexity was defined using the modulation complexity score (MCS).[20] MCS varies from 0 for highly modulated to 1 for non-modulated plans. MCS for VMAT was defined by Masi et al.[20] as:

$$MCS_{arc} = \sum_{i=1}^{I-1}\left[\frac{(AAV_{cpi} + AAV_{cpi+1})}{2} * \frac{(LSV_{cpi} + LSV_{cpi+1})}{2} * \frac{MU_{cpi,i+1}}{MU_{arc}}\right] \tag{8}$$

Where, $MU_{cpi,i+1}$ indicates the MU delivered between two successive control points, AAV is aperture area variability and LSV is leaf sequence variability, CP is control point, is coordinate of leaf position, pos_{max} is possible maximum positional variations, I, N, A is the number of control points, movable leaves in the jaws, and leaves in the arc respectively. AAV_{cp}, pos_{max}, and LSV_{cp} are defined as:

$$AAV_{cp} = \frac{\sum_{a=1}^{A}\left(\langle Pos_a\rangle_{leftbank} - \langle Pos_a\rangle_{rightbank}\right)}{\sum_{a=1}^{A}\left(\langle \max(Pos_a)\rangle_{leftbank\in arc} - \langle \max(Pos_a)\rangle_{rightbank\in arc}\right)} \quad (9)$$

$$pos_{\max}(CP) = \left\langle \max(pos_{n\in N}) - \min(pos_{n\in N})\right\rangle_{leafbank} \quad (10)$$

$$LSV_{cp} = \left(\frac{\sum_{n=1}^{N-1}\left(Pos_{\max} - \left|\left(Pos_n - Pos_{n+1}\right)\right|\right)}{(N-1)*Pos_{\max}}\right)_{leftbank} * \left(\frac{\sum_{n=1}^{N-1}\left(Pos_{\max} - \left|\left(Pos_n - Pos_{n+1}\right)\right|\right)}{(N-1)*Pos_{\max}}\right)_{rightbank} \quad (11)$$

RESULTS

Delta4

For the QA deliveries carried out using the Delta4 device, the results from the Gamma Index analysis are illustrated as box plots in Figure 1 for SRS using VMAT, Figure 2 for SBRT using VMAT, and Figure 3 for SBRT using IMRT (with FFF photon beams). For these box plots, the box width, termed the interquartile range (IQR), delineates the 25th and 75th percentiles. The box "whiskers" extend 1.5×IQR. The red line represents the median gamma pass rate (GP). The plus symbols (+) indicates outliers beyond the whiskers. The mean Gamma pass rates and standard deviation have been labeled on the boxplot. Using the Delta4, the average Gamma pass rates are all over 90% for single intracranial target VMAT SRS [Figure 1 a)] and multiple intracranial target VMAT SRS [Figure 1 b)] when applying criteria of 5%/1mm, 4%/1mm, 3%/1mm and 2%/1mm, respectively. All the SRS cases had a pass rate above the 90% universal action criteria with the 3%/1mm Gamma Index criteria. For VMAT SBRT [Figure 2(d)] and IMRT SBRT/HIGRT(FFF) cases [Figure 3] using criteria of 4%/1mm, 3%/3mm, 3%/2mm, 3%/1mm and 2%/1mm, the average Gamma pass rates are all over 90%. All SBRT cases pass the universal Gamma pass rate (90%) when applying 4%/1mm criteria.

Portal Dosimetry

For the QA deliveries carried out using Portal dosimetry, the results from the Gamma Index analysis are illustrated in Figure 4. For IMRT single intracranial target cases [Figure 4 a)], the average GP is all above 97% for 4%/1mm, 3%/3mm, 3%/2mm and 3%/1mm. All the cases pass the universal gamma pass rate (90%) when applying 3%/1mm criteria. The average GP is also high for IMRT SBRT extracranial targets cases [Figure 4 b)] when applying 4%/1mm, 3%/3mm, 3%/2mm, 3%/1mm, 2%/1mm and all the cases are over the 90% gamma pass rate when using 4%/1mm criteria.

