# Develop a novel non-coplanar trajectory optimization algorithm for an efficient 4pi Spot-scanning Proton Arc (SPArc-4pi) treatment delivery

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## Abstract

This study aims to develop the first 4pi dynamic proton arc optimization algorithm which searches for efficient arc trajectories in 4pi space, explores the potential dosimetric improvements in multiple disease sites. Then we demonstrate its feasibility through simulation using a clinical proton therapy system.

## Introduction

The degree of freedom has been recognized as a key factor in particle beam therapy, such as improving the dose conformity and linear energy transfer distributions. Therefore, proton arc therapy has drawn significant interest in the Society of Radiation Oncology as a potentially efficient and optimal treatment option for cancer patients. However, state-of-the-art spot-scanning proton arc therapy (SPArc) still relies on single or dual- co-planar arc trajectories, which limits its capacity to advance the treatment outcome further. There is an urgent need to explore particle beam therapy's full potential via 4pi. This work presents the very first evaluation of 4pi proton arc algorithm under simulation scenario, showing the potential of further improving plan quality with non-coplanar arc while achieving non-inferior delivery efficiency.

## Methods and Materials

Dynamic Programming, originally from control theory, was translated into this new concept of the 4π SPArc optimization algorithm ($SPArc_{-4pi}$) for the trajectory search and route decision-making. It breaks down the complicated and high-computational-demand main problem into a series of small sub-problems and searches for delivery-efficient 4pi arc trajectories through an iterative approach. Three different disease sites, e.g., head & neck, partial brain, and clival brain chordoma, were used for testing purposes. Conventional Intensity Modulated Proton Therapy (IMPT) and 2D co-planar arc ($SPArc_{-2d}$) plans were generated as a benchmark. Treatment delivery efficiency was evaluated through a published and validated dynamic arc system controller. Plan quality was assessed through target coverage and organ at risk (OAR) sparing.

