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Experimental Validation of Ultrafast Proton Therapy Using Pin Ridge Filters

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ABSTRACT

Purpose: Pin-ridge filters (pRFs) have emerged as a promising hardware-based approach for ultrafast proton beam delivery through upstream proton fluence modulation. While pRF-based planning techniques having been explored computationally, experimental implementation has been limited by challenges in fabricating patient-specific pRFs and validating the resulting highly modulated dose distributions using conventional quality assurance tools. This study presents a comprehensive end-to-end experimental framework for pRF-based ultrafast proton therapy, with emphasis on practical fabrication and dosimetric verification techniques.

Methods: Patient-specific pRF models for two plans were generated in RayStation using our iterative spot-reduction algorithm adapted to a water-phantom geometry for patient-specific QA (PSQA). The pRFs were fabricated using a large-format fused deposition modeling 3D printer with natural PLA filament. Each pRF was positioned on solid water, and its placement was verified using matched kV-kV imaging prior to irradiation. Absolute dose measurements were acquired using a MatrixxPT ionization chamber array at seven depths, while relative dose distributions were assessed using EBT3 Gafchromic film. Agreement between the planned and measured doses was evaluated using gamma analysis with multiple acceptance criteria.

Results: Across all 30 measured pRF fields, gamma pass rates exceeded 90% for all evaluated criteria. Mean pass rates were 98.29 ± 0.46% (3%/3 mm), 97.39 ± 0.54% (3%/2 mm), and 96.21 ± 0.68% (2%/2 mm). Lower pass rates were observed at distal depths, with an average of 92.5 ± 1.57% for the 3%/2 mm criterion. Film measurements yielded pass rates of 96-99% at mid-range depths and 90-94% near the distal edge, consistent with increased film quenching effects.

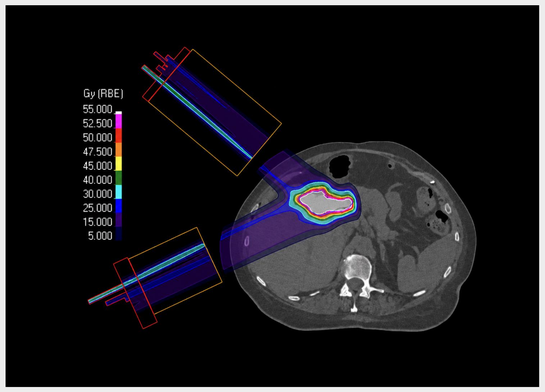
Conclusion: Our end-to-end pRF planning, fabrication, and measurement workflow demonstrates that standard PSQA techniques can be used to verify pRF-based ultrafast proton therapy plans. These results support the feasibility of pre-clinical and clinical translation of pRF-based ultrafast proton therapy using existing clinical PSQA infrastructure.

INTRODUCTION

- Pin ridge filters (pRFs) use variable pin thicknesses, governed by the Ma et al. formalism, to generate spread-out Bragg peak–like dose distributions from monoenergetic proton beams while substantially reducing treatment time compared with conventional IMPT.
- Although pRF-based ultrafast proton therapy has been studied computationally, experimental validation remains limited by challenges in fabrication, setup uncertainty, and selection of appropriate dosimetric validation methods.
- This work develops and evaluates a complete end-to-end workflow for pRF fabrication, patient-specific quality assurance, and dosimetric evaluation.

METHODS AND MATERIALS

- Patient-specific pRFs for two treatment plans were generated in RayStation and transferred to a water-phantom geometry for patient-specific QA.
- The pRFs were fabricated using fused deposition modeling with natural PLA filament, positioned on solid water, and aligned using kV-kV imaging.
- Absolute and relative dose measurements were acquired using MatrixxPT and EBT3 film at seven depths and compared with calculated dose using multiple gamma criteria.



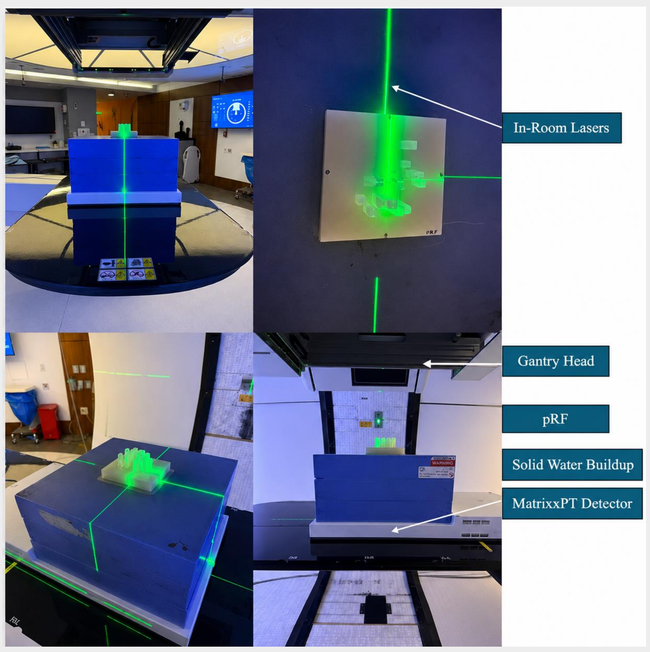


Figure 1: Top: Sample two-beam pRF plan in RayStation. Bottom: Experimental setup with pRF, solid water, and MatrixxPT.