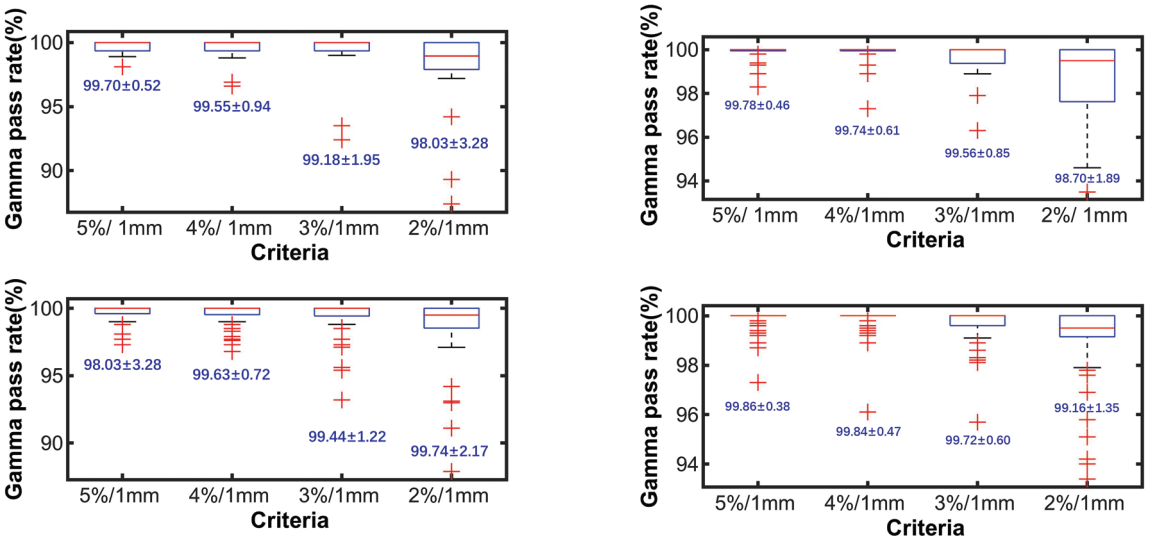


Figure 1. Gamma Index agreement for Delta4 QA of SRS cases using VMAT, stratified by treatment site: a) Single intracranial target. b) Multiple intracranial targets. It is also stratified by plan analysis and all the field analysis. c) Single intracranial target field. d) Multiple intracranial targets field. No outliners are below 90% Gamma pass rates.

