Abstract

Dynamically collimated proton therapy (DC-PT) is a derived form of pencil beam scanning proton therapy (PBS-PT) and is gaining interest in the field of radiation therapy. In pencil beam scanning, near-monoenergetic beamlets of protons are magnetically swept across target volumes in successive energy layers at depths dictated by the Bragg peak depth. The achievable dosimetric benefits associated with PBS are largely dependent on pencil beam width, which can be reduced through collimation. Therefore, a Dynamic Collimation System (DCS) was proposed by Hyer et al. in 2014 to enable energy layer-specific collimation in PBS-PT, or DC-PT. This work focuses on the development and validation of the dosimetric benefits proposed by the DCS through Monte Carlo methods and experimental techniques using the clinical prototype of the DCS equipped to the PBS-PT system located at the Miami Cancer Institute (MCI).

First, a Monte Carlo beam model was developed using uncollimated beam measurements performed at MCI. This uncollimated beam model was then extended to include the beam-modifying components of the DCS and subsequently validated against measurements of DCS-collimated beamlets. Additionally, the model of DCS' accessory range shifter, which is required to treat at depths below 4 cm in water, was validated in terms of water equivalent thickness and spot size broadening. Novel beam and DCS modeling techniques that were necessitated by the focused design of the DCS trimmers were developed to achieve excellent agreement with experimental data. Collimated beamlet measurements consisting of integral depth dose curves and two-dimensional profiles were used to verify the increase in entrance dose and sharpened penumbra caused by collimation, respectively.

Following the development of the Monte Carlo model, simple and complex treatment plans were developed to characterize the dosimetric benefits of the DCS and mechanically integrate

the DCS with the PBS beamline at MCI. The treatment plans consisted of cubic target geometries that were treated with multiple energy layers, where reductions in penumbra were parametrized as a function of treatment depth, lateral field size, and trimmer-to-surface distance. Through this, it was found that the achievable penumbra with the DCS was independent of the lateral field size, and for non-range shifted plans, the trimmer-to-surface distance. For range shifted plans, increases in the trimmer-to-surface distance were found to directly reduce the achievable penumbra. Penumbra reductions of up to 64% were observed at a depth of 5 cm with the use of the DCS. The cubic plans allowed for an idealized geometry that was favorable to facilitate initial investigations into treatment plan creation and optimization. Additionally, the multi-energy cubic plans did not require integration between the DCS trimmers and beam scanning controller, which was not available at the time. Because of this, the trimmers and beam delivery were operated independently, and trimmers were moved in between energy layers. Optimized plan parameters were written to PBS layer definition files for delivery and measurements were performed using radiochromic film and an ionization chamber array to validate simulations.

Treatment plans for clinically relevant target geometries were then developed following the successful characterization of the cubic plans. These plans significantly differed from the cubic plans in that they required the trimmers to move on a spot-by-spot basis, which is the expected clinical delivery scenario. To accomplish this, treatment planning methods that were used for the cubic plans were extended to support treatment planning for clinically relevant delivery patterns, where trimmer configurations were strategically selected to yield the most efficient and conformal treatments. Treatment plans were created for multiple target shapes placed at various depths that were treated with and without the range shifter. Normal tissue rinds, which are a region of expansion into the healthy tissue surrounding the target, were evaluated to gauge the effectiveness of collimation. Through this, dose reductions of up to 12% and 45% were

observed within 10- and 30-mm normal tissue rinds. Subsequent measurements were then carried out for one of the target shapes at three depths. To accomplish delivery, the DCS trimmer control system was integrated with the beam scanning controller system to move the trimmers on a spot-by-spot basis. Measurements were then performed to provide insight into the accuracy of the fully integrated delivery and validity of the simulated normal tissue dose reductions.

This work presents a significant advancement in the development of the DCS technology. Prior to this work, literature supporting the use of the DCS primarily consisted of computational treatment planning studies and experimental studies of single beamlet irradiations. These contributions were invaluable to the continued interest in the development of the DCS and ultimately led to the design and fabrication of a clinical DCS prototype with intentions for integration with a clinical delivery system. Therefore, this work builds upon the existing literature by providing the first experimental evidence that demonstrates the dosimetric benefits of the DCS for composite treatment fields. Additionally, the methods utilized in this work have been applied to other aspects of the DCS implementation, such as the development of dose calculation algorithms and the establishment of mechanical tolerances.

In conclusion, the Dynamic Collimation System significantly improves the lateral dose conformity in PBS-PT. The utility of DC-PT delivered with the DCS has been thoroughly demonstrated through computational and experimental studies. Now fully integrated with a clinical delivery system, the DCS is quickly advancing toward clinical use. This dissertation has provided the first experimental data supporting the effectiveness of DC-PT with the DCS and other aspects of the DCS implementation that will contribute to safe and effective clinical use.