High-Quality Proton Dose Generation for Pencil Beam Scanning Via Attention Cyclemamba-Driven Architecture

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Objective:

Intensity-modulated proton therapy (IMPT) with pencil beam scanning (PBS) delivers sequential proton spots as the fundamental delivery unit. By tuning each spot's spatial position, energy level, and fluence intensity, it enables layer-by-layer tumor target dose coverage. Monte Carlo (MC) simulation is the dose calculation gold standard: it accurately replicates proton-tissue interactions and generates high-precision dose distributions, but suffers from low efficiency and long runtime. Mechanistically, dose calculation accuracy depends on ion count per spot (10,000 ions clinical standard); higher counts improve dose quality but linearly extend simulation time, delaying treatment plan design and reducing clinical workflow efficiency. To address this, this study proposes a deep learning approach to enhance dose calculation efficiency.

Methods:

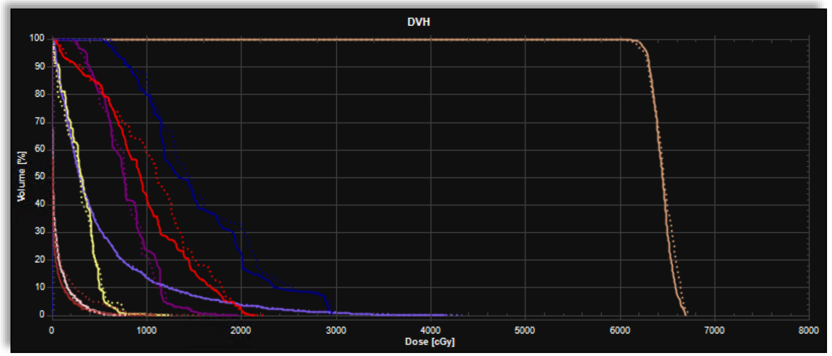
This study proposes a high-precision dose generation strategy based on an Attention-enhanced CycleMamba network. By seamlessly incorporating the gamma pass rate loss function into the network training framework, the strategy efficiently and accurately converts low-precision dose distributions from low-ion-count simulations for individual beam spots into high-precision proton dose distributions that meet the requirements of clinical application.

Results:

Our method efficiently generates high-quality dose distributions (100,000 ions per spot) for a single radiotherapy plan within 45 seconds. Validated via gamma analysis with a 10% dose threshold, the gamma pass rates under the 3 mm/3%, 2 mm/2% and 1 mm/1% criteria reached 99.26%±0.58%, 98.03%±0.64% and 96.21%±1.36%, respectively. Notably, the gamma pass rate still exceeded the 95% clinical threshold even under the stringent 1 mm/1% criterion. Pixel-level dose error analysis further confirmed that the absolute dose error was constrained to 0.51 Gy±0.05 Gy.

Conclusion:

This method enables efficient and accurate enhancement of dose distribution quality for simulations with low ion counts, thereby shortening the time required for clinical treatment plan design.



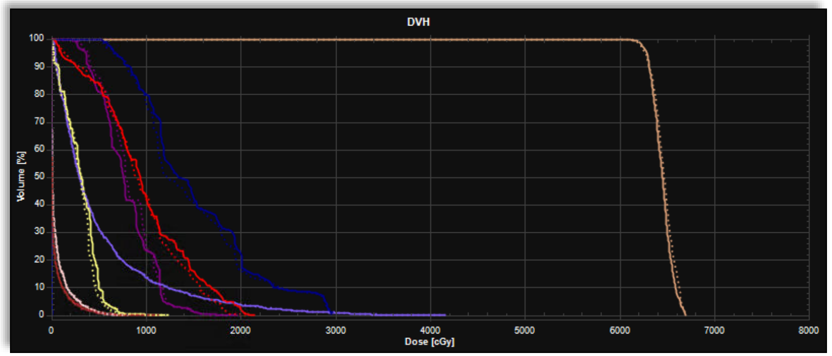


Figure 1: Rapid optimization of dose accuracy for low ion/spot condition

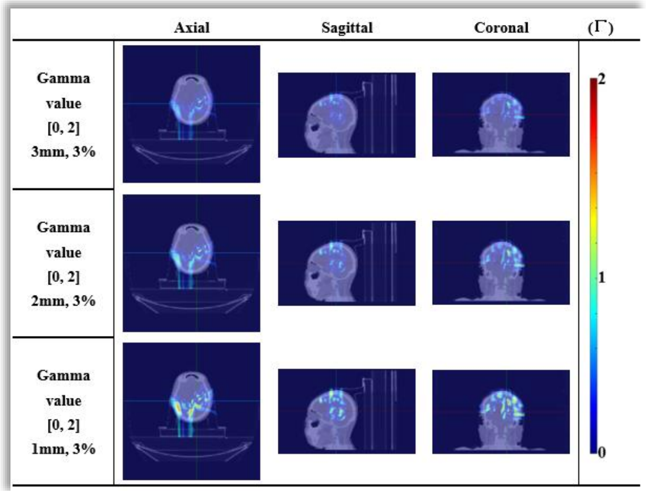


Figure 2: Gamma maps
(under 3mm 3%, 2mm 3%, and 1mm 3% criteria)

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