Application of TG-218 to SRS and SBRT Pre-Treatment Patient Specific QA

by

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Medical Physics Program

Duke Kunshan and Duke University

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Thesis submitted in partial fulfillment of
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ABSTRACT

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Abstract

Purpose: Updated recommendations for pre-treatment QA of patient-specific intensity modulated radiation therapy (IMRT) and Volumetric modulated arc therapy (VMAT) quality assurance (QA) were recently published by the AAPM task group TG-218. While the traditionally most common QA analysis is to use a Gamma index with dose & spatial analysis criteria of 3% & 3mm, respectively, TG-218 recommends a tighter spatial tolerance of 2mm for standard IMRT QA, and that even tighter tolerances should be considered for stereotactic radiosurgery (SRS) and stereotactic body radiotherapy (SBRT). Our purpose is to report our experience with applying the TG-218 recommendations to a large clinical SRS and SBRT program. In addition, a new SRS technique was recently developed at Duke, called Conformal Arc Informed Volumetric Modulated Arc Therapy (CAVMAT), which is designed to be less sensitive to configuration and delivery errors. We measured the agreement of CAVMAT for pre-treatment QA and compared it to the current standard (VMAT) to evaluate whether CAVMAT is more robust to delivery errors than VMAT.

Methods: We re-analyzed the pre-treatment QA with respect to the TG-218 recommendations. For Portal Dosimetry (Varian Medical Systems, Palo Alto, CA), this included IMRT brain (n=25) and SBRT / hypofractionated image guided radiotherapy (HIGRT) cases that utilize flattened photon beams (n=18). For Delta4 (ScandiDos, Madison, WI) this included single target SRS (n=24), multiple target SRS (n=25), SBRT

cases using VMAT (n=74), and SBRT cases using IMRT with FFF photons (n=23). For ArcCHECK (Sun Nuclear, Melbourne, FL)), we take 25 single target VMAT SRS cases and 25 multiple target VMAT SRS cases. For SRS MapCHECK(Sun Nuclear, Melboume, FL), we analyze 10 multiple target VMAT SRS cases with 16 targets. A Gamma analysis was performed with 6 spatial/dose criteria combinations: 3%/3mm, 3%/2mm, 3%/1mm, 2%/1mm, 4%/1mm, 5%/1mm. We then calculated the TG-218 action limit and tolerance limit per plan type and compared to the "universal" TG-218 action limit of 90% having a Gamma <1.

To compare CAVMAT and VMAT, log file analysis and pre-treatment QA was performed for 10 patients with 20 plans (10 VMAT, 10 CAVMAT) with 46 targets in total. 10 VMAT plans were re-planned using CAVMAT, and the dosimetric effect due to treatment delivery errors was quantified for V_{6Gy}, V_{12Gy}, and V_{16Gy} of healthy brain along with the maximum, average and minimum doses of each target. Gamma analysis of VMAT and CAVMAT plans was performed using Delta4 and SRS MapCHECK with 3% / 1mm, 2% / 1mm, 1% / 1mm criteria to assess the agreement during patient specific quality assurance.

Result: For Portal Dosimetry QA of IMRT brain and SBRT/HIGRT using a 3%/1mm criteria, the TG-218 action limit was 99.68, and 90.14, respectively; with 3.68% and 3.68% of cases failing the universal 90% criteria. For Delta4 QA of single target SRS, multiple target SRS, and SBRT IMRT with FFF using a 3%/1mm criteria, the TG-218 action limit was 93.64, 97.12, and 92.01, respectively; with 0%, 0%, and 0% of cases failing the

universal 90% criteria. For Delta4 QA of SBRT VMAT using a 4%/1mm criteria, the TG-218 action limit was 94.47, with 100% passing. For ArcCHECK QA of single target and multiple target SRS VMAT using a 3%/2mm criteria, the TG-218 action limit was 98.06 and 96.59 respectively, with 100% passing. For SRS MapCHECK QA of multiple target SRS VMAT cases using 3%1mm criteria, the TG-218 action limit was 99.24 with 100% passing.

The average increase in $V_{6Gy,}$ V_{12Gy}, V_{16Gy} due to treatment delivery errors as quantified using the trajectory logfile was 0.94 ± 1.43, 0.90 ± 1.38%, and 1.23 ± 1.54% respectively for VMAT, and 0.035 ± 0.14%, 0.14 ± 0.18%, and 0.28 ± 0.24% for CAVMAT. The average change to target maximum, average, and minimum dose due to delivery errors was 0.53 ± 0.46%, 0.52 ± 0.46%, and 0.53 ± 0.56%, for VMAT, and 0.16 ± 0.18%, 0.11 ± 0.08%, and 0.03 ± 0.24% for CAVMAT. There was no significant difference in magnitude of MLC discrepancies during delivery for VMAT and CAVMAT. For Gamma analysis with strict 1% / 1mm criteria, the average passing rate of VMAT gamma analysis is 94.53 ± 4.42%, while that of CAVMAT is 99.28 ± 1.74%.

Conclusion: For most QA devices, spatial tolerance of pre-treatment QA for SRS/SBRT can be tightened to 1mm while still maintaining an in-control QA process. The gamma criteria to 3%/1mm for all SRS cases and SBRT with IMRT and transitioning to a 4%1mm criteria for SBRT with VMAT have a spatial tolerance that is appropriate for the radiotherapy technique while not resulting in an excessive false positive failure rate. The

CAVMAT treatment planning technique resulted in superior gamma analysis passing rate for each gamma analysis criteria.

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1. Introduction

This thesis is divided into two distinct, but related projects. The first project is titled, "Application of TG-218 action limits to SRS and SBRT Pre-Treatment Patient Specific QA", and investigates a tighter clinical criterion for patient specific pre-treatment quality assurance of SRS and SBRT. Gamma analysis is carried out in order to show the feasibility of different techniques and QA devices. The second project, "Comparison of patient specific QA agreement for VMAT and CAVMAT," analyzes two different techniques: VMAT and CAVMAT. It was performed in conjunction with the thesis projects of two other students: Thomas Cullom and Kai-Cheng Chuang. The thesis project of Thomas Cullom focused on developing the CAVMAT technique, and his contribution to this work included providing the VMAT and CAVMAT plans and DVH analysis for this project. Kai-Cheng Chuang contributed to this project by providing the Python code to modify DICOM plan files and incorporate the MLC positions from the treatment delivery as recorded in the trajectory files. The trajectory file and pre-treatment QA delivery and analysis were carried out by the author of this thesis.

2. Application of TG-218 to SRS and SBRT Pre-Treatment Patient Specific QA

2.1. 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 [3,12], and questions remain about effectiveness of commonly used criteria [13,14]. 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.

2.2. Materials and Methods

2.2.1. Overview

We re-analyzed the pre-treatment using 4 different QA devices with 249 QA plans respect to the TG-218 recommendations. Gamma analysis was performed with 6 spatial/dose criteria combinations: 3%/3mm, 3%/2mm, 3%/1mm, 2%/1mm, 4%/1mm,

5%/1mm. We calculated the TG-218 action limit and tolerance limit per plan type and compared to the "universal" TG-218 action limit of 90% with a Gamma <1. Then we analyzed the correlation related to gamma passing rate (GP).

2.2.2. QA Devices

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

The first QA device included in this study is the Delta4 (ScandiDos, 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. The Delta4 system consists of 1069 p-type diodes on two near-orthogonal planes embedded in a cylinder PMMA phantom with 22cm diameter[15]. 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, by comparing delivered fluence acquired as an integrated image with the Electronic Portal Imaging Device (EPID)[16] (aSi-500) with a prediction made using Varian's Portal Dosimetry Image Prediction (PDIP) algorithm[17].

A third device, 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). ArcCHECK is a cylindrical (21cm diameter) water-equivalent phantom with a three-dimensional array of 1386 diode detectors (0.8x0.8 mm^2 active area per detector) at 10 mm spacing[18]. ArcCHECK measures every 50 milliseconds, with all measurement data saved as a function of time[18].

The final device included in the study is the SRS MapCHECK(Sun Nuclear, Melboume, FL);; this device was recently acquired at our institution for use with VMAT SRS cases. 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[19]. The detector is placed in a StereoPHAN phantom for non-coplanar irradiation.

2.2.3 Criteria analysis

Gamma index is a widely used comparison metric from pre-treatment QA, proposed in 1998 by Low et al.[20] 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.

2.2.4 Patient case selection

All cases were delivered using a Truebeam STx linear accelerator (Varian Medical Systems, Palo Alto, CA). For each of the devices, a set of at least 20 pre-treatment QA measurements were re-analyzed, after which technique and plan specific action and tolerance limits are calculated. The number of cases for each combination of device and site are given in Table 1 along with the analysis criteria.

