ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPM059

DEVELOPMENT OF RELIABLE VHEE/FLASH PASSIVE DOSIMETRY METHODS AND PROCEDURES AT CLEAR*

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Abstract

The electron beam at CERN Linear Accelerator for Research (CLEAR) has been employed to study the potential utility of very high energy electrons (VHEE) for radiotherapy, including the so-called FLASH regime. An important part of these studies revolves around the development of reliable dosimetry methods, given that generally accepted standards are partly lacking for electron beams in the 100 MeV range and even more so in the ultra-high dose rates (UHDR) conditions needed for FLASH. Passive dosimetry methods, such as radiochromic films are presumed to be energy- and dose-rate independent and constitute an indispensable tool for VHEE studies. Furthermore, the development and testing of new modalities for active UHDR dosimetry relies heavily on them for validation and cross-calibration. In this context, efforts have been made to establish reliable and systematic approaches for passive dosimetry at CLEAR. This paper describes studies related to the processing of radiochromic films.

INTRODUCTION

In the context of real-time dosimetry studies for high dose-rates at CLEAR, radiochromic films have been the main tool for benchmarking. This is due to the fact that they are passive and their dose rate response is assumed to be linear, as opposed to active devices which often suffer from saturation effects [1]. Another benefit is that they have good two-dimensional spatial resolution. This is of particular importance at CLEAR, a 200 MeV electron linac, which exhibits a Gaussian transverse beam distribution. Two-dimensional information about the dose distribution is thus important when assessing the beam size and the delivered dose. However, the fact that they are passive, single-use detectors which require calibration, makes them a time-consuming tool to use and prone to uncertainties. There are several suggested protocols describing good practices for film dosimetry. Yet, as they are for different applications, they all have a different emphasis on efficiency and accuracy. In order to establish a reliable and reproducible protocol suitable for dosimetric studies at CLEAR, the common parameters entailed in many film dosimetry protocols have been assessed.

* Work supported by the Research Council of Norway (NFR Grant No. 310713) and Centre Hospitalier Universitaire Vaudois (CHUV).
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PREPARATION

Films are consistently cut to 35 × 40.5 mm and engraved using a laser cutter. This both simplifies the preparation, as well as ensuring that they fit inside the 3D-printed sample holders that are used to move samples in and out of the beam in CLEAR [2]. It is however important to ensure that the laser power is not so high that it will damage the film by introducing artifacts. The recommendation is to not use the outer 1 mm if this cutting method is used [3]. After cutting, they are kept in black plastic bags at a location where they will not be exposed to sunlight, as they are highly sensitive to UV light and also temperature increases. All handling of films should be done using gloves or a suction pen to avoid fingerprints or scratches to the film.

CALIBRATION

Various types of Gafchromic™ films covering different dose-ranges are currently being used at CLEAR; EBT-3 (0.1 - 10 Gy), MD-V3 (1 - 100 Gy) and HD-V2 (10 - 1000 Gy). Each production batch of a given type is calibrated at the eRT6 electron linac at Centre Hospitalier Universitaire Vaudois (CHUV) in Lausanne. This facility provides a nominal energy between 5 and 6 MeV and a near-flat beam across the film area [4]. For each calibration set, two films are positioned in front of a calibrated Advanced Markus Chamber within a solid water phantom. Each pair of films are then irradiated in geometric progression, covering the dose-range of interest. This minimises the number of data points needed make a good fit between the data and a function of the form

$$OD_x(D) = -\log\left(\frac{a + bD}{D - c}\right), \quad (1)$$

where OD_x is the optical density for color channel x, D is the calibration dose, and a, b, and c are the parameters to be fitted [5]. For each dose measured by the ion chamber, the corresponding optical density is determined by calculating the mean optical density across a part of the film (omitting the edges) for each of the two films, and then taking the average of the two values. The same process is applied to the background (i.e. unexposed) films to establish a baseline, which is then subtracted from the exposed films to find the net optical density. Figure 1 shows the relationship the measured optical density and the delivered dose for a set of calibration films.