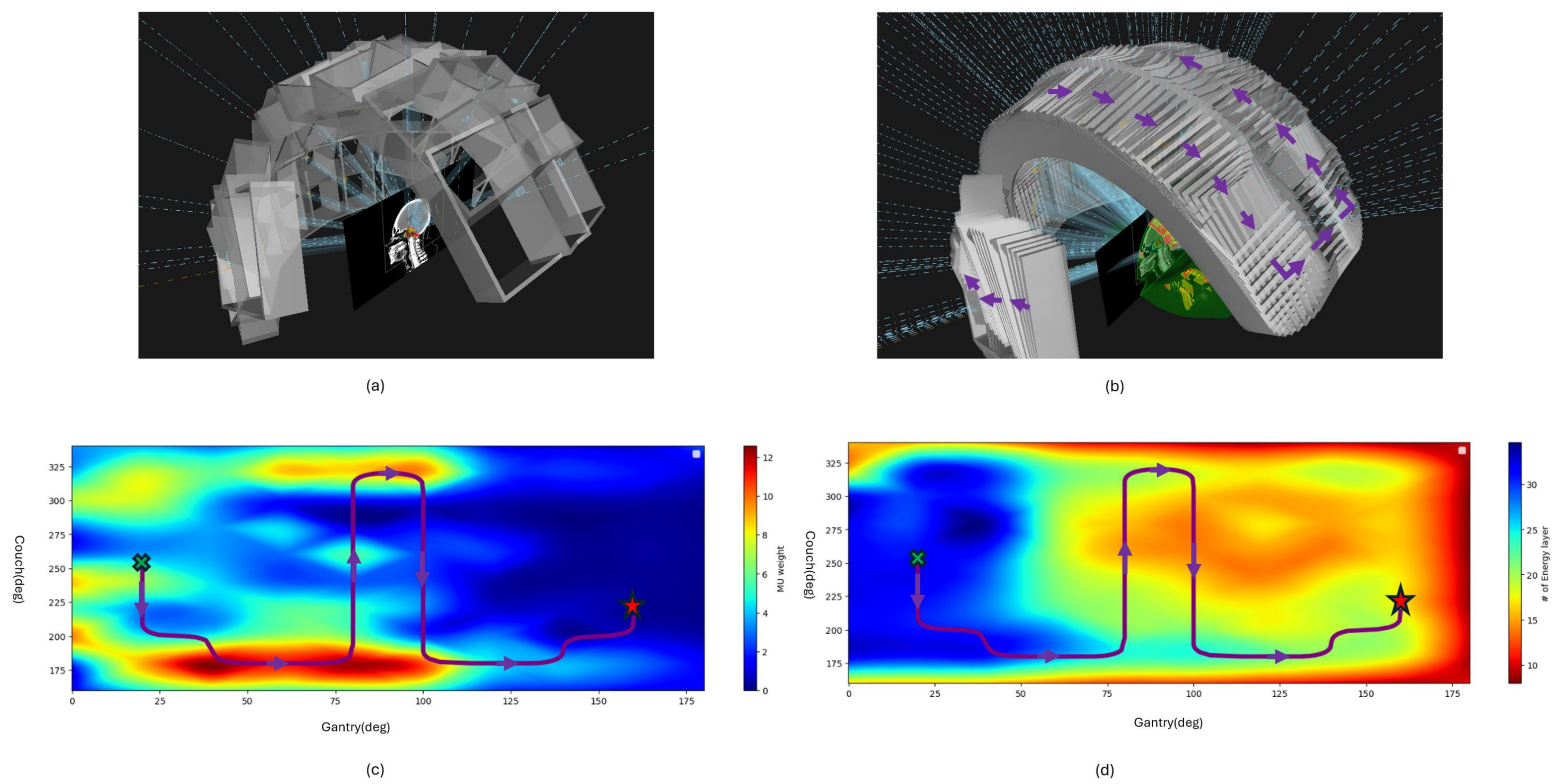


Figure 1. Trajectory search result of DP-optimization after resampled for chordoma cancer as an example. (a) is initial control point placement, (b) is resampled $SPArc_{-4pi}$ control point placement, (c) is the heatmap of weighting for initial control points, (d) is the heatmap of energy layer number for initial control points. The purple line is $SPArc_{-4pi}$ gantry and couch track.

## Results

The new $SPArc_{-4pi}$ demonstrated superior dosimetric performance across various evaluation metrics for all three disease sites. The simulation result shows that $SPArc_{-4pi}$ is able to be delivered within a reasonable time of around 5 to 11 mins, which is comparable to the $SPArc_{-2d}$ plans.

