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Motion-Inclusive Dose Reconstruction for Scanned Pencil Beam Scanning Proton Therapy

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Key Finding: Motion-inclusive dose reconstruction was successfully implemented using finalized clinical PBS proton therapy plans, enabling realistic evaluation of respiratory interplay effects and future investigation of motion-induced changes in dose gradients and modulation.

INTRODUCTION

Respiratory motion can significantly affect dose delivery in thoracic pencil beam scanning (PBS) proton therapy due to the interplay between patient breathing and dynamic spot delivery. **Standard treatment planning often does not account for the actual timing of spot delivery and repainting, potentially masking clinically relevant motion-induced dose deviations.** This project developed a motion-inclusive dose reconstruction workflow that uses finalized clinical treatment plans, beam delivery timing information, and patient-specific 4DCT data to estimate the delivered dose distribution under realistic treatment conditions. The resulting dose can be evaluated using existing clinical software and standard plan assessment tools.

METHODS AND MATERIALS

Data Inputs
- Clinically approved RayStation PBS plans and corresponding patient 4DCT datasets

Delivery Modeling
- Developed a Python-based workflow to estimate spot delivery timing
- Incorporated machine-specific parameters
  - Spot delivery time
  - Spot switching time
  - Energy-layer switching time
- Explicitly modeled repainting delivery when utilized

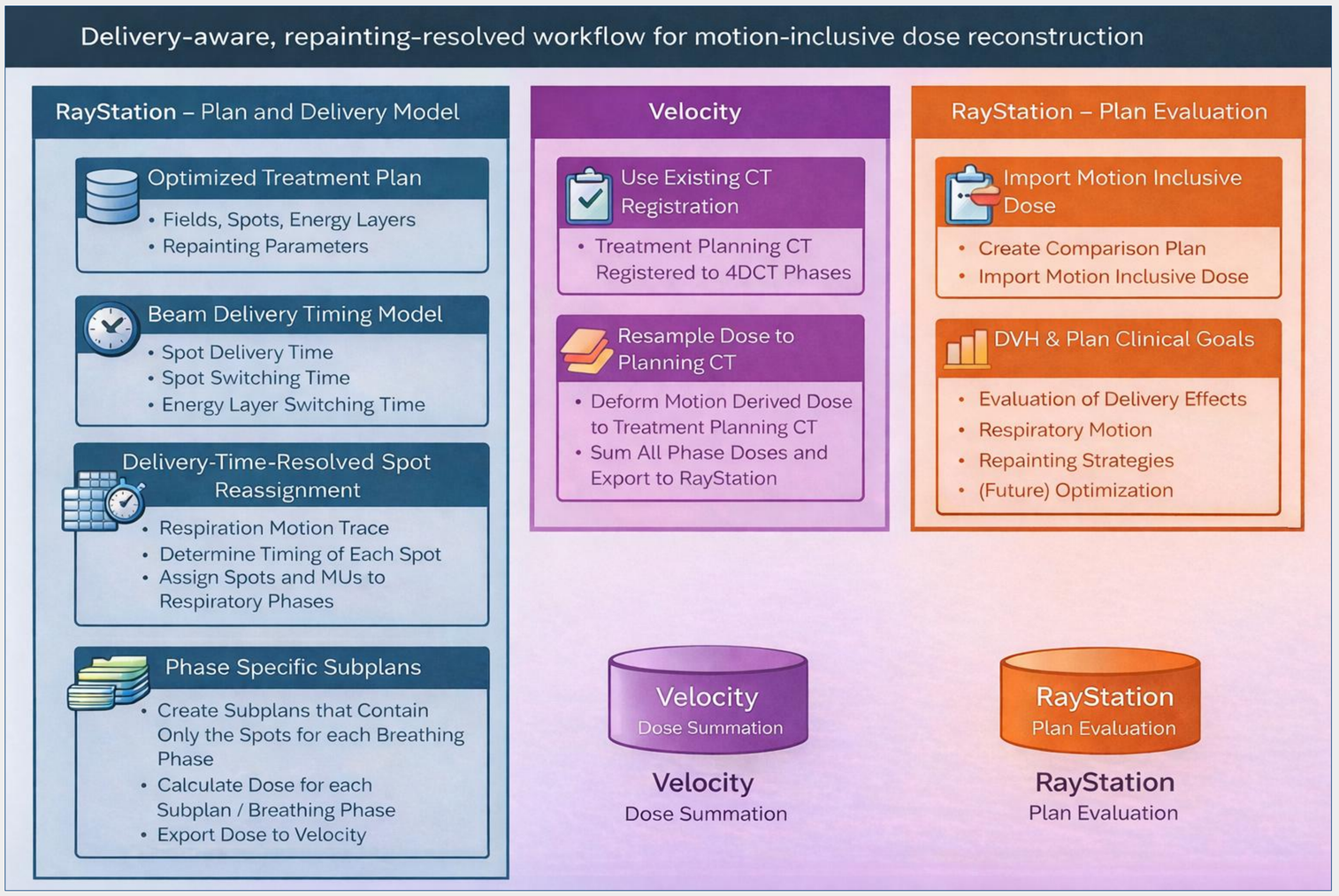
Motion Assignment
- Assigned spots to respiratory phases based on predicted delivery time
- Split monitor units when spot delivery crossed multiple respiratory phases
- Generated respiration phase-specific treatment subplans

Dose Calculation and Reconstruction
- Calculated phase-specific doses on corresponding 4DCT images in RayStation
- phase-specific doses on corresponding 4DCT images in RayStation
- Summed registered doses to generate motion-inclusive delivered dose

Evaluation
- Imported reconstructed dose into RayStation
- Evaluated with DVHs and standard clinical plan objectives

RESULTS

- Successfully reconstructed delivery-consistent, motion-inclusive dose distributions from finalized clinical PBS plans
- Accurately incorporated:
  - Multiple treatment fields
  - Multiple energy layers
  - Repainting strategies
- Robustly tracked spot delivery across respiratory phases
- Generated summed doses compatible with standard RayStation evaluation tools
- Maintained a clinically practical workflow requiring approximately 30 minutes per treatment plan
- Processing time was primarily driven by dose calculation and dose registration/ resampling



CONCLUSIONS

A clinically deployable workflow was developed to reconstruct motion-inclusive dose distributions for PBS proton therapy by explicitly modeling spot delivery timing and repainting from finalized treatment plans. This framework provides a platform for future investigation of the dosimetric impact of respiratory motion on dose gradients, modulation complexity, and treatment plan robustness.