Utilizing Fiber-Optic Cherenkov Radiation for Electron Beam Dosimetry at Ultra High Dose Rates
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Abstract
As a standard method of cancer treatment, conventional radiation therapy (RT) involves a fractionated dose, delivered over approximately 10 to 30 minutes [6]. In 2014, FLASH-RT was introduced as a radiotherapy method that reduced radiation effects in normal tissue without compromising on its anti-cancer effects [7]. Unlike conventional radiation therapy, FLASH-RT utilizes an ultra-high dose rate (> 100 Gy/s), delivering the same amount of dose in milliseconds rather than minutes. RARAF’s FLASH irradiator, is able to achieve much higher FLASH dose rates, locally termed as ’superFLASH’ [1]. With instantaneous dose rates up to 30 MGy/second (0.2 - 150 Gy per pulse and 360 pulses per second), many real-time traditional dosimetric methods (like the Advanced Markus ion chamber) fail in this mode, due to signal oversaturation. This report will investigate the feasibility of a fiber optic Cherenkov radiation (FOCR) system as an alternative real-time beam monitor. After a total of five trial runs, it is observed that the FOCR system does work as intended, when certain conditions in the accelerator hall line up. A dual-series trend is observed over four out of five trials, where the remaining trial data successfully and completely correlated with the actual dose observed. The consistency of outlier measurements implies an unknown, systematic variable being overlooked, most likely due to the variance of the Clinac beam width. Though further development of this system is needed, the experiments conducted provide a satisfactory starting point for a real-time electron beam monitor at ultra high dose rates.

Keywords: ultra high dose rate, electron beam dosimetry, fiber optic Cherenkov radiation, FLASH-RT

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1 Introduction

Conventional radiotherapy (RT) has long been a commonly used and well-studied method of cancer treatment, and RT practices continue to improve as we learn more about tumor biology, medical imaging, and dose delivery. Conventional RT is limited by normal tissue toxicity [6]. Normal tissue toxicity describes the collateral damage dealt to surrounding healthy tissue. Though more dose may be more efficient in killing cancerous tissue, severe radiation-induced side effects pose a risk to a patient’s overall health. A 2014 study introduced a method that may be able to work around these limitations, known as FLASH radiotherapy (FLASH-RT) [7]. FLASH-RT delivers radiation at ultra high dose rates. While conventional RT delivers dose in a matter of minutes (2 Gy/min) and must be fractionated, FLASH-RT is often delivered in short pulses, with a much higher dose rate (> 100 Gy/s) [6].

Columbia University’s Radiological Research Accelerator Facility (RARAF) has modified a decommissioned Clinac 2100C (Varian Medical Systems, Palo Alto, CA) to deliver FLASH dose rates. The modified Clinac can use dose rates even higher than those typically involved in FLASH-RT, dubbed ‘superFLASH’ mode. Dose rates in superFLASH mode can reach up to 30 MGy per second. However, superFLASH irradiations are difficult to study due to the oversaturation of ion beam dosimeters at such high dose rates [1].

In order to study and take advantage of the theoretical benefits of superFLASH dose rates, a real-time beam monitor is needed. This paper gives a brief overview of failed dosimetric methods and analyzes the feasibility of a fiber-optic Cherenkov radiation (FOCR) system as an alternative real-time dosimeter.

2 Background

2.1 Motivations: The FLASH Effect on Healthy Tissue

Conventional RT is limited by radiation-induced side effects. When conducting radiotherapy, the irradiation of critical organs is often unavoidable. Customization of the delivered dose (shape, fractionation, etc.) is common in order to reduce dose delivered to these areas. Even so, this limits the curative potential of conventional RT for tumors located in close proximity to critical organs. While conventional dose rates fall around 2 Gy per minute, FLASH dose rates can be anywhere above 100 Gy per second. Preclinical data on FLASH-RT suggests that administering a single, high dose of ionizing radiation via FLASH-RT achieves the same tumor-killing as conventional RT, with better normal tissue protection. It is theorized that FLASH-RT produces this effect by taking advantage of the differing oxygen levels between normal and cancerous tissue (cancerous tissue is hypoxic, whereas normal tissue is well-supplied with oxygen). FLASH dose rates cause oxygen depletion and transient hypoxia in healthy tissue surrounding the target, raising the healthy tissue’s tolerance to radiation while exhibiting the same tumor-killing effects [6].

