Correlation of Target Volume, Surface Area, and Position with Gamma Knife SRS Plan Quality Metrics

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ABSTRACT

Purpose: To retrospectively evaluate the correlation between Gamma Knife SRS plan quality metrics and target geometric characteristics using correlation analyses.
Methods: Thirty-five clinically approved single-target Gamma Knife Icon plans were retrospectively analyzed. All plans were generated using Leksell GammaPlan® (Version 11.4.2) with Lightning inverse optimizer for Leksell Gamma Knife® Icon™. Plan quality metrics included Paddick Conformity Index (PCI), Gradient Index at 50% and 10% prescribed dose ($GI_{50\%}$ and $GI_{10\%}$), and Efficiency Index at 50% and 10% prescribed dose ($\eta_{50\%}$ and $\eta_{10\%}$). Geometric parameters included target volume, surface area, and normalized position (0–1, relative to midline). Pearson correlation analysis assessed relationships between individual geometric parameters and metrics. Spearman rank correlation analysis was performed for combined geometric parameters. Statistical significance was established at $p < 0.05$.
Results: Mean target volume was 11.56 cm³ (range: 0.45–72.12 cm³); mean surface area was 33.12 cm² (range: 3.44–111.51 cm²); mean normalized position was 0.395 (range: 0.12–0.92). PCI & high-dose metrics demonstrated no statistically significant correlation with geometric parameters. Conversely, low-dose metrics exhibited moderate correlations: $GI_{10\%}$ negatively correlated with volume ($r = -0.551$, $p < 0.01$), surface area ($r = -0.637$, $p < 0.01$), and position ($r = -0.634$, $p < 0.01$); $\eta_{10\%}$ showed positive correlations with volume ($r = 0.614$, $p < 0.01$), surface area ($r = 0.554$, $p < 0.01$), and position ($r = 0.491$, $p < 0.01$). Spearman analysis confirmed similar patterns for combined parameters, with $GI_{10\%}$ and $\eta_{10\%}$ demonstrating the strongest correlations when position was included with surface area, volume, respectively ($r = -0.713$ and $r = 0.634$; $p < 0.01$).
Conclusion: The Leksell Gamma Knife Lightning optimizer generates treatment plans with consistent high-dose quality metrics across varying target geometric characteristics. However, low-dose volume optimization demonstrates geometry-dependent behavior, with larger peripheral targets achieving superior dose gradients and efficiency.

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INTRODUCTION

Stereotactic radiosurgery (SRS) has emerged as a precision treatment modality for intracranial lesions, offering high conformity and steep dose gradients that maximize tumor control while minimizing normal tissue toxicity. Plan quality assessment in SRS remains fundamental to ensuring optimal therapeutic outcomes and patient safety. The relationship between target geometric characteristics and achievable plan quality remains an area of active investigation. Target volume, surface area geometry, and spatial position within the cranium collectively influence the degrees of freedom available for inverse planning optimization and the achievable gradient characteristics.

The objectives of the present study are to (1) retrospectively evaluate the correlation between established plan quality metrics (PCI, $GI_{50\%}$, $GI_{10\%}$, $\eta_{50\%}$ & $\eta_{10\%}$) and target geometric characteristics (volume, surface area, normalized intracranial position) in single-target Gamma Knife Icon plans optimized with Lightning, and (2) determine whether high-dose plan quality metrics are statistically preserved across varying target geometries while low-dose peripheral behavior remains geometry-dependent.

METHODS AND MATERIALS

This retrospective, single-institution study analyzed thirty-five clinically delivered Gamma Knife SRS plans. All treatment plans were generated using the Leksell Gamma Knife Icon radiosurgery unit (Elekta Medical Systems, Stockholm, Sweden) with the associated Treatment Planning System (TPS) Leksell GammaPlan® version 11.4.2. The Leksell Gamma Knife Lightning inverse plan optimizer, the most recent generation of inverse planning algorithms available for the Icon system, was employed for all plans.

Plan quality metrics included Paddick Conformity Index (PCI), Gradient Index at 50% and 10% prescribed dose ($GI_{50\%}$ and $GI_{10\%}$), and Efficiency Index at 50% and 10% prescribed dose ($\eta_{50\%}$ and $\eta_{10\%}$). Geometric parameters included target volume, surface area, and normalized position (0–1, relative to midline).