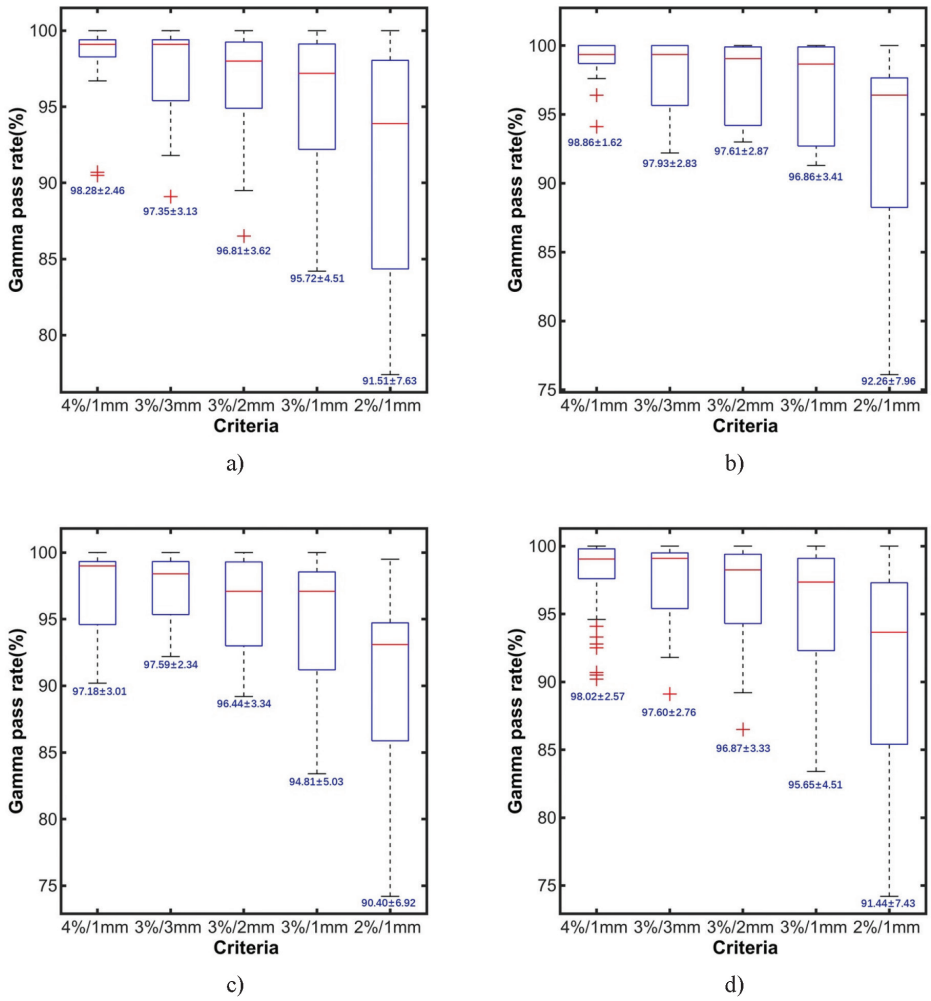


Figure 2. Gamma Index agreement for Delta4 QA of SBRT cases using VMAT, stratified by treatment site: a) liver; b) lung; c) spine; d) all sites combined.

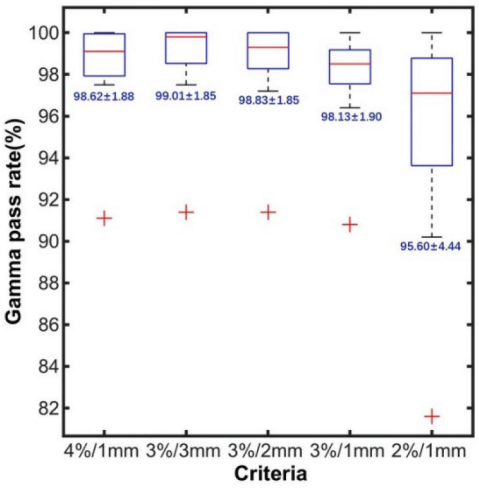


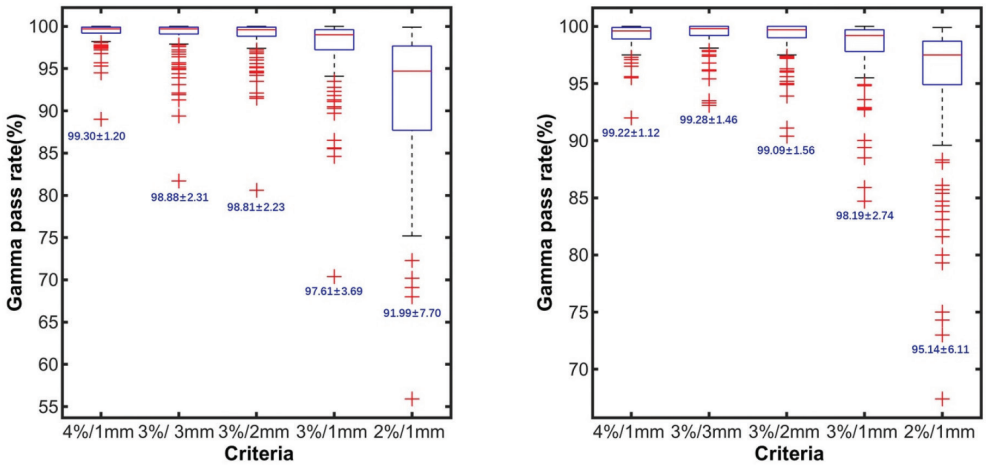
Figure 3. Gamma Index results of Delta4 QA for SBRT cases utilizing IMRT with FFF photons (Extracranial targets).

ArcCHECK

For the QA deliveries carried out using the ArcCHECK, the results from the Gamma Index analysis are illustrated in Figure 5. For ArcCHECK, the average GP is over 90% for single intracranial target VMAT SRS [Figure 5 a)] and multiple intracranial targets VMAT SRS [Figure 5 b)] when applying criteria of 4%/1mm, 3%/3mm, 3%/2mm, 3%/1mm and 2%/1mm. We can see from Figure 5 that when we apply 3%/2mm, all the cases pass the 90% universal Gamma pass rate.