In 2019, the first clinical use of FLASH-RT was performed. After the resulting tumor response, the authors concluded that FLASH-RT was both feasible and safe. Though FLASH-RT is a relatively new idea, the possible benefits could lead it to become a dominant method in curing tumors in radiation-sensitive areas or even replace conventional RT altogether [7]. However, the optimal dose rate for this protective effect has yet to be determined. Studying the superFLASH dose rates
achieved by the modified RARAF Clinac is crucial in identifying the upper limits of the FLASH effect.

2.2 Dosimetry at Ultra High Dose Rates

At ultra high dose rates, nicknamed at RARAF as ‘superFLASH’ dose rates, dosimetric methods become very limited. Though the Advanced Markus ion chamber (AMIC) can be used for lower FLASH-RT dosimetry, it saturates at 0.5 Gy per pulse. In comparison, the dose rates studied averaged at approximately 2.5 Gy per 5 microsecond pulse. RARAF has conducted trial runs of a variety of dosimetric methods. Using a coupled nanosecond timing scintillator-PMT system, pulse width at FLASH-RT dose rates could be measured. However, the PMT became oversaturated in superFLASH mode, resulting in inaccurate data [1].

Another method, the pulse-transformer-type pickup detector, was examined.

Figure 2: A diagram of the described pulse-transformer-type pickup detector.

The pickup detector consisted of a coil wound on a magnetic core, connected to a shunt resistor [9]. The detector was then coupled with an amplifier and connected to a multi-channel analyzer (MCA) and oscilloscope. It was placed in a fixed position where the beam diameter was approximately 1 cm, and the dose rate is $>100$ Gy/pulse. This dose rate corresponds to $3\times10^{11}$ electrons per 5 microsecond pulse. The beam passes directly through the center of the coil. Similarly to the AMIC and
the scintillator-PMT system, the pickup detector was discarded because of unusual signal readings. Instead of the ideal unipolar pulse (that was later seen using the proposed FOCR system), the pickup detector signals were non-uniform and had lots of ringing.

As a result, radiochromic film is used as a reference point for dose. Radiochromic film is self-explanatory: when irradiated, EBT3 film (the type used throughout this study) becomes more opaque. After irradiation, the film is scanned, and its optical density is compared to that of non-irradiated film. The film-dose calibration curve of EBT3 film (the specific type used in this study) has been done at higher FLASH rates, so it is used as a primary reference point for dose [8]. In order to accurately study superFLASH dose rates, the collection of accurate, real-time dose measurements is crucial. Film dosimetry, while more accurate and less prone to oversaturation, is not a substitute for a real-time beam monitor, since it is a passive dosimetry method that cannot be reused. An active monitor is necessary to stop the beam when the prescribed dose has been reached. This specific use requires the dose estimate within a millisecond or two at most (< 1/360 Hz) in order to send a stop signal before the next pulse is sent. The lack of a real-time dosimeter is the focus of the following experiment.

2.3 The Precedent for the Proposed FOCR System

Optical fibers are mostly protected from noise due to external factors and ambient conditions like temperature, pressure, etc. They are also completely insensitive to electronic (RF) noise, a prominent background signal near RF-based linear accelerators like the one used. However, when irradiated, several processes occur within the optical fiber. Fluorescence, phosphorescence, and photo-darkening are three of these aforementioned processes [5]. As fiber optic materials and techniques have developed, the effect of these processes has been reduced. The generation of Cherenkov radiation is another one of these processes. This process, like fluorescence and phosphorescence, generates light within the optical fiber.

Fiber-optic Cherenkov radiation (FOCR) is another term for dispersive wave generation or non-solitonic radiation. Cherenkov emission is generated in optical fibers when charged particles (in our case, electrons) pass through the fiber core at a velocity greater than the local speed of light [5]. The velocity of 6 MeV electrons (used in this study) is $0.994c$, while the speed of light in silica is $c/1.45$. This Cherenkov radiation will be generated in the core of any fiber with a core refractive index greater than 1.

