Characterization of a Newly Designed Diode Dosimeter for UHDR FLASH Radiotherapy

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Abstract:

Purpose: A newly designed diode EDGE Detector has been characterized for use in an UHDR electron beam and demonstrated appropriateness for UHDR FLASH radiotherapy dosimetry.

Methods: Dose linearity, mean dose rate, and dose per pulse dependencies of the EDGE Detector were quantified and compared with dosimeters including a W1 scintillator detector, radiochromic film, and ionization chamber, irradiated with a 10 MeV UHDR beam. The dose, dose rate and dose per pulse were controlled via an in-house developed scintillation-based feedback mechanism, repetition rate of the linear accelerator, and source-to-surface distance, respectively. Depth-dose profiles and temporal profiles at single pulse resolution were compared to the film and scintillation measurements, respectively. The radiation-induced change in response sensitivity was quantified via irradiation of ~5kGy.

Results: The EDGE Detector agreed with film measurements in the measured range with varying dose (up to 70 Gy), dose rate (nearly 200 Gy/s), and dose per pulse (up to 0.63 Gy/pulse)
on average to within 2%, 5%, and 1%, respectively. The EDGE Detector signal was proportional to IC measured dose, and mean dose rate in the bremsstrahlung tail to within 0.4% and 0.2% respectively. The EDGE Detector measured percent depth dose agreed with film to within 3% and per pulse output agreed with W1 scintillator to within 4%. The radiation-induced response decrease was 0.4% per kGy.

Conclusions: The EDGE Detector demonstrated dose linearity, mean dose rate independence, and dose per pulse independence for UHDR electron beams. It can quantify the beam spatially, and temporally at sub millisecond resolution. It’s robustness and single pulse detectability of treatment deliveries can potentially lead to its implementation for in vivo FLASH dosimetry, and dose monitoring.

Keywords: Diode, EDGE Detector, FLASH, Ultra High Dose Rate, Film, Ionization Chamber

1. Introduction
Recent advances in FLASH radiotherapy from delivery of ultra-high dose rate (UHDR, >40Gy/s) beams has further expanded the requirements of dosimetry tools to provide accurate dose delivered during treatments. The FLASH effect, or reduction in normal tissue damage with equivalent tumor control, was demonstrated in vivo in both small animals1–5, large animals6, and human treatment7. UHDR beam deliveries in preclinical and clinical studies typically occur in less than a second, requiring dose, mean dose rate, and dose per pulse independent dosimeters in the FLASH regime (>40 Gy/s, >0.1 Gy/pulse, >10^5 Gy/s intrapulse) with high temporal resolution8 and fast readout.
Currently there are several types of dosimeters utilized for characterizing UHDR beams and its dosimetry. Ion chambers (IC), a charge-based detector considered the gold standard in dosimetry due to their consistency and reliability, can provide real time monitoring of the beamline albeit requiring correction for ion recombination effects and reduced response at UHDR\textsuperscript{9,10}. Alanine, and film\textsuperscript{11,12} chemical-based detectors, as well as OSLD’s\textsuperscript{12}, a radioluminescence based detector, have been utilized for in vivo dosimetry but lack temporal resolution and require processing and read out post irradiation. Gafchromic film has also been shown to measure beam profiles due to their submillimeter spatial resolution\textsuperscript{13}. Alternatively, scintillation and Cherenkov emission-based detectors can provide real time dose measurements at millimeter and microsecond resolution\textsuperscript{14,15}. Nonetheless there is a lack of studies investigating the use of solid-state detectors such as diodes for FLASH dosimetry. Diode detectors have often been used to characterize conventional external beam irradiators due to their real time read out, high sensitivity, reliability and robustness\textsuperscript{16}. Diodes are a viable option for small field dosimetry including IMRT plans with small beamlets, due to their small radiation sensitive volume\textsuperscript{17}.

In this study, a modified EDGE Detector (Sun Nuclear Corp, Melbourne, FL) was characterized in UHDR electron beams with regards to dose linearity, mean dose rate dependence, and dose per pulse dependence of the detector response. A W1 scintillator detector\textsuperscript{18} (Standard Imaging, Middleton, WI), and EBT-XD Gafchromic film Ashland Advanced Materials, Bridgewater NJ), which have been demonstrated to be dose rate independent in previous studies\textsuperscript{19}, and an IC (Exradin A28, Standard Imaging, Middleton, WI) served as reference. The IC was positioned in the bremsstrahlung tail of the beam to circumvent its dose rate dependence. The beam’s depth and temporal profiles were then characterized with the
EDGE Detector and compared with film and W1 detectors, respectively. The potential utility of the EDGE Detector under UHDR FLASH conditions is discussed.