Table 1 Type of cases and criteria applied. Acronyms: SRS: Stereotactic Radiosurgery (single target), SIMT: Single Isocenter Multiple Target SRS, SBRT: Stereotactic Body Radiotherapy

Device	Site	Plans	Fields	DD (%): / DTA(mm):	1 / 1	2 / 1	3 / 1	3 / 2	3 / 3	4 / 1	5 / 1
Delta4	SRS	24	71			x	x	x	x	x	x
	SIMT	25	92			x	x	x	x	x	x
	Liver	21	44			x	x	x	x	x	
	Lung	14	30			x	x	x	x	x	
	Spine	20	78			x	x	x	x	x	
	All	74	215			x	x	x	x	x	
	(SBRT FFF)	23	156			x	x	x	x	x	
ArcCHECK	SRS	25	106			x	x	x	x	x	
	SIMT	25	213			x	x	x	x	x	
SRS MapCHECK	SIMT	10	39		x	x	x	x	x		
Portal Dosimetry	Brain	25	163			x	x	x	x	x	
	SBRT (NOT FFF)	18	136			x	x	x	x	x	

2.2.5 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), which is a factor to evaluate the complexity of a plan in the treatment planning and quality assurance processes[21].

2.2.6 Action and tolerance limit

Action and tolerance limits were calculated following TG-218 recommendations for each Gamma Index criteria combination for each treatment technique listed in Table 1. These technique 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 below the action limit, the plan may require further investigation[4]. Action limit, as defined by TG-218, is given in equation (1), where ΔAis the difference between the upper and lower action limits, usually written as $\pm$A/2 shown as equation (2). T is the process target value and $\sigma^2$and $\bar{x}$ are the process variance and process mean, respectively. The constant β is a combination of process capability.

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

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

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”[11]. Hence if the QA is below the action limit, the plan may require further investigation.

Tolerance is defined as "the boundaries within which a process is considered to be operating normally, subject to only random errors”[3] shown as equation 3-5

$$\text{Center line}=\frac{1}{n}\sum_{1}^{n} x \tag{3}$$

$$\text{Upper control limit=center line+2.660*}\overline{MR} \tag{4}$$

$$\text{Lower control limit=center line-2.660*}\overline{MR} \tag{5}$$

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

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

Tolerance limits:

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

Tolerance limits should be used as warning limits so that when exceeding tolerance limits, it indicates that the process is changing and needs attention. Hence if the QA is below the tolerance limit, the QA device may require further investigation, may need to be recalibrated, etc.[3].

2.3 Results

2.3.1 Delta4

Gamma index test results of single target VMAT SRS, multiple target VMAT SRS and VMAT SBRT and IMRT SBRT/HIGRT(FFF), are shown as figures 1-3. The average Gamma Pass rate (GP) is 99.7±0.52, 99.55±0.94, 99.79±0.34, 99.69±0.57, 99.18±1.95, 98.03±3.28 respectively for single target VMAT SRS, 99.78±0.46, 99.74±0.61, 99.81±0.42, 99.71±0.68, 99.56±0.85, 98.7±1.89 respectively for multiple target VMAT SRS when applying criteria 5%1mm, 4%1mm,3%3mm, 3%2mm,3%1mm and 2%1mm. For criteria 4%1mm,3%3mm, 3%2mm,3%1mm and 2%1mm, the average GP is 98.82±1.41, 989.01±1.85, 98.82±1.41, 98.83±1.85, 97.23±2.95, 96.67±3.44, 92.96±6.58 for VMAT SBRT case and 98.62±1.88, 92.11±0.45, 95.6±4.4 for IMRT SBRT/HIGRT(FFF) case.

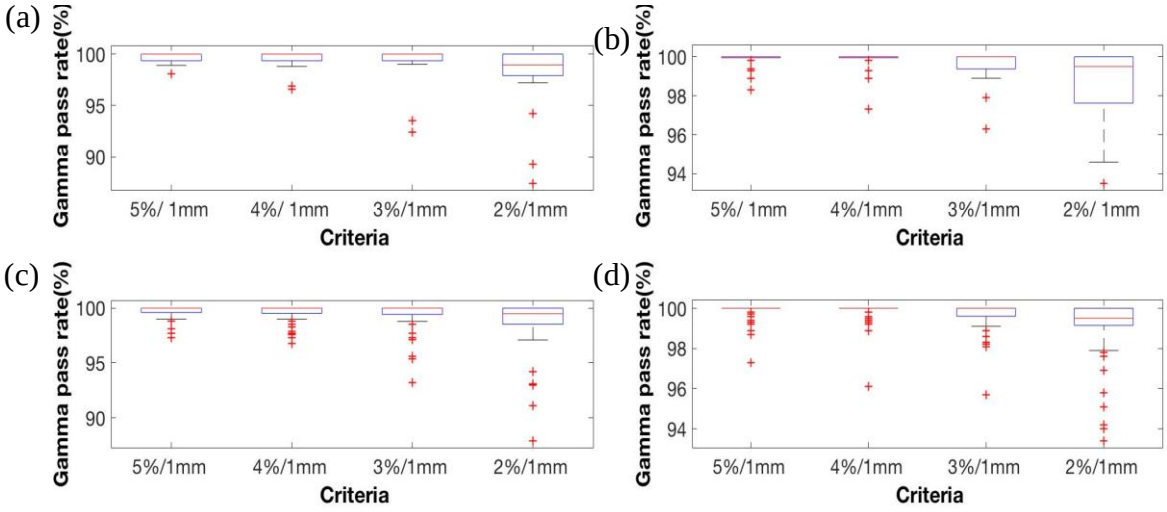


Figure 1Comparison of different criteria with gamma index<1 using Delta4 for (a) single target VMAT SRS plan (b) single target VMAT SRS field (c) multiple target VMAT SRS plan (d) single target VMAT SRS field. All the SRS cases applying 3%1mm pass the 90% passing rate.

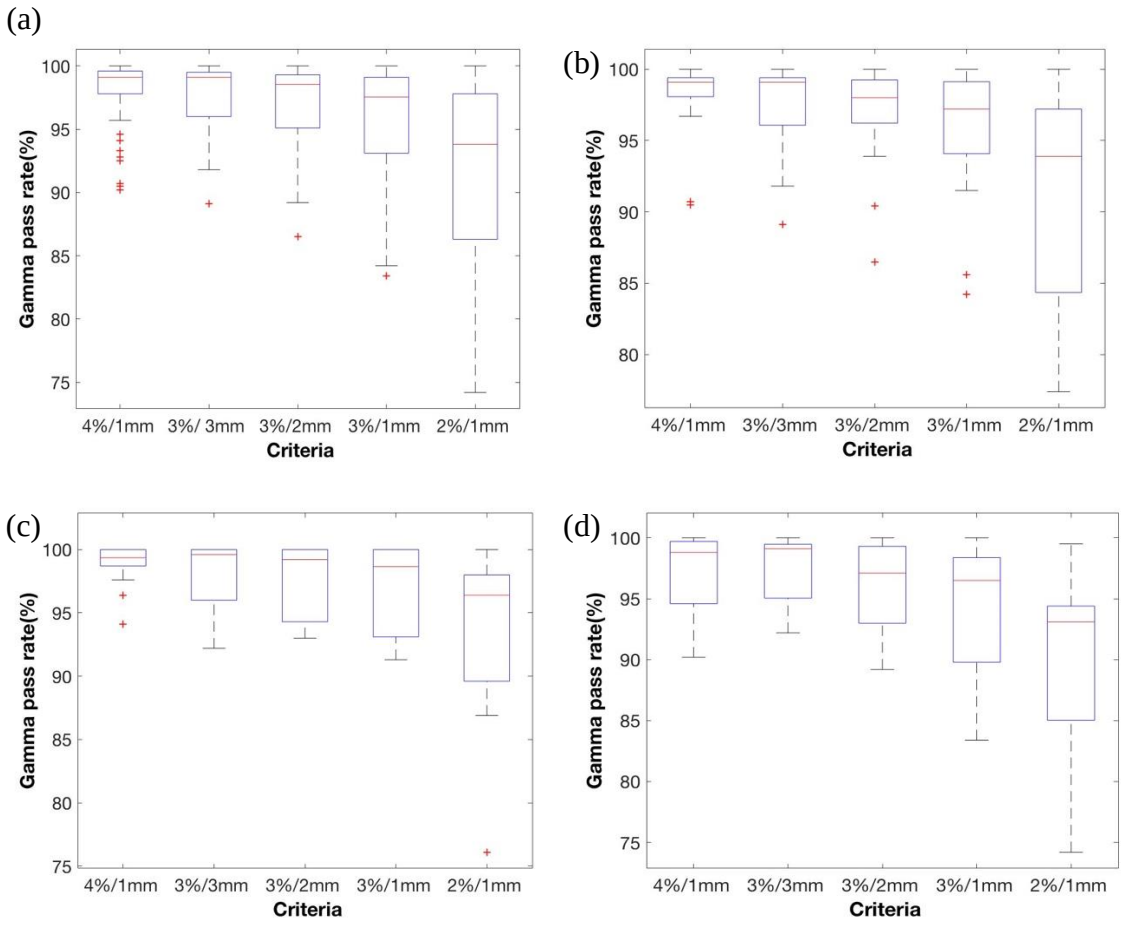


Figure 2 Delta4 Gamma analyses for (a) VMAT SBRT (combine all the sites) (b) VMAT SBRT for liver cases (c) VMAT SBRT for lung cases (d) VMAT SBRT for spine cases. All the SBRT cases applying 3%1mm pass the 90% passing rate.

