Linear Energy Transfer Distributions In Dose-Optimized Pencil Beam Scanning Proton Therapy, Delivered Using a Dynamic Collimation System

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ABSTRACT

Introduction: Dose-optimized proton pencil beam scanning (PBS) treatments collimated with the Dynamic Collimation System (DCS) can reduce healthy-tissue dose, but their effects on linear energy transfer (LET) are not well understood.

Methods: Three intracranial, three-field IMPT plans were simulated in a custom Geant4 Monte Carlo framework to compare dose and dose-averaged LET (DLET) between DCS-collimated and uncollimated plans.

Results: All Monte Carlo dose comparisons achieved gamma pass rates above 94%. DCS reduced the mean dose in the 10-mm PTV ring by 20.3% ± 5% but increased mean DLET by 9.1% ± 5%, while OAR DLET changes varied by structure.

Conclusion: The reduction in dose to target-adjacent healthy tissue does not necessarily correspond to LET reduction when comparing dose-optimized DCS-based PBS treatment plans with dose-optimized uncollimated plans. This motivates the need for LET-aware evaluation and optimization of DCS treatment plans.

REFERENCES

1 Hyer et al., Med. Phys., 41(9), 2014
2 Smith et al., App. Clin. Med. Phys., 26(1), 2025
3 Bennett et al., Med. Phys., 50(11), 2023

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INTRODUCTION

The Dynamic Collimation System (DCS; Fig. 1) was developed for lateral penumbra reduction in low-energy pencil beam scanning (PBS) proton therapy[1]. It uses orthogonal collimation trimmers to intercept individually scanned proton beam spots near the target periphery.

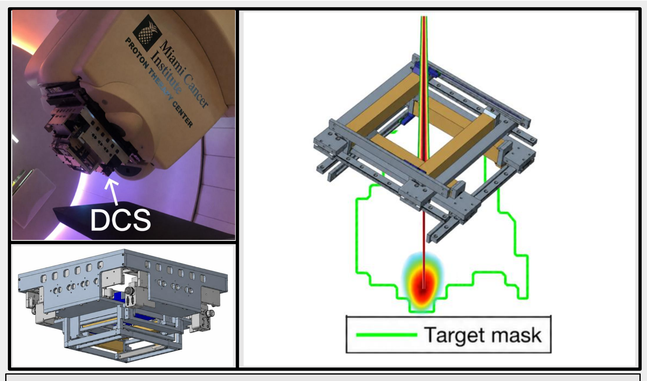

Figure 1: Multi-pane image of DCS architecture. Right pane illustrates per-spot collimation functionality of the DCS

Clinical goal of DCS: improve healthy tissue sparing while preserving target coverage

1. Risk of critical organ damage increases with larger lateral dosimetric penumbra in PBS.
   - DCS reduces mean dose to healthy tissue by 20% within 10 mm of target boundary
2. Risk of critical organ damage increases with elevated dose-averaged linear energy transfer (dLET) in proton therapy
   - Beamlets collimated with the DCS show an accentuated dLET distribution and a sharper, more compact beamlet dose profile[2] (Fig. 2)

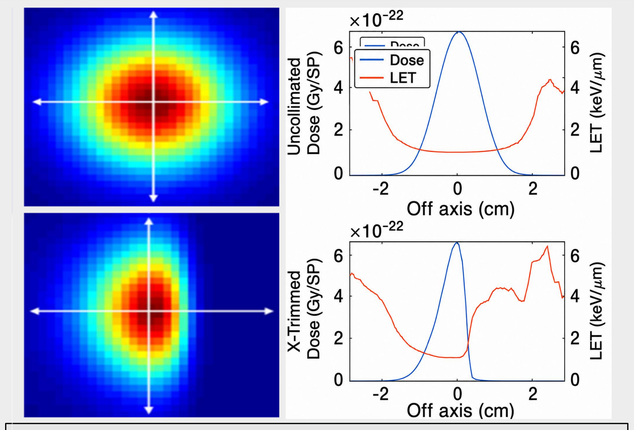

Figure 2: The spot dose distributions for an uncollimated (top left) and collimated (bottom left) beamlet. Corresponding lateral dLET (orange) and dose (blue) profiles are shown adjacent to each distribution map.

OBJECTIVE

The purpose of this study was to evaluate the dLET distributions from a subset of clinically representative, dose-optimized DCS plans. The DCS is currently a preclinical research prototype being prepared for clinical use. Although the DCS has shown dosimetric benefit, the LET distributions that are produced during active collimation are an active area of interest given the biological implications of high LET radiation.