2. Materials and Methods

2.A Description of EDGE Detector and Electrometer

2.A. i. EDGE Detector

The commercially available SNC model 1118 EDGE Detector is an N type diffused junction silicon diode with a nominal sensitivity of 30 nC/Gy. It is encased in a brass housing with an entrance window centered over the active junction of 0.8 x 0.8 mm². Detector assembly is terminated with a triaxial connector, with the center pin to the junction, middle guard shield to the die base, outer braid to the brass housing.

2.A. ii. Electrometer

The PC electrometer (PCE, SNC Model 1014) functions with the operational amplifier (OP-AMP) input connected to the radiation detector, with the OP-AMP feedback capacitor connected between the output and input of the OP-AMP. A 16-bit bi-polar Analog to Digital Converter (A2D) samples the output of the OP-AMP every 100 microseconds. Its voltage resolution is 0.15259 mV per A2D count and charge resolution is 15.3 fC per A2D count. Between each A2D measurement, a microcontroller determines LINAC pulse occurrence by A2D interval subtraction and initiates a charge pump when required, based upon voltage level near bottom or top of amplifier range. Thus, the PCE measures charge from each pulse. For this application, the feedback capacitor, input resistance, input buffer capacitor, resistor in the bucket pump and the temporal controls of the charge pump in the PCE were modified by the manufacturer.
2.B. Setup

A clinical LINAC (Varian Clinac 2100 C/D) was converted to deliver UHDR 10 MeV electron beams at the isocenter by retracting the x-ray target and flattening filter and letting the electron beam normally intended to produce photons pass through the beamline. Prior to conducting experiments, consistency of the beam dose per pulse and spatial distribution (shift, FWHM, flatness, symmetry) was verified via optical imaging of a scintillation screen on a solid water phantom. A W1 point scintillator detector was coupled to a gated integrating amplifier and a real-time controller for dose monitoring and feedback control loop. The controller was programmed to integrate dose and provide feedback to the LINAC when the prescribed dose was delivered, which stopped the beam after delivery of desired dose through a reed relay connected to a real-time position management gating switchbox (Varian Inc, CA).

For comparison of the EDGE Detector to W1 and radiochromic film, the experimental setup shown in Figure 1a was used. For each radiation delivery, the response of the W1 scintillator and the EDGE Detector were measured with the cumulative dose recorded by EBT-XD Gafchromic film. The W1 scintillation detector was in between a 1 cm thick solid water phantom (superficial) and 1.15 cm thick solid water phantom with the end of the fiber aligned to the isocenter. The EDGE Detector was below the 2.15 cm of solid water phantom with another 5 cm of the solid water to provide full backscatter. The film, flattened on top of the phantom, measured dose at the surface. The uncertainty in dose at the surface was measured to be within 1.2% of the mean delivered dose. The calibration of the W1 scintillation was based on the manufacturer’s suggestions for determining calibration coefficients (gain and Cherenkov to light ratio (CLR)). This setup was used to measure the detectors’ response with respect to varying mean dose rate, dose, dose per pulse, and per pulse beam output. The mean dose rate was varied.
by changing the repetition rate of the LINAC, while the dose per pulse was varied by changing
the source to surface distance. The dose was varied by utilizing the beam stopping mechanism
integrated with the W1 scintillator\textsuperscript{21}.

For comparison of the EDGE Detector to IC the setup shown in Figure 1b was used,
again the EDGE and IC measured output simultaneously during each delivery from the LINAC.
The IC was in the bremsstrahlung tail (17 cm depth) of the electron beam to mitigate potential
ion recombination effects from UHDR beams\textsuperscript{9}. The IC correction factors for charge collection
efficiency ($P_{\text{ion}}$) and polarity ($P_{\text{pol}}$) were measured/verified to be near unity with bias voltages at
300V/150V and 300V/-300V respectively. The IC response at 17 cm depth was calibrated to the
dose measured with radiochromic film at 2 cm depth. The calibration was then utilized to display
the comparison of the EDGE Detector's response in UHDR conditions and the IC response in the
bremsstrahlung tail of the electron beam in terms of dose for all future measurements, which
included characterizing the EDGE Detector's response to dose, mean dose rate, and long-term
stability. The long-term stability was evaluated based on 500 deliveries, each with an average
dose of 10.5 Gy.

The percent depth dose (PDD) curve required additional solid water build-up of varying
thickness, which were placed in between the 1.15 cm slab and the EDGE Detector. The source to
surface distance of 100 cm and the alignment of the detectors with the central axis of the beam
were maintained in the process.
Figure 1. a. Setup for data acquisition from both the W1 detector and characterization of the EDGE Detector. Film on top of the stack of solid water phantom was used for calibration of the W1 detector and verifying dose for each delivery. b. Set up for data acquisition from both IC in the Bremsstrahlung tail (17 cm depth) and EDGE Detector (both calibrated to dose measured at 2 cm depth from film. c. Example Snapshot data acquired from the EDGE Detector.