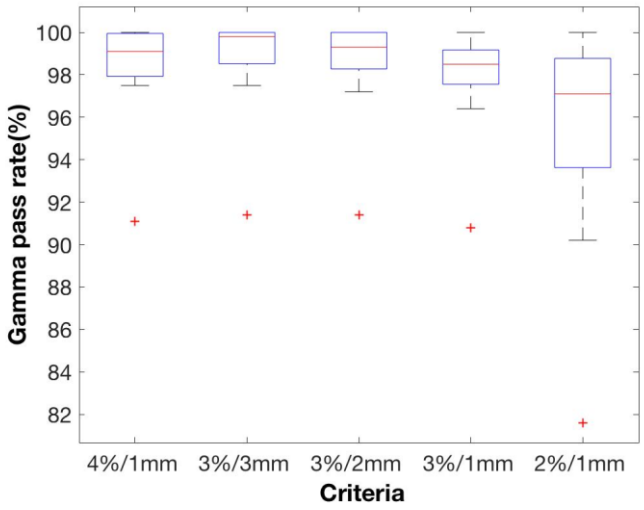


Figure 3 Delta4 Gamma analyses for IMRT SBRT FFF cases

2.3.2 Portal dosimetry

The gamma pass rate of IMRT brain and SBRT/HIGRT(FFF) are shown as figure 4. We can see that from figure 4, for IMRT cases the GP is 99.3±1.2, 98.88±2.31, 98.81±2.23, 97.61±3.69 of 4%1mm, 3%3mm, 3%2mm and 3%1mm. All the cases pass the universal GP when applying 3%1mm criteria. The average GP is 99.22±1.12, 98.19±2.74, 95.14±6.11 for SBRT/HIGRT cases by applying 4%1mm, 3%1mm, 2%1mm and all the cases are over the 90% gamma index when using 4%1mm criteria.

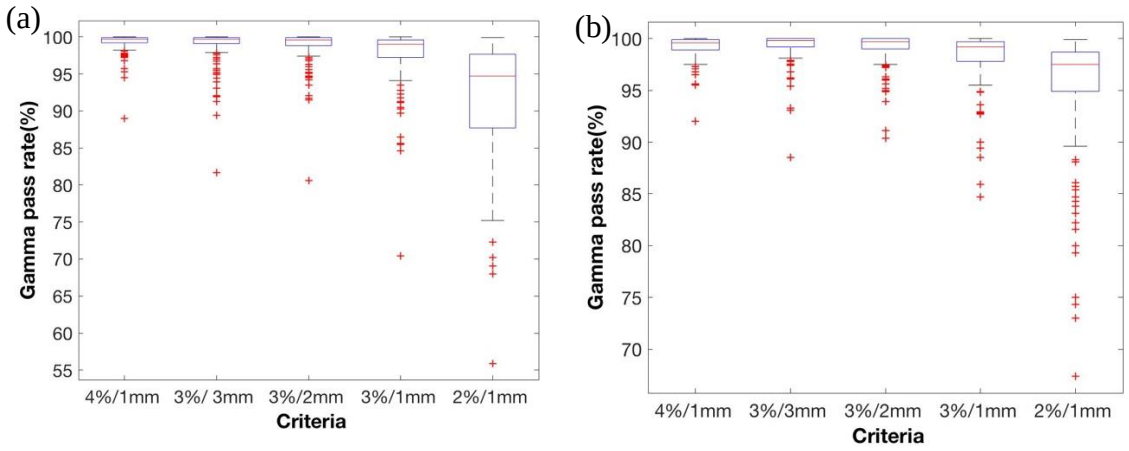


Figure 4Portal Dosimetry Gamma analyses for (a) IMRT Brain (b) IMRT SBRT (NOT FFF).

2.3.3 ArcCHECK

For ArcCHECK, the average gamma passing rate is 98.14±2.08, 99.76±0.6, 99.56±0.76, 97.2±2.83, 94.04±4.34 for single target VMAT SRS and 98.64±2.77, 99.74±0.61, 99.47±1.01, 97.5±2.17, 94.16±4.8 for multiple target VMAT SRS by 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% GP and has a similar action limit as calculated by 3%1mm.

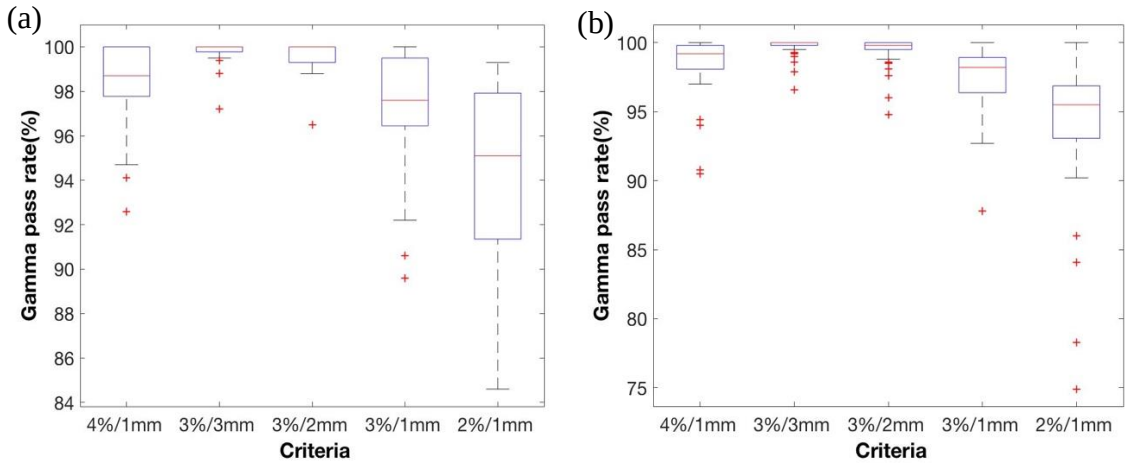


Figure 5Gamma analyses using ArcCHECK (a)single target VMAT SRS (b) multiple targets VMAT SRS. By applying 3%2mm criteria, the average passing rate is nearby 100%.

2.3.4 SRS MapCHECK

The gamma result of SRS MapCHECK QA is shown as figure 6. For ten multiple target SRS cases, the average gamma passing rate for 3%2mm, 3%1mm, 2%1mm and 1%1mm are 99.96±0.11, 99.87±0.22, 99.56±0.77, 98.27±2.08 respectively. The average GP for dose difference of 3%, 2%, 1% at 10%threshold are 97.84±2.37, 93.54±4.46 and 76.77±9.46 respectively.

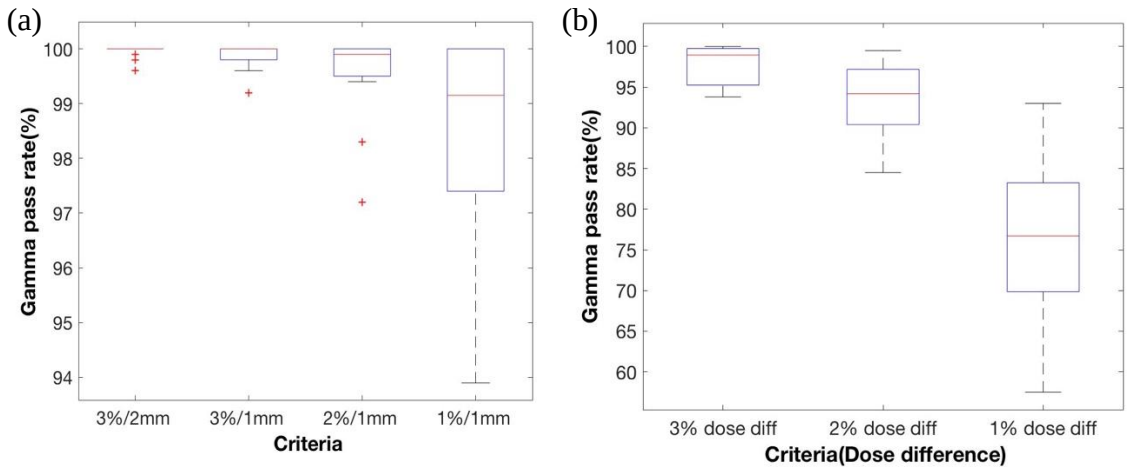


Figure 6 QA analyses using SRS MapCHECK for multiple target VMAT SRS (a) gamma analyses (b) dose difference analyses. The average passing rate is extremely high with a 3%2mm criteria.

