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A scintillator-based approach to spatial and temporal dosimetry in UHDR electron irradiation

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Abstract. The clinical translation of FLASH-radiotherapy remains limited by the lack of accurate dosimetry at ultra-high dose rates (UHDR), as many conventional detectors exhibit strong dose-rate dependence or insufficient temporal resolution. Scintillation detectors, with their fast response and high spatial capability, represent a promising alternative. In this study, a scintillator-camera system designed to provide pulse-resolved temporal and high-resolution spatial dosimetry for pulsed UHDR electron beams was evaluated. A thin-film scintillator was irradiated using a modified 10 MeV clinical linear accelerator delivering an average dose rate of ≈ 200 Gy/s at 200 Hz pulse repetition frequency. The system demonstrated excellent linearity ($R^2 = 0.998$) across the investigated DPP range (0.06–2.1 Gy). The duration of the scintillator afterglow (~ 1 ms) was well below the 5 ms interpulse interval, ensuring clean temporal separation of pulses. Pulse-by-pulse spatial profiles showed high reproducibility, enabling reliable assessment of beam symmetry and flatness. These findings demonstrate that scintillator-based imaging can provide accurate, pulse-resolved UHDR dosimetry with simultaneous 2D spatial information.

1. Introduction

Ultra-high dose-rate (UHDR) irradiation (≥ 40 Gy/s) has been shown to reduce normal tissue (NT) toxicity while maintaining tumor control comparable to conventional dose-rates (CONV, ~ 0.1 Gy/s) across multiple animal models and biological endpoints, now known as the FLASH effect¹. FLASH radiotherapy has generated substantial interest due to its potential to improve the therapeutic ratio, shorten treatment times, and the potential to reduce margins related to organ motion.

However, clinical implementation remains difficult because accurate dosimetry under UHDR conditions is still challenging². Many detectors routinely used in conventional radiotherapy fail to perform reliably at these extreme dose rates. Ionization chambers, the primary reference instruments recommended by the International Atomic Energy Agency for external beam dosimetry, exhibit pronounced dose-rate dependence due to ion recombination effects at UHDR².

Passive detectors such as radiochromic film are largely dose-rate independent and have therefore been widely adopted in UHDR measurements³. However, they require long post-irradiation waiting times before readout, preventing immediate dose verification. Although these detectors offer excellent spatial resolution, they lack the temporal resolution needed to resolve individual pulses in pulsed UHDR delivery. Consequently, there is a critical need for a detector that is dose-rate independent, fast-responding, and capable of resolving both the spatial and temporal characteristics of UHDR beams.

This motivates the exploration of alternative detector technologies. Scintillation detectors offer several advantages, including submillimeter-scale spatial resolution and fast temporal response on the order of milliseconds, making them promising candidates for UHDR dosimetry⁴.

To further address the dosimetric challenges associated with UHDR delivery, a scintillation-based dosimetry system capable of achieving both fast temporal and high spatial resolution was evaluated. We focus specifically on UHDR electron beams, assessing dose linearity at high DPP as well as pulsed-resolved spatial information, both of which will be essential for a successful clinical translation of UHDR radiotherapy.



2. Material and methods

2.1 Configuration of the camera and scintillator system

The radiation source used was an Elekta Precise clinical linear accelerator that had been modified to deliver a 10 MeV UHDR electron beam⁵. Under these conditions, the accelerator can achieve an average dose rate of ≈ 200 Gy/s at dose maximum in water, at isocenter. The radiation is delivered in 3.5 μ s electron pulses at a pulse repetition frequency (PRF) of 200 Hz.

The experimental setup consisted of a Basler boost (boA1936-400cca) high-speed camera, a (5×5 cm², 565 μ m) thin-film scintillator (BrightLeafTM, BrightComSol, Vienna, Austria) positioned at a source-to-surface distance of approximately 65 cm and mounted at a 45° angle relative to the beam axis (field size 10×10 cm²). The camera was placed 25 cm from the scintillator at a 90° angle relative to the beam axis. The camera was connected to a computer via a CXP cable. The Pylon Viewer software package (Basler AG, Ahrensburg, Germany) was used for camera control. Image acquisition was triggered by the linac's PFV-V signal which sends an electrical trigger signal to the camera before each radiation pulse. This allowed individual pulses to be captured in real time with the scintillator. Each radiation pulse therefore generated a single image, acquired at 1024×1024 pixels and an 8-bit monochrome depth (maximum pixel value 254). Scintillation light-intensity was quantified as pixel value. All images were processed and analyzed in Spyder (Anaconda, Python 3.13.9).

2.2 Dose response under UHDR irradiation

Given the fixed PRF of 200 Hz (i.e., 5 ms between each pulse), the scintillator's afterglow (delayed phosphorescence) must be sufficiently short to avoid signal contamination from subsequent pulses. To verify this, repeated measurements were performed in which the same number of pulses and the same delivered dose were acquired at varying camera exposure times, ranging from 10 to 4000 μ s. By increasing the exposure time while keeping all other parameters constant, the temporal (afterglow) characteristics of the scintillator could be assessed.

