

Impact of Multi-Leaf Collimator (MLC) Uncertainty on the Quality of Single-Isocenter Multi-Target Radiotherapy for Brain Tumors

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Abstract: Purpose: To quantify the dosimetric and patient-specific quality assurance impact of multileaf collimator (MLC) positioning uncertainty in single-isocenter multi-target (SIMT) stereotactic radiotherapy for brain tumors.

Methods: A retrospective/simulation-based dataset of 25 patients with 62 intracranial targets treated with SIMT stereotactic radiosurgery or fractionated stereotactic radiotherapy was analyzed. Plans were generated in Eclipse, RayStation, and Monaco for TrueBeam STx, Varian Edge, and Elekta Versa HD platforms. Prescriptions ranged from 18 to 24 Gy in 1 to 3 fractions. Planned and delivered plan-quality indices, target coverage metrics, organ-at-risk doses, MLC tracking errors, and portal-dosimetry gamma pass rates at 3%/1 mm were extracted from the workbook. Paired planned-versus-delivered comparisons, Pearson correlation analysis, and simple linear regression were performed.

Results: The mean total MLC error was 0.62 ± 0.17 mm (range 0.25-0.90 mm). Delivered plans showed statistically significant degradation in conformity index (mean ΔCI 0.087), gradient index (mean ΔGI 0.45), homogeneity index (mean ΔHI 0.042), D95% (mean $\Delta D95\%$ -2.33%), and D98% (mean $\Delta D98\%$ -2.71%; all paired $p < 0.001$). Total MLC error correlated with gamma pass rate ($r = -0.67$, $p < 0.001$), $\Delta D95\%$ ($r = -0.46$, $p = 0.022$), and ΔGI ($r = 0.46$, $p = 0.019$). Regression estimated a 9.7% gamma-pass-rate decrease and 3.1% D95% loss per 1-mm increase in total MLC error.

Conclusion: MLC uncertainty in the 0.25-0.90 mm range measurably degraded target coverage, dose fall-off, and gamma pass rate in SIMT brain stereotactic treatments. The findings support stringent MLC commissioning, routine high-resolution MLC QA, and SIMT-specific patient QA rather than reliance on generic IMRT/VMAT tolerances alone.

Keywords: multileaf collimator; MLC uncertainty; single-isocenter; multi-target SRS; brain metastases; gamma analysis; patient-specific QA; stereotactic radiotherapy.

1 Introduction

Single-isocenter multi-target stereotactic radiosurgery and stereotactic radiotherapy have become attractive options for patients with multiple brain metastases because they reduce treatment time and improve clinical throughput compared with multiple-isocenter workflows. However, the same efficiency advantage creates a narrower technical margin for error: off-axis targets, steep dose gradients, small fields, non-coplanar arcs, and dynamic MLC motion can amplify the clinical impact of mechanical and dosimetric uncertainties [1-7].

Recent work has emphasized that SIMT plan quality

depends on target number, target size, target-to-isocenter distance, rotational uncertainty, dose-gradient behavior, and technique selection, including VMAT, HyperArc, DCAT, and dedicated multiple-metastasis planning modules. [8-11]. In parallel, MLC modeling and leaf-position accuracy have emerged as critical contributors to delivery accuracy, especially for small-field SRS where submillimeter errors can alter target coverage and normal brain dose. [16-20].

AAPM TG-218 provides consensus methodology for measurement-based IMRT QA, and TG-142 remains a foundational accelerator QA reference, but SIMT SRS adds technical challenges that justify procedure-specific tolerances and end-to-end verification [12-15]. The present

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analysis uses the attached institutional Excel dataset to generate an AAPM-style manuscript evaluating how measured and simulated MLC uncertainty affects target coverage, plan-quality indices, organ-at-risk dose, and gamma analysis in brain SIMT treatments.

2. Materials and Methods

2.A. Study design and cohort

The dataset comprised 25 patients and 62 intracranial targets treated from 2024 to 2026 using SIMT stereotactic radiotherapy. Patient age ranged from 36 to 74 years (mean 55.92 ± 11.83 years). The number of targets per patient ranged from 1 to 4, with a mean of 2.48 ± 0.87 targets. Prescribed dose ranged from 18 to 24 Gy delivered in 1 to 3 fractions.

2.B. Treatment planning and delivery platforms

Plans were generated in Eclipse, RayStation, and Monaco and delivered or simulated on TrueBeam STx, Varian Edge, and Elekta Versa HD linacs using a high-definition 120-leaf MLC model. The planning endpoints extracted from the workbook included conformity index (CI), gradient index (GI), homogeneity index (HI), D95%, D98%, Dmax%, target-level dose metrics, and OAR maximum/volume metrics.