The summary of action limit and failure rate are provided in table 2. For Delta4, a 3% / 1mm criteria can be applied for single target VMAT SRS, multiple target 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, this criteria resulted in a lower action limit, so that a more appropriate choice may be 4%1mm. When we combine all the SBRT cases with different sites, the results also show applying 4%1mm has no failing case compared to applying 3%1mm criteria. For Portal Dosimetry, 3%1mm criteria shows us a high action limit which is over 90% for both IMRT brain and IMRT SBRT. For different QA devices, there is different best criteria. For ArcCHECK, 3%2mm shows better result than 3%1mm criteria with all the case pass the 90% passing

rate and the action limit is nearly 100%. For SRS MapCHECK, when we apply 3%1mm, the action limit is similar to that when 3% 2mm is applied and the failure rate is zero.

Table 2 Failing percent of all the cases tested

QA device	Type of cases	2%1mm	3%1mm	3%2mm	3%3mm	4%1mm	5%1mm
Delta4	single target VMAT SRS	88.5 (8.33%)	93.64 (0%)	98.68 (0%)	98.1 (0%)	96.88 (0%)	98.2 (0%)
	multiple target VMAT SRS	93.12 (0%)	97.12 (0%)	97.78 (0%)	98.62 (0%)	98 (0%)	98.48 (0%)
	SBRT (ALL)	67.44 (25%)	82.22 (10%)	87.02 (5%)	89.58 (0%)	90.8 (0%)	
	SBRT (liver)	67 (19%)	81.72 (9.52%)	86.51 (4.76%)	88.54 (0%)	90.25 (0%)	
	SBRT (lung)	67.26 (28.57%)	86.51 (0%)	89.5 (0%)	89.4 (0%)	93.7 (0%)	
	SBRT (spine)	63.49 (20%)	77.43 (25%)	85.16 (5%)	89.57 (0%)	87.28 (0%)	
	SBRT with IMRT (FFF)	81.24 (4.35%)	92.01 (0%)	93.44 (0%)	93.7 (0%)	93 (0%)	
Portal Dosimetry	IMRT Brain	96.67 (30.6%)	99.68 (3.68%)	99.24 (0.61%)	99.23 (1.2%)	99.58 (0.61%)	
	SBRT (Other)	76.57 (15.44%)	90.14 (3.68%)	94.58 (0%)	95.11 (0%)	95.91 (0%)	
ArcCHECK	single target VMAT SRS	77.88 (24%)	87.45 (4%)	97.34 (0%)	98.05 (0%)	89.84 (0%)	
	multiple target VMAT SRS	77.3 (16%)	90.08 (4%)	96.59 (0%)	98.01 (0%)	93.3 (0%)	
SRS MapCHECK	multiple target VMAT SRS	97.35 (0%)	99.24 (0%)	99.65 (0%)	99.65 (0%)		

2.3.5 Correlation analysis

We analyzed the relationship between MCS, average MLC field size and gamma pass rates shown as figure 7. MCS is modulation complexity score to evaluate the complexity of a treatment plan[21] where a larger value indicates a less complex plan. The results show that there is no significant correlation between MCS or average MLC field size with gamma passing rate for VMAT SRS and SBRT cases.

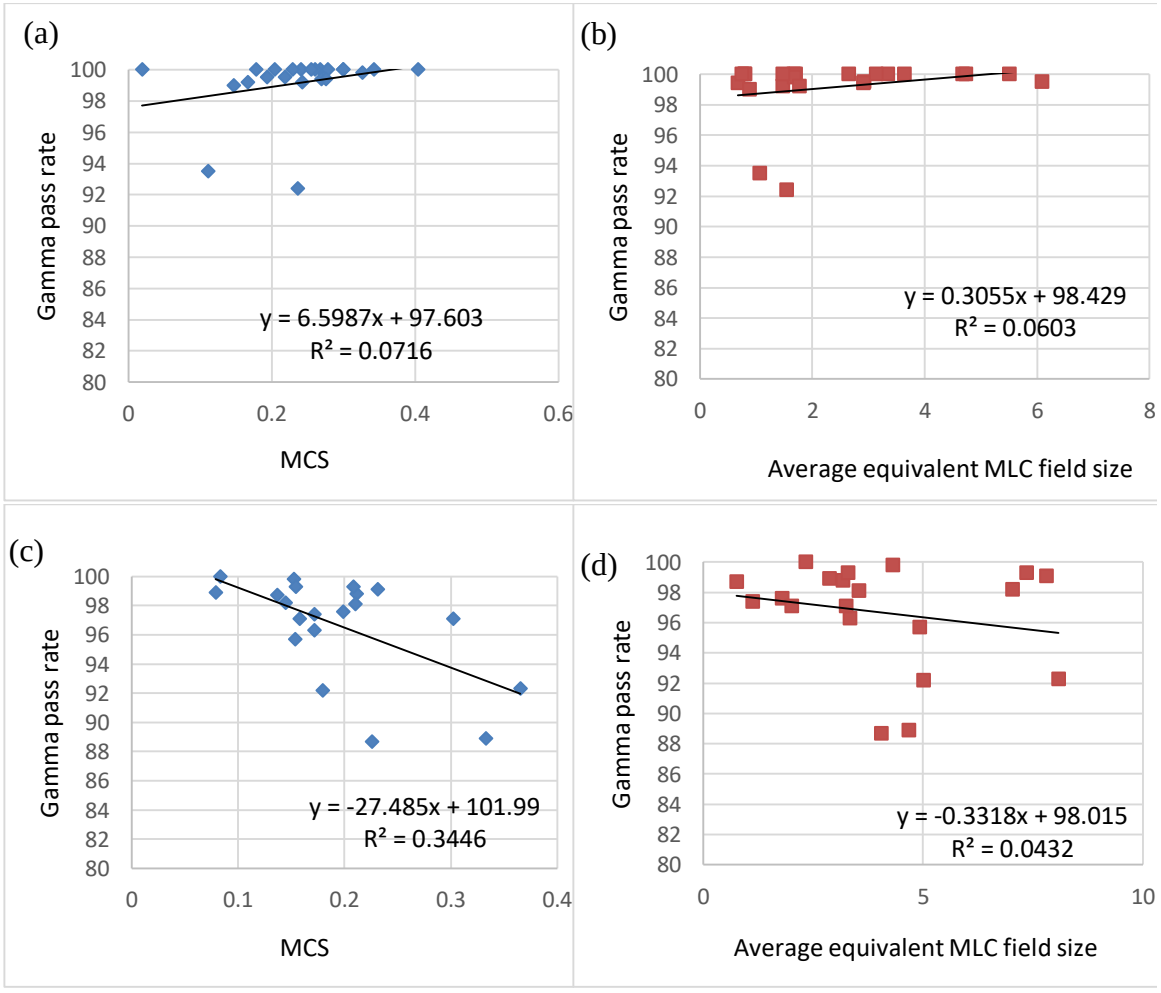
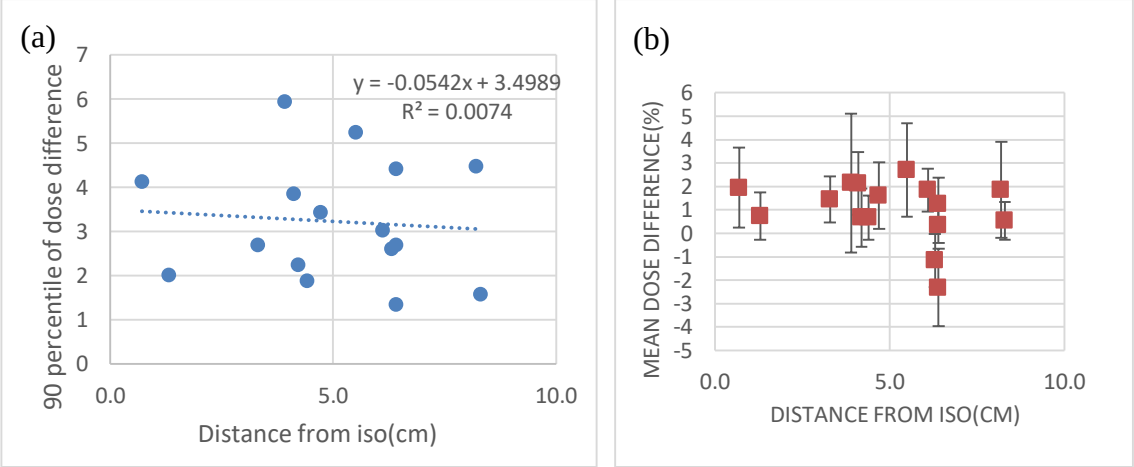


Figure 7Relationship between MCS, average MLC field size and gamma index in different technique using Delta4: (a)Correlation between MCS and gamma in SRS cases (b)Correlation between MLC effective field size and gamma in SRS cases (c) Correlation between MCS and gamma in SBRT cases (d) Correlation between MLC field size and gamma in SBRT cases.

For the SRS MapCHECK, we analyzed the relationship between distance from iso, PTV volume and gamma index for dose measurements above 50% of the maximum dose shown in figure 8. The 90 percentile and error bar show that there is no correlation with distance from iso or PTV volume with gamma passing rate for VMAT SRS cases at high dose area.



