

Feasibility of Utilizing Spot-Scanning Proton Arc (SPArc) for Whole Lung Irradiation and Mitigate the Breathing-Induced Interplay Effect

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INTRODUCTION

Whole lung irradiation (WLI) has been a key component in the management of pulmonary metastasis in children. The five year OS with and without WLI was 61% and 49%, respectively, based on the European Intergroup Ewing Sarcoma report. WLI significantly improves local control of lung disease and leads to a trend toward better progression-free survival (PFS). Spot-scanning proton arc (SPArc) therapy¹ is the first robust and delivery-efficient rotational proton technique. The new proton treatment planning and delivery technique allow the gantry to rotate while irradiating proton spots and switching energy layers.

AIM

We reported a case study: a 13-year-old teenager with malignant neoplasm of bone and articular cartilage who presented with bilateral whole lung metastasis. The patient received 1500cGy in 10 fractions of whole-lung irradiation (WLI) using volumetric modulated arc therapy (VMAT) in June 2021, and comparisons plans were generated using Intensity Modulated Proton Therapy (IMPT) and SPArc.

METHOD

- The patient dataset analyzed in this study was approved by the Institutional Review Board and selected the database from the Department of Radiation Oncology, Beaumont Health. A 13-year-old teenager presented in April 2021 with malignant neoplasm of bone and articular cartilage who presented with bilateral whole lung metastasis (Figure 1A). The patient received 1500cGy in 10 fractions of WLI using VMAT in June 2021. The lung internal target volume (ITV) was the maximum lung expansion volume defined as the minimum intensity projection bilateral lung volume on four-dimensional CT simulation scans, including lung expansions into the anterior and posterior costophrenic recesses and bilateral hila. The ITV is 1919.75 cm³. The heart was contoured on computed tomography (CT) scan by the attending physician. The daily fraction dose was 150 cGy. The total prescription dose was 1500 cGy to PTV using VMAT. Due to the large size of the target, conventional photon radiotherapy, VMAT, delivered a significant dose to the heart and body integral dose. Therefore, Intensity Modulated Proton Therapy (IMPT) and a new treatment technique, SPArc therapy, were suggested for a comparison study in terms of the organ-at-risks (OARs) sparing and treatment delivery feasibility.
- The clinical VMAT plan used three 360 degree arcs with 6 MV based on the Elekta HD. The IMPT plan was generated using two iso and four treatment fields (Figure 1B) based on the single field optimization approach in a clinical treatment planning system (TPS) (RayStation version 6, Stockholm, Sweden). SPArc plan was generated in the same TPS through in-house scripting. The SPArc plan used a full 360 degree arc trajectory with 2.5-degree frequency via a single isocenter (Figure 1C). The proton beam model is based on the IBA ProteusONE[®] synchrocyclotron proton system energy range from 70 to 227 MeV, with spot size 1-sigma in air measurement ranging from 3.3 mm to 7.9 mm. Both IMPT and SPArc applied the same robust optimization parameters (± 5 mm setup and $\pm 3.5\%$ range uncertainties). The final dose is computed with a dose grid of 3mm. Prescription is 1500cGy in 10 fractions. VMAT, IMPT, and SPArc plans were normalized to at least 98% of the ITV should receive the prescribed dose. Heart dose-volume histograms (DVHs) and integral body dose were evaluated among the VMAT, IMPT, and SPArc nominal plans.
- Delivery efficiency of IMPT and SPArc were simulated based on the previously published machine delivery sequence model² based on an IBA ProteusONE[®] proton machine and the prototype DynamicArc[®] delivery system. The VMAT delivery time was acquired from the LINAC machine logfile.
- The interaction effect of proton treatment for IMPT and SPArc was estimated based on the delivery sequence. The 4DCT dataset has 10 phase images simulating the patient's breathing cycle as 4s. The interplay effect was assessed based on the 4D dynamic dose accumulation method³ for ten different starting phases, assuming the breathing pattern remains the same. To calculate a single fraction 4D dynamic dose, the dose calculated on each phase image was accumulated via the deformable image registration to the reference phase (phase 50%). D98 (Dose received by 98% of target volume) of the target is used to estimate the target coverage.