C. MLC uncertainty model and QA metrics

MLC uncertainty was represented by patient-level systematic MLC error, random MLC error, total MLC error, bank-specific mean errors, and maximum observed MLC error. Portal dosimetry gamma analysis was recorded at 3%/1 mm. In this manuscript, delivered-minus-planned differences are reported as Δ values; therefore, positive Δ CI, Δ GI, and Δ HI indicate degraded conformity, dose fall-off, or homogeneity, whereas negative Δ D95% and Δ D98% indicate reduced target coverage.

3.D. Statistical analysis

Descriptive statistics are reported as mean $\pm$ standard deviation with range. Planned and delivered values were compared using paired t-tests. Pearson correlation quantified associations between total MLC error and dosimetric endpoints. Simple linear regression estimated the slope of change per 1-mm increase in total MLC error. Two-sided $p < 0.05$ was interpreted as statistically significant. Given the sample size and retrospective/simulation-based design, the results should be interpreted as hypothesis-generating and clinically directional rather than as definitive tolerance limits.

The cohort was balanced by sex (13 female, 12 male). Most treatments were single-fraction (20/25), with 5 patients receiving 3 fractions. The most common target counts were 2 targets (10 patients) and 3 targets (9 patients).

Table 1: Cohort and treatment characteristics.

Characteristic	Value
Patients	25
Targets	62
Age, years	55.92 ± 11.83 (36-74)
Targets per patient	2.48 ± 0.87 (1-4)
PTV volume, cc	6.91 ± 3.85 (0.51-14.97)
Distance from isocenter, cm	3.18 ± 2.94 (0.00-7.98)
Prescription dose, Gy	18-24
Fractions	1-3
TPS distribution	Eclipse: 12, RayStation: 11, Monaco: 2
Linac distribution	Varian Edge: 10, TrueBeam STx: 8, Elekta Versa HD: 7

3.B. MLC uncertainty and QA performance

The mean systematic MLC error was 0.52 ± 0.20 mm, the mean random MLC error was 0.32 ± 0.10 mm, and the mean total MLC error was 0.62 ± 0.17 mm. The mean gamma pass rate was $93.35 \pm 2.49\%$. Using TG-218-style conventional IMRT QA benchmark language as a reference point, 8/25 cases were $\geq 95\%$, 14/25 were between 90% and 95%, and 3/25 were $< 90\%$.

Table 2: MLC uncertainty and patient-specific QA performance.

Parameter	Mean	SD	Min	Max
Systematic MLC error, mm	0.52	0.20	0.11	0.80
Random MLC error, mm	0.32	0.10	0.12	0.50
Total MLC error, mm	0.62	0.17	0.25	0.90
MLC max error, mm	0.37	0.14	0.04	0.59
Gamma pass rate, %	93.35	2.49	88.10	97.30

3.C. Planned versus delivered plan quality

Delivered plans showed statistically significant degradation across all evaluated plan-quality and target-coverage endpoints. The largest clinically directional effects were reductions in D95% and D98%, increases in GI, and

3 Results

3. A. Cohort, target, and treatment characteristics

increases in Dmax%.

Table 3: Planned versus delivered dosimetric endpoints.

Metric	Planned	Delivered	Δ delivered-planned	Paired p	Effect size dz
CI	1.25 $\pm$ 0.06	1.33 $\pm$ 0.07	0.09 $\pm$ 0.04	<0.001	2.33
GI	3.63 $\pm$ 0.45	4.08 $\pm$ 0.45	0.45 $\pm$ 0.17	<0.001	2.63
HI	0.19 $\pm$ 0.03	0.24 $\pm$ 0.03	0.04 $\pm$ 0.01	<0.001	3.60
D95 (%)	99.33 $\pm$ 0.63	97.00 $\pm$ 1.28	-2.33 $\pm$ 1.17	<0.001	-1.99
D98 (%)	97.86 $\pm$ 0.85	95.16 $\pm$ 1.31	-2.71 $\pm$ 1.12	<0.001	-2.42
Dmax (%)	107.77 $\pm$ 1.93	110.93 $\pm$ 2.40	3.16 $\pm$ 1.18	<0.001	2.66

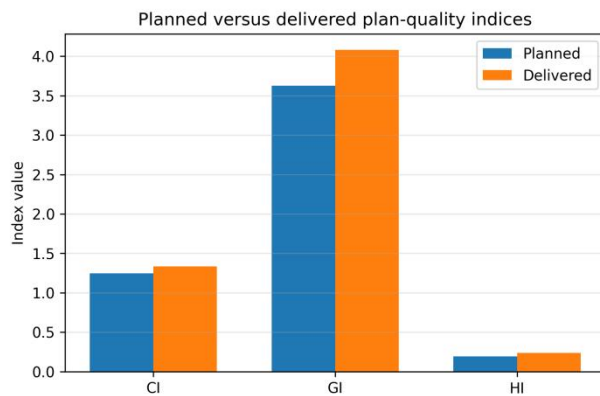


Fig.1: Planned versus delivered plan-quality indices. Delivered CI, GI, and HI increased, indicating degraded conformity, dose fall-off, and homogeneity.