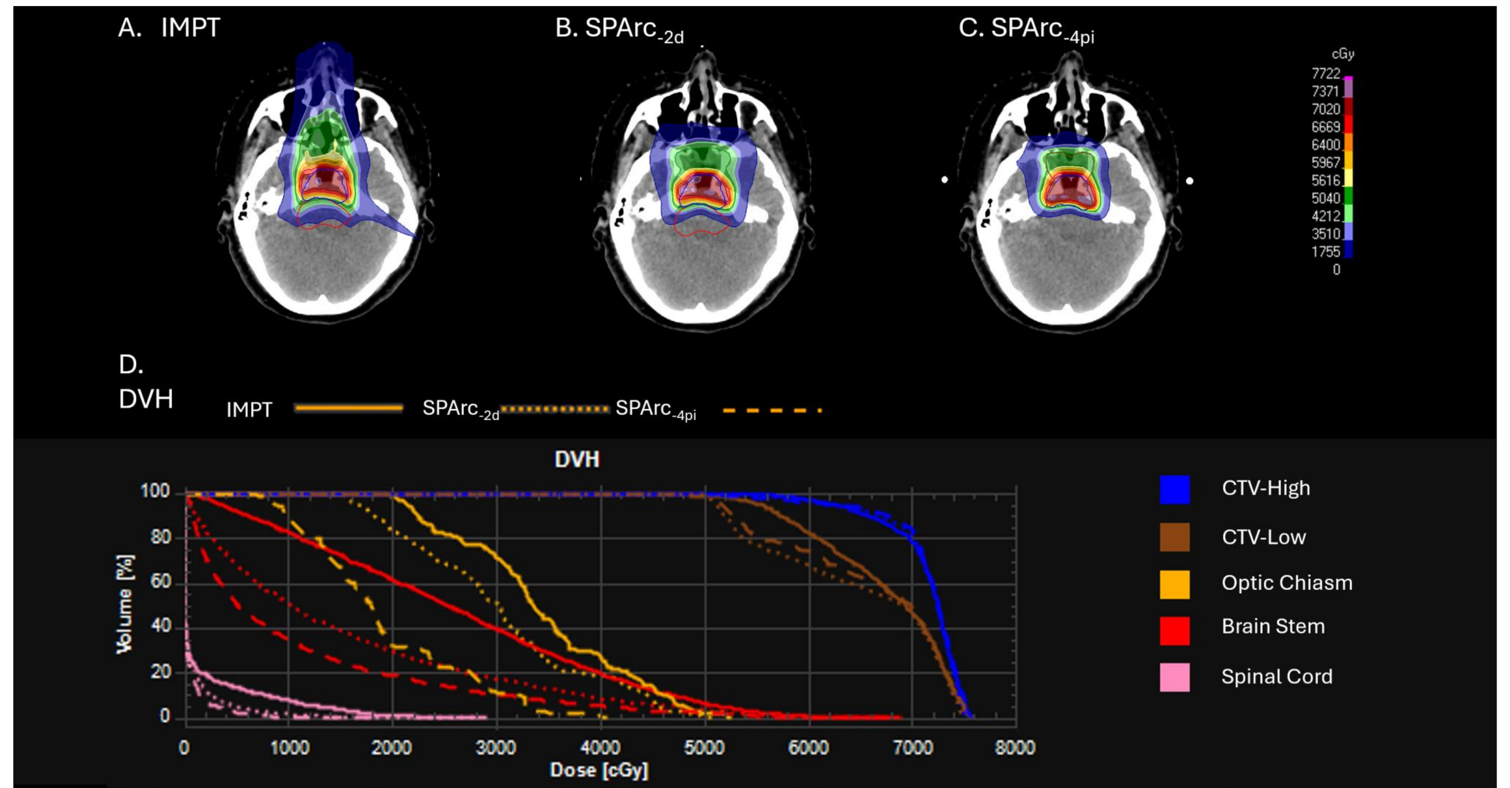


Figure 2. The plan quality and DVH comparison among IMPT, $SPArc_{-2d}$, and $SPArc_{-4pi}$ plan for Clival Chordoma cancer. (A) IMPT ;(B) $SPArc_{-2d}$; (C) $SPArc_{-4pi}$; (D) DVH shows the dosimetric difference among IMPT, $SPArc_{-2d}$, and $SPArc_{-4pi}$.

## Discussion

This is the first study to investigate the feasibility of utilizing a greater degree of freedom in plan optimization and treatment delivery in particle beam therapy. The $SPArc_{-4pi}$ optimization framework is derived from solutions to the classic 0-1 knapsack problem, which is to select an optimized subset from a set of objects with different costs and values with a total cost limitation in typical DP algorithms, adapted to operate within the 4pi spatial domain to address the treatment planning and delivery requirements from the spherical surface geometry. This study incorporates DP into the $SPArc_{-4pi}$ optimization algorithm to search for the optimal plan quality and trajectory for efficient treatment delivery and then benchmarked it with conventional multi-field IMPT and state-of-the-art $SPArc_{-2d}$ plans.

## Conclusions

The study introduced the first optimization algorithm for $SPArc_{-4pi}$ technique. It not only showed $SPArc_{-4pi}$ 's potential to improve the plan quality via a greater degree of freedom compared to the conventional IMPT and state-of-art 2D co-planar $SPArc_{-2d}$ technique but also demonstrated its feasibility for future clinical implementation based on the current proton beam therapy system's machine characteristics.

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