Temporal Sensitivity of Synchronous Proton Pencil Beam Scanning and Dynamic Collimation

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ABSTRACT

Purpose: Dynamic collimation is emerging as a next-generation energy-specific collimating technology that can drastically improve the lateral and distal conformity of Pencil Beam Scanning (PBS) proton therapy. Current treatment delivery approaches rely on static step-and-shoot techniques. As such, it was the focus of this work to investigate the temporal sensitivity of spot scanning and collimator synchronous sequencing using a sliding window delivery approach to improve treatment efficiency.

Methods: A time-based Monte Carlo treatment delivery model was developed for the Dynamic Collimation System (DCS) to evaluate the sensitivity of a simulated asynchronous delivery between the beam scanning controller and the preprogrammed sequencing DCS trimmer blades. Treatment deliveries were simulated in Geant4, which were modeled using a time series of the beam delivery system and DCS controller that discretizes a composite treatment simulation into fixed time points. Simulation executables were run in a Geant4 model of the DCS, incorporating a sigmoid kinematic model of DCS motion to derive simulation time points from log files obtained from patient-specific quality assurance measurements. Asynchronous deliveries were simulated by systematically offsetting the time series between the beam scanning controller and DCS and evaluating the constancy of the resultant dose distribution using gamma analysis.

Results: Communication delays between the PBS scanning controller and DCS account for 23% of the total treatment delivery time for collimated treatments, improving the treatment efficiency by nearly 22 seconds for each field if omitted. A continuous delivery approach that omitted communication delays exhibited moderated sensitivity to synchronization errors; the average 3%/3mm gamma pass rate for treatment fields simulated with a 100 ms offset was 94.8% (+/- 0.5%).

Conclusions: DCS treatment efficiency may be further improved with a sliding-window delivery technique. However, monitoring the synchronization of these treatments would be necessary to ensure their delivered dosimetric accuracy.

Acknowledgements

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REFERENCES

[1]Hyer et al., Med. Phys., 41(9), 2026
[2]Smith et al., Med. Phys., 64(20), 2019
[3]Vu and Du et al., Cancers, 18(10), 2026

INTRODUCTION

The Dynamic Collimation System (DCS) is a next-generation proton therapy technology that reduces healthy tissue damage by sculpting the lateral penumbra to the target periphery during pencil beam scanning (PBS) using four rapidly sequenced trimmer blades[1]. DCS treatments are currently delivered within a PBS step-and-shoot technique, in which the beam is paused while the trimmers move to their next position[2], incurring costly communication delays, plotted in Figure 1, between the beam scanning controller and the DCS. This work investigates a *sliding-window* delivery technique in which the trimmers are sequenced simultaneously as the beam is delivered. Eliminating these delays could enable faster treatments and spot-specific collimation, but the sensitivity of plan quality to synchronization errors remains unknown.

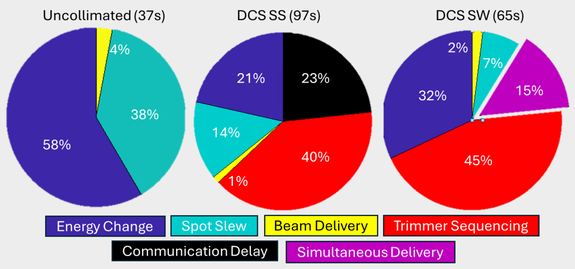

Figure 1: Treatment delivery charts showing the portion of time required for different components of treatment delivery. Plots shown for the conventional uncollimated treatment, DCS-collimated step and shoot (SS) and sliding window (SW) techniques.

METHODS AND MATERIALS

- A previously benchmarked Geant4 Monte Carlo model of the DCS was used to simulate three experimentally validated DCS-collimated IMPT treatment fields[3].
- A temporal simulation framework reconstructed each delivery from machine log files, discretizing it into fixed time points (Figure 2).
- The original step-and-shoot delivery was converted to a continuous sliding-window delivery by removing the communication delay window and synchronizing trimmer motion with each spot group.
- Asynchronous deliveries were then simulated by systematically offsetting the beam scanning and trimmer timelines.
- Simulated patient-specific QA dose profiles were compared against the nominal delivery by gamma analysis (3%/3 mm, 10% low-dose threshold).

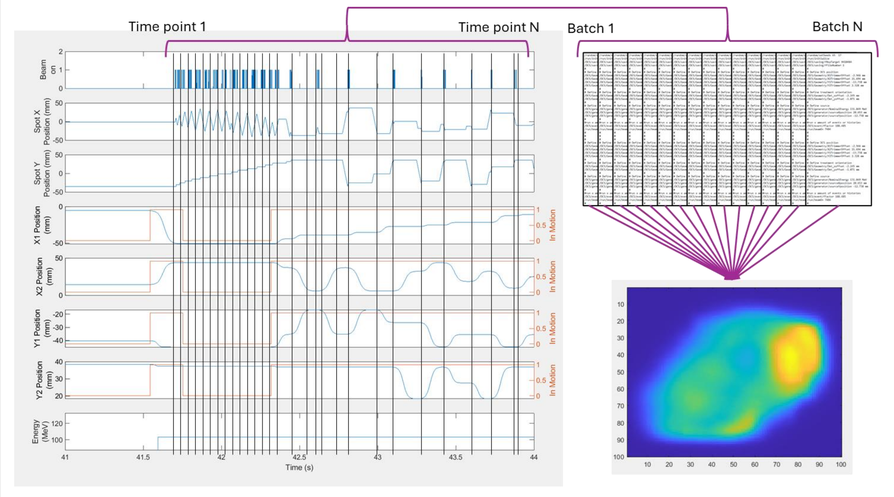

Figure 1: Temporal simulation architecture for DCS treatment simulations. Dynamic modeling of the beamline and DCS collimator kinematics are used to discretize simulation timepoints into "snapshots" of the system geometry when the beam is being delivered.