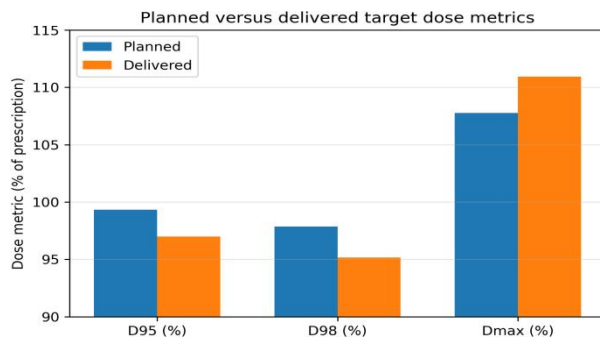


Fig.2: Planned versus delivered target dose metrics. Delivered D95% and D98% decreased, while Dmax% increased.

3.D. Relationship between MLC uncertainty and dosimetric degradation

Total MLC error showed a strong inverse association with gamma pass rate ($r=-0.67$, 95% CI -0.84 to -0.38, $p<0.001$). It also correlated with increased GI ($r=0.46$, $p=0.019$) and reduced D95% ($r=-0.46$, $p=0.022$). Correlations with Δ CI, Δ HI, Δ D98%, Δ Dmax%, and V12Gy were weaker or not statistically significant in this dataset.

Table 4: Pearson correlations between total MLC error and dosimetric/QA endpoints.

Endpoint	Pearson r	95% CI	p
Δ CI	0.14	-0.27 to 0.51	0.494
Δ GI	0.46	0.08 to 0.73	0.019
Δ HI	0.28	-0.13 to 0.61	0.181
Δ D95%	-0.46	-0.72 to -0.07	0.022
Δ D98%	-0.20	-0.55 to 0.21	0.331
Δ Dmax%	-0.02	-0.41 to 0.38	0.934
Gamma pass rate	-0.67	-0.84 to -0.38	<0.001
Normal brain V12Gy	0.14	-0.27 to 0.51	0.491

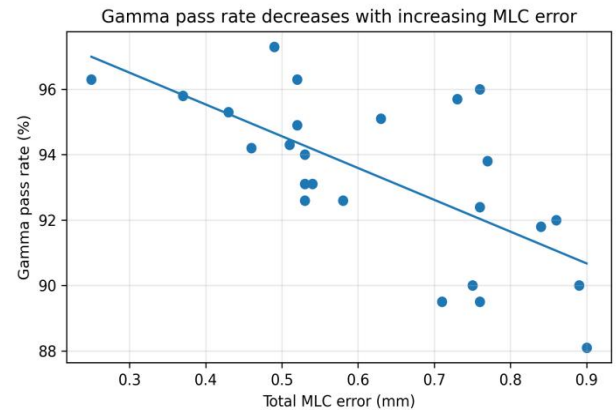


Fig.3: Gamma pass rate versus total MLC error. Linear regression slope: -9.72% per mm; $R^2=0.45$; $p<0.001$.

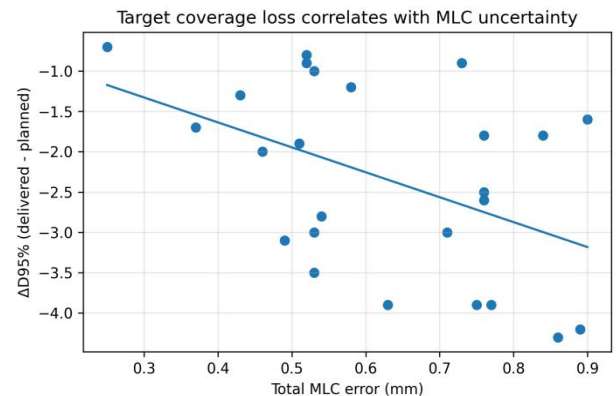


Fig.4: Δ D95% versus total MLC error. Linear regression slope: -3.09% per mm; $R^2=0.21$; $p=0.022$.

