Abstract

FLASH radiotherapy has demonstrated the potential to reduce normal-tissue toxicity while maintaining tumor control when radiation is delivered at ultra-high dose rate (UHDR). UHDR delivery regimes challenge the conventional dosimetry chain: ionization chambers can experience severe, non-linear recombination losses, beam-monitoring signals can be distorted by charge accumulation in insulating media, and electrometer accuracy may be compromised by short, high-amplitude current transients. My overall goal for this work is to strengthen beam monitoring and absorbed-dose determination in electron FLASH by systematically investigating key components of the measurement chain and by proposing practical mitigation and alternative absorbed dose estimation strategies.

Experiments were performed primarily with a clinical Mobetron electron linac operated in ultra-high dose per pulse (UHDPP) mode, using pulse-resolved acquisitions to characterize beam delivery and detector response. Beam current transformers were used for pulse-to-pulse monitoring and were calibrated against radiochromic film for absorbed dose to water estimation. Charge accumulation effects were evaluated in liquid water and water-equivalent configurations, and shielding/grounding approaches were implemented to mitigate artifacts. The charge collection efficiency (CCE) of air-vented ionization chambers was investigated under varying atmospheric pressure conditions at the primary standards laboratory in Germany, and a pressure-scaling approach was developed for empirically determined CCE functions. A pulse-to-pulse oscilloscope-based method was developed to extract the fast component of the ionization chamber signal and compute the approximate free-electron fraction, thereby enabling free-electron charge-based CCE estimation from experimentally measurable quantities. Finally, commercial electrometers were evaluated using both controlled in-lab pulse injection (waveform generator and capacitor-based current generation), circuit simulations, and irradiation measurements.

A systematic beam-delivery analysis identified operating conditions that improved pulse-to-pulse stability and reduced delivery uncertainty. Charge accumulation in water and insulating materials was shown to perturb charge-based monitoring signals under certain conditions; practical mitigation strategies (including Faraday shielding and electrical grounding) improved robustness, and an aqueous Faraday cup was demonstrated as a cost-effective complementary monitoring tool. Ionization chamber CCE was shown to vary with atmospheric pressure in UHDPP beams; a simple scaling rule reduced pressure-related bias while adding minimal uncertainty. The free-electron-based CCE approach provided agreement with an experimental reference CCE over clinically relevant UHDPP conditions when the fast pulse component was clearly identifiable. This method showed limitations at low dose per pulse when pulse-shape morphology hindered robust separation of fast and slow components. Electrometers exhibited linear response under controlled in-lab pulse injection and circuit simulations over the tested range, while irradiation measurements revealed small but systematic differences attributable to coupled system-level effects (detector, cabling, phantom environment, and grounding).

This thesis provides an integrated, system-level perspective on FLASH beam monitoring and dosimetry using charge-based detectors. The findings offer practical guidance for (i) selecting stable beam configurations, (ii) mitigating charge-accumulation artifacts for reliable pulse-to-pulse monitoring, (iii) correcting pressure-dependent recombination effects in air-vented ionization chambers, (iv) alternative methods for determining the CCE using (approximate) free-electron charge, and (v) validating electrometers and the full measurement chain under realistic UHDPP conditions. Together, these contributions support more accurate and reliable absorbed dose determination and beam monitoring for electron FLASH radiotherapy.