Traditional fiber optic dosimetry, used for proton and photon beams, seeks to factor FOCR out, as it is a byproduct of Compton scattering [4]. Because the desired variable in optical dosimetry is the scintillating fluorescence caused within the optical fiber by photons, FOCR from Compton electrons is an unwanted source of noise. As the Cherenkov spectrum emitted within the optical fiber is similar to that of the desired scintillating signal, noise from FOCR is especially unwanted, and factoring it out is an ongoing challenge in photon and proton beam optical dosimetry. In contrast, electron beam optical dosimetry is able to take advantage of FOCR [5].
3 Methods

3.1 Modified Varian Clinac 2100C Setup

From 2019 to 2021, RARAF modified a decommissioned Varian Clinac to deliver both FLASH and superFLASH dose rates. Due to space restrictions, the bed was discarded, and the gantry rotation was disabled, leaving the beam pointing upwards permanently.

![RARAF's modified Varian Clinac 2100C](image)

Using a multi-channel analyzer (MCA), the signal from the Clinac's built-in ion chamber is displayed in the control room. Because the built-in ion chamber saturates in superFLASH mode, the MCA reads from the appropriate detector channel instead.

As for safety precautions, the leakage radiation has been mapped and high radiation rooms are locked off during Clinac use, with lower radiation areas clearly labeled as "no linger" zones. The accelerator hall contains multiple interlocks to ensure that it is vacated and locked during use.

While doing typical FLASH irradiations, the Clinac operates in service mode using the 9 MeV electron setting. In contrast, superFLASH dose rates are achieved by operating in 6 MV photon mode with a retracted target. In superFLASH mode, the per-pulse electron current is increased by a factor of 50, with the repetition rate increased by an additional factor of two. This allows the beam to overcome the low photon yield at 6 MeV, allowing clinically relevant photon dose rates. The removal of the target allows us to get ultra high electron dose rates in this mode. The remaining changes can be reviewed in a 2022 publication detailing the conversion process.

3.2 Fiber Optic Cherenkov Radiation (FOCR) System

3.2.1 FOCR System Equipment Characteristics

An integral part of the FOCR-based dosimetry setup is the Cherenkov emission spectrum. Generally, Cherenkov radiation can vary along a continuous spectrum of wavelengths from the ultraviolet region...
to the visible part of the light spectrum.

![Figure 4: The Cherenkov emission spectrum for a PMMA fiber.](image)

Though its spectrum through different fiber core types has not been studied, in polymethyl methacrylate (PMMA) optical fibers, Cherenkov emission is most prominent in wavelengths less than 500 nm and peaks at around 450 nm, though lower wavelengths will likely be prominently detected as well [5]. Thus, it is appropriate to use high OH or solarization-resistant fibers, coupled with an appropriate photodetector.

Due to the need to eliminate FOCR, various studies have been done regarding its characteristics. It has been shown that Cherenkov light is positively correlated with field size; similarly, FOCR shows dependence on the irradiated length of optical fiber. Thus, any FOCR-based dosimetry setup should be stationary throughout measurement. Angular variation is also an influential variable when measuring the intensity of FOCR signals. However, this angular variation solely depends on the refractive index difference between the core and the cladding of the fiber [2]. FOCR peak intensity is proportional to the cube of the fiber core radius, cementing that any FOCR-based dosimeter must be stable throughout every measurement, both in materials and in physical setup.

Depth dose characteristics should also be taken into account. Near a solid-gas boundary, dose is lower and not always reproducible. Electrons ionize the solid medium, forming energetic secondary electrons. These secondary electrons may escape into the air, reducing locally deposited dose and interfering with the desired signal. As a result, Solid Water (polystyrene) can be used to lessen dose loss and improve signal accuracy.

### 3.2.2 Physical Setup

The physical setup of the proposed system consists of an above-beam fiber-optic setup connected to a switchable gain photodetector. The photodetector signal is then transmitted to the RARAF Console Room, where it is displayed on both the multi-channel analyzer and on a digital oscilloscope. The actual fiber-optic setup is located above the beam head at a 90 cm source-to-surface distance (SSD), using a solarization-resistant fiber with a plastic-silica core (ThorLabs M113L02). A 5 mm thick plate of water-equivalent RW3 material (polystyrene with titanium oxide admixture; LAP of America Laser
Applications, L.L.C., Boynton Beach, FL) lays below the fiber. (This water-equivalent material is commonly known as Solid Water.) The fiber is inserted snugly into a hole drilled into another 5 mm thick plate of Solid Water. A roughly 2" x 2" piece of EBT3 radiochromic film is placed on top of the second plate of Solid Water, and is subsequently covered by a third plate of 5 mm thick solid water.