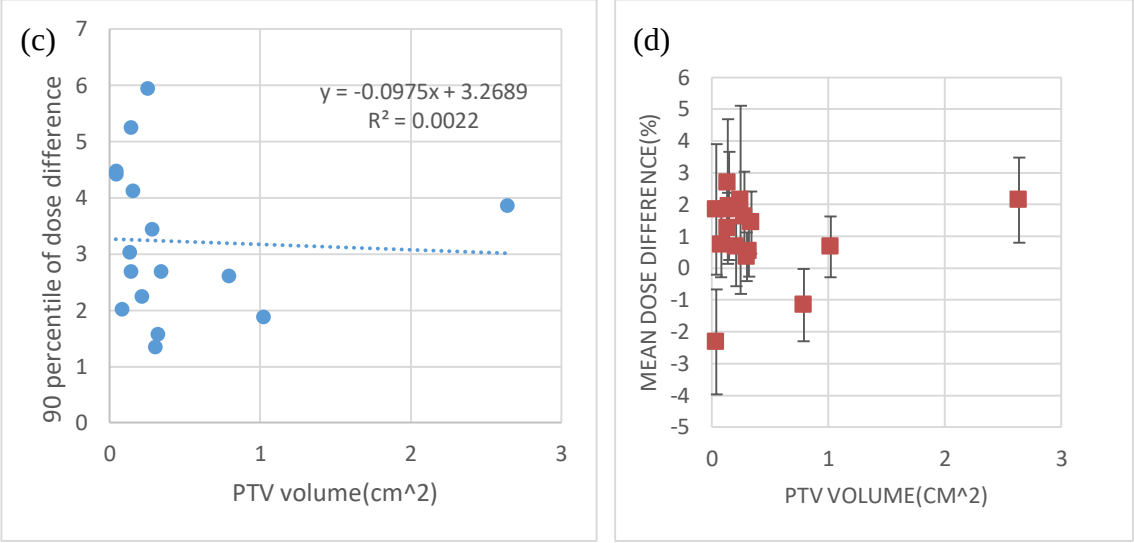


Figure 8 Relationship between distance from iso, PTV volume measured by Eclipse and gamma index using SRS MapCHECK: (a) 90th percentile VS distance from iso (b) Error bar of VMAT dose difference (c) 90th percentile VS PTV volume(d) Error bar of VMAT dose difference. The error bars represent ± standard deviation of the mean dose difference. 90th percentile refers to the 90th percentile of the absolute difference between planned and measured dose for measurement points above 50% of the maximum dose.

2.3.6 Tolerance limit

The calculated tolerance limit for all cases is shown as table 3. The tolerance is all over 95% universal standard at 3%1mm SRS case and 4%1mm when using Delta4. Tolerance is near 100 at 3%2mm when using ArcCHECK and SRS MapCHECK.

Table 3 Tolerance limit of gamma index in different criteria using four QA devices

DEVICE\ CRITERIA	TECHNIC	5%1 MM	4%1 MM	3%3 MM	3%2 MM	3%1 MM	2%1 MM	1%1 MM
DELTA4	VMAT Single target SRS	98.5	97.7	98.8	98.4	95.6	90.9	

	VMAT Multiple target SRS	98.9	98.5	99.1	98.5	97.6	92.8	
	VMAT SBRT (ALL)		92.5	91.1	88.9	84.6	75.1	
	VMAT SBRT (liver)		93.1	91.2	89.1	84.9	74	
	VMAT SBRT (lung)		95.6	91.6	91.0	89.1	78	
	VMAT SBRT (spine)		87.7	88.6	86.6	78.4	71.4	
	IMRT SBRT/HIGRT (FFF)		94.7	94.9	94.4	93.7	83.6	
PORTAL DOSIMETRY	IMRT Brain		97.7	96.3	96.1	92.9	81.9	
	IMRT SBRT(Other)		97.7	97.3	96.9	94.4	87.1	
ARCCHECK	VMAT Single target SRS		90.9	98.6	97.4	88	77.9	
	VMAT Multiple target SRS		95.1	99	98.2	92.6	83.1	
SRS MAPCHECK	VMAT Multiple target SRS			99.6	99.5	99.4	96.9	92.2

2.4 Discussion

By applying TG-218, we found that the ideal analysis criteria depended on each patient specific QA technology. For SRS, 3%1mm proves more robust gamma result and 4%1mm for SBRT. There may because the requirement for SRS treatment technic is

stricter than SBRT. SRS technics require smaller margins and higher spatial resolution as the lesions could be 1 cm or less than 1cm in size.[22] Due to the SRS and SBRT technique's high dose gradients, a tighter criterion is necessary for SRS and SBRT cases.

Detector resolution also influences patient specific quality assurance results[23]. When detectors have higher spatial resolution, the gamma passing rate and the action limit for patient's specific quality assurance tended to improve, likely due to less partial volume averaging[23]. For instance, Figure 9 compares the Gamma pass rate for the Delta4 device and SRS MapCHECK device for 10 multiple 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.

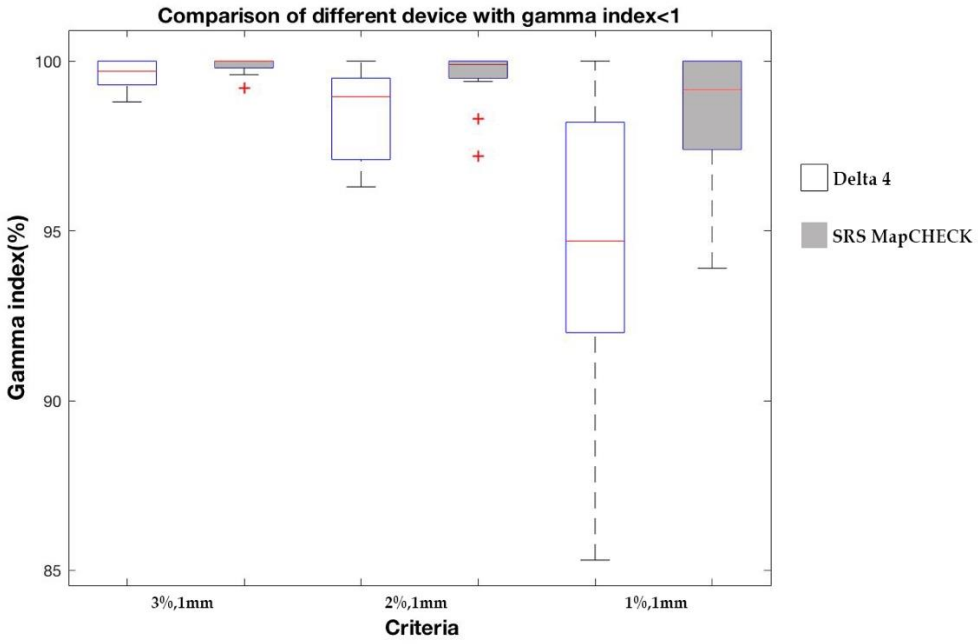


Figure 9 Comparison of Delta4 and SRS MapCHECK Gamma Analysis for 10 multiple target VMAT SRS cases

While the results here demonstrate what passing 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 some complexities such as small field size, sharp gradients area, and heterogeneous structures will influence the dose deposition[24], due to the proximity of the spinal canal.

One limit of this study is that we didn't analyze the relationship between plan error or MLC error with changing criteria. Previous studies showed that the MLC misalignments will influence the gamma index.[25] There are general treatment errors of detecting 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.

2.5 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, a stricter criteria of 3%1mm for SRS and 4%1mm for SBRT cases using Delta4 and Portal Dosimetry, and

3%2mm for ArcCHECK SRS cases could be applied with acceptable action and tolerance limits. Highly stringent criteria (1%/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 iso changes and gamma passing rates.

3. Comparison of patient specific QA agreement for VMAT and CAVMAT

3.1 Introduction

Recently a new treatment planning strategy for multi-target SRS was developed at Duke, which is entitled Conformal Arc Informed VMAT (CAVMAT). This technique combines intuitive MLC motions of dynamic conformal arcs with the flexibility of inverse optimization[26]. Targets are assigned to subgroups which maximize MLC blocking between targets and field weights are optimized to limit MU variation. Inverse optimization is performed to improve dose and conformity to each target.

Because CAVMAT uses dynamic conformal arcs with limited inverse optimization, the resulting treatment plans are expected to be less complex than VMAT. Because of this, we anticipate that CAVMAT plans will be more robust to errors in machine delivery and beam modeling which will result in improved agreement for patient specific QA. In order to quantify whether this is indeed the case, for both VMAT and CAVMAT plans we quantified the dosimetric effect in clinical treatment plans due to machine delivery errors as quantified using the trajectory log file, and we performed pre-treatment quality assurance using the Delta4 and SRS MapCHECK, and compared the agreement with the calculated dose from the treatment planning system.

