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Automated CyberKnife MLC Planning for Complex Central Nervous System Radiosurgery Using a Heuristic Optimization Framework

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Background

- **The CyberKnife system** is a frameless, image-guided robotic technology used to deliver stereotactic radiosurgery and radiotherapy [1]. Doses can be very conformal to target while respect the dose tolerances of surrounding healthy tissues because of the degree of freedom from large number of noncoplanar beams. However, the planning remains extremely **labor-intensive**, with plan quality highly dependent on planner expertise and extensive manual iteration.
- Automation has been used extensively in LINAC to improve the planning efficiency [2]. With a recently commissioned CyberKnife machine in RayStation, we explored the use of RayStation scripting for **automated CyberKnife planning**.
- The study proposed a PTV volume-partitioning strategy and an adaptive optimization process that dynamically adjusts optimization priorities based on unmet clinical goals.

Materials/Methods

- RayStation 2023B was used
  - Node initialization in large target limits later optimization.
  - Optimization results cannot be guaranteed to pass QA.
- We proposed
  - **Geometry-Driven Initialization**: The PTV is partitioned into subregions with characteristic dimensions smaller than 9 cm to guide node arrangement and promote uniform target coverage.
  - **Iterative Heuristic Optimization**: for each optimization step, increasing weights for unmet objectives, tightening OAR constraints when its loss value is too small.
  - **Automated Plan Exploration**: keeping segment per direction to less than 1.2 can guarantee QA success and varying max directions per plan can affect the plan quality. The optimal plan is selected based on dosimetric quality and delivery efficiency, followed by minimal manual fine-tuning.

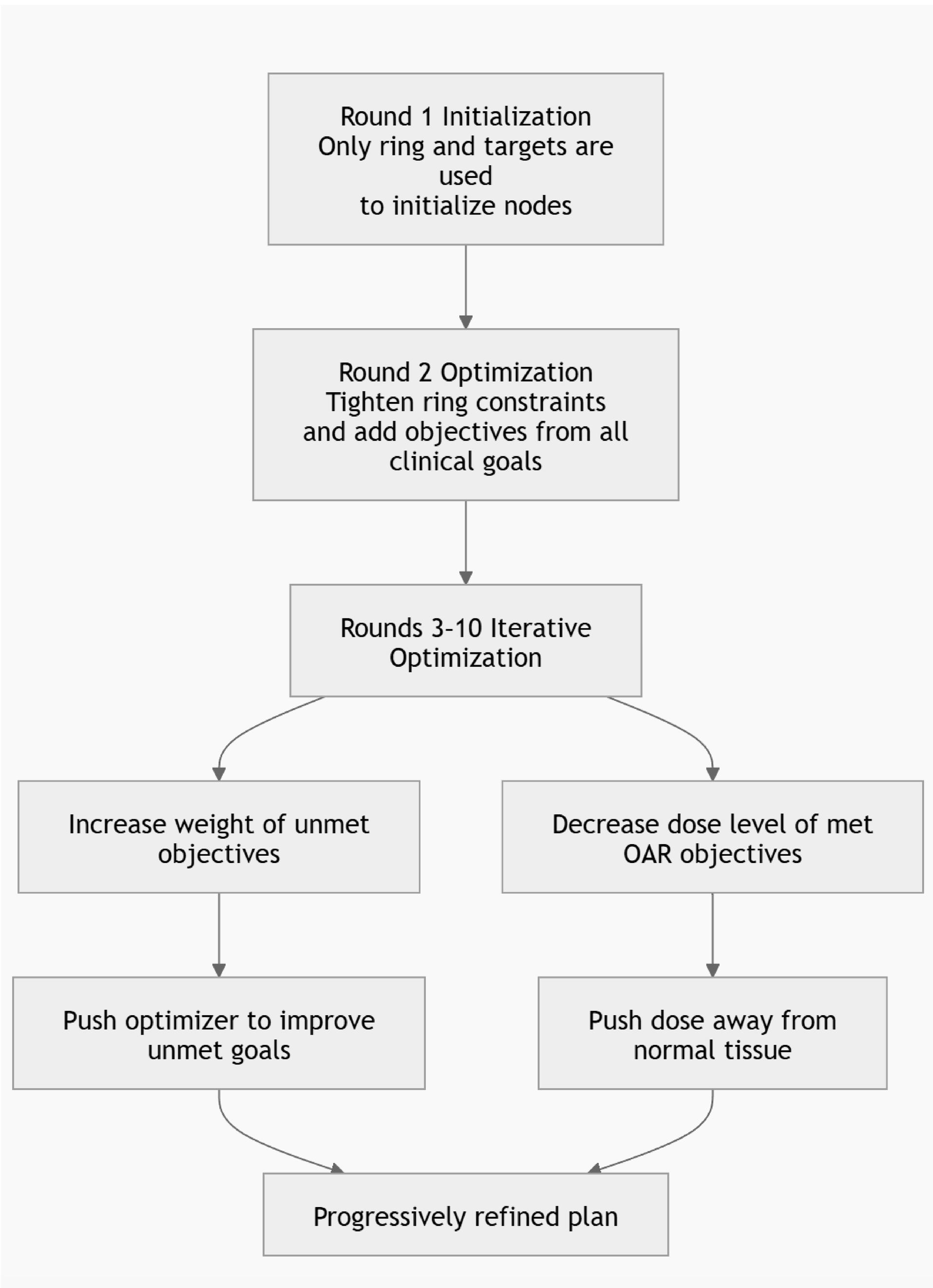

Figure 1. Illustration of optimization process.