The dose linearity of the system readout (grey value) was evaluated by delivering pulse sequences with varying DPP, achieved by adjusting the linac gun settings⁵. Pulse trains of 10–110 pulses were delivered, and the resulting scintillation output was compared against dose measurements using radiochromic film (GafChromic EBT-XD, Ashland, Bridgewater, NJ, USA) placed adjacent to the scintillator. For this part an exposure time of 1 ms was used. Signal intensity was estimated with a region of interest selected at the center of the scintillator. Delivered doses ranged from 6–21 Gy. Longer pulse sequences were required to ensure sufficient film exposure, as at the lowest DPP (0.06 Gy), a single pulse would have produced a dose too low for reliable film readout. The radiochromic films were scanned 24 h post-irradiation using a flatbed photo scanner (Epson Perfection v850 Pro, Nagano, Japan) at consistent orientation and using the red channel, similar as during calibration. An dose uncertainty of 4% was estimated for the radiochromic film³.

2.3 Pulse-resolved spatial information

To investigate the pulse-resolved spatial distribution, a sequence of 10 pulses was measured repeatedly. For each pulse, a line profile was extracted to assess the reproducibility and stability of the spatial response. In parallel, a heatmap was generated from one of the pulses to estimate the signal distribution across the scintillator film. The heatmap was produced by normalizing each pixel to the average pixel intensity within a smaller central ROI, providing a relative measure of the spatial uniformity of the scintillation signal.

3. Results

The dose response of the scintillator system, expressed as pixel value, demonstrated good linearity over the measured DPP interval of 0.06–2.1 Gy and average dose rate of 12–420 Gy/s ($R^2 = 0.998$), as seen in Figure 1a. With the 8-bit monochrome pixel-depth and the given camera settings, the maximum achievable pixel intensity is 254. In our setup, this corresponds to a saturation threshold of approximately 3.13 Gy per pulse.

The scintillator afterglow was measured to be approximately 1 ms (Figure 1b), well below the interpulse interval. This ensures that each pulse is captured without residual signal contaminating the subsequent one (Figure 1c). Based on this afterglow, the PRF could theoretically be doubled without compromising signal integrity. The lower intensity observed for the first pulse in Figure 1c is a known characteristic of the linac used, where the dose in the first pulse is consistently lower than subsequent pulses. The intensity of this can be controlled in our configuration, a feature that has been investigated in a previous publication⁶.

