Evaluation of Random Spot-Wise Monitor Unit Delivery Errors in Spot-Scanning Proton Arc Therapy

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Innovation / Impact

Spot-scanning proton arc therapy (SPArc) introduces a fundamentally different error behavior compared with fixed-beam intensity modulated proton therapy (IMPT). Because SPArc distributes dose contributions across a very large population of low-weight spots delivered at many different gantry angles, monitor unit (MU) uncertainties at the individual spot level may average out rather than accumulate. However, this hypothesis has not previously been tested using accurate machine delivery sequencing model. This study introduces a generalized framework to quantify the dosimetric consequences, random spot-wise MU deviations in SPArc plans. By applying stochastic perturbations directly to optimized plans and assessing their impact on dose metrics, the study provides foundational evidence that the highly distributed nature of SPArc inherently limits sensitivity to random MU uncertainties. This characterization is directly relevant for defining expected delivery tolerances and guiding future quality assurance strategies for proton arc therapy

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INTRODUCTION

Spot-scanning proton arc therapy (SPArc) is an emerging proton delivery technique that improves dose conformity by delivering proton beams continuously during gantry rotation. Because SPArc relies on thousands of individual proton spots, stochastic spot-wise monitor unit (MU) delivery errors may accumulate and alter the delivered dose distribution. The dosimetric impact of these random delivery uncertainties has not been systematically investigated. This study evaluates the robustness of SPArc against stochastic spot-wise MU delivery errors using a machine-specific delivery simulation framework.

METHODS AND MATERIALS

Four representative clinical cases from distinct disease sites—brain stereotactic radiosurgery (SRS), lung, liver, and prostate—were selected to encompass a range of target sizes and anatomical locations. For each case, a clinically optimized SPArc treatment plan was generated. Spot-wise independent MU delivery errors were simulated using a Gaussian distribution with standard deviations of 1%, 2%, and 3%, representing realistic random delivery uncertainties. Perturbed dose distributions were recalculated and compared with nominal plans using target coverage and organ-at-risk (OAR) dosimetric metrics. Three-dimensional (3D) gamma analysis was also performed for evaluation

RESULTS

Across all four disease sites (brain SRS, lung, liver, and prostate) and simulated spot-wise MU error magnitudes of 1–3%, dosimetric deviations relative to nominal SPArc plans remained minimal. The largest target coverage difference (3 cGyE <0.2%) was observed in the brain SRS case under 3% spot-wise MU perturbation, while the lung, liver, and prostate cases demonstrated smaller variations across all error levels. OAR dosimetric metrics represented similarly limited sensitivity across all disease sites, with absolute and relative differences remaining below 1 unit and 0.2%, respectively. 3D gamma analysis demonstrated 100% passing rates for all disease sites and MU error scenarios, indicating excellent agreement between perturbed and nominal dose distributions.

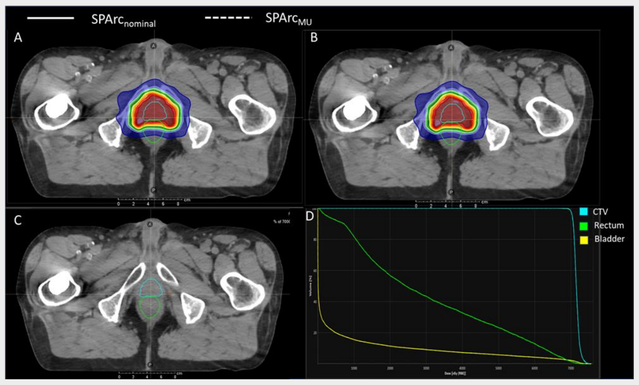

Figure 1. A. Nominal SPArc dose distribution (SPArc$_{nominal}$) (prostate cancer). B. SPArc dose distribution following stochastic spot-wise monitor unit perturbation (SPArc$_{MU}$) (prostate cancer). C. Dose difference between SPArc$_{nominal}$ and SPArc$_{MU.}$ D. DVH difference between SPArc$_{nominal}$ and SPArc$_{MU}$

DISCUSSION

- Across all evaluated treatment sites, stochastic spot-wise monitor unit perturbations within clinically realistic ranges resulted in only minor deviations from nominal dose distributions.
- Target dose metrics remained highly stable across all perturbation levels, with maximum changes limited to a few centigray even under the largest simulated uncertainty.

CONCLUSIONS

SPArc demonstrates strong robustness to random spot-wise MU delivery errors across diverse anatomical sites. Dosimetric perturbations remain minimal, with complete gamma agreement observed under all tested stochastic conditions. These results characterize the baseline delivery robustness of SPArc with respect to spot-level MU uncertainty and provide quantitative evidence to inform future proton arc therapy quality assurance design.