Dynamic Sequencing Optimization for Synchrocyclotron-Based Proton Arc Therapy

Peilin Liu, MD, PhD[1]; Xiaoda Cong, MS[1]; Lewei Zhao, PhD[2], Gang Liu, PhD[3],Xiaoqiang Li, PhD[1] and Xuanfeng Ding, PhD[1]
[1]Corewell Health William Beaumont University Hospital, [2]Medstar Georgetown University Hospital,
[3]Cancer Center, Union Hospital, Tongji Medical College

2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

Innovation/Impact

This work introduces a dedicated sequencing optimization framework that bridges static SPArc planning outputs with the realities of synchrocyclotron-based arc delivery. By incorporating machine timing characteristics, pulse-level spot information, and delivery-constrained spot-weight adjustment, the proposed approach enables accurate translation of optimized plans into executable treatment sequences. The framework addresses a critical gap between treatment planning and delivery for proton arc therapy and provides a practical pathway toward safe and reliable clinical implementation of dynamic proton arc techniques on synchrocyclotron platforms.

INTRODUCTION

Spot-scanning proton arc (SPArc) therapy combines the physical advantages of proton therapy with continuous arc delivery. However, most current SPArc planning approaches assume static beam delivery and do not account for the synchrocyclotron-based proton therapy systems with rotating gantries. This mismatch between nominal planning assumptions and actual treatment delivery may result in dose deviations, particularly for highly precise treatments such as stereotactic radiosurgery (SRS).

Table 1. Nominal plan quality comparison

Case number	Plan name	D98 of GTV_total (cGyE)	V12 of normal brain tissue (%)	V8 of normal brain tissue (%)
1	$SPArc_{static}$	1849	1.45	2.91
	$SPArc_{sequencing}$	1874	1.42	2.95
2	$SPArc_{static}$	1806	1.02	2.23
	$SPArc_{sequencing}$	1806	0.88	1.91
3	$SPArc_{static}$	1885	2.67	4.79
	$SPArc_{sequencing}$	1908	2.67	4.83
4	$SPArc_{static}$	2054	3.39	6.57
	$SPArc_{sequencing}$	2061	3.39	6.57
5	$SPArc_{static}$	1851	3.04	5.46
	$SPArc_{sequencing}$	1864	3.00	5.36

METHODS AND MATERIALS

A five-step sequencing optimization framework was developed to bridge static SPArc planning and dynamic delivery on a synchrocyclotron-based system. The framework consists of: Machine-specific modeling of delivery times, spot disassembling, embedding delivery timing information into control points, spot-weight tuning, and reconstruction of optimized energy-layer sequences. Five patients with multiple brain metastases SRS cases were retrospectively analyzed. Delivery accuracy, dosimetric plan quality, and treatment efficiency were evaluated using reconstructed dose distributions derived from virtual machine logfiles.

RESULTS

The new algorithm significantly improved delivery accuracy while maintaining plan quality and efficiency. For the total gross tumor volume, the mean absolute D98 deviation between planned and reconstructed doses decreased from 77.4 ± 66.2 cGyE (4.6 ± 3.7%) in static SPArc plans to 9.6 ± 7.2 cGyE (0.5 ± 0.3%) after optimization. For the worst-case metastasis, D98 deviation decreased from 184.4 ± 127.8 cGyE (9.7 ± 5.6%) to 19.0 ± 13.3 cGyE (1.0 ± 0.6%), while D2 deviation decreased from 148.4 ± 103.5 cGyE (6.8 ± 4.2%) to 13.2 ± 10.2 cGyE (0.6 ± 0.4%). Target coverage and normal brain dose metrics were not statistically different between plan types ($p > 0.05$). Total dynamic delivery times differed by less than 1 second.

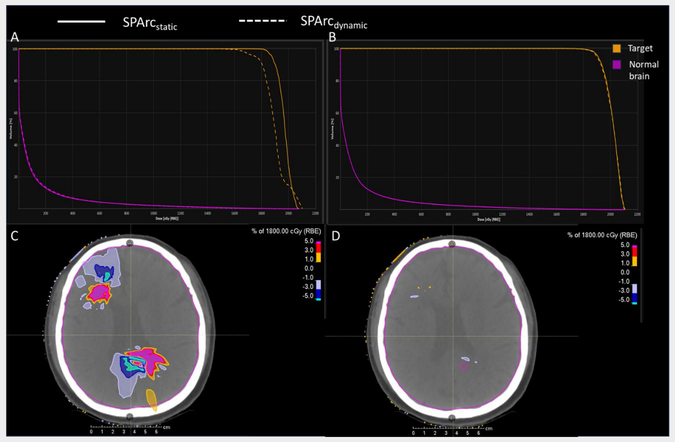

Figure 1. A. Dose difference between static treatment plan ($SPArc_{static}$) and dynamic delivery ($SPArc_{dynamic}$) before sequencing optimization. B. Dose difference between static treatment plan ($SPArc_{static}$) and dynamic delivery ($SPArc_{dynamic}$) after sequencing optimization. C. Dose distribution difference between static treatment plan ($SPArc_{static}$) and dynamic delivery ($SPArc_{dynamic}$) before sequencing optimization. D. Dose distribution difference between static treatment plan ($SPArc_{static}$) and dynamic delivery ($SPArc_{dynamic}$) after sequencing optimization

DISCUSSION

- Delivery inaccuracy in dynamic proton arc therapy arises mainly from temporal misalignment between continuous gantry rotation and the pulsed, three-pulse spot delivery of synchrocyclotron systems — static SPArc wrongly assumes ideal gantry–spot synchronization.
- Embedding machine-specific timing (pulse structure, 6°/s rotation, 0.6°/s² acceleration limits) into optimization delivers each spot at its intended gantry angle, sharply reducing planned-vs-delivered dose deviations.
- Accuracy is gained at no efficiency cost: identical spot and energy-layer counts and <1 s difference in delivery time — critical for brain SRS, where a short treatment time limits intra-fractional uncertainty.
- The framework is modular — the delivery-timing model is its only machine-dependent component, so it can be adapted to cyclotron and synchrotron systems and to other sites and fractionation schemes.

CONCLUSIONS

This sequencing optimization framework effectively mitigates inconsistencies between static planning and dynamic delivery for synchrocyclotron-based proton arc therapy, substantially improving delivery accuracy without compromising dosimetric quality or treatment efficiency.

CONTACT

Peilin Liu
Corewell Health William Beaumont University Hospital
Email: Peilin.Liu@corewellhealth.org

© Poster Template by Genigraphics® 1.800.790.4001 www.genigraphics.com