Atlas-Based Prediction of Plan Quality and Treatment Time for Gamma Knife Stereotactic Radiosurgery of Brain Metastases

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INTRODUCTION

- **Gamma Knife (GK)** stereotactic radiosurgery widely used to treat brain metastases via highly conformal dose distributions.
- Treatment time and plan quality are directly related and depend on multiple factors such as target size, location, and shape[1,2] as well as source strength at the time of treatment.
- Objective plan quality assessment can be difficult due to these multivariable dependencies.
- A-priori knowledge of achievable plan quality vs. treatment time could provide a valuable benchmark to guide planning, evaluation, and facilitate treatment booking.

OBJECTIVES

1. **Construct a large atlas of brain metastases to establish quantitative relationships between target characteristics, treatment time, and achievable plan quality.**
2. **Evaluate the predictive value of target characteristics for determining achievable GK plan quality & treatment time.**

METHODS

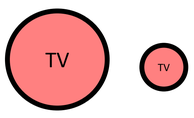
PATIENT COHORT AND DATASET COLLECTION

A retrospective dataset of 2,681 brain metastases from 989 patients treated on Gamma Knife ICON® (Elekta) between 2021–2025 was analyzed. Treatment plans were created using Leksell GammaPlan v11.1.1–11.4.2.

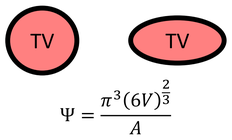
TARGET CHARACTERISTICS

For each target, three geometric descriptors were calculated:

Target volume [cc]



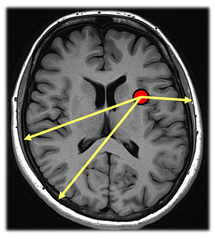
Sphericity



$$\Psi = \frac{\pi^{\frac{1}{3}}(6V)^{\frac{2}{3}}}{A}$$

where Ψ is sphericity, V is target volume, and A is target surface area

Mean radial distance from target center to skull [mm]

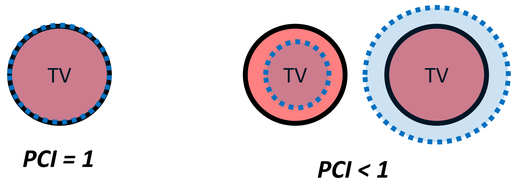


PLAN QUALTIY METRICS

Three planning outputs were evaluated:

i) Paddick Conformity Index $PCI = \frac{TV \cap PIV}{TV \times PIV}$

where TV is target volume and PIV is prescription isodose volume



PCI = 1 ***PCI < 1***

ii) Treatment (Tx) time *(normalized by Rx and Co-60 source strength)*

iii) Number of shots used

- Plans are comprised of multiple shots; each is a focused set of radiation beamlets delivered to a point in the target.

METHODS (cont.)

MACHINE LEARNING ANALYSIS

- A Histogram Gradient Boosting model[3,4] was trained to predict each planning output from the geometric descriptors.
- Model performance was assessed using 5-fold cross-validation.

MODEL INTERPRETATION

- Partial dependence plots were used to identify how strongly target characteristics influenced plan quality and treatment time.

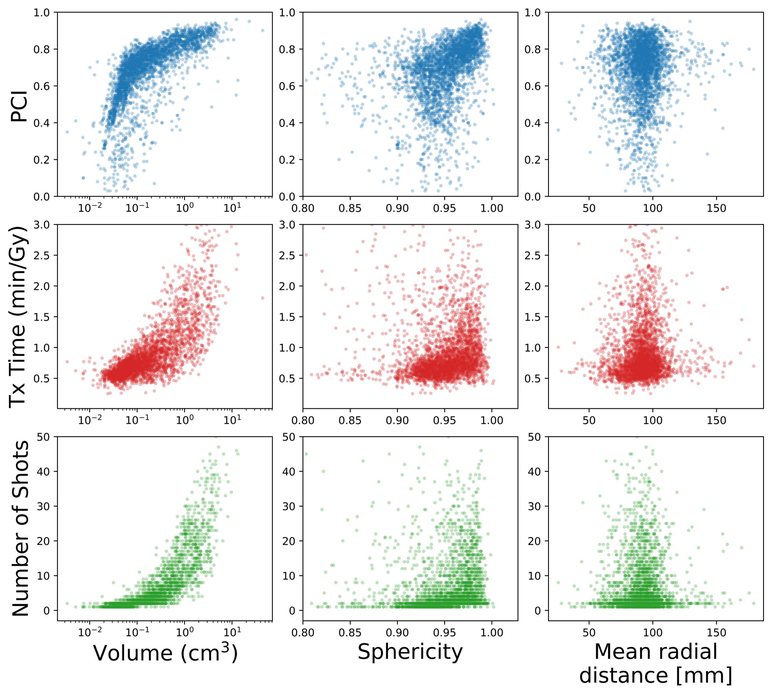


Figure 1. Raw data used to build the atlas. Scatter plots of PCI (blue), normalized treatment time (red), and number of shots (green) versus target volume, sphericity, and mean radial distance. (N = 2681 brain metastases, 989 patients)