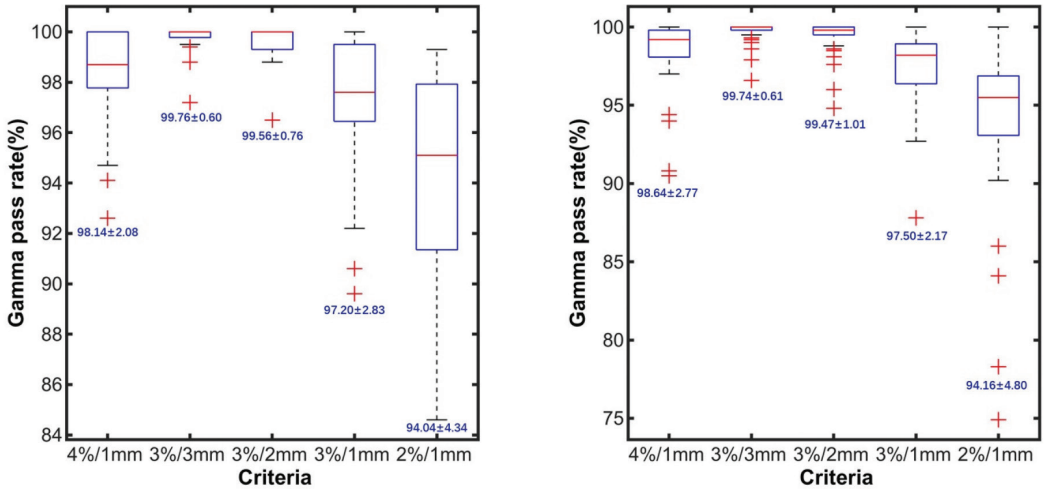
SRS MapCHECK

For the QA deliveries carried out using the SRS MapCHECK, the results from the Gamma Index analysis



a) b)

Figure 4. Gamma Index agreement for Portal dosimetry QA of IMRT cases using flattened photons stratified by treatment site: a) intracranial, and b) extracranial.



a) b)

Figure 5. Gamma Index agreement for ArcCHECK QA of VMAT cases stratified by treatment site: a) Single intracranial target; b) Multiple intracranial targets.

are illustrated in Figure 6. For twenty multiple intracranial targets SRS cases [Figure 6 a)], the average GP for 3%/2mm, 3%/1mm, 2%/1mm and 1%/1mm are all above 97%. The average passing rates using a dose difference criteria (no spatial component) [Figure 6 b)] of 3% and 2% are over 90%. Zero cases fail the universal pass rate of 90% when using a Gamma criteria of 3%/1mm.

Action limits

The summary of action limits is provided in Table 2. For Delta4, a 3% /1mm criteria can be applied for single intracranial target VMAT SRS, multiple intracranial targets VMAT SRS, and SBRT with IMRT (FFF) with the acceptable action limit above 90% and no cases failing the 90% general passing rate. However, for SBRT of lung, liver and spine, these criteria resulted in a lower action limit, so that a more appropriate choice may be 4%/1mm, which also has no failing case as opposed 3%/1mm. For Portal Dosimetry, 3%/1mm criteria results in action limit of over 90% for both intracranial IMRT and extracranial IMRT. For different QA devices, there are different optimal criteria. For ArcCHECK and SRS MapCHECK, respectively, 3%/2mm and 2%/1mm appear optimal with all