Pearson's correlation analysis was used to assess linear relationships between target's individual geometric parameters (volume, surface area, position) and each plan quality metric. Spearman's rank correlation analysis was employed to evaluate correlations with combined target geometric parameters and assess cumulative effects of more than one geometric factors on plan quality metrics. Combined target geometric parameters analyzed included volume + surface area, volume + position, surface area + position, and volume + surface area + position; for these combined parameters, a composite geometric parameter rank was calculated from the normalized sum of the individual parameter ranks. Statistical significance was established at $p < 0.05$.

RESULTS

A total of 35 clinically approved Gamma Knife SRS plans were analyzed across a range of target pathologies, with target volumes from 0.454 to 72.119 cm³, surface areas from 3.442 to 111.508 cm², and normalized target positions from 0.124 to 0.923, indicating coverage of both central and peripheral cranial locations. All plan quality metrics were clinically acceptable, with mean PCI 0.790 ± 0.094, $GI_{50\%}$ 2.927 ± 0.328, $GI_{10\%}$ 32.814 ± 7.827, $\eta_{50\%}$ 0.435 ± 0.065, and $\eta_{10\%}$ 0.146 ± 0.030.

Pearson analysis showed negligible or weak, non-significant correlations between PCI, $GI_{50\%}$, $\eta_{50\%}$ and all individual geometric parameters, whereas $GI_{10\%}$ correlated negatively with volume, surface area, and position, and $\eta_{10\%}$ correlated positively with the same variables, indicating that low-dose plan quality was more sensitive to target geometry than high-dose conformity. Spearman analysis of combined geometric parameters confirmed these trends, with $GI_{10\%}$ and $\eta_{10\%}$ showing significant moderate for volume + surface area, volume + position, surface area + position, and all three parameters combined, while $\eta_{50\%}$ showed only weak associations in a few combinations. Overall, the results indicate that the Lightning optimizer maintains robust conformity and high-dose gradient performance across varying target geometries, but low-dose spread and efficiency are influenced more clearly by target size and position.

Table 1. Pearson and Spearman correlation coefficients between individual and combined geometric parameters (volume, surface area, normalized position) of the target and plan quality metrics

Plan Parameters		Pearson			Spearman's Rank			
		Volume	Surface Area	Position (d_{norm})	Volume + Surface Area	Volume + Position	Surface Area + Position	Volume + Surface Area + Position
PCI	r	0.276	0.131	0.085	0.213	0.324	0.228	0.299
	p value	0.108	0.453	0.628	0.220	0.057	0.188	0.081
$GI_{50\%}$	r	-0.134	-0.194	-0.045	-0.262	-0.100	-0.083	-0.180
	p value	0.444	0.263	0.798	0.128	0.567	0.637	0.301
$GI_{10\%}$	r	-0.551	-0.637	-0.634	-0.430	-0.668	-0.713	-0.610
	p value	0.001	0.000	0.000	0.010	0.000	0.000	0.000
$\eta_{50\%}$	r	0.327	0.205	0.043	0.314	0.353	0.250	0.355
	p value	0.055	0.238	0.805	0.066	0.038	0.148	0.036
$\eta_{10\%}$	r	0.614	0.554	0.491	0.401	0.634	0.552	0.565
	p value	0.000	0.001	0.003	0.017	0.000	0.001	0.000