RESULTS

- Predictive performance varied across plan quality metrics and is summarized in Table 1.
- Strongest performance for number of shots (R^2 = 0.768), explaining approximately 77% of the observed variation.
- Prediction accuracy high for normalized treatment time (R^2 = 0.645).
- Moderate performance was observed for PCI (R^2 = 0.587).

	RMSE (actual vs. predicted)	R^2
PCI	**0.106** [0.104 – 0.110]	**0.587** [0.567 – 0.601]
Normalized treatment time	**0.297 min/Gy** [0.289-0.305] *e.g. 6.2 min for Rx = 21 Gy at time of source calibration*	**0.645** [0.638 – 0.653]
Number of shots	**3.82** [3.657 – 3.958]	**0.768** [0.759 – 0.783]

Table 1. Predictive performance of the target geometry-based model for relevant Gamma Knife planning metrics. Model accuracy is reported using root mean square error (RMSE) and coefficient of determination (R^2) obtained from 5-fold cross-validation. 95% CI shown in brackets.

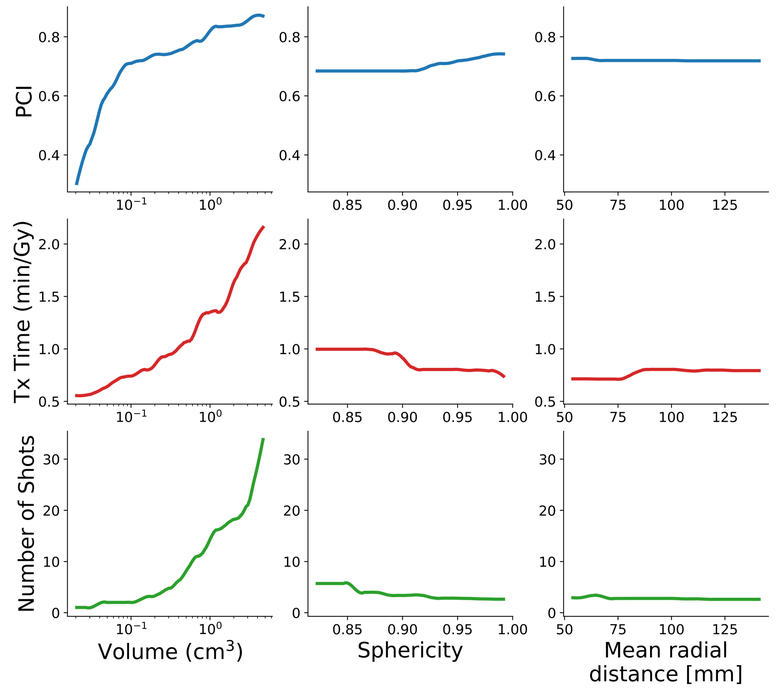


Figure 2. Partial dependence plots showing the relationships between target volume, sphericity, and mean radial distance on PCI (blue), normalized treatment time (red), and number of shots (green).

DISCUSSION

- Simple geometric descriptors explain substantial variation in Gamma Knife planning outcomes.
- Target volume is the dominant predictor of PCI, normalized Tx time, and number of shots used.
- Nonlinear relationships found between volume and plan metrics.
- Predictive model performed best for number of shots and normalized treatment time.
- Prediction of PCI was more modest, potentially due to additional factors not captured by the model (e.g. target location relative to other targets and organs-at-risk, planner preference for plan quality-Tx time tradeoffs).
- Impact of sphericity was smaller than target volume and mean radial distance had minimal impact across all outputs.
- Limitation - Atlas represents the experience and clinical preferences of a single center and may not be applicable elsewhere.

CONCLUSION

A small set of simple target features can be used to estimate Gamma Knife plan quality and treatment time and could support planning, objective plan quality evaluation, and appointment scheduling.

REFERENCES

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