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Design and Optimization of a Novel Translating Checkerboard Range Shifter to Enable Efficient Proton Arc Therapy

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ABSTRACT

Purpose: Dynamic proton arc therapy has the potential to improve dose conformality and delivery efficiency but remains limited by accelerator energy-layer switches during continuous gantry rotation. This study presents a translating Checkerboard Range Shifter (CRS) that mechanically generates three additional effective proton energy layers from a single accelerator-selected energy, reducing accelerator switching.

Methods: A nozzle-mounted CRS containing four polycarbonate Treatment Areas dynamically translates in two dimensions using fixed cardinal-direction steps. The first Treatment Area preserves the nominal accelerator-selected energy, whereas the remaining three generate progressively lower effective energy layers. Ninety-four clinically delivered discrete (step-and-shoot) proton arc treatment plans from an external institution were retrospectively analyzed. Patient-specific DICOM spot coordinates and energy layers were used by an in-house path-finding optimization algorithm to determine the CRS translation pathway that minimized movement time while ensuring complete proton spot capture. Treatment Area sizes from 3 × 3 to 6 × 6 cm² and translation step sizes from 2 to 6 cm were evaluated. Optimal polycarbonate thicknesses will be determined from average energy differences between consecutive energy layers.

Results: Interim analysis of the first 34 treatment plans demonstrated that a 5 × 5 cm² Treatment Area with a 6 cm translation step produced the shortest average CRS movement time per treatment (20.29 ± 6.64 s), whereas a 3 × 3 cm² Treatment Area with a 5 cm translation step produced the longest (38.85 ± 12.49 s). Larger Treatment Areas and step sizes were associated with shorter average CRS movement times.

Conclusion: The proposed CRS reduces accelerator energy-layer switching during dynamic proton arc therapy. Completion of the 94-plan analysis will establish the optimal CRS geometry and polycarbonate thicknesses for prototype development, patient-specific dosimetric validation, and clinical translation.

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INTRODUCTION

Dynamic proton arc therapy has the potential to improve dose conformality, treatment robustness, and delivery efficiency compared with conventional intensity-modulated proton therapy (IMPT). However, its widespread clinical implementation is limited by the large number of accelerator energy-layer switches required during continuous gantry rotation, which interrupt beam delivery and prolong treatment.

The Checkerboard Range Shifter (CRS) is a novel nozzle-mounted device designed to reduce accelerator energy-layer switching by mechanically generating three additional effective proton energy layers from a single accelerator-selected energy. The CRS dynamically translates in two dimensions during treatment, allowing multiple effective energy layers to be delivered without repeated accelerator energy changes.

This study retrospectively analyzes clinically delivered discrete (step-and-shoot) proton arc treatment plans to optimize the CRS geometry and design, identifying the Treatment Area (defined as the area of permissible spot capture) dimensions and translation step size that minimize CRS movement time while ensuring complete proton spot capture.

METHODS AND MATERIALS

CRS Design: A translating Checkerboard Range Shifter (CRS) containing four polycarbonate Treatment Areas was designed to mechanically generate one nominal and three additional effective proton energy layers. Treatment Areas were separated by a 2-cm no-fly zone to prevent proton spots from intersecting adjacent polycarbonate thickness boundaries during CRS translation. During treatment, the CRS dynamically translates in two dimensions using fixed cardinal-direction steps (N,S,E,W).

Retrospective Analysis: Ninety-four clinically delivered discrete (step-and-shoot) proton arc treatment plans from an external institution were retrospectively analyzed. Patient-specific DICOM spot coordinates and energy-layer information were extracted for optimization.

Path-Finding Optimization: Proton energy layers were grouped into four-layer bins and assigned Q1–Q4 labels. An in-house path finding optimization algorithm determined the CRS translation pathway minimizing movement time while ensuring all proton spots were captured, appropriately. Treatment Area sizes from 3 × 3 to 6 × 6 cm² and translation step sizes from 2 to 6 cm were evaluated assuming 500 ms CRS motion per step.