When the parameters a, b and c have been established for a given film batch, Eq. (2) may be used to deduce the dose

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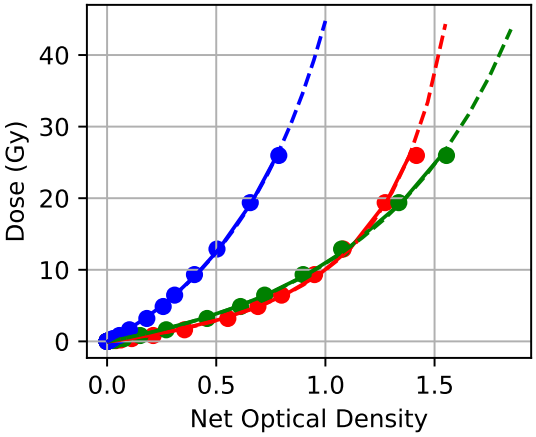

Figure 1: The calibration curve for a batch of EBT-3 films irradiated at eRT6, showing the relationship between optical density and dose for the three color channels. The dots and solid lines correspond to EBT3 calibration data and their corresponding fitted functions. The dashed lines show the extrapolation of this data for higher optical densities.

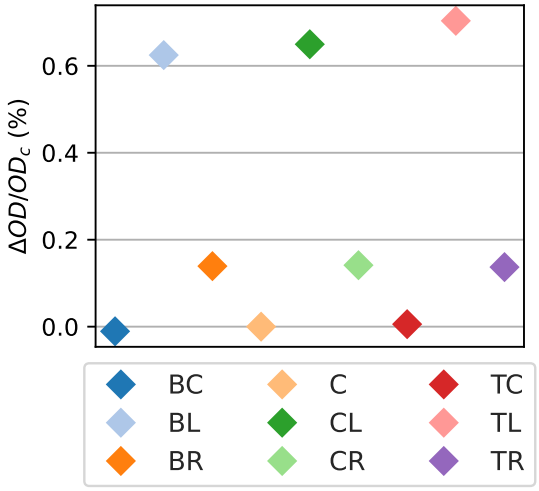

Figure 2: The relative change in optical density w.r.t. the center scan, for subsequent scans at different positions on the scanner plate. Here, T=top, B=bottom, C=centre, L=left and R=right.

from the digitized films.

$$D(OD_x) = \frac{a - c \cdot e^{-OD_x}}{e^{-OD_x} - b} \quad (2)$$

SCANNING

All films are digitized to .tif files at 48 bit (16 bit per RGB channel) and 300 dpi using an Epson Perfection V800 flatbed scanner. The scanning process itself can potentially be a source of error. The first thing to do is to ensure that the scanner plate is as clean as possible to limit the noise in the digitized images. As previously reported, the orientation of the film on the scanner has a significant impact on the optical density, and it is thus crucial to be consistent with scanning orientation, with respect to that of the calibration batch [2]. As for other effects which have been mentioned in literature, an assessment of their magnitude and importance for our application has been made.

Position Effect

It is recommended that the films are always scanned at the centre of the scanner plate, and to be consistent with the scanning position. Figure 2 shows the relative error between eight extremity positions and the center position of the scanner. It is clear that scanning along the left edge of the scanning plate yields the biggest difference, and there is little difference when scanning along a given longitudinal axis. To ensure consistent positioning and orientation a mask may be used, as shown in Ref. [2].

Warm-up Effect

Ensuring a stable scanner temperature throughout the scanning process by performing 5-10 preview scans before digitizing the films has been recommended [6][3]. This is in order to avoid that the first few films in a set are digitized under different (non-random) conditions from the following films.

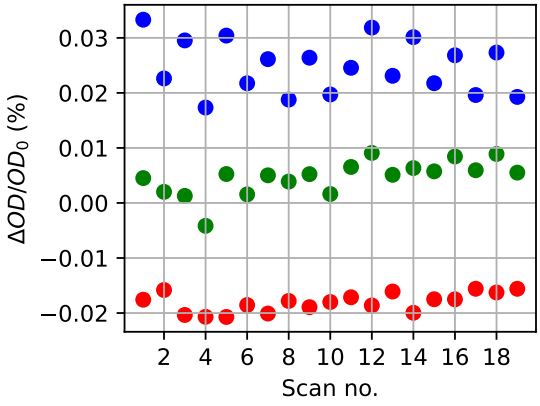

Figure 3: The deviation in optical density relative to the first scan, for subsequent scans of the same film. The colors correspond to the distinct RGB channels.

Figure 3 shows the relative error in optical density w.r.t. the first scan for the three color channels. As the scanner warms up after being switched on, the effect of performing multiple warm-up scans seems almost negligible. However, the fluctuations seems to be more prominent in the beginning, and performing ~ 5 preview scans does not affect the overall scanning time significantly.

Multiple-scan Effect

Several protocols for radiochromic film processing also suggest that averaging over multiple film scans is required in order to limit noise due to scanner fluctuations [3, 6–9].