2. C EDGE Detector Data Acquisition

The EDGE Detector acquired data during delivery in “Snapshot” mode and an example of its response from a delivery can be seen in Figure 1c. The data can be acquired with a sampling rate of 10 kHz. The step-like patterns indicate delivery of a signal pulses. The raw data from the electrometer was processed in MATLAB (Mathworks, Natick, MA) to derive information about each pulse in a delivery and the total accumulated signal. The EDGE response (cumulative and single pulse) was then compared to the other dosimeters including accumulated dose for film, W1, and IC as well as single pulse W1 response.

3. Results
Figure 2. W1 and EDGE Detector response in comparison to Gafchromic film and IC with varying dose. The intended dose delivery was controlled based on W1 detector response.

Figure 3. W1 and EDGE Detector response in comparison to Gafchromic film with varying mean dose rate. The mean dose rate was varied by changes the repetition rate of the pulses delivered by the LINAC. EDGE/IC₁ and EDGE/IC₂ were acquired with decreasing and increasing repetition rates respectively.
**Figure 4.** W1 and EDGE Detector response in comparison to Gafchromic film with varying SSD. The dose per pulse was varied by changing the source to surface distance and adjusting the couch’s vertical position.

**Figures 2-4** suggests the independence of EDGE Detector’s response and W1 with respect to dose, mean dose rate, and dose per pulse. The W1 agreed with film measured dose with varying dose (2.4-33 Gy), dose rate (30 - 180 Gy/s), and dose per pulse (0.17-0.63 Gy/pulse) on average to within 2%, 3%, and 4%, respectively. The EDGE Detector agreed with film measured dose with varying dose, dose rate, and dose per pulse on average to within 2%, 5%, and 1%, respectively. The EDGE Detector agreed with IC measured dose (1.9 Gy – 70 Gy), and mean dose rate (31 -190 Gy/s) to within 0.4% and 0.2% respectively. The IC’s $P_{\text{ion}}$ and $P_{\text{pol}}$ was measured to be $1.04\pm0.02$ and $0.99\pm0.01$, which is $\sim1$ when considering the uncertainty (associated with the film which provided reference dose in comparison to charge collected). Thus, no correction factor was applied and assumed to be unity.

**Figure 5 and 6** demonstrated the utility of the EDGE Detector for characterizing the electron FLASH beam. The EDGE Detector can measure the PDD of the electron beam (Fig 5),
which agreed with the film measured PDD to within 3%. The EDGE also provides per pulse
dose or beam output as indicated by the agreement between W1 and EDGE Detector (Fig 6) to
within 4% on average, including during the variability in the first 30 pulses.

The EDGE Detector also shows long term stability from dose delivery of at least 5 kGy.

As shown in Figure 7, there has been approximately 2% reduction in response from over 500
deliveries of ~10.5 Gy.

![Figure 5. a. Percent depth dose curve (PDD) measured by film and EDGE Detector for the 10 MeV UHDR electron beam. b. Difference between PDD fitted to Film profile and EDGE Detector measurements](image)
Figure 6. a. Relative per pulse beam output from the LINAC delivering UHDR electron beams measured by both the W1 and the EDGE Detector. b. Relative difference between EDGE detector and W1 scintillator response.

Figure 7. Long term sensitivity of the EDGE Detector with respect to the response of the IC.

4. Discussion
Characterizing the EDGE Detector with standard dosimeters such as the IC and film and radioluminescence based detector (W1 scintillating fiber) presented the advantages and shortcomings of each. Film has been utilized for characterizing UHDR beam lines, from experimental linac\textsuperscript{12} to converted clinical linac\textsuperscript{10,20,22} to heavy particle beam lines\textsuperscript{4}. This can be attributed to its high spatial resolution and dose rate linearity, requiring a read out via a flatbed scanner post irradiation, thus it accurately provides dose distribution (both lateral and PDD). Nonetheless, figures 4-6 suggests that the uncertainty (from both individual measurements, or uncertainty bars, as well as the range for dose, dose rate, and dose per pulse) can be as much as 5\% in comparison to the EDGE Detector and 4\% in comparison to the W1 scintillation detector deeming radiochromic film useful as a qualitative dosimeter. Furthermore, the agreement between the film and the EDGE Detector for the PDD’s demonstrate their energy independence to within 4\%.