RESULTS

- MatrixxPT measurements showed high agreement at proximal and middle depths, with overall mean gamma passing rates of 98.29 ± 0.46% for 3%/3 mm, 97.39 ± 0.54% for 3%/2 mm, and 96.21 ± 0.68% for 2%/2 mm.
- Both MatrixxPT and EBT3 film demonstrated reduced agreement near the distal edge; the MatrixxPT mean decreased to 90.6 ± 2.0% for 2%/2 mm, while film passing rates decreased from approximately 96%–99% at middle depths to 90%–94% distally.
- More than 85% of MatrixxPT measurements exceeded a 94% passing rate for 3%/2 mm, with no measurements below 90%; the distal reduction was consistent with steep dose gradients, detector-resolution limitations, and film under-response in high-LET regions.

Figure 2: pRF pass rate distributions relative to the most distal measurement plane.

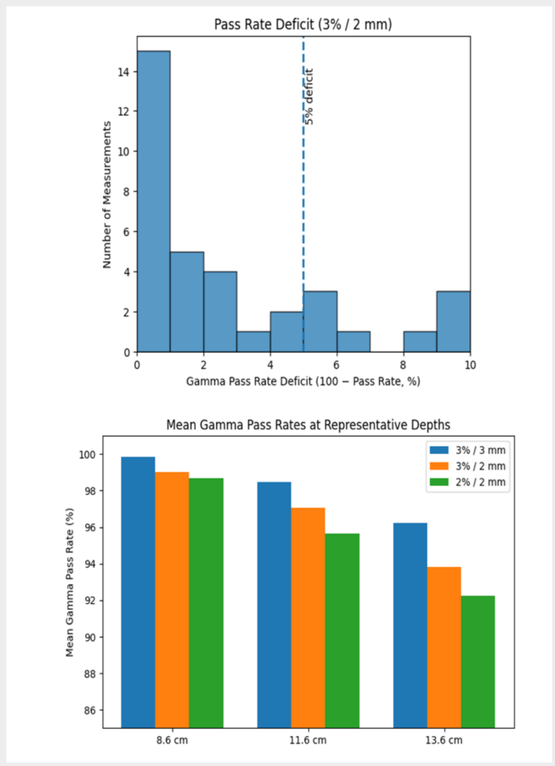


Figure 3: Top: Distribution of gamma pass rate deficit for the 3%/2mm criterion across all measured pRF fields. Bottom: Mean gamma pass rates at three representative depths for all evaluated gamma criteria.

DISCUSSION

- Both patients showed strong overall agreement between planned and measured pRF dose distributions using the MatrixxPT.
- Agreement generally decreased at greater depths, and EBT3 film demonstrated a similar trend near the distal region.
- The depth-dependent reduction is consistent with steep dose gradients, increased range sensitivity, detector-resolution limitations, and LET-dependent film quenching.

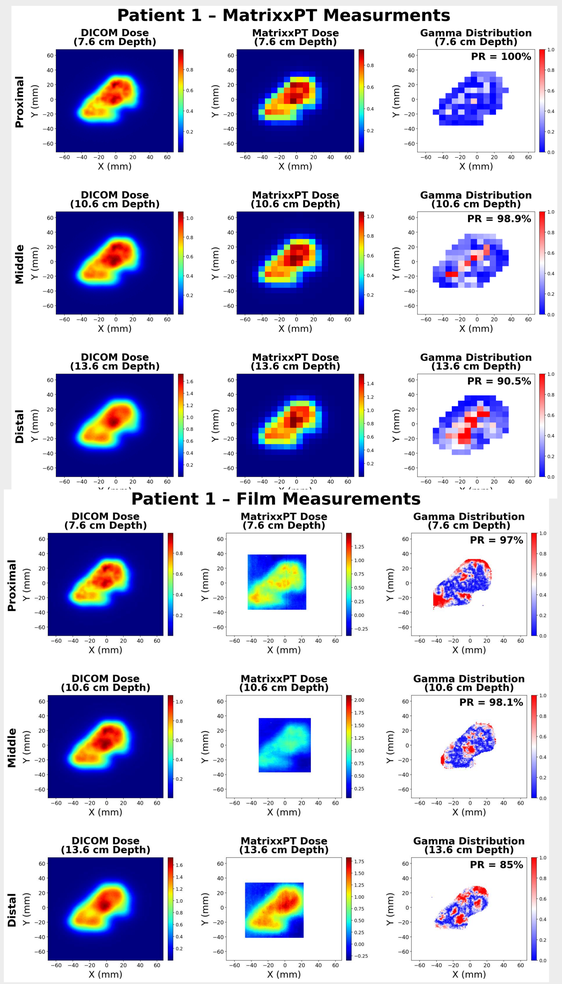


Figure 4: Top: Simulated, MatrixxPT, and gamma distributions for Patient 1. Bottom: Top: Simulated, film, and gamma distributions for Patient 1.

CONCLUSIONS

Patient-specific pRF dose distributions were successfully fabricated, delivered, and verified with high agreement using standard clinical PSQA tools. These results support continued preclinical development and future translation of pRF-based ultrafast proton therapy.

REFERENCES

1. Zafar, A.J., et al., *Ultrafast Proton Delivery with Pin Ridge Filters (pRFs): A Novel Approach for Motion Management in Proton Therapy.* arXiv preprint arXiv:2502.01593, 2025.
2. Ma, C., et al., *Streamlined pin-ridge-filter design for single-energy proton FLASH planning.* Medical Physics, 2024. **51**(4): p. 2955–2966.