Ph. D. Thesis Title: Optimization of Beamline Elements and Shielding in a Preclinical MV Bremsstrahlung FLASH Irradiator

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ABSTRACT:

FLASH radiotherapy is an emerging modality that takes advantage of observed tissue-sparing effects that occur at dose rates above 40 Gy/s [1]. While the so-called FLASH Effect has been shown to occur using electrons, protons, and low-energy photons (<600 keV), the underlying biological mechanism is still disputed [1]. In order to obtain greater clarity regarding the biological mechanism, and the preclinical, the experimental systems must be created with irradiation parameters that span a wide range of achievable dose rates and pulse frequencies.

The FLASH-Experimental X-ray small Animal Conformal Therapy (FLASH-EXACT) system, as a part of the Pluridirectional High-energy Agile Scanning Electronic Radiotherapy project, is a preclinical external beam radiotherapy device. It uses high-energy bremsstrahlung (>10 MeV) of a high-power electron beam (>12 kW) produced by a novel compact linear accelerating structure built at the SLAC National Accelerator Laboratory expanding the range of photon energies that have investigated the FLASH effect. Due to the high-energy bremsstrahlung radiation and high workload, shielding and beam-shaping solutions are needed to create a safe and well-characterized experimental apparatus to raise the level of technological readiness in anticipation of the clinical FLASH radiotherapy machines.

This work focuses on the design and metaheuristic optimization of the beamline elements and shielding, as well as the experimental verification of methods used in their development. The novel application of multilayered shielding produces volumetric and mass-efficient shielding that mitigates photoneutron contamination and reduces the shielding burden on the radiation vault used to house the FLASH-EXACT. A comparison is made between the common radiation shielding assessment tools used in the MeV bremsstrahlung radiotherapy machines: the Monte Carlo radiation transport uses the code FLUKA, and the empirical methods reported in the National Council on Radiation Protection and Measurement Report 151. The effects of the assumptions used in the formulation of the empirical method are shown to lead to an overly conservative estimation of the dose to personnel when polyethylene is incorporated in the treatment head shielding. The beamline elements that shape the transverse and axial dose distribution in the experimental sample are optimized through a flexible hybridized Genetic and Nelder-Mead Simplex Search Algorithm, which automates the production of high-performing configurations of the beamline for a variety of desired field sizes (0.1225 cm^2 at 56 Gy/s and 1 cm^2 at 435 Gy/s) while simultaneously incorporating thermal protection and electron contamination criteria for the bremsstrahlung converter. To further address the thermal challenges associated with the bremsstrahlung-based FLASH radiotherapy machines, design sensitivities of the vacuum window and new bremsstrahlung converter configurations are assessed using two finite element analysis codes to ensure there is a reasonable safety margin with respect to thermal and structural loading failure during the operation of the FLASH-EXACT system.

References:

1. N. Esplen, M. S. Mendonca, and M. Bazalova-Carter, “Physics and biology of ultrahigh dose rate (flash) radiotherapy: A topical review,” Physics in Medicine & Biology, vol. 65, no. 23, 23TR03, 2020.