ICs are considered the gold standard for characterizing and commissioning of clinical beams. One of the advantages over radiochromic film is their precision as it can meet the requirements of annual QA according to AAPM’s TG51 report of ensuring beam dose consistency to within 1\%. However, ICs experience a significant loss of their collection efficiency in UHDR beams, which is why the reference IC was placed in the bremsstrahlung tail of the beam, where collection efficiency can be considered constant for all measurement setups used in this study. The comparison of the EDGE Detector and the IC, as shown in Figure 2 and 3, agreed within 0.4\% for both dose and mean dose rate, which means in consequence, that the EDGE detector in conjunction with the modified PCE has a dose rate and mean dose rate independence within that range. It is worth noting that at lower doses delivered in Figure 2, there is a slight deviation away from unity (~1\%) and greater uncertainty bar when comparing EDGE
and IC, which can be attributed to very low dose within the first few pulses. The mean dose rate (repetition rate) independence of the EDGE contrasts the sensitivity drop seen by other diode detectors investigated by Jursinic\textsuperscript{23} (2013), which may be attributed to the EDGE detector being used in conjunction with the modified PCE. The mean dose rate was tested with increasing and decreasing repetition rate (EDGE/IC\textsubscript{1}, EDGE/IC\textsubscript{2} in \textbf{Figure 3}) and there was minimal measured dependency. Ultimately the agreement suggests that the EDGE Detector is precise and can potentially be utilized for annual QA of a FLASH beam line.

Using an IC in the bremsstrahlung tail of the beam as reference can be utilized if the geometry of the set up (e.g., SSD, field size, gantry rotation) is kept constant while other beam output parameters are varied. For example, the LINAC’s repetition rate and dose delivery were varied in \textbf{Figure 2} and \textbf{3}. However this technique could not be utilized for varying dose per pulse, because dose distribution would change as the source to surface distance is changed\textsuperscript{14,15}. So, the ratio of the dose measured at superficial depths (from the EDGE) to the dose at the Bremsstrahlung region would not be consistent. If the dose per pulse is varied by utilizing the pulse structure of the beamline (i.e., pulse width, and pulse height), the IC can be used as the reference for characterizing another dosimeter, like the EDGE Detector.

The W1 scintillation detector benefits from its high temporal resolution (~microsecond), which was utilized to verify the EDGE Detector’s accuracy in measuring the electron beams dose per pulse. The two dosimeters agreed within 4\% on average for single pulses. This per pulse dose agreement potentially implies dose per pulse independence to at least 0.63 Gy/pulse of the EDGE and W1 detectors. However, the W1 exhibits more radiation damage as there was 16\% reduction in response per kGy of dose according to Ashraf et al\textsuperscript{20}, while the EDGE Detector exhibited a reduction in response ~0.4\% per kGy. This is further supported by Fig 6b, where
EDGE and W1 relative response exhibited a difference of >5% for several pulses beyond 35 delivered pulses.

The EDGE Detector seems to exhibit the advantages of the other dosimeters used to characterize it in this study. Its detector in previous studies\textsuperscript{24} characterized small fields indicating high spatial resolution like film. In this study the detector provided the PDD curve but may in the future be utilized for lateral profiles of UHDR small fields and patient specific cutouts. Nonetheless the detector will require characterization under small fields, directional dependence, and temperature dependency under UDHR conditions. While IC is often utilized for a machine's annual QA due to its high precision and reproducibility\textsuperscript{25}, the EDGE Detector also agreed with the IC to within <0.4% difference. It also benefits from fast readout like that of an IC, without the concern of correction for the ion recombination at UHDR. It may also be utilized as a dosimetry tool \textit{in vivo} during FLASH treatment of small or large animals like that used by Ashraf et al\textsuperscript{21} with the W1 scintillation detector. The 0.1 ms sampling rate can ensure resolving single pulses of the UHDR electron beam similar to the W1 scintillator, with reduced damage from radiation. Thus, the EDGE Detector may be a candidate for controlling and stopping UHDR beam delivery based on prescribed dose. Furthermore, if EDGE Detectors can be placed laterally in four cardinal directions closer to the beam source (e.g., before the applicator or cutout), the beam may potentially be stopped based on potential changes in symmetry and shift analogous to the monitor chambers controlling the beam in conventional clinical LINACs.

5. Conclusion

This study demonstrated that the EDGE diode detector can be used for characterization of UHDR electron beams. It is linear with dose, dose per pulse, and mean dose rate with an average
decline in sensitivity of 0.4% per kGy. It exhibited several of the benefits of other dosimeters including fast read-out, and precision comparable to the gold standard ionization chambers. It recorded real time single pulse beam delivery like scintillation-based detectors, with high spatial resolution though at a courser resolution than radiochromic film. It exhibited reduced radiation damage compared to the W1 scintillation detector, but still its sensitivity fade must be considered when used over long time periods.

The EDGE Detector’s submillisecond temporal resolution and energy independence at the MeV energy range suggests potential to characterize electron beams spatially and at single pulses. Its utility can potentially be expanded beyond small field dosimetry, to provide in vivo dose during FLASH experiments, as well as monitor beam profiles and stop beam down to single pulses. This will require further development of the technology, implementation into a beam monitoring and stopping device, and verification of minimal perturbation on the beam delivered to the biological subjects.

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