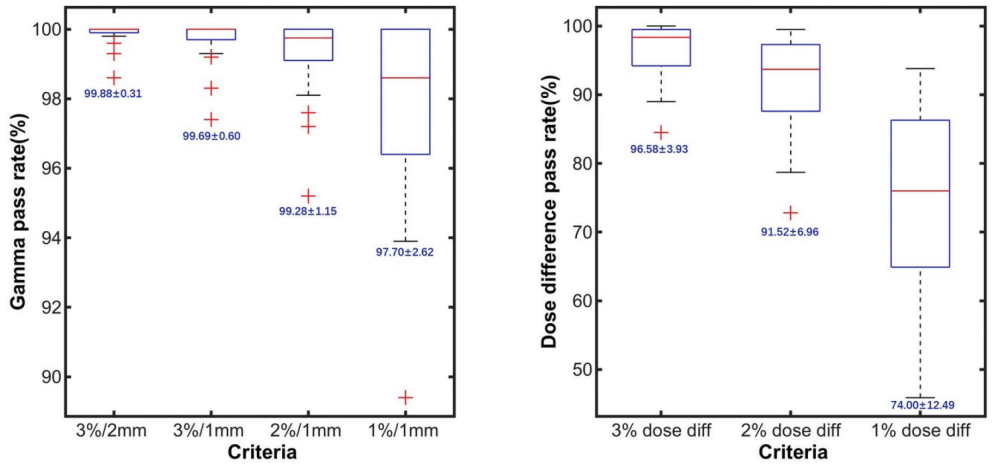


Figure 6. QA agreement for SRS MapCHECK QA of VMAT cases of multiple intracranial targets for: a) Gamma Index agreement, and b) Dose difference agreement.

Table 2. Action limit and percentage of cases failing a 90% general Gamma pass rates with different criteria using four QA devices. The percentages in parentheses are the failing rate of each type of case (under 90% of Gamma pass rates)

QA device	Technique	Site	4% 1mm	3% 3mm	3% 2mm	3% 1mm	2% 1mm	1% 1mm
Delta4	VMAT	Single intracranial target	96.88 (0%)	98.81 (0%)	98.06 (0%)	93.64 (0%)	88.50 (8.30%)	
	VMAT	Multiple intracranial targets	98.00 (0%)	98.62 (0%)	97.78 (0%)	97.12 (0%)	93.12 (0%)	
	VMAT	Liver	90.99 (0%)	87.69 (0%)	85.52 (8%)	81.36 (12%)	65.76 (32%)	
	VMAT	Lung	94.06 (0%)	89.48 (0%)	88.80 (0%)	86.09 (0%)	66.69 (31%)	
	VMAT	Spine	87.64 (0%)	89.92 (0%)	85.36 (4%)	78.31 (20%)	64.49 (24%)	
	VMAT	Combined Liver, Lung, & Spine	90.27 (0%)	89.02 (0%)	86.30 (5%)	81.19 (12%)	65.98 (29%)	
	IMRT(FFF)	Extracranial targets	93.00 (0%)	93.71 (0%)	93.44 (0%)	92.01 (0%)	81.24 (4.40%)	
Portal Dosimetry	IMRT (non-FFF photons)	Single intracranial target	99.58 (0.61%)	99.23 (1.20%)	99.24 (0.61%)	98.68 (3.68%)	96.67 (30.60%)	
	IMRT (non-FFF photons)	Extracranial targets	95.91 (0%)	95.11 (0%)	94.58 (0%)	90.14 (3.68%)	76.57 (15.44%)	
ArcCHECK	VMAT	Single intracranial target	89.64 (0%)	98.05 (0%)	97.34 (0%)	87.45 (4%)	77.88 (24%)	
	VMAT	Multiple intracranial targets	93.30 (0%)	98.01 (0%)	96.59 (0%)	90.08 (4%)	77.30 (16%)	
SRS MapCHECK	VMAT	Multiple intracranial targets			99.02 (0%)	97.97 (0%)	95.92 (0%)	89.54 (5%)

the cases passing the 90% passing rate and action limit over 95%.

Tolerance limits

The calculated tolerance limits for all cases are shown in Table 3. The tolerance limits are all over 95% universal standard at 3%/1mm for SRS cases using Delta4 and 4%/1mm for Portal Dosimetry. Tolerance limit also fits TG218 standard[3] at 3%/2mm and 3%/1mm when using ArcCHECK and SRS MapCHECK respectively.

Correlation analysis

We analyzed the relationship between MCS, average MLC field size and Gamma pass rates of Delta4 SRS and SBRT cases as shown in Figure 7. MCS is modulation complexity score to evaluate the complexity of a treatment plan where a larger value indicates a less complex plan.[20] As seen in the Figure, there appears to be a threshold equivalent MLC field size, above which all Gamma Index pass rates were very high (~97%). However, the results do not show a conclusive quantifiable correlation between MCS or average MLC field size with Gamma passing rate for VMAT SRS and SBRT cases.

For the SRS MapCHECK, we analyzed the relationship between distance from the isocenter, the PTV volume, and the pass rate for a dose difference for measurement points above 50% of the maximum dose, which is shown in Figure 8. The 90th percentile of dose difference and mean dose difference results exhibit no correlation with distance from isocenter or PTV volume for VMAT SRS cases within the high dose areas.