CRS Thickness Optimization: Average energy differences between Q1–Q2, Q2–Q3, and Q3–Q4 across the retrospective patient cohort will be converted to water-equivalent and corresponding polycarbonate thicknesses to determine the final CRS design.

RESULTS

Interim analysis of the first 34 clinically delivered proton arc treatment plans identified the **5 × 5 cm²** Treatment Area with a **6 cm translation step** as the optimal CRS configuration, producing the shortest average, per treatment, CRS movement time (**20.29 ± 6.64 s**). The 6 × 6 cm² Treatment Area with a 6 cm translation step produced the second-shortest movement time (24.41 ± 9.10 s), whereas the 3 × 3 cm² Treatment Area with a 5 cm translation step was the least efficient configuration (38.85 ± 12.49 s). Overall, larger Treatment Area and translation step sizes were associated with shorter average CRS movement times, suggesting they more effectively capture the clustered proton spot distributions characteristic of clinically delivered proton arc therapy while reducing the mechanical translation required during treatment delivery.

DISCUSSION

This interim analysis demonstrates the feasibility of a translating Checkerboard Range Shifter to reduce reliance on accelerator energy-layer switching during dynamic proton arc therapy. Larger Treatment Areas and translation step sizes consistently reduced CRS movement time, illustrating the trade-off between mechanical efficiency and geometric flexibility. Because the optimization was performed using clinically delivered patient treatment plans, these findings provide a practical framework for selecting CRS design parameters that balance delivery efficiency with complete proton spot coverage. Reducing accelerator energy-layer switching has the potential to improve delivery efficiency while preserving continuous gantry rotation, supporting the future implementation of dynamic proton arc therapy. Completion of the full 94-patient cohort will enable optimization of the CRS geometry and polycarbonate thicknesses using clinically representative energy-layer distributions. Future work includes prototype fabrication, experimental validation, patient-specific dosimetric evaluation, and integration with optimized energy-layer sequencing to assess the clinical feasibility of the proposed system.

CONCLUSIONS

A translating Checkerboard Range Shifter offers a practical approach to reducing accelerator energy-layer switching during dynamic proton arc therapy while maintaining complete proton spot coverage. Interim results demonstrate the feasibility of the proposed concept and identify favorable design parameters for efficient mechanical translation. Ongoing analysis of the complete 94-patient cohort will guide prototype development and subsequent dosimetric and experimental validation toward clinical implementation.