3.2 Materials and Methods

10 VMAT plans were re-planned using CAVMAT and both the original VMAT and the CAVMAT plans were delivered to Delta4 phantom. The dosimetric change in the treatment plan due to delivery errors was quantified using trajectory log files. The MLC and gantry positions recorded in the trajectory files were imported into the DICOM treatment plan file, which was then re-imported into the planning system and dose calculated. Dose statistics included V_{6Gy}, V_{12Gy}, and V_{16Gy} of healthy tissue, as well as maximum, mean, and minimum dose to each target. For the Delta4 delivery, Gamma analysis and dose difference analysis was performed on the VMAT and CAVMAT plans. The SRS MapCHECK was also used to assess the agreement between calculated and measured dose for patient specific QA. Correlation with PTV volume, distance from iso and dose difference were quantified.

3.2.1 Case selection

We selected 10 cases of VMAT intracranial radiosurgery who were previously treated and used CAVMAT technology to re-plan them. Considering only the case of single fraction treatment, the target size is limited to the equivalent sphere diameter smaller than 2 cm. Each selected case consisted of 3 to 8 brain metastases and 20 Gy was assigned to each target in a single fraction. A total of 46 treatment targets were included and analyzed in this study.

3.2.2 CAVMAT Technique

CAVMAT consists of three main steps: target subgrouping, field weight optimization, and limited inverse optimization[26]. CAVMAT technology involves placing planned goals in subgroups for individual processing. Select the target subgroup so that you can find a collimator to properly block between multiple targets. Perform field weight optimization to produce a more uniform plan for mu and dose for each arc. Using eclipse version 15.6 (Varian Medical Systems, Palo Alto, CA) to use Progressive Optimization (PO) algorithm 15603 for limited reverse optimization. CAVMAT has been shown to significantly reduce the volume of healthy tissues receiving low doses[27].

3.2.3 Logfile analysis

Ten VMAT and CAVMAT plans were prepared and uploaded to the Delta 4 QA system and delivered for clinical QA plan of SRS. Twenty plans were delivered using Varian Truebeam STx. To minimize differences, all plans use the same Varian Truebeam STx linear accelerator delivery for delivery of clinical VMAT plans. After the plans were delivered, the delivered (actual) MLC location is automatically stored in the trajectory log file of the Truebeam System. A Python script Python v.3.7 (Python Software Foundation, Wilmington, DE) was used to extract the delivered (actual) MLC location at each control point from the trajectory log file and rewrite the MLC location to the original DICOM-RT file. The new DICOM-RT file with the delivered (actual) MLC location was re imported

back to treatment planning system15.6 (Varian Medical Systems, Palo Alto, CA) for analysis, and dose was recalculated.

The planned and delivered dose statistics were analyzed for both VMAT and CAVMAT; this included clinically relevant statistics such as the volume of healthy tissue receiving 6 Gy (V_{6Gy}), 12 Gy (V_{12Gy}), 16 Gy (V_{16Gy}), PTV dose difference, and minimum target coverage (percentage of target volume receiving the 20 Gy prescription dose). In addition, MLC leaf positions and gantry angles at each control point of VMAT and CAVMAT arcs as recorded in the trajectory files were analyzed to compare magnitude of errors for both CAVMAT and VMAT.

3.2.4 QA analysis

The 20 VMAT and CAVMAT plans were delivered to the Delta4 and SRS MapCHECK phantoms. After delivery, the dose difference and gamma analysis were calculated using the Delta4 software and SNC Patient software. Analysis criteria included the fraction of measurement points with absolute dose difference less than 3%, 2% and 1% criteria. Gamma analysis criteria included 3%2mm, 3% / 1mm, 2% / 1mm and 1% / 1mm.

3.2.5 Dose difference correlation factor

Delivered dose and planned dose of VMAT and CAVMAT QA plans for these ten patients were compared for dose points above 50% of the maximum dose. We quantified the relationship between PTV volume, distance from isocenter and mean dose difference.

3.3Results

3.3.1 MLC Evaluation of VMAT and CAVMAT

In terms of magnitude of MLC errors, the 10 VMAT and CAVMAT plans were comparable; substantial variation was not found. The absolute average MLC position error for the VMAT plans was 0.017 ± 0.012 mm, compared to 0.023 ± 0.019 mm for the CAVMAT plans. In terms of gantry position error, the absolute average gantry position error for the VMAT plans was 0.0148 ± 0.323 degree, compared to 0.01793 ± 0.336 degree for the CAVMAT plans. A paired sample T-test for MLC position and gantry degree error between the VMAT and CAVMAT gave p value of 0.398 and 0.467, respectively. There is no significant difference in MLC position and gantry degree errors between VMAT and CAVMAT.

3.3.2 Logfile Results

Figure 10 shows the average dose increase due to delivery errors for V_{6Gy} was 0.94 ± 1.43%, V_{12Gy} was 0.90 ± 1.38%, and V_{16Gy} was 1.23 ± 1.54%. In comparison, for CAVMAT the average V_{6Gy} decreased by 0.035 ± 0.14%, while V_{12Gy} and V_{16Gy} increased by 0.14 ± 0.18% and 0.28 ± 0.24%, respectively.

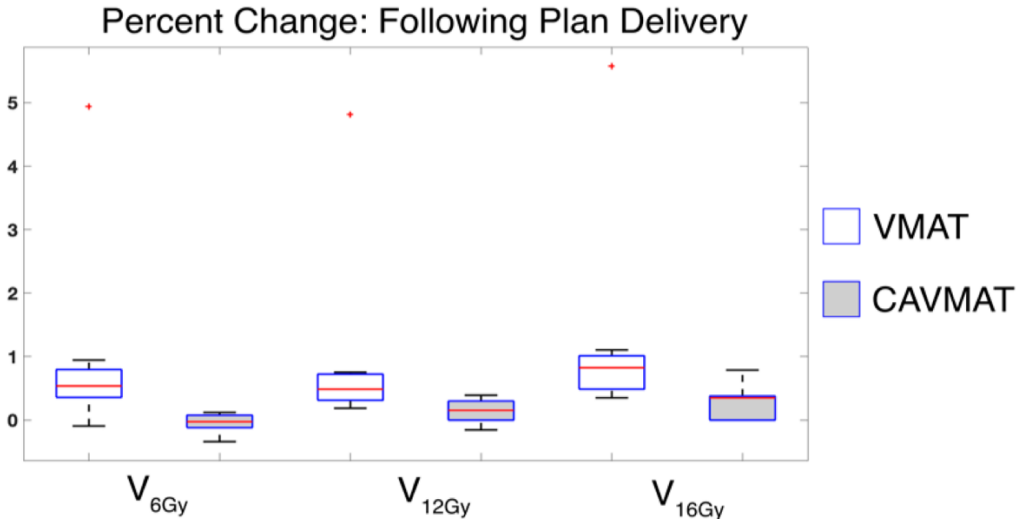


Figure 10 Comparison of VMAT and CAVMAT of logfile analysis at the volume of healthy tissue receiving 6 Gy (V_{6Gy}), 12 Gy (V_{12Gy}), and 16 Gy (V_{16Gy})

The VMAT program after delivery showed a slight increase in the mean and minimum target doses. The average maximum, average and minimum dose of each target increased by 0.53 ± 0.46%, 0.52 ± 0.46% and 0.53 ± 0.56%, respectively. In contrast, the average maximum, average and minimum of CAVMAT plan increased by 0.16 ± 0.18%, 0.11 ± 0.08%, and 0.03 ± 0.24%, respectively. Figure 11 below illustrates the percentage change in the maximum dose for each of the 46 targets after delivery of the treatment plan.

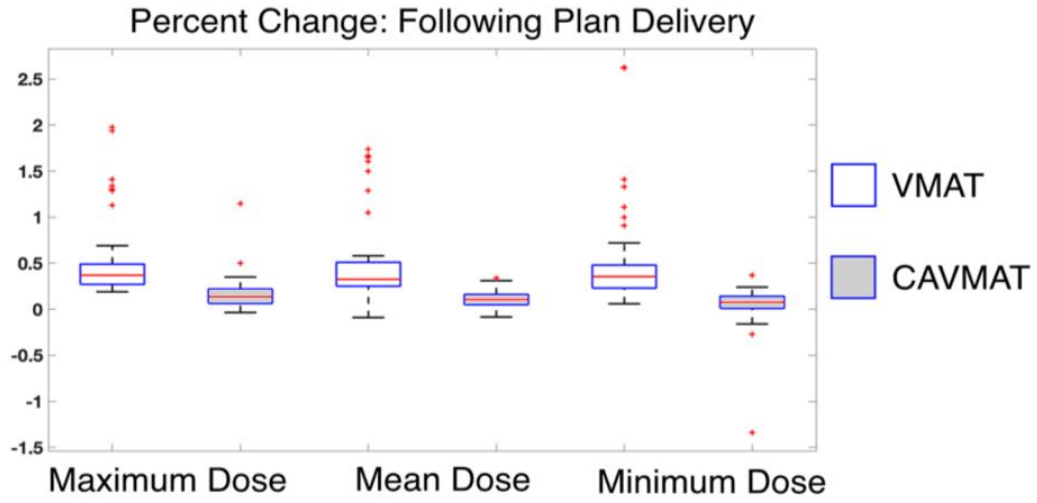


Figure 11 Comparison of the difference between VMAT, CAVMAT and their logfiles at maximum dose, mean dose and minimum dose.

