Robust Single-Isocenter Selection for Multi-Target SRS Using Weighted Expected Dice Similarity Coefficient

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ABSTRACT

PURPOSE:
This study investigated the efficacy of a weighted expected Dice similarity coefficient (wDSC) framework for optimizing isocenter placement in single-isocenter multi-target (SIMT) stereotactic radiosurgery (SRS).

METHOD:
Fifteen cases comprising randomly generated and clinical GTV-based spherical targets (3-11 targets per case) were evaluated. Center of surface area (CSA), geometric mean (GeoM), cand minimum-volume (MinVol) isocenters were calculated for comparison. A weighted expected Dice similarity coefficient (wDSC) framework was developed in which rotational setup uncertainties (σ_r = 0.5°) were modeled using Monte Carlo sampling (N = 3000). For each target, an expected DSC was computed from simulated rotational perturbations about candidate isocenters. Expected DSC values were combined using inverse-volume weighting (β = 0.6) to emphasize smaller targets, and the isocenter was optimized using the Nelder-Mead algorithm to maximize the resulting wDSC. Robustness was evaluated by applying ±1° rotations about each candidate isocenter and comparing the minimum DSC across targets.

RESULTS:
The wDSC isocenter achieved the highest minimum worst-case DSC in 10 of 15 cases. In the remaining cases, it produced higher mean worst-case DSC despite similar minimum values. Geometric approaches maintained high overlap for large targets (>0.85) but allowed small-target DSC to decrease to 0.1. In contrast, wDSC optimization increased the small-target lower bound to approximately 0.45 while preserving large-target coverage.

CONCLUSION
wDSC-based optimization improves isocenter robustness in SIMT SRS by reducing rotational sensitivity of small targets and providing more consistent target coverage without compromising larger targets.

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INTRODUCTION

Single-isocenter multitarget stereotactic radiosurgery (SIMT SRS) is an efficient approach for treating multiple intracranial lesions by treating all targets from a single isocenter. However, small rotational deviations can cause target displacements that increase with distance from the isocenter, making peripheral and small lesions more vulnerable to geometric misalignment. Conventional geometric-based isocenter selection methods reduce overall target-to-isocenter distance but do not account for differences in target susceptibility to rotational error.

The Dice similarity coefficient (DSC) quantifies geometric overlap between original and displaced target volumes and provides a useful measure of robustness to rotational uncertainty. Because a given displacement causes a greater relative loss of overlap in smaller lesions, DSC can capture target-specific vulnerability that may be overlooked by conventional geometric approaches. This study proposes a weighted expected DSC (wDSC) framework for isocenter optimization to improve robustness for vulnerable targets in SIMT SRS.