The setup is centered at the beam crosshairs, which stay stable throughout the experiment. Because these markers are unchanging, we are able to ascertain that the fiber, laid across the vertical beam alignment line, and the film, centered on the crosshairs, have consistent position and theoretical beam coverage throughout different trials. The 90 cm SSD utilized during this experiment corresponds to prior estimates of approximately 2.5 Gy per pulse, with the average pulse width being 5 microseconds. During this experiment, the film is irradiated using a single pulse at this height. Each film is irradiated in the same day, with no more than 3 minutes between films.

### 3.2.3 Calibration and Measurement

Initial calibration consisted of reference measurements for peak-to-peak voltage, taken using the digital oscilloscope. Reference measurements of peak-to-peak voltage were taken with the Clinac beam off at various gain settings, seen in Tab. 1.
Pulse shape analysis was done at both the 60 dB and 50 dB gain settings, though it was determined that the pulse height at 60 dB oversaturated the MCA. Unlike the oversaturation and ringing observed using prior methods, the FOCR system displayed a clean, unipolar pulse at the 50 dB gain setting.

Figure 7: The pulse shape seen on the oscilloscope from the FOCR measurement.

The voltage given by the photodetector output is transmitted to the RARAF console room and displayed using both the MCA and a digital oscilloscope. Compared to the oscilloscope, the MCA had a consistent 30 mV offset over a 1 V signal. Because the variance between the two measurements is kept constant, the FOCR-dose correlation will not be affected despite which data is used. For convenience, any analysis will be done with the MCA readings.

3.2.4 Methodological Difference between Trials

A total of 5 trial runs were conducted. The first trial run was conducted prior to the conception of the customized Solid Water plates. During Trial 1, the optical fiber was placed on top of one 5-mm thick plate of Solid Water, with the film placed underneath it. As mentioned earlier, dose is lessened at a solid-gas boundary, due to the escape of secondary electrons. Besides the lack of top Solid Water plate, Trial 1 was identical to the discussed methodology above. Despite many similarities, Trial 1 data was discarded in the analysis due to the possible dose loss.

Trial 3 also differed from the initial setup, as the correlation at 40 dB gain was analyzed. However, a less distinctive pulse height was observed using this setting. Though this did not cause much difference, it was slightly harder to identify maximum dosage measured from the FOCR system. Thus, subsequent trials switched back to the 50 dB setting. In the following sections, this trial data was normalized to fit the scaling used with the gain set at 50 dB.
3.3 Comparison to EBT3 Radiochromic Film

After the EBT3 Gafchromic film is irradiated, it is scanned in transmission mode using the EPSON V700, with a DPI of 300 and a bit-depth of 48-bit. Then, it is analyzed in Matlab. The script in question uses the red channel for dose construction, converting the film scans into dose maps. The difference in optical density between irradiated and non-irradiated film is analyzed, and a dose histogram is generated in user-selected regions.

**Figure 8:** An example of the EPSON V700 film scans (left) and the resulting dose maps (right).

\[
\text{Optical Density} = - \log_{10}\left( \frac{\text{Pixel Value Irradiated}}{\text{Pixel Value Control}} \right)
\]

\[
\text{Dose} = \left( \frac{0.7404 \times \text{Optical Density}}{0.818 - \text{Optical Density}} \right)
\]

**Figure 9:** Relevant equations for optical density (above) and dose (below) calculated in the Matlab script.

4 Data and Analysis

4.1 Initial Trial Analysis in Python

A script `ReadDose.py` was written in Python in order to calculate the average dose from the dose histogram produced. The script identifies film in the dose distribution, with the output producing the average dose and standard deviation of dosage. `ReadDose.py` also filtered out irrelevant data: namely, data mistakenly taken due to detector sensitivity and dose values more than 3 sigmas away from the overall average dose. Selection regions can also be customized to look at certain fractions of film. The output (average dose and standard deviation in accordance with order irradiated) is saved to a .csv file for future reference in further analysis. A similar script, `ReadOsc.py` was written for the digital oscilloscope data.