DISCUSSION

By applying TG-218[3], we found that a 3%/1mm criteria for SRS cases and 4%/1mm for SBRT cases can be applied while still maintaining an in-control QA process. The difference between SRS and SBRT may be due to the fact that SRS volumes are smaller, so that more of the measurement points fall within a dose gradient. Thus the Gamma Index may be higher since dose

Table 3. Tolerance limit of Gamma Index with different criteria using four QA devices.

Device	Technique	Site	4% 1mm	3% 3mm	3% 2mm	3% 1mm	2% 1mm	1% 1mm
Delta4	VMAT	Single intracranial target	97.69	98.84	98.45	95.62	90.87	
	VMAT	Multiple intracranial targets	98.45	99.08	98.49	97.59	92.84	
	VMAT	Liver	92.84	90.94	88.81	84.86	73.72	
	VMAT	Lung	95.67	90.82	89.56	87.68	74.69	
	VMAT	Spine	88.87	90.97	86.86	80.29	73.20	
	VMAT	Combined Liver, Lung, & Spine	92.01	90.33	87.84	83.02	73.37	
	IMRT (FFF)	Extracranial targets	94.69	94.91	94.37	93.74	83.59	
Portal Dosimetry	IMRT (non-FFF photons)	Single intracranial target	97.71	96.31	96.11	92.91	81.93	
	IMRT (non-FFF photons)	Extracranial targets	97.71	97.27	96.91	94.38	87.14	
ArcCHECK	VMAT	Single intracranial target	90.91	98.58	97.38	87.97	77.88	
	VMAT	Multiple intracranial targets	95.14	98.95	98.17	92.57	83.12	
SRS MapCHECK	VMAT	Multiple intracranial targets			99.34	98.38	96.28	90.06