METHODS

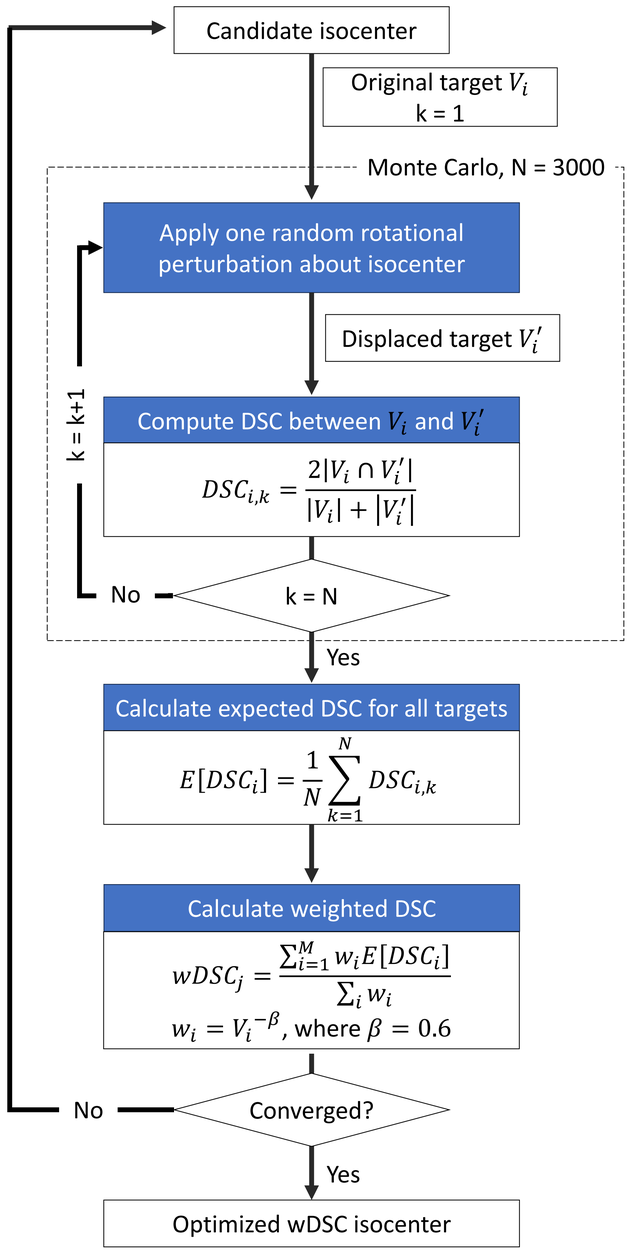

Figure 1. Workflow of the wDSC optimization. Monte Carlo sampling estimates the expected DSC under probable rotational setup uncertainties. The weighted DSC is iteratively maximized to determine the isocenter.

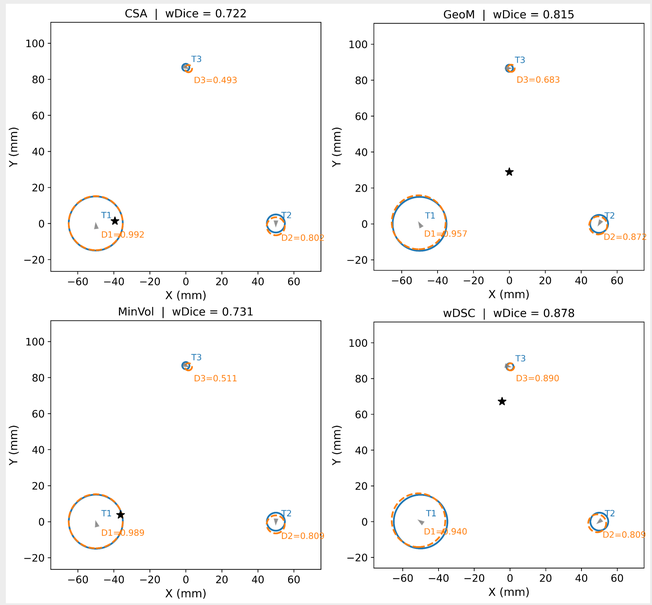

Figure 2. Comparison of CSA, GeoM, MinVol, and wDSC isocenters in a 2D under ±1° rotation. The wDSC isocenter increased the smallest-target DSC from 0.49-0.68 to 0.89 while maintaining high DSC for larger targets.

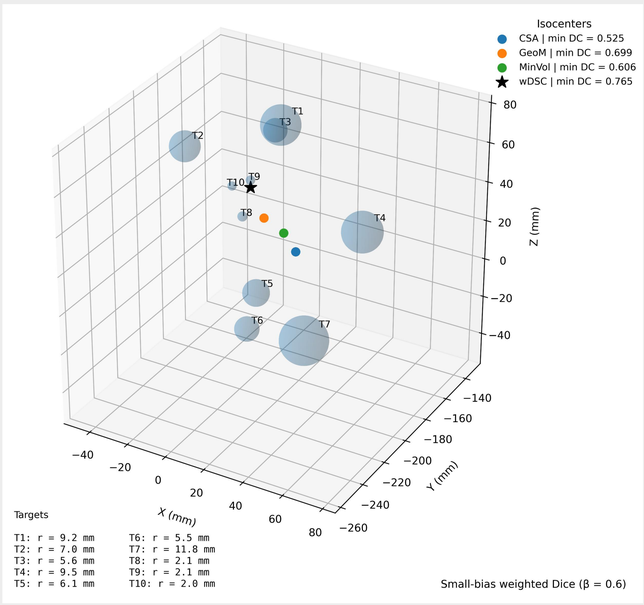

Figure 3. Comparison of GeoM, COM, CSA, MinVol, and wDSC isocenters in a 3D case. The wDSC isocenter achieved the highest minimum worst-case DSC under ±1° rotation (0.77 vs. 0.52–0.70).