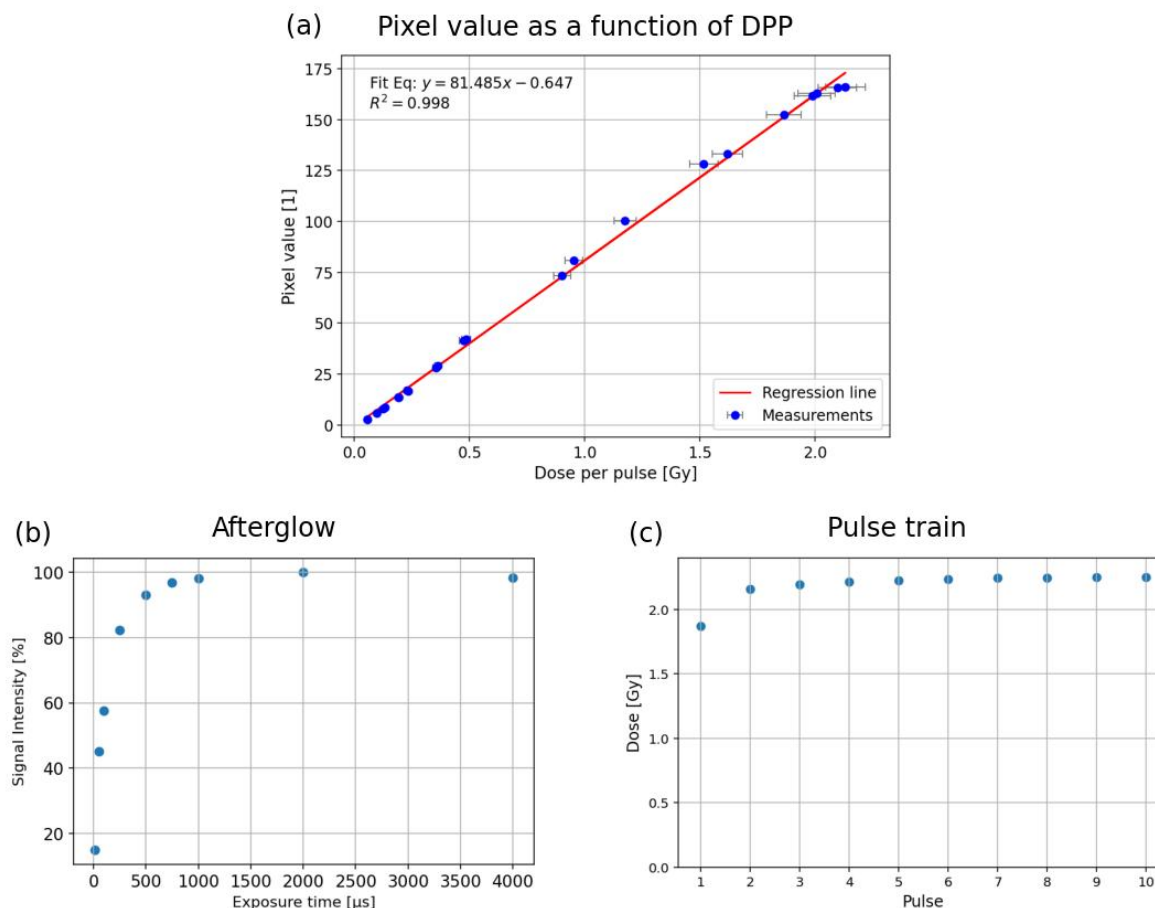


Figure 1: Grey value as a function of dose per pulse (a), afterglow quantified as signal intensity as a function of exposure time (μ s) (b) and an example of a pulse-resolved measurement for 10 pulses (c) where signal output has been converted to dose using the intensity to dose calibration established earlier with radiochromic film.

Figure 2 presents the pulse-resolved spatial resolution of the system. Figure 2a displays the scintillator's intensity distribution after irradiation, and Figure 2b shows the corresponding centered dose profile obtained from a train of nine pulses. The dashed line in (a) indicates the exact row used to generate the profile in (b).

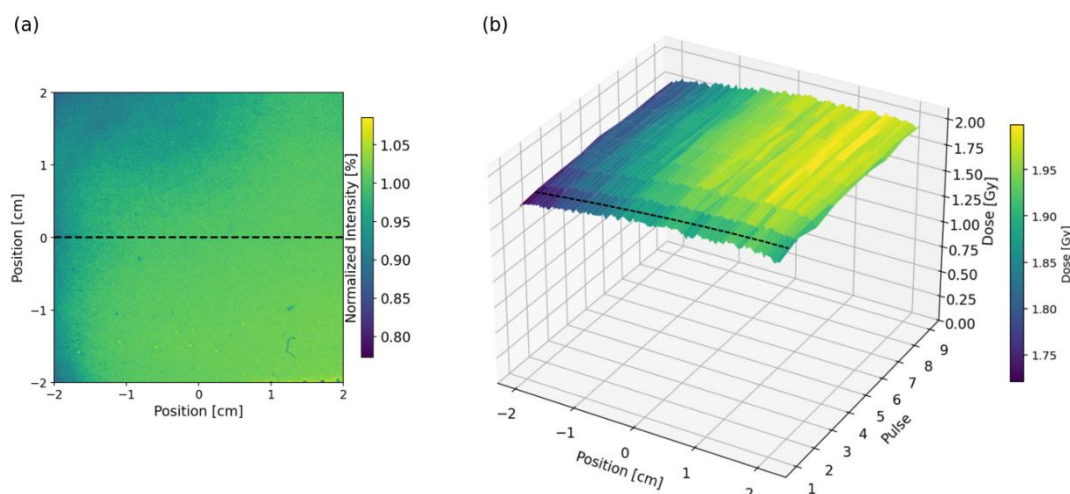


Figure 2: (a) Signal intensity distribution of the scintillator. (b) Pulse-resolved spatial distribution illustrated by a centered dose profile obtained for 9 pulses. The dashed line in (a) marks the exact row used to extract the profile shown in (b).

4. Discussion & Conclusion

In this work, a scintillator-based approach to spatial and temporal dosimetry in UHDR electron irradiation was investigated. The system successfully provided per-pulse temporal and 2D spatial information. The measured image intensity exhibited a linear response with dose per pulse, independent of the DPP (within the tested range of 0.06-2.1 Gy per pulse), as verified using radiochromic film. By providing online information on the DPP, the present method offers sufficient temporal resolution to enable “pulse-train”-level control of dose delivery, thereby shifting the paradigm from simply counting delivered pulses to actively, in real time, measuring the delivered dose. Real-time determination of DPP could, for example, allow dynamic adjustment of the final pulse intensity (e.g., by tuning the PFN delay time, see *Konradsson et al.*⁶) to achieve a dose delivered closer to the prescribed dose with greater precision. Furthermore, the system’s ability to resolve individual pulses with high spatial accuracy makes it potentially possible to assess pulse-by-pulse symmetry and flatness, important for a successful clinical implementation. As efforts toward clinical implementation of UHDR radiotherapy accelerate, reliable tools capable of characterizing both dose and beam structure are essential, and the presented approach represents one possible solution. Future work will focus on improving the readout software to enable real-time beam monitoring, with the capability to perform dose calculations as pulse-trains are delivered.

The variation in signal intensity observed across the scintillator (Figure 2) highlights a current limitation of the experimental setup. Future work will include resolving any potential misalignment. One possible explanation could be the 45° viewing angle. However, the asymmetry is predominantly lateral rather than vertical, making the viewing angle an unlikely cause. A more plausible explanation is that the scintillator film was not positioned exactly along the central beam axis but instead shifted toward one side, resulting in a non-uniform exposure.

5. Conflict of interest

The authors declares that the Department of Medical Radiation Physics at Lund University has a research agreement with BrightComSol.

6. References

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