The aforementioned dose files are then reloaded into Python and two linear regressions are done.
In the first, the photodetector output voltages from the FOCR system are correlated to their corresponding average film dose. Then, the FOCR-film measurement pairs were correlated to each other.

4.2 Organized Trial Data

Using the initial trial analysis, it was observed that the data grouped into two subsets, each with a similar linear correlation between individual data points. Each trial contained one series that fit most of the data (subsequently referred to as Series 1) and a second series that fit the trial outliers (subsequently referred to as Series 2).

![Figure 10: Visualization of Trial 1 data in Microsoft Excel.](image)

For each series in an individual trial, the respective series trends predict the average dose within approximately 6% (0.15 Gy). Though this value indicates that the fit of these series is very good, a truly successful real-time beam monitor should be able to blindly distinguish which measurements go in which series. Otherwise, a second dose verification will be needed, defeating the purpose of the reusable, real-time beam monitor. The factors of correlation were fit using a simple linear correlation. The data collected over the four relevant trials was plotted in Python (then transferred over to Microsoft Excel for neatness and record-keeping purposes).

4.3 Notable Relations and Post-Experiment Analysis

Each outlier series consists of average dose measurements approximately 0.45 Gy higher than its respective Series 1 predicts. These outliers occur consecutively and are consistent with non-outliers
Figure 11: An example of the dual-series trend observed in Trial 2. Further data visualizations for Trials 3 and 5 may be seen in the appendix.

4.4 Variation in Dose Across Trials

On a positive note, Trial 4 marked the first successfully correlated trial run. This trial creates a baseline so that we can further examine the difference between a fully correlated dataset versus the dual series trend observed in past trials.

Using the full dataset collected over the five trials, a predictive algorithm was scripted into Python. This algorithm was scripted with the intention of matching a given pulse to its corresponding trend line (out of the three trends mentioned before). The script, CorrectDose.py, was given the dose file as input, along with several other variables extracted from digital oscilloscope readings and photodetector settings (i.e. gain, average/minimum/maximum voltage, pulse width, etc.). This input was broken up into a training group and a test group. CorrectDose.py then used the Python metrics package to blindly identify the most correlated features with the coefficients found from the simple linear plots of each trend (the slope and the intercepts). The script then identifies the one trend (out of the three observed) to match the data. The algorithm has a successful prediction rate of only 65%. Though it matches more than half of the data, this is still not a favorable success rate. The analyses done through both the predictive algorithm and the initial linear regression imply some systematic variable is being overlooked.
5 Discussion of External Factors

As previously mentioned, the organized variance between trial runs and outliers points to a systematic variable being overlooked. This unknown variable could come from a multitude of external factors.

5.1 Regarding Fiber-Optic and Film Consistency

Fiber-optic based detectors are unique in that external environmental factors, such as temperature, pressure, and humidity rarely affect what occurs inside the fiber core. After the irradiation done during this experiment, fiber-optic degradation is unlikely, as it only begins after a large (kGy-scale) dose is accumulated. Though we use ultra high dose rate electrons, the amount of accumulated dose delivered is low due to the 5 microsecond pulse width.

A stable film-dose correlation of EBT3 film has only been studied up to 0.84 Gy per 4 s pulse, in comparison to our 2.5 Gy per 5 microsecond pulse. Within this difference in dose rate, the EBT3 film behavior should be constant [8]. Oversaturation, while unlikely, may be possible, and the film-dose calibration curve could be different at superFLASH dose rates.

5.2 Clinac Stability

The unknown variable seen in the study dataset is most likely due to an unstable property of the beam itself. Scaling at superFLASH dose rates could cause otherwise innocuous changes to produce extreme effects. There are a few likely candidates for systematic sources of dose variation, which will be discussed in the following sections.

Figure 12: Visualization in Excel of successful trial.
5.2.1 A Sidenote about Beam Reproducibility

The mode that produces superFLASH dose rates is not an intended use of the original Varian Clinac 2100C. As previously stated, superFLASH dose rates are achieved through the use of the 6 MV photon mode with a retracted target. The 6 MV photon mode is modified to produce high electron dose rates. This uncharacteristic use of the 6 MV photon mode heavily affects the reproducibility of beam dose, as the Clinac nears the limits of the electron gun. Thus, the beam itself varies in dosage across pulses. The variance of dose across all pulses can be seen below, with the orange lines showing the average film dose of each pulse measured.