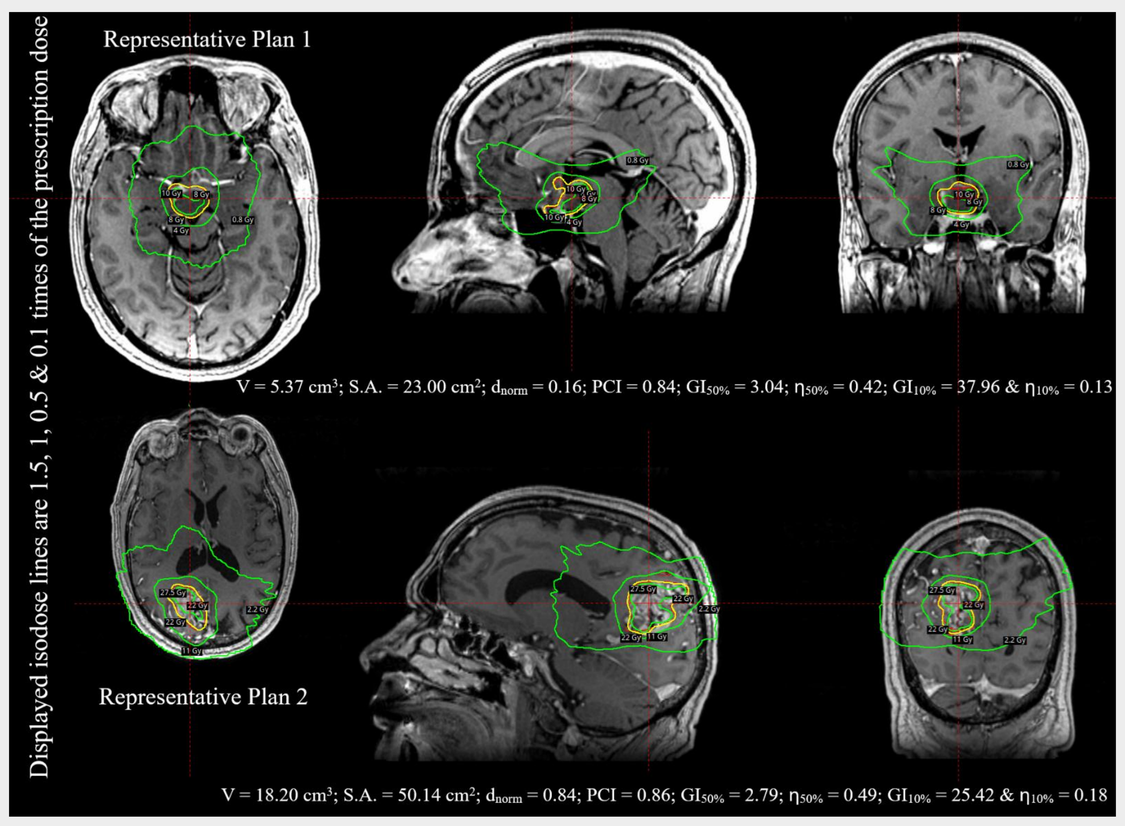

Figure 1: Dose distribution and indices comparison of two representative cases (small central vs large peripheral).

DISCUSSION

This retrospective analysis of 35 Gamma Knife SRS plans provides novel insights into the relationship between target geometric characteristics and plan quality metrics achieved through the Leksell Gamma Knife Lightning inverse plan optimizer. The findings demonstrate that contemporary inverse planning algorithms achieved consistent plan quality across varying target geometries, with important nuances specifically related to low dose volume.

The most significant finding in this analysis is the moderate correlation between $GI_{10\%}$ and $\eta_{10\%}$ with target geometric characteristics, in stark contrast to the lack of significant correlation for PCI & 50% prescription isodose metrics even with combined target geometry (volume + surface area + position). This dissociation suggests that the inverse optimizer demonstrates optimization behavior wherein high-dose and intermediate-dose parameters are consistently achieved across different target geometries with slight trade-offs in low-dose (10% isodose) regions.

CONCLUSIONS

This retrospective correlation analysis of 35 single-target Gamma Knife SRS plans demonstrates that the Leksell Gamma Knife Lightning inverse plan optimizer generates treatment plans with consistent plan quality metrics across varying target geometric characteristics (volume 0.454–72.119 cm³, surface area 3.442–111.508 cm², normalized position 0.124–0.923). Plan quality metrics at the prescription isodose and 50% prescription isodose level (PCI, $GI_{50\%}$ and $\eta_{50\%}$) showed no statistically significant correlation with target geometric parameters, while 10% isodose level metrics ($GI_{10\%}$ and $\eta_{10\%}$) exhibited moderate correlations with target geometry—particularly larger peripheral targets demonstrating superior low dose gradient characteristics and efficiency. Future investigations should evaluate whether these geometric relationships extend to multi-target plans, lesions with adjacent critical structures, and other inverse planning algorithms, while machine learning approaches that incorporate these relationships may aid in predictive modeling of achievable plan quality.

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