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Impact of Machine-Specific Parameters on Proton Beam Delivery Accuracy of Mevion Hyperscanning System: Lessons from One-Year PSQA Failure Analysis and Planning Strategy Refinement

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Abstract

To identify key factors influencing proton beam delivery accuracy with a Mevion Hyperscanning system equipped with Adaptive Aperture, and to address parameters contributing to patient-specific quality assurance (PSQA) failures through planning technique optimization.

Introduction

This study introduces a comprehensive evaluation framework tailored specifically to the Mevion Hyperscanning system, whose energy-layer generation differs fundamentally from conventional cyclotron based proton systems. Unlike large scale proton machines that deliver wide range of fixed energies directly from cyclotron and adjust output using a downstream energy selection system, the Mevion hyperscanning generates single energy ~230 MeV, and each clinical energy is generated by mechanically inserting and retracting energy degrading plates inside the treatment nozzle. This mechanical plate motion system alters beam quality, spot size, and output characteristics in ways unique to Mevion hyperscanning, and these variations directly influence beam delivery accuracy and ultimately PSQA performance.

By incorporating these machine specific physical characteristics—nozzle walkout, snout extension states, and the interaction between energy degradation and spot scanning into the planning evaluation, the study moves beyond standard PSQA analysis performed on traditional machines. This extensive work represents a comprehensive approach that integrates mechanical physics, beam modeling behavior, and optimization strategy, ultimately producing a robust and clinically adaptable framework to minimize PSQA failures on Mevion systems, and preventing patient care delays.

Methods and Materials

We conducted a retrospective review of twelve treatment plans that failed PSQA over a one-year period. Each case was analyzed for common characteristics related to nozzle position, beam computation setting, adaptive aperture, optimization objectives and planning parameters. After identifying contributing factors, we implemented modifications to planning and optimization strategies and tested revised plans to evaluate their impact on PSQA pass rates.

Results

Our results revealed multiple factors, individually or collectively, with effects ranging from moderate to significant. Fully retracted or extended snout position was a major contributor to PSQA failures, it is due to slight nozzle walkout affecting adaptive aperture alignment.

Use of beam-specific maximum dose limits and beam specific uniform dose objectives for multi-field optimization (MFO) plans were also identified as significant factors. Additionally, avoidance structures can introduce uncertainty in collimated beam delivery. Furthermore, static apertures demonstrated slightly higher gamma criteria compared to dynamic apertures, likely due to their design and the trimming of only peripheral spots rather than all spots.

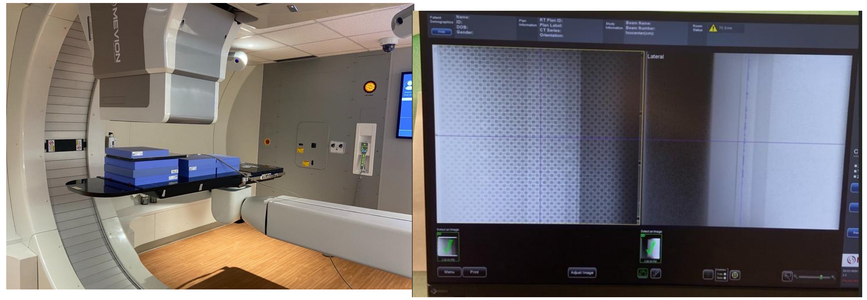

Figure 1 .PSQA setup, and to orthogonal kV images used for alignment.

Conclusions

Systematic evaluation of PSQA failures on the Mevion Hyperscanning system revealed that machine-specific characteristics—such as snout positioning, adaptive aperture, planning objectives and computation setting—play a critical role in proton beam delivery accuracy. Implementing strategic adjustments to planning and optimization maintain beam delivery accuracy and eliminate QA failures. This study emphasizes the importance of incorporating adaptive aperture and refining planning considerations into clinical workflows to enhance treatment reliability and improve delivery accuracy.

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