The average target coverage of the VMAT plans compare to VMAT logfile changed by 0.15 ± 0.24% following delivery (decreasing from 99.65% to 99.50%). For CAVMAT, target coverage changed by 0.01 ± 0.28% (decreasing from 99.67% to 99.65%).

3.3.3 QA Results

3.3.3.1 Delta4

For the gamma analysis of 10 delivery plans, for the 3% / 1mm criteria, the average passing rate of VMAT plan is 99.61 ± 0.43%, while that of CAVMAT is 99.98 ± 0.06%. As shown in Figure 12 below, the strict gamma analysis criteria had a large effect on the passing rate for VMAT. For the criteria of 2% / 1mm, the average passing rate of VMAT was 98.54 ± 1.29%, while that of CAVMAT was 99.98 ± 0.06%. In addition, for the more

stringent criteria of 1% / 1mm, the average passing rate of VMAT gamma analysis is 94.53 ± 4.42%, while that of CAVMAT is 99.28 ± 1.74%.

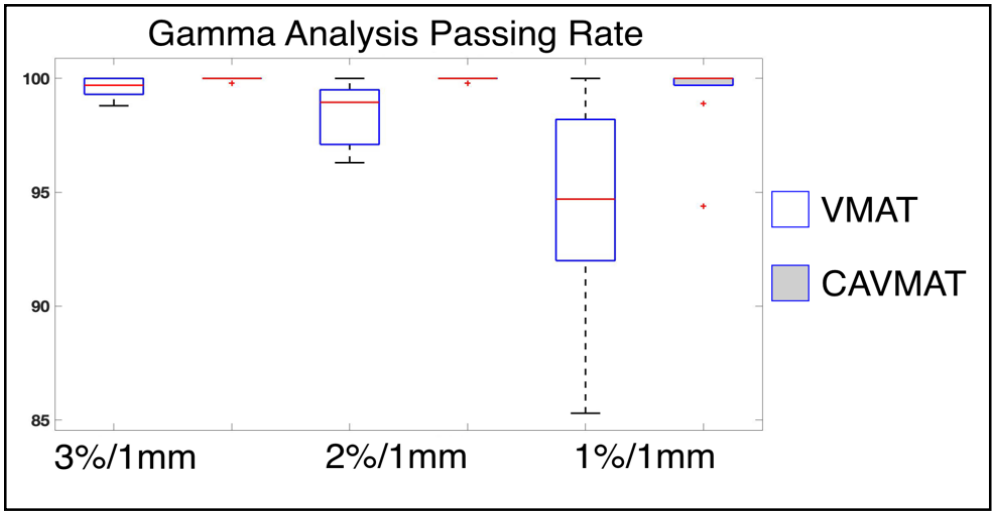


Figure 12 Comparison of VMAT and CAVMAT of gamma analysis using Delta4 at different criteria. CAVMAT has a high gamma passing rate than VMAT nearby 100%.

The dose differences of the gamma analysis of VMAT and CAVMAT are shown in Figure 13 below. For the 3% dose difference criteria, the average passing rate for VMAT was 96.03 ± 4.44%, while that of CAVMAT was 99.17 ± 0.74%. With a dose difference criterion of 2%, the average passing criteria of VMAT was 91.74 ± 5.89%, while that of CAVMAT was 97.91 ± 1.36%. For the strictest 1% dose consistency criteria, the average passing rate of VMAT was further reduced to 74.78 ± 13.00%, while that of CAVMAT was 86.16 ± 6.38%.

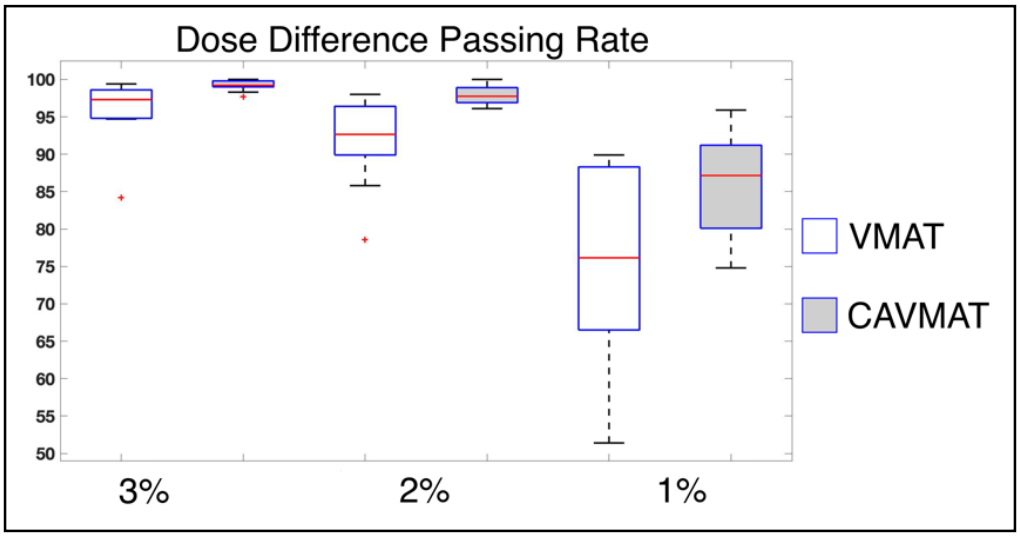


Figure 13 Comparison of VMAT and CAVMAT of dose difference analysis using Delta4 at different criteria. For CAVMAT, CAVMAT has a high passing rate than VMAT at 3%,2%, even 1% dose difference.

CAVMAT had a higher gamma passing rate than VMAT; for gamma analysis, only 1 or two CAVMAT case is not 100% passing rate and still over 99.5%. For dose difference analysis, no case failed for 3% dose difference and even 2% dose difference.

3.3.3.2 SRS MapCHECK

For the dose difference analysis of 10 delivery plans, the gamma passing rate is shown as figure 14 as 99.95±0.11%, 99.87±0.22%, 99.56±0.77% and 98.27±0.28% for the 3%2mm, 3%1mm, 2%1mm and 1%1mm criteria, respectively. The gamma passing for CAVMAT rate is 99.96±0.13%, 99.85±0.42%, 99.66±0.73%, and 98.94±1.52% compared with VMAT. For dose difference analysis, the dose difference passing rate for VMAT is 97.84±2.37% for 3% dose difference, 93.54±4.46% for 2% dose difference and 76.77±9.46%

for 1% dose difference, compared with 98.12±2.53%, 94.26±4.57% and 81.01±9.17% respectively.