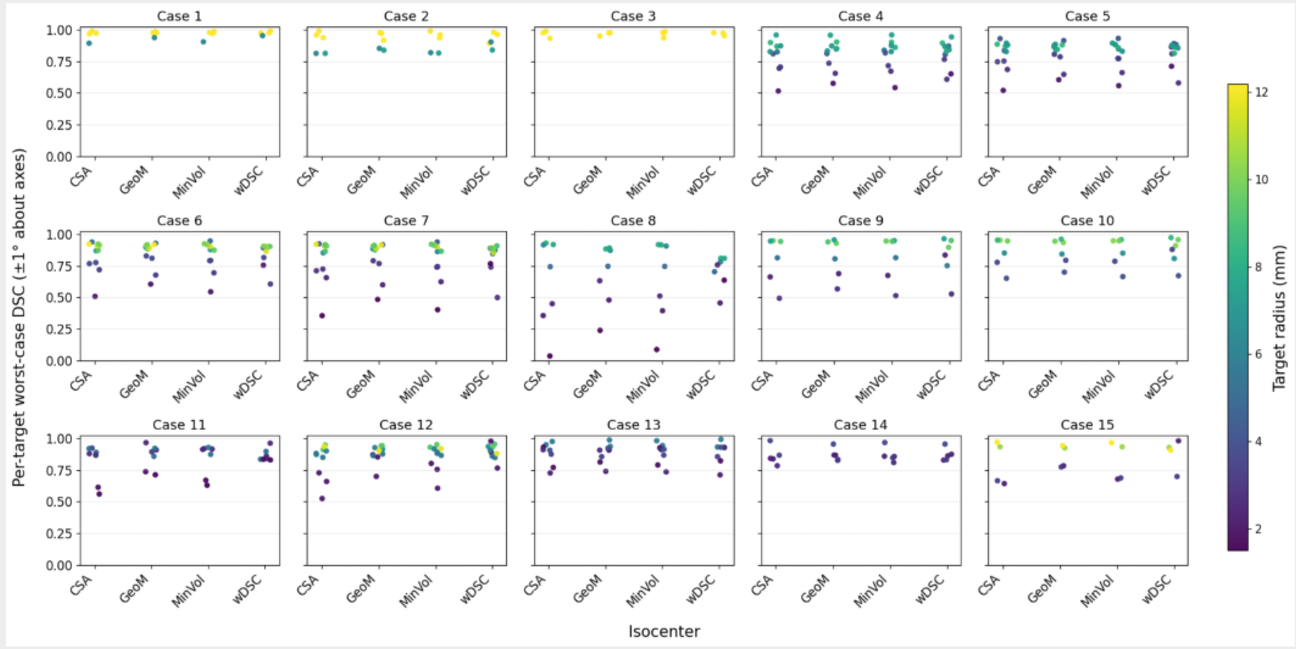

Figure 4. Per-target worst-case DSC under ±1° rotation across all isocenter definitions for fifteen cases. The wDSC isocenter achieved the highest minimum worst-case DSC in 10 of 15 cases and demonstrated reduced variability overall, indicating more consistent target overlap under rotational uncertainty.

RESULTS AND DISCUSSION

2D and 3D examples in Figures 2 and 3 show improved geometric overlap for vulnerable targets using the wDSC isocenter. Figure 4 summarizes per-target worst-case DSC across all 15 cases, demonstrating higher mean DSC and lower variability with the wDSC isocenter. **The wDSC-optimized isocenter achieved the highest minimum worst-case DSC in 10 of 15 cases.** In the remaining cases, optimization converged toward a GeoM-like solution because of similar target sizes, however, the wDSC isocenter still produced higher mean worst-case DSC across targets. Geometric isocenters generally maintained high worst-case DSC for large targets (>0.85) but allowed small-target DSC values to decrease to approximately 0.10. In contrast, **the wDSC isocenter increased the small-target lower bound to 0.45 without compromising large-target performance.**

The current study used spherical targets and geometric overlap metrics without dosimetric evaluation. Future work will validate the framework using clinical target shapes and dosimetric endpoints, while exploring weighting schemes that incorporate target distance from the isocenter and patient-specific margin requirements.

CONCLUSION

The proposed wDSC framework improved robustness to rotational uncertainty through target-specific weighting during isocenter optimization. Compared with conventional geometric methods, it reduced overlap loss while maintaining performance across larger lesions.

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