METHOD AND MATERIALS

- 3 intracranial patients planned for an uncollimated & DCS-collimated delivery
- Spot weight optimization and initial dose calculation performed using the Astroid TPS[3]
- HybridTrim, a DCS-specific optimization framework was used to perform additional trimmer aware optimization in DCS plans
- Dose and LET simulated in Geant4 Monte Carlo (MC) for each treatment plan

- Physics modules:
  - EM opt4, QGSP_BIC_HP, HP elastic, ion binary cascade, stopping, decay.
- 3-mm dose and unrestricted dLET grid
- MC simulation error ≤2% to voxels within 5% low-dose threshold of plan
- MC dose validated against TPS with 3%/3-mm gamma; 5% low dose threshold of MC dose
  - 94.5% minimum gamma pass rate across plans

RESULTS

Compared DCS MC vs. uncollimated MC among dose & dLET differences (Fig. 3)

-Healthy tissue within 10 mm of target:

- mean dose decreased over 13%; (Table 1)
- dLET90 avg. increase: 1.16 (±0.60) keV/μm

- Changes within Target dLET:
  - dLET90 avg. increase: 0.08 (±0.05) keV/μm

	Rind 10mm		Target
Pt.#	Δ mean dose (Gy) (DCS – No DCS)	Δ dLET90 (keV/μm) (DCS – No DCS)	Δ dLET90 (keV/μm) (DCS – No DCS)
P1	−6.31 (−13.9%)	+0.63 (+14.0%)	+0.13 (+13.4%)
P2	−12.5 (−26.3%)	+1.82 (+35.7%)	+0.08 (+8.9%)
P3	−12.1 (−24.7%)	+1.08 (+22.0%)	+0.04 (+3.9%)

Table 1: Mean Dose and dLET differences to the target and to the healthy tissue 10 mm from target boundary (Rind10mm) .

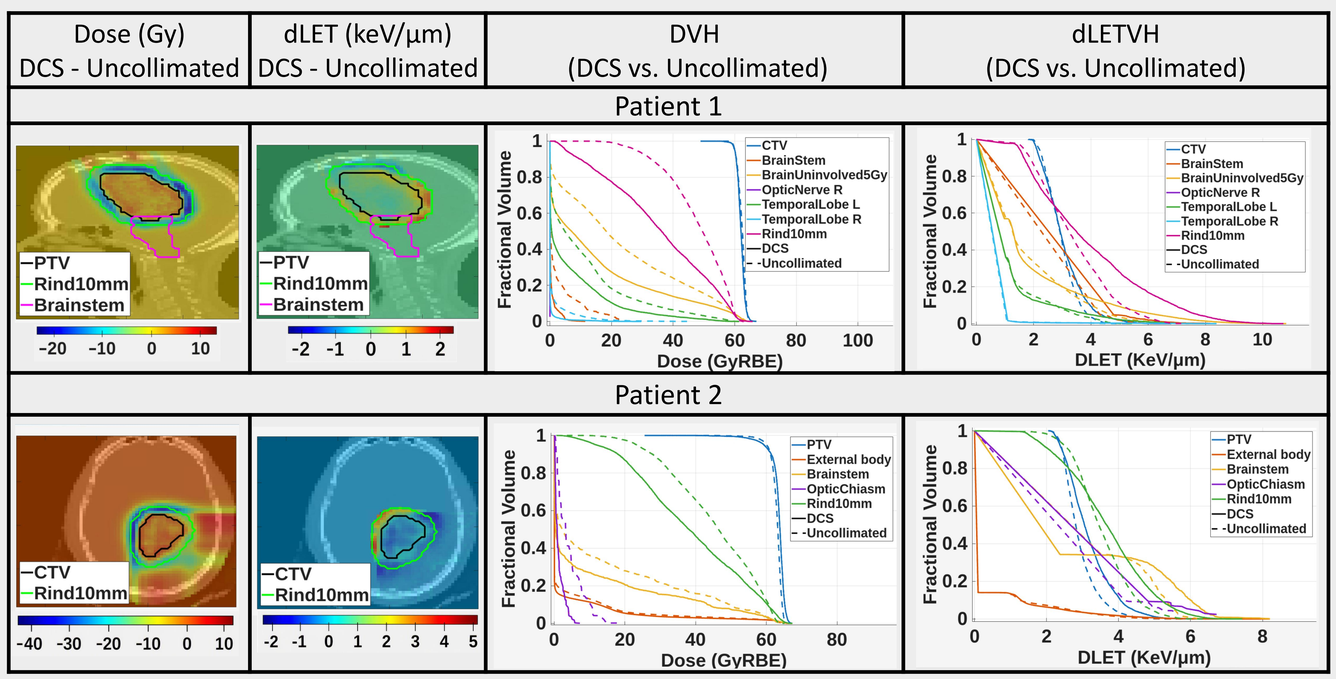

Figure 3: Dose difference plots, dose-average LET (dLET) difference plots, dose-volume histograms (DVH), and dose-average LET volume histograms (dLETVH) for two dose-optimized uncollimated and DCS-collimated IMPT treatment plans.

CONCLUSION

Dose-optimized treatment plans utilizing the DCS exhibit an accentuated LET environment compared to those that were uncollimated. Our simulation results indicate that dose-optimized DCS treatments result in an average increase to the dLET90 of 0.1 keV/μm within the target and 1.2 keV/μm to the adjacent healthy tissue. The biological impact and potential of this effect remains to be exploited; in addition to the dose distribution, this work as also showed the potential of the DCS to shape the dLET distribution to steer high LET further within the target while providing enhanced sparing to LET-sensitive critical-organ volumes.

DISCUSSION & INNOVATION

- This study presents the first framework to simulate dose and LET from the DCS during energy-specific collimation in PBS.

- The results and the tools from this study motivate and serve as a necessary step to enable DCS-specific LET-informed optimization, respectively.

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