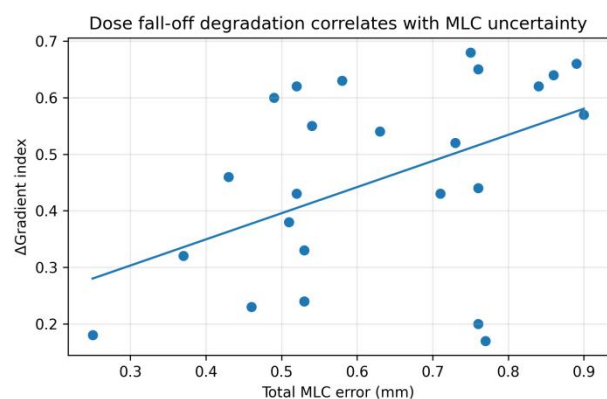


Fig. 5: Δ GI versus total MLC error. Linear regression slope: 0.46 per mm; $R^2=0.22$; $p=0.019$.

3.E. Target-level off-axis analysis and OAR doses

At the target level, the mean PTV volume was 6.91 ± 3.85 cc, and the mean target-to-isocenter distance was 3.18 ± 2.94 cm. Target distance from isocenter was not significantly correlated with target D95% ($r=-0.04$, $p=0.748$), suggesting that MLC uncertainty and plan-specific modulation factors may be more explanatory in this dataset than off-axis distance alone.

Table 5: Organ-at-risk dose summary.

OAR parameter	Mean	SD	Min	Max
Brainstem Dmax, Gy	11.52	1.67	8.32	14.37
Optic chiasm Dmax, Gy	8.75	1.57	6.19	11.84
Normal brain V12Gy, cc	14.68	6.49	5.10	24.70
Left optic nerve Dmax, Gy	6.89	1.50	4.40	9.40
Right optic nerve Dmax, Gy	7.29	1.77	4.41	9.75

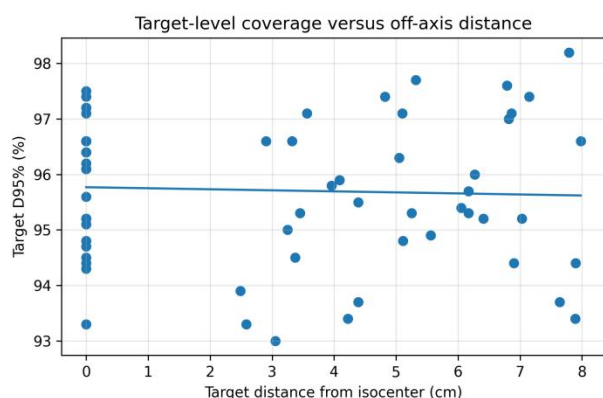


Fig. 6: Target-level D95% versus distance from isocenter. No significant association was observed in this dataset.

4 Discussion

This analysis shows a consistent signal: submillimeter-to-near-millimeter MLC uncertainty degrades SIMT brain stereotactic treatment quality. The practical consequence is not abstract. The dataset demonstrated lower D95% and D98%, higher GI, higher HI, higher Dmax%, and lower gamma pass rate as MLC uncertainty increased. The most operationally useful finding is the regression estimate that gamma pass rate decreased by approximately 9.7 percentage points per 1-mm total MLC error, while D95% decreased by approximately 3.1 percentage points per 1-mm total MLC error.

The direction of these findings is aligned with recent SRS-specific work showing that MLC error, DLG modeling, rotational uncertainty, and off-axis QA methods are not optional details in SIMT brain treatment.[23-26]. Katayama et al. reported that MLC errors alter target coverage and normal brain dose in single-isocenter multiple-target SRS, with DCAT and VMAT showing technique-specific robustness differences.¹ The present dataset adds a patient-level correlation and regression view using clinically familiar endpoints: gamma pass rate, D95%, GI, and OAR dose.

From a clinical physics standpoint, the uncomfortable but important interpretation is that a generic gamma result is not enough. A plan may pass a conventional QA criterion while still carrying clinically relevant target-coverage degradation for small off-axis targets. Conversely, a failing gamma result should not be treated merely as a measurement nuisance; in this dataset, it tracked meaningfully with total MLC uncertainty. This supports a workflow in which gamma analysis is paired with MLC log-file review, high-resolution MLC QA, off-axis Winston-Lutz or equivalent SIMT spatial testing, and plan-quality sensitivity review.