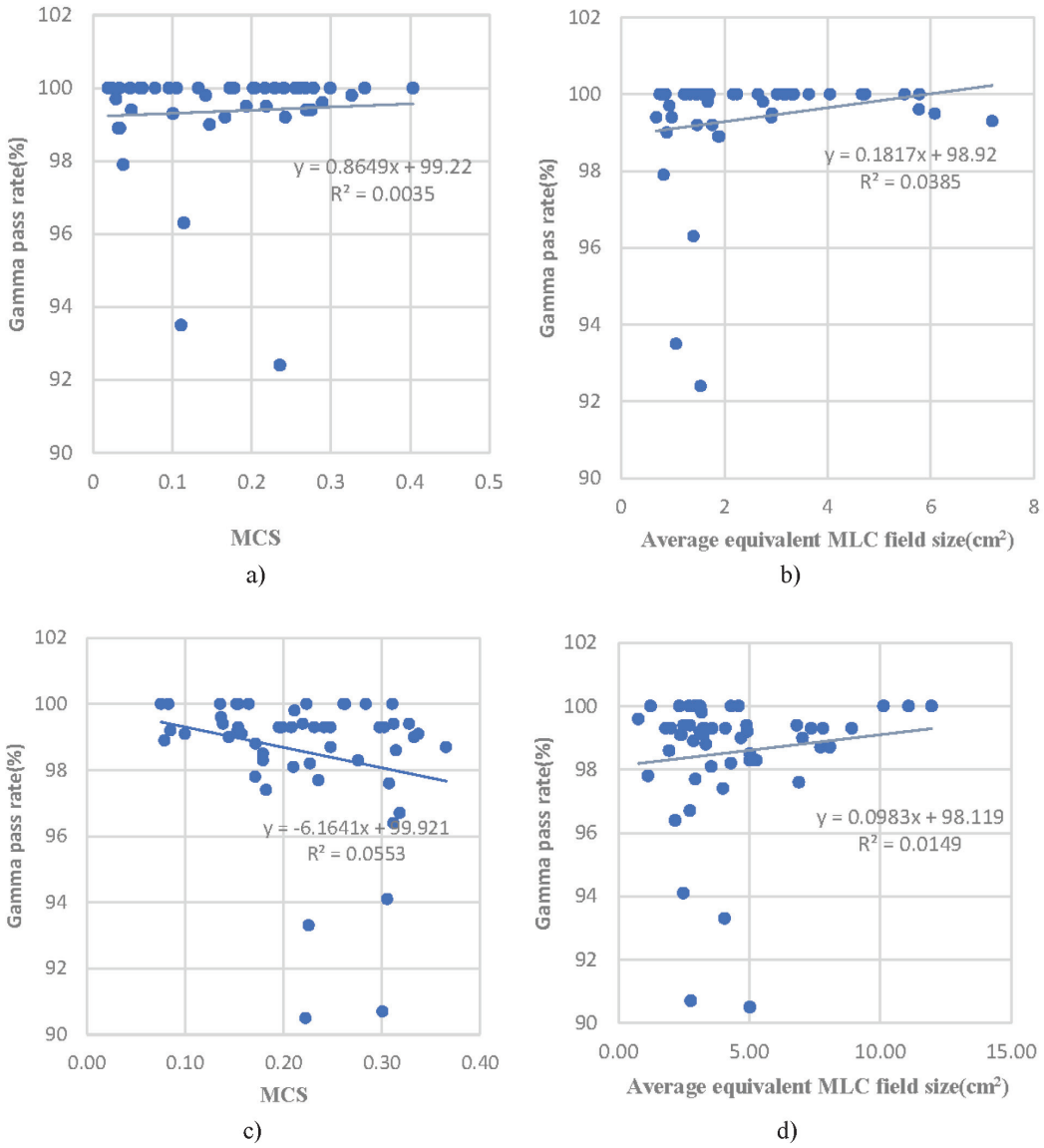


Figure 7. Relationship between MCS, average MLC field size and Gamma pass rate of SRS and SBRT cases in Delta4. Correlation between a) MCS vs Gamma in SRS; b) MLC effective field size vs Gamma in SRS; c) MCS vs Gamma in SBRT; d) MLC field size vs Gamma in SBRT.

differences may be masked by small distances. Due to the SRS and SBRT technique's high dose gradients and small margins, a tighter criterion may be necessary for SRS and SBRT cases.

Detector resolution also influences patient specific quality assurance results.[22] When detectors have higher spatial resolution, the gamma passing rate and the action limit for patient specific quality assurance tended to improve, likely due to less partial volume averaging.[22] For instance, Figure 9 compares the Gamma pass rate for the Delta4 device and SRS MapCHECK device for 10 multiple intracranial target VMAT SRS cases with criteria of 3%/1mm, 2%/1mm and 1%/1mm. The improved agreement of the SRS MapCHECK may be due to its higher spatial resolution and smaller detector size.

While the results here demonstrate what pass rates were achievable for various QA devices and analysis criteria, the choice of analysis criteria should also consider the potential clinical effects of a discrepancy. For instance, with the SBRT spine cases, the action limit was lower than other sites, likely due to the complexity of the treatment plan and dose distribution. SBRT spine cases usually include complexities such as small field size, sharp gradients area, and heterogeneous structures that influence the dose deposition[23], due to the proximity of the spinal canal.