Though the variance in measured dose will not affect the studied FOCR-film dose correlation, it is worth noting that this lack of reproducibility and the dual-series trend seen in this study may be derived from similar factors.

5.2.2 Variance in Beam Width

As previously mentioned, the nature of our superFLASH mode nears the limits of the Clinac’s electron gun, possibly causing beam instability. The most probable factor to consider is the variance in beam width. An unstable beam width can cause change over both days and pulses, depending on the rate at which the beam expands and contracts. Due to the relatively small section of film irradiated during this experiment, fluctuation of beam width would not be qualitatively obvious, but the effects on dose scaling can be seen. Measured FOCR is dependent on the length of optical fiber irradiated, as the signal is generated within the fiber optic as opposed to by the beam itself [2]. Thus, variance in beam width would heavily affect the relationship between the FOCR detector output and the actual dose measured. Changing beam width could be due to the multitude of reasons, one being the limiting factors of the electron gun. The Space-Charge Effect would also cause spreading of the beam. Although the space-charge effect usually occurs during multi-pulse experiments, it is worth noting that high dose rate electrons can limit the further emission of electrons from a surface (i.e. electrons in the fiber from previous pulses may be repelling incoming electrons). Changing beam width due to the limits of the electron gun is the most probable cause of the observed dual-series trend.

![Figure 13: An example of dose variation within one trial, using Trial 4.](image)
5.2.3 Temperature Variation

It has been observed that standard FLASH dosage varies with temperature. This phenomenon has been observed specifically with the FLASH irradiator used at RARAF [1]. However, the effects of temperature variation on dose have only been measured over a yearlong timeframe, so the impact of day-to-day temperature fluctuations is unknown.

![Figure 14: A graph of dose variation due to temperature fluctuation over a year.](image)

6 Summary and Conclusions

Studies done on the FLASH effect show that high dose rate delivery causes a protective effect in normal tissue. Taking advantage of this phenomenon could lead to major advancements in cancer treatment. Specifically, further research into the optimal dose rate for the FLASH effect may bypass the limits of conventional radiation therapy and allow us to better treat tumors near critical organs. This report discussed a possible dosimetry method for single-pulse irradiations at ultra high dose rates (locally nicknamed 'superFLASH' dose rates).

The proposed system is based on the measurement of fiber-optic Cherenkov emission (FOCR). A total of five trials were completed using the methods described above. The successful complete correlation seen in Trial 4 demonstrates that the FOCR system does operate as intended, when certain conditions in the accelerator hall line up. A standard predictive algorithm was scripted in Python post-analysis, with a focus on predicting trend coefficients based on the collected trial data. As a result, the algorithm had an accuracy rate of 65%. The accuracy rate of the predictive algorithm and the results of the initial analysis point to an unknown variable that remains unaccounted for. Before the FOCR system can be used to monitor superFLASH mode experiments consistently and accurately, this variable must be identified and factored into the system calculations. The aforementioned variable is most likely to be variance in the electron beam width. Change in the beam width is more likely to affect fiber-optic output, as the intensity and amount of Cherenkov radiation generated within an optical fiber is dependent on the fraction of fiber irradiated. In contrast, change in beam width would be unnoticeable in the experiment’s film measurements, as the area of the film used was
much less than any possible beam fluctuations would be. This variance in beam width would most likely be caused by electron gun instability.

The successful trial observed demonstrates that the studied FOCR system is a feasible method of monitoring superFLASH experiments in real time. Though there are still unresolved issues with the method, further development of the FOCR system would lead to a more thorough understanding of the upper limits of the FLASH effect, as well as a better understanding of general tumor behavior at ultra high dose rates.

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8 References


9 Appendix

9.1 Visualization of Data for Trials 3 and 5

Figure 15: Trial 3

Figure 16: Trial 5
9.2 Variation in Dose Across Trials

**Figure 17: Trial 1**

**Figure 18: Trial 2**
Figure 19: Trial 3