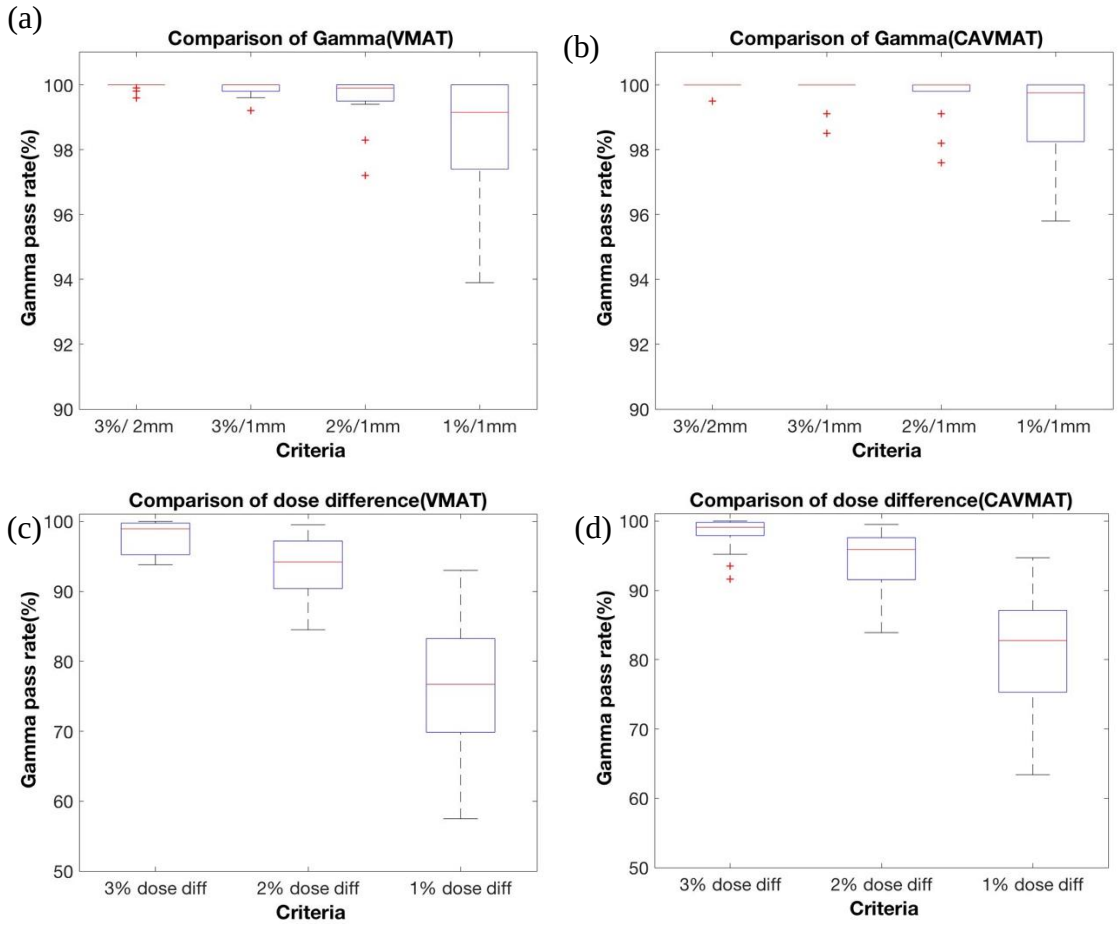
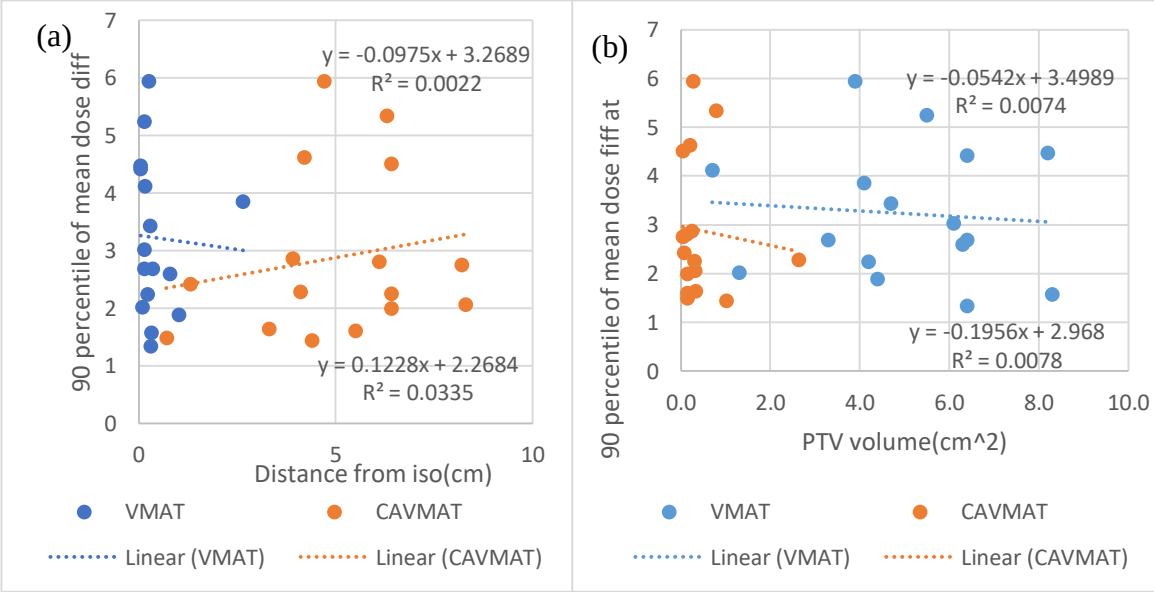


Figure 14 Comparison of VMAT and CAVMAT of gamma analysis using SRS MapCHECK at different criteria of (a)VMAT, (b)CAVMAT. Comparison of VMAT and CAVMAT of dose difference analysis using SRS MapCHECK at different criteria of (c)VMAT, (d)CAVMAT

3.3.4 Dose difference correlation factor:

For SRS MapCHECK, we analyzed the relationship between distance from iso, PTV volume and gamma index for measurement points above a 50% threshold shown in figure 15. The 90th percentile and error bar show that there is no correlation with distance from iso or PTV volume with mean dose difference for VMAT and CAVMAT cases at high dose area.



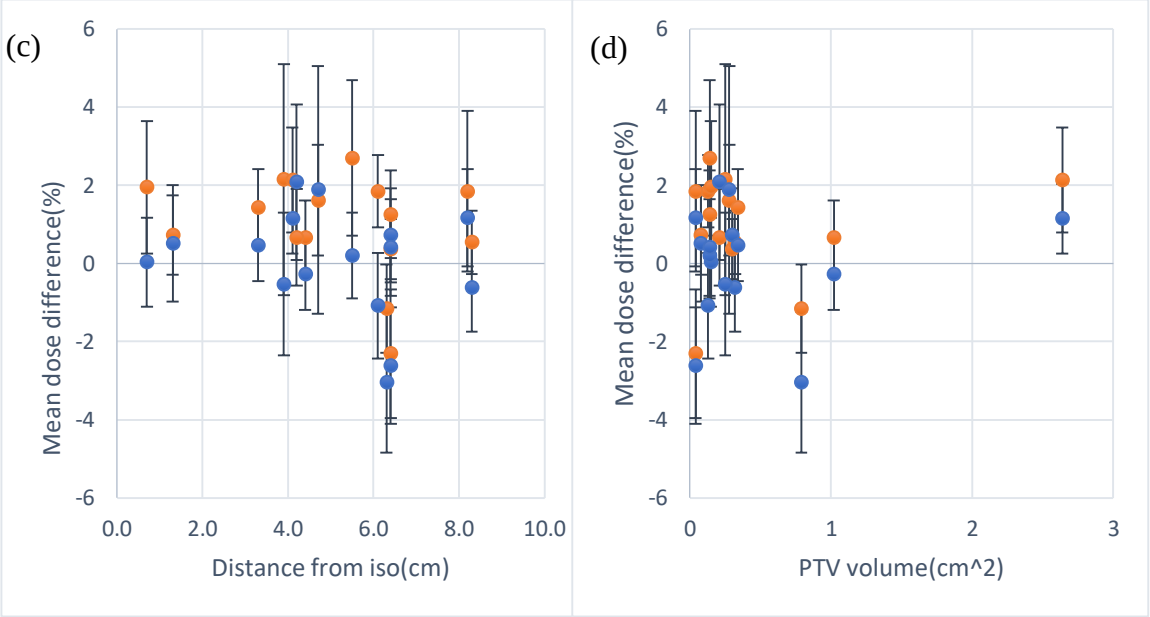


Figure 15 Relationship between distance from iso, PTV volume measured by Eclipse and gamma index, dose difference measured by SRS MapCHECK: (a) 90 percentile VS distance from iso (b) 90 percentile VS PTV volume (c) Error bar of VMAT and CAVMAT dose difference with distance from iso (d) Error bar of VMAT and CAVMAT dose difference with PTV volume. The error bars represent ± standard deviation of the mean dose difference.90th percentile 90% of the mean dose difference at 50% threshold

3.4 Discussion

Volume modulated arc therapy (VMAT) allows the use of dynamic multi leaf collimator (MLC), variable dose rate and variable gantry speed in the case of VMAT to provide a highly conformal dose distribution.[28]It is necessary to ensure the treatment planning and accurate implementation of VMAT. Since the use of MLC establishes a complex dose distribution, the accuracy and repeatability of MLC must be monitored

regularly to ensure that the actual location of MLC during treatment corresponds to the planned location.[28] Especially for the conformal dose distributions with VMAT, the dose error caused by a small changes in MLC position and gantry position error may have a greater impact than traditional treatment plans.[29]However, in some cases, the physical movement of MLC may be different from the expected movement planned in the treatment plan. Betzel showed that a 3 mm MLC position random error could result in a 0.7% change in the mean dose of PTV[30]. Our study quantified the MLC and gantry discrepancies at treatment delivery as recorded in the trajectory log files for both VMAT and CAVMAT. The result is very small and comparable, which shows that the both VMAT plan and CAVMAT plan are accurate and the linear accelerator can deliver CAVMAT plan as effectively as VMAT plan.

The gamma analysis from pre-treatment QA in this study highlighted the robustness of the CAVMAT treatment planning technique. For each gamma analysis criteria, CAVMAT technology provides excellent gamma analysis passing rate, especially in 1%/1mm criteria. The dose difference passing rate follows a same trend with gamma analysis, indicating that the dose consistency of CAVMAT is greater than that of VMAT. Because the log file analysis indicated that the dose differences from delivery errors is relatively small, one possibility for the better agreement in Gamma Analysis for CAVMAT may be indicative of less uncertainty in the dose calculation algorithm for these types of plans (rather than less uncertainty in treatment delivery).

3.5 Conclusion

From log file analysis, CAVMAT better maintained the prescription dose and coverage of each target, as well as the volume of healthy tissue receiving low dose. CAVMAT also provides superior gamma analysis pass rate for each gamma analysis criteria, especially in the case of strict analysis criteria (1% / 1mm). Compared with VMAT, the powerful characteristics of CAVMAT and its robustness to delivery and dose calculation uncertainties make it a potentially effective planning technique for multiple brain metastasis treatment.

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