The lack of significant correlation between target-to-isocenter distance and target-level D95% should not be over-read. The target-level sheet did not include target-specific planned-versus-delivered deltas, rotational errors, target shape descriptors, or arc-specific MLC modulation complexity. Prior studies indicate that off-axis geometry and rotation can be important, particularly for small targets and large offsets.⁹⁻¹⁴ The current result suggests only that distance alone did not explain target D95% in this dataset once treatment planning and MLC factors were mixed across platforms.

Operationally, these findings argue for a SIMT brain SRS QA program that treats MLC performance as a high-risk process variable. The minimum defensible package should include baseline and routine high-resolution MLC tests, periodic verification of DLG/transmission modeling, patient-specific QA with criteria appropriate to SRS spatial resolution, log-file or trajectory-log review when available, and end-to-end off-axis tests that challenge target positions

away from isocenter [23-26].

5 Limitations

The dataset contains 25 patients and 62 targets, which is adequate for exploratory analysis but underpowered for definitive tolerance-limit derivation.

The workbook does not include target-specific planned-versus-delivered deltas, target shape complexity, monitor units, control-point aperture metrics, leaf-speed metrics, couch/gantry/collimator delivery logs, or independent measurement uncertainty.

The gamma criterion was recorded as 3%/1 mm, but the workbook does not specify dose threshold, normalization method, detector resolution, or whether gamma was global or local. These details materially affect interpretation under AAPM TG-218-style methodology.

The analysis mixes TPS and linac platforms. This improves external realism but reduces the ability to isolate one machine, one MLC model, or one planning algorithm.

Because the dataset appears simulation/retrospective rather than prospectively controlled, the results should be used to justify QA refinement and further validation, not as a stand-alone clinical policy.

6 Conclusion

MLC positioning uncertainty measurably degraded SIMT brain stereotactic radiotherapy quality in this dataset. Total MLC error was significantly associated with lower gamma pass rate, reduced D95%, and worsened gradient index. The results support tightening MLC QA and integrating SIMT-specific spatial/dosimetric verification into routine clinical practice. A sensible next step is a larger prospective validation study using machine log files, target-specific delivery reconstruction, and predefined MLC tolerance bands.

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Conflict of Interest

The authors should disclose any financial or non-financial conflicts of interest. Placeholder: The authors declare no conflicts of interest.

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Data Availability Statement

The dataset analyzed for this manuscript was provided as an Excel workbook by the user. Public sharing status should be confirmed by the study investigators.

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Appendix A. Patient-Level Analytical Dataset**Appendix Table A1. Patient-level values used for the primary correlation analysis.**

Patient	Targets	Total MLC error (mm)	ΔCI	ΔGI	$\Delta D95\%$	Gamma pass rate (%)	Brain V12Gy (cc)
PT-001	1	0.52	0.041	0.43	-0.90	96.30	5.10
PT-002	2	0.76	0.062	0.44	-2.50	89.50	22.40
PT-003	1	0.46	0.096	0.23	-2	94.20	6.70
PT-004	3	0.49	0.133	0.60	-3.10	97.30	16.90
PT-005	2	0.63	0.100	0.54	-3.90	95.10	24.70
PT-006	2	0.76	0.061	0.20	-2.60	96	15.70
PT-007	3	0.76	0.122	0.65	-1.80	92.40	23.50
PT-008	1	0.52	0.119	0.62	-0.80	94.90	9.70
PT-009	3	0.75	0.060	0.68	-3.90	90	20.20
PT-010	2	0.77	0.080	0.17	-3.90	93.80	15.60
PT-011	2	0.90	0.107	0.57	-1.60	88.10	19.40
PT-012	4	0.71	0.095	0.43	-3	89.50	6.20
PT-013	3	0.73	0.081	0.52	-0.90	95.70	8
PT-014	2	0.58	0.064	0.63	-1.20	92.60	7.70
PT-015	3	0.43	0.036	0.46	-1.30	95.30	18.70
PT-016	2	0.84	0.036	0.62	-1.80	91.80	21.90
PT-017	4	0.86	0.166	0.64	-4.30	92	20
PT-018	3	0.54	0.133	0.55	-2.80	93.10	5.60
PT-019	3	0.37	0.066	0.32	-1.70	95.80	22.30
PT-020	2	0.53	0.146	0.24	-3	93.10	12.10
PT-021	3	0.53	0.111	0.33	-3.50	92.60	12.90
PT-022	4	0.89	0.099	0.66	-4.20	90	7.10
PT-023	3	0.25	0.078	0.18	-0.70	96.30	19.70
PT-024	2	0.51	0.036	0.38	-1.90	94.30	8.60
PT-025	2	0.53	0.037	0.24	-1	94	16.30