- Case study
  - 11 spine cases (PTV 46.3–438.1 cm³) and 6 brain metastases cases (PTV 1.3–50.9 cm³).
  - Average planner time was reduced to **less than 25 minutes** for both spine and BM cases, compared to 0.5–3 days for manual planning.

Results

- The PTV subdivision can improve the dose conformality (Figure 2).
  - Available nodes is more with the division strategy.

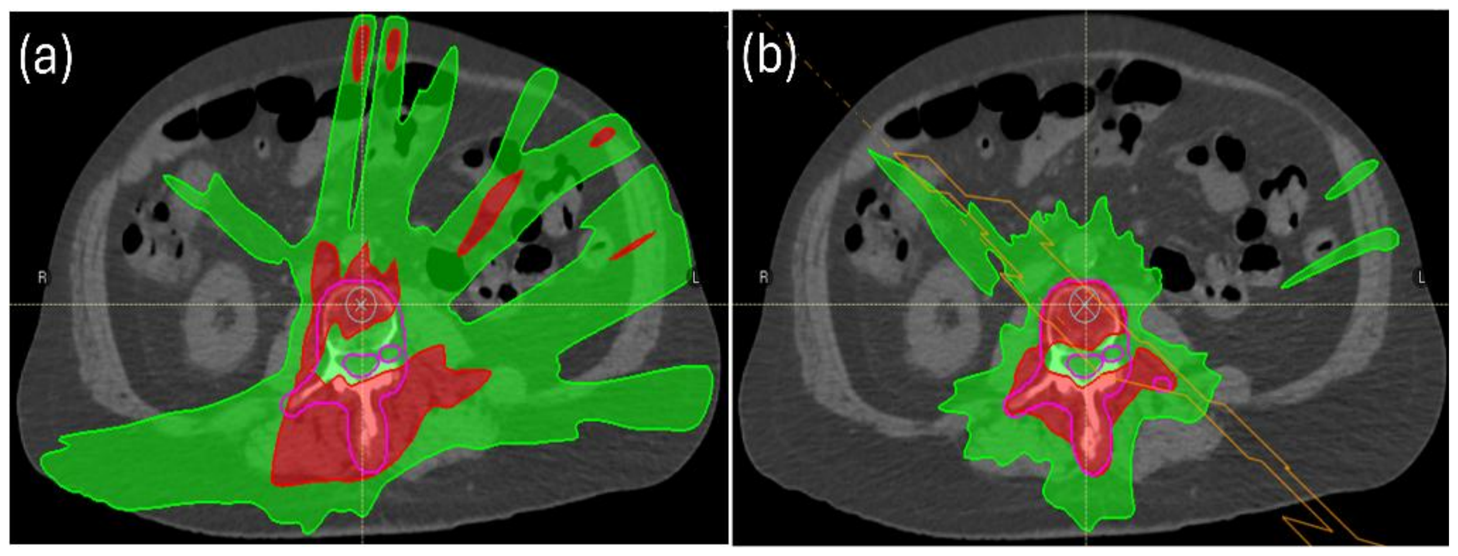

Figure 2. Example spine CyberKnife plan (PTV = 439.92 cm³). (a) Whole-PTV optimization and (b) subregion-based optimization. Green and red contours denote 50% and 100% of the prescription dose, respectively.

- Dose statics are comparable for large enough targets (Figure 3).
  - Equivalent radius defined as $r_{eq} = \left(\frac{3V_{PTV}}{4\pi N_{PTV}}\right)^{1/3}$.
  - Clinical plan (Cone) are doing better for r_{eq} less than 0.8 cm