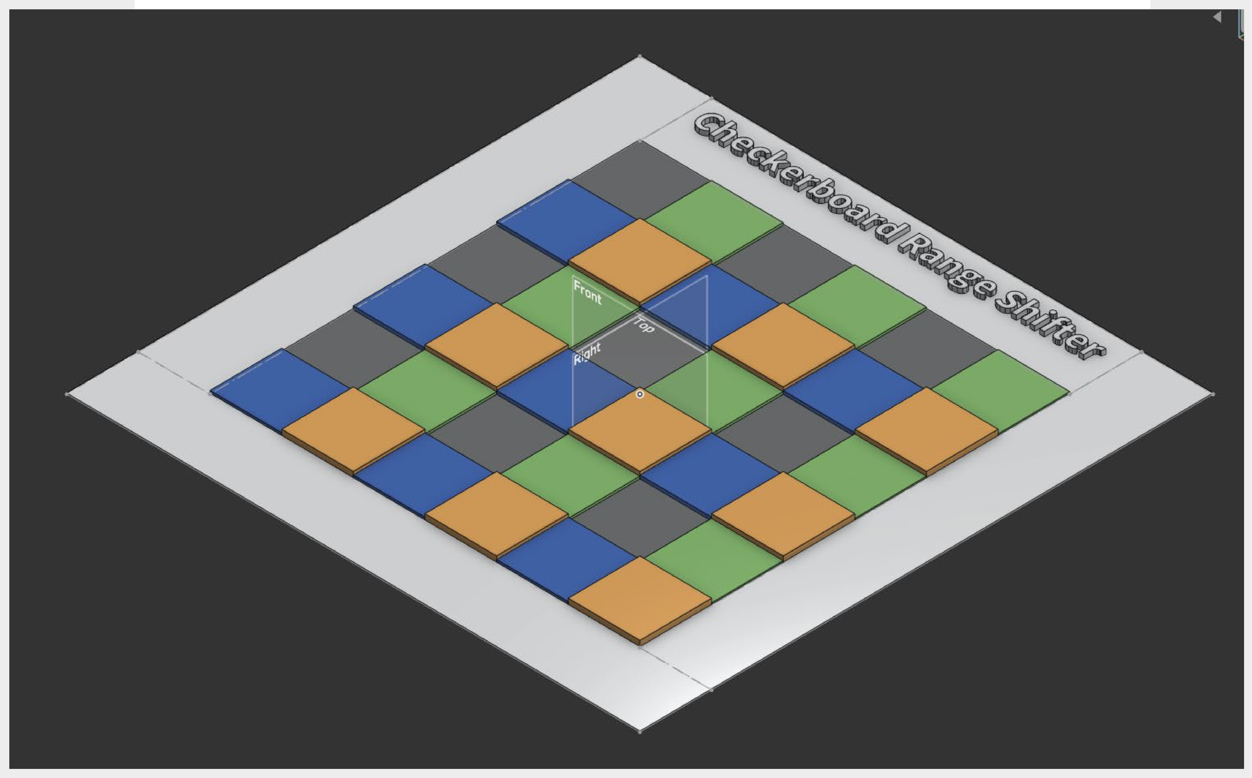

Figure 1. 3D model of the nozzle-mounted translated CRS, with treatment areas color-coded by polycarbonate thickness to generate the four effective energy layers (Q1-Q4) for proton spot delivery