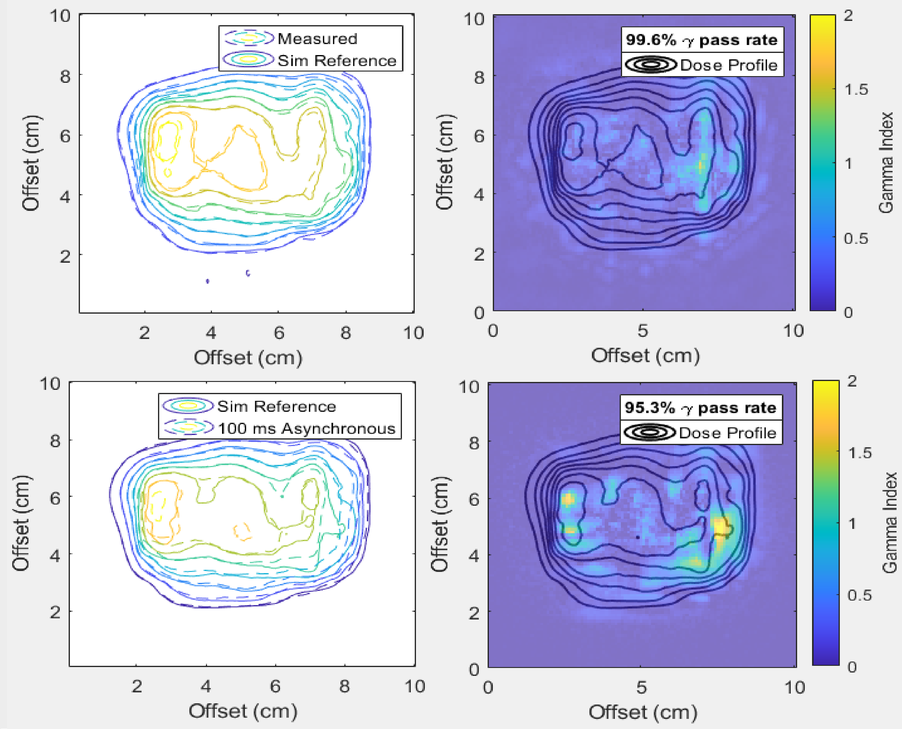

Figure 3:(Top Row) Simulated and Matrixx-measured DCS dose profiles obtained at the Miami Cancer Institute are shown for a single treatment field. (Bottom Row) Comparison of dose distributions delivered by incorporating a 100 ms offset within the temporal Monte Carlo model. Gamma pass rates are shown for 3%/3mm criteria and 10% low-dose threshold. Dosimetric failures are localized near regions where many spots are delivered within a short window of collimator sequencing.

RESULTS

- The temporal model was baselined against measured IMPT dose profiles for each field, achieving a minimum gamma pass rate of 99.5% (Figure 3, top row).
- Systematic asynchronization offsets of up to 200 ms were then simulated for the sliding-window delivery and compared against their respective synchronous baselines using the same clinical gamma criteria.
- The average pass rate fell from 99.1% at a 75 ms offset to 94.8% at 100 ms, and below 58% beyond 200 ms (Figure 4); a representative field delivered with a 100 ms error is shown in the bottom row of Figure 3.
- Removing the beam-DCS communication delay accounted for 23% of the total delivery time — an improvement of nearly 32 seconds per field (Figure 1)
- The sliding-window technique is susceptible to temporal error: synchronization must be maintained within roughly 100 ms to keep dosimetric accuracy inside the PSQA tolerance.

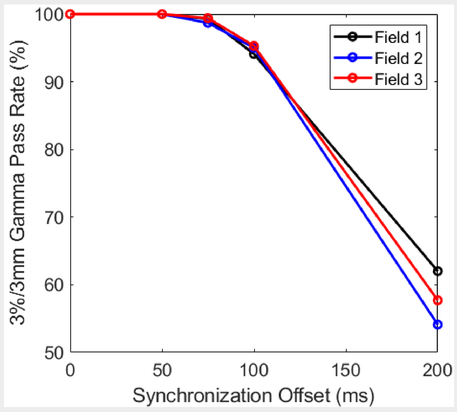

Figure 4: Gamma pass rates for three treatment fields as the synchronization error between the DCS and beam scanning controller is increased.

DISCUSSION

Dosimetric failures are localized to regions where large numbers of spots were delivered within a short window of trimmer movement (Figure 3). The current step-and-shoot grouping algorithm, which optimizes transition time, often places large groups of otherwise-uncollimated spots within a single large collimator opening, making these regions more sensitive to temporal errors. Distributing spots equally among collimator positions could reduce this sensitivity.

Synchronization errors may be further mitigated using interventional quality controls. For example, a real-time feedback module within the DCS could independently validate trimmer positioning and ensure treatment is delivered within a specified synchronization window.

CONCLUSIONS

This work presents the first temporal Monte Carlo framework capable of evaluating synchronization sensitivity for DCS-collimated PBS treatments, enabling direct simulation of a novel collimated PBS sliding-window delivery technique to improve treatment efficiency over conventional step-and-shoot methods. Dosimetric accuracy was retained for treatment deliveries subjected to synchronization errors up to 100 ms. Future work will investigate interventional approaches that can improve delivery synchronizations using real-time monitoring systems.

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