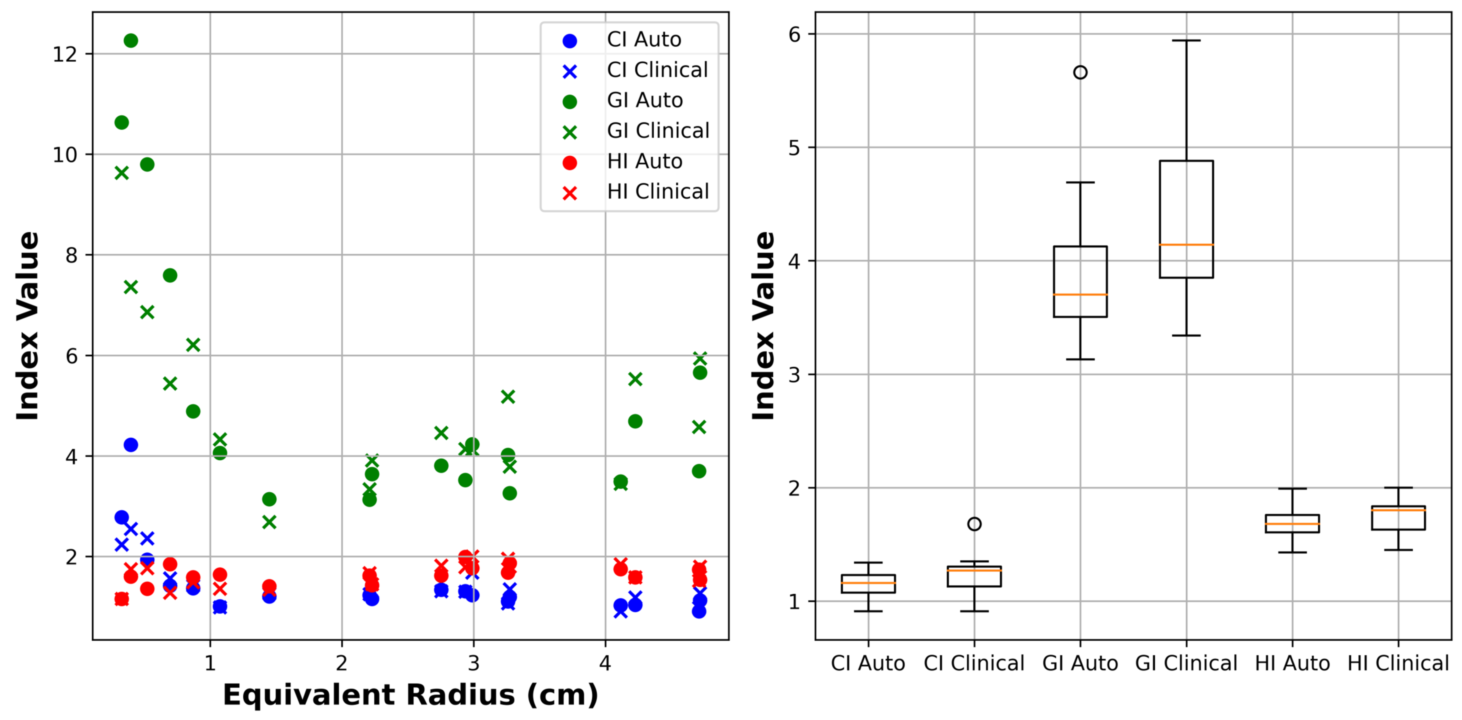

Figure 3. Left: Scatter plot of CI, GI, and HI values for all cases. Right: Box plot of CI, GI, and HI for cases with equivalent radius larger than 0.8 cm.

- All QAs with PTW 1600 pass (Figure 4).
  - 2 mm/2%.

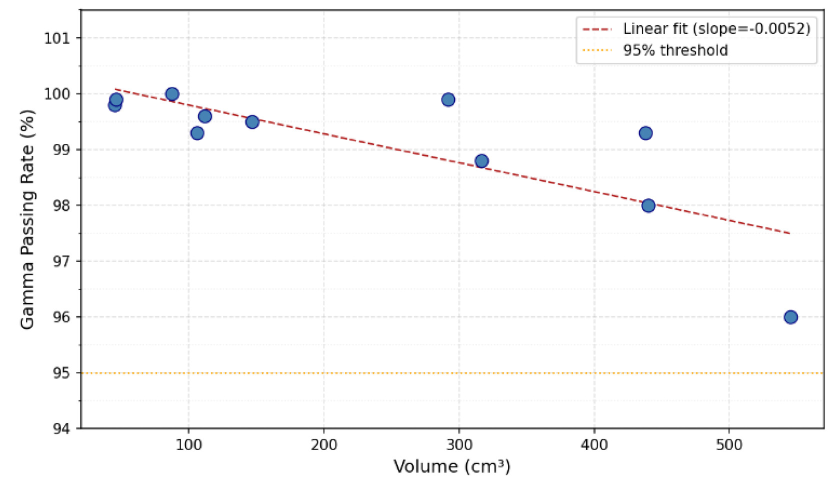

Figure 4. QA passing rates for all auto plans.

Conclusions

- We demonstrated that the RayStation scripting–based automated CyberKnife planning framework reduces planning time significantly while maintaining plan quality, offering a practical approach to improve efficiency and standardize high-quality CyberKnife planning.
- Further study on including more clinical plans is warranted.

References

[1] Kilby, Warren, et al. "A technical overview of the CyberKnife system." Handbook of robotic and image-guided surgery (2026): 221-241.

[2] Hirotaki, Kouta, et al. "Fully automated volumetric modulated arc therapy planning for locally advanced rectal cancer: feasibility and efficiency." Radiation Oncology 18.1 (2023): 147.