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RESULTS

1 Result of diagnostic assessment

The patient's SPArc plan was compared with IMPT and VMAT plan, as shown in Figure 1. SPArc has a total MU less than IMPT but slightly more energy layers and spot numbers.

2 Result of dose metrics comparison

The SPArc plan significantly spared the dose delivered to the healthy tissue, compared to the IMPT and VMAT plan, while providing similar coverage to the clinical target volumes. More specifically, the mean dose to the heart was 541 cGy in SPArc plan, compared with 848 cGy in the IMPT plan, and 956 cGy in the VMAT plan, respectively. D50 (Dose received by 50% of volume) of the heart was 306 cGy for SPArc, 913 cGy for IMPT, and 912 cGy for VMAT. The integral body dose was 136 Gy-L in VMAT, 112 Gy-L in IMPT, and 98 Gy-L in SPArc.

3 Result of delivery efficiency comparison

The LINAC logfile showed that VMAT took 317 seconds to deliver all three arcs. Based on the IBA ProteusONE[®] delivery sequence model calculation, it would cost the IMPT plan 746 seconds to irradiate all the energy layers and spots at the fixed gantry angle. Assuming the 1-RPM of gantry rotation speed and 5 minutes iso shift and imaging validation time, the total IMPT treatment for WLI is approximately 1046 seconds. In contrast, SPArc does not require any iso shift and the spot irradiation, and energy switching happens during the dynamic arc delivery. The total SPArc treatment time is 423 seconds calculated based on the DynamicARC[®] delivery sequence model, which reduced 60% of the total treatment delivery time compared to the four field IMPT.

4 Result of interplay effect evaluation

The mean and standard deviation of D98 calculated from the interplay effect was 1445 \pm 19 cGy for SPArc, and 1385 \pm 26 cGy for IMPT, respectively (see Figure 2). The SPArc simulation result has a higher dose in target coverage than the IMPT simulation result (T-test, p-value<0.01).

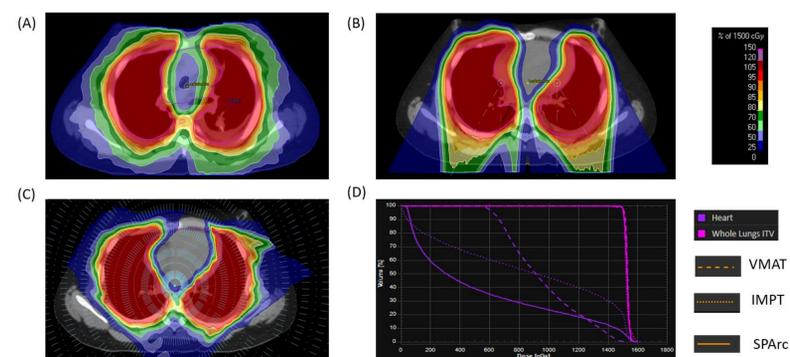


Figure 1. The SPArc versus IMPT and VMAT treatment plan. (A) VMAT plan dose (B) IMPT plan dose (C) SPArc plan dose (D) DVH comparison.

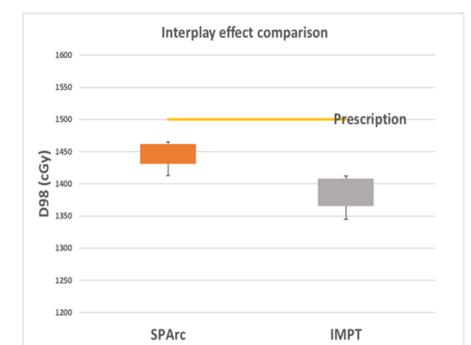


Figure 2. Comparison of interplay effect between SPArc and IMPT.

CONCLUSIONS

SPArc technique showed a significant dosimetric benefit in cardiac and patient's body integral dose sparing compared to VMAT and IMPT in the WLI. Additionally, SPArc could simplify the clinical workflow with a single iso and improve the treatment delivery efficiency as well as interplay effect through the arc trajectory compared to the IMPT.

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