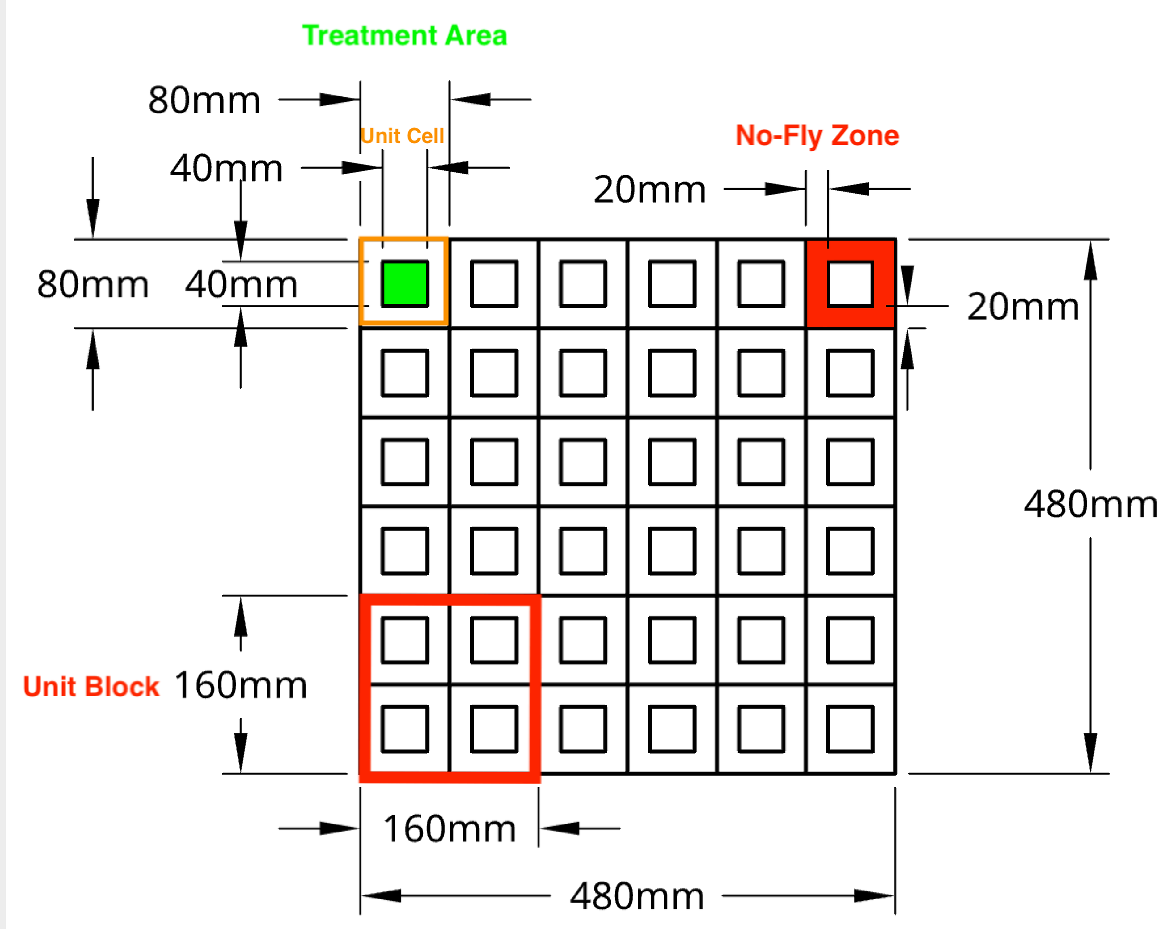

Figure 2. Cross-sectional view of the CRS showing repeating four-cell unit blocks (treatment areas/green) with varying polycarbonate thicknesses (orange) that define treatment areas and the no-fly zone (red-shaded). A 4x4 cm² treatment area is shown here for concept.

Treatment Area (cm²)	Step Size (cm)	Mean Total Steps	Mean Travel Distance (mm)	Mean Empty Steps	Mean Turns	Mean Total Spots Captured	Mean Board Movement Time (s)	Mean Optimization Time (s)
3 × 3	2	764.30	15285.00	74.30	297.70	4161.59	38.21	2436.38
3 × 3	3	731.10	21934.00	39.50	388.10	5013.09	36.56	2089.08
3 × 3	4	761.50	30459.00	76.50	364.60	4454.79	38.07	2272.06
3 × 3	5	777.00	38849.00	99.30	401.60	3978.94	38.85	2054.93
3 × 3	6	762.80	45769.00	75.50	440.40	4289.68	38.14	1985.47
4 × 4	2	757.00	15139.00	82.10	225.20	4418.97	38.11	2127.37
4 × 4	3	712.50	21375.00	45.80	314.40	5222.03	35.71	1910.53
4 × 4	4	683.40	27338.00	32.50	263.50	5587.21	34.17	1495.46
4 × 4	5	750.50	37525.00	78.40	380.60	4943.32	37.53	1859.71
4 × 4	6	704.20	42254.00	39.00	369.20	5286.09	35.21	1716.44
5 × 5	2	753.00	15060.00	103.30	193.70	4486.53	37.65	1998.91
5 × 5	3	710.60	21319.00	55.90	301.50	5192.18	35.53	1830.24
5 × 5	4	652.70	26108.00	36.20	320.70	5486.21	32.64	1513.90
5 × 5	5	571.40	28569.00	16.60	265.00	5589.53	28.57	1002.60
5 × 5	**6**	**405.90**	**24351.00**	**44.30**	**193.60**	**3886.53**	**20.29**	**582.88**
6 × 6	2	748.70	14973.00	123.90	171.90	4351.52	37.43	1720.85
6 × 6	3	688.90	20666.00	61.80	235.20	5105.12	34.44	1575.11
6 × 6	4	641.10	25645.00	42.10	281.70	5263.76	32.06	1389.12
6 × 6	5	608.30	30414.00	28.80	229.00	5379.97	30.41	1063.67
6 × 6	6	488.20	29295.00	12.10	235.10	5380.82	24.41	521.21

Table 1. Mean CRS motion and optimization parameters for each treatment area and step size combination. Values represent the average across all patient treatment plans (n=34).