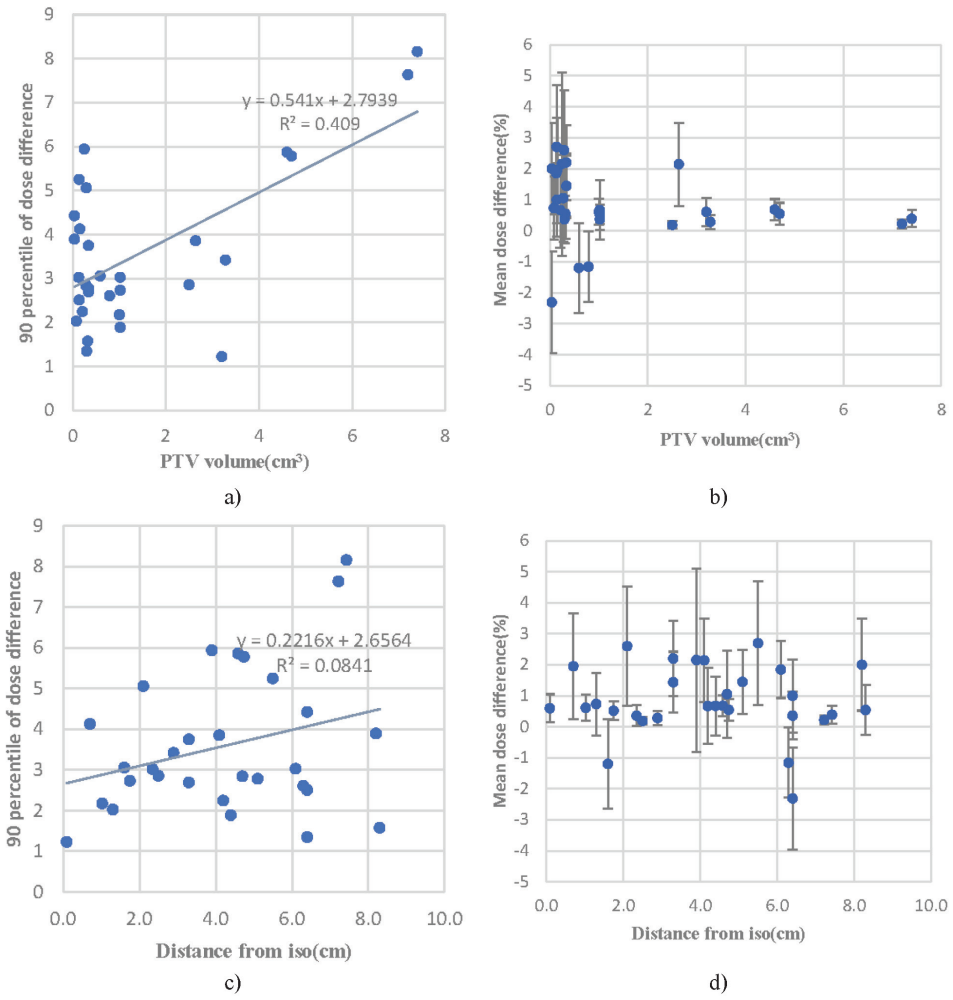


Figure 8. Relationship between distance from isocenter, PTV volume and dose difference of SRS Multiple intracranial targets cases measured with the SRS mapCHECK: a) 90th percentile of dose difference vs PTV volume; b) Corresponding mean VMAT dose difference; c) 90th percentile vs distance from iso; d) Corresponding mean VMAT dose difference. The error bars represent ± one standard deviation of the mean dose difference. 90th percentile refers to dose difference for measurement points with dose above 50% of the maximum dose.

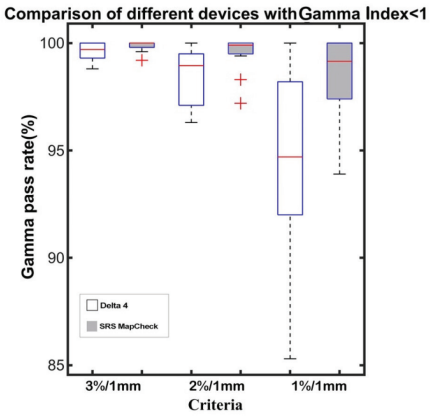


Figure 9. Comparison of Delta4 and SRS MapCHECK Gamma Analysis for 20 multiple intracranial target VMAT SRS cases

One limitation of this study is that we did not analyze the relationship of treatment planning system error or MLC error with changing criteria. Previous studies showed that the MLC misalignments will influence the Gamma Index.[24] There are general delivery errors such as MLC errors and gantry errors that were not evaluated in this study. Future studies may investigate planning and delivery sensitivity to changing criteria and the correlation of other factors and Gamma pass rate.

CONCLUSION

Applying the TG-218 recommendations to SRS and SBRT cases resulted in more stringent gamma

criteria with a higher action level than the generalized passing rate for all devices in the study. Compared to the standard criteria of 3%/3mm, stricter criteria of 3%/1mm for SRS and 4%1mm for SBRT cases using Delta4 and Portal Dosimetry, 3%/2mm for ArcCHECK and 3%/1mm for SRS MapCHECK SRS cases could be applied with acceptable action and tolerance limits. Highly stringent criteria (2%/1mm) could be applied for multiple target SRS using the SRS MapCHECK. These new spatial criteria have a spatial tolerance that is appropriate for the radiotherapy SRS and SBRT technique while not resulting in an excessive failing rate. No correlations were observed between plan complexity, average MLC field size, dose-volumetric changes, distance from isocenter changes and gamma passing rates and dose difference pass rates.

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Authors' disclosure of potential conflicts of interest

Dr. Adamson reports ownership of Clearsight RT LLC which is unrelated to this project. Other authors have nothing to disclose.

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