Abstract

Proton therapy offers significant dosimetric advantages over conventional photon radiotherapy due to the characteristic Bragg peak, enabling precise dose deposition to tumors while minimizing irradiation of surrounding healthy tissues. Pencil Beam Scanning (PBS) and Intensity Modulated Proton Therapy (IMPT) have further enhanced this precision. However, challenges remain in optimizing lateral dose fall-off and improving treatment efficiency. Dynamically Collimated Proton Arc Therapy (DC-PAT) emerges as a promising modality, aiming to combine the advantages of spot-specific dynamic collimation with those of an arc delivery to achieve superior dose conformity and organ sparing. Despite its potential, DC-PAT faces substantial hurdles related to treatment planning complexity, delivery efficiency, system integration, and quality assurance (QA). This dissertation focuses on developing and evaluating foundational tools and methodologies to address these challenges, specifically utilizing the Dynamic Collimation System (DCS) prototype, to advance DC-PAT towards clinical feasibility.

The research presented herein encompasses three principal areas of investigation. Firstly, to address treatment planning and delivery efficiency, a novel post-processing "Cut-Sort-Group" (CSG) algorithm was developed and evaluated for DC-PAT plans. The CSG algorithm incorporates three components: (1) "Cut," which eliminates low-weight control points; (2) "Sort," which employs a novel Sliding-Window Energy Layer Sorting (SWELS) algorithm to minimize time-consuming low-to-high energy transitions; and (3) "Group," which utilizes ant colony optimization to group collimated spots into shared trimmer configurations, thereby reducing trimmer motion time. Applied to DC-PAT plans for three cranial cases, the CSG algorithm, with optimized parameters (SWELS window size of 25°, mean spot group size between 6 and 10), demonstrated

a substantial reduction in expected beam delivery times by up to 65%, achieving clinically feasible total treatment times of approximately 10 to 13 minutes. Crucially, these significant efficiency gains were achieved while preserving essential dosimetric plan quality (target coverage, homogeneity, conformity) and without substantially compromising plan robustness under simulated delivery uncertainties.

Secondly, this work developed critical tools and procedures for the accurate delivery and dosimetric verification of DC-PAT. A systematic investigation of gantry angle-dependent isocenter drift for the DCS-equipped nozzle was conducted using kV imaging. This resulted in the development and validation of a corrective look-up table (LUT) that successfully reduced DCS-radiation field misalignment to within 0.5 mm for X trimmers and 0.1 mm for Y trimmers, essential for accurate collimation during arc deliveries. The feasibility of using n-type silicon diodes (specifically, Sun Nuclear EDGE™ diodes, similar to those in the ArcCHECK® device) for patient-specific QA in the plateau region of proton arc beams was assessed. These diodes exhibited high short-term precision, dose linearity up to 10 Gy, and minimal energy or dose-rate dependence (<2%) in the plateau region. While significant sensitivity degradation with accumulated proton dose (5-9% per 100 Gy) was observed, the estimated per-fraction damage for typical arc QA was found to be potentially manageable with appropriate recalibration schedules. Furthermore, a novel cylindrical acrylic phantom for Gafchromic™ EBT3 film dosimetry was designed and constructed, with Monte Carlo simulations verifying its suitability for high-resolution 2D dose verification in the plateau region of DC-PAT treatment beams, thereby avoiding LET-dependent film under-response.

Thirdly, a comprehensive MATLAB-based log analysis toolkit was developed to facilitate detailed understanding and modeling of DCS performance during treatment delivery. This toolkit

automates the parsing of complex machine log files, enabling rapid quantification of delivery accuracy, including spot positional errors (typically <0.2 mm), delivered monitor units, and DCS-specific parameters like trimmer positioning precision (mean error generally <0.04 mm across various motor jerk settings). A key output of this work is a novel empirical sigmoid model accurately describing DCS trimmer motion dynamics during slew times, derived from over 14,300 logged trimmer movements. This model, which predicts trimmer trajectories based on displacement and motor jerk (mean RMSE < 0.1 mm, $R^2 > 0.99$ for normal motion), led to a more accurate method for calculating Trimmer Displacement Time (TDT). This improved TDT calculation demonstrated the potential to reduce previously estimated DCS delivery times by 30-50% compared to simplistic kinematic models and provided a means to identify anomalous trimmer behaviors. The toolkit also supports the generation of log-based Proton Layer Definition (PLD) files, enabling dose reconstruction for supplementary QA.

In conclusion, this dissertation provides significant advancements in treatment planning algorithms, delivery correction mechanisms, novel QA tools, and sophisticated system modeling for DC-PAT. The CSG algorithm offers a pathway to clinically efficient plan delivery. The developed isocenter correction, diode characterization, and film phantom design contribute to robust and accurate treatment verification. The log-based trimmer motion model and analysis toolkit enhance understanding of the DCS, improve delivery time predictions, and provide powerful tools for post-delivery analysis and QA. Collectively, these contributions address key challenges in DC-PAT, advancing this innovative modality closer to clinical implementation and offering the potential for more precise and effective cancer radiotherapy.