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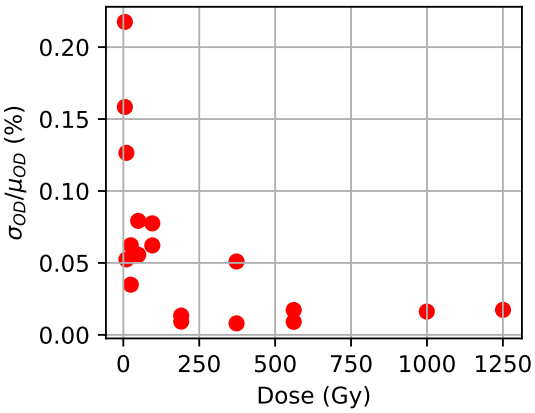

Figure 4: Each dot represents the error in optical density estimated for 5 consecutive scans of the same film for of a set of HD-V2 calibration films.

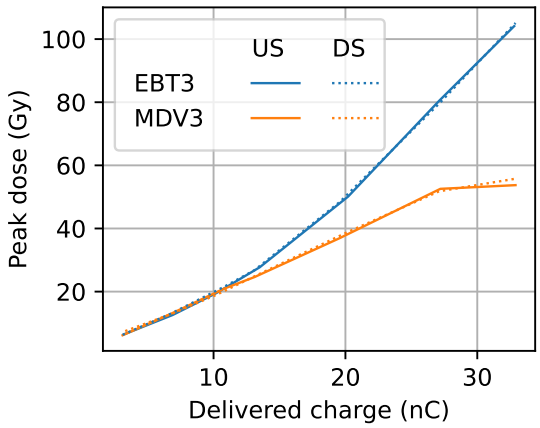

Figure 5: The dose as a function of delivered charge for EBT-3 and MD-V3 films. Here, US=upstream and DS=downstream.

These studies state standard deviations in the order of 0.15 - 0.2 % between consecutive scans.

Figure 4 shows that this is in line with what was found at CLEAR, and that the effect is more significant for lighter films or lower doses. However, performing the consecutive scans shortly after one another, affects the temperature of the film, which in turn affects their coloring. It has however been shown that this scanner-induced coloring can be reversed by waiting up to 15 minutes between scans [10].

Evidently, this comes at a cost of greatly increased processing time. This may be worthwhile in a medical setting, where a small number of films are used for verification and quality assurance. In an experimental setting however, where statistics over a large number of films is directly used for correlation with other variables, this may be accepted as a random error, applied to all films in the set. It is however important to be aware of the effect and its magnitude, in particular in case more precise measurements are required.

DYNAMIC RANGE

According to the manufacturer, the Gafchromic^{TM} EBT-3 films exhibit optimal dose response between 0.2 and 10 Gy, while their dynamic range is stated to be 0.1 - 20 Gy [11]. To test to what extent the optimal range is conservative, and if the full dynamic range can be safely exploited, a test exceeding this range was designed in which EBT3 and MDV3 films were irradiated simultaneously. They were irradiated in water at a water depth of 23 mm using a pre-scattering screen to enlarge the beam. For each target charge/dose, one holder with an EBT3 and an MDV3 film placed back to back, one upstream of the other, were irradiated to ensure that both films were exposed to the same beam. The sequence was repeated with the order of the two films in each holder reverted. Figure 5 shows a clear discrepancy between EBT-3 and MD-V3 for doses higher than 20 Gy. This may be explained by the fact that that the film itself reaches a saturation around the OD values in Figure 1 where the green curve starts getting steep. The slightest change in OD in this region will have a significant impact on the resulting dose.

CONCLUSIONS

The protocol for efficient and reliable film dosimetry at CLEAR is under continuous improvement. As the films are used in large quantities, compromise made between reliability and efficiency is sometimes necessary. For the preparation, scanning, and handling the crucial point is to *always* follow the same procedure as was done for the calibration films in question.

It has been shown that the full dynamic range of the EBT-3 films can be used for dosimetry. That being said, as the dose predictability at CLEAR is currently sub-optimal, it would be advisable to stay below 20 Gy with some margin for EBT-3, in order to avoid over-shooting without the ability to assess the delivered dose.

There are still a few elements of the protocol which need to be evaluated in order to ensure a satisfactory balance between accuracy and efficiency for the applications at CLEAR. Quantifying the calibration drift over time and comparing with the effect of background subtraction would help investigate the validity of the calibration factors and establish a suitable time-interval between re-scans of the calibration films.

Moreover, the effect of using various filters to remove noise should be investigated. Median filters or Wiener filters could both be used to filter out dust particles, and other artifacts which introduce measurement noise that will be amplified when converting to dose [3]. This would simplify the extraction of useful characteristics such as beam size and peak dose. However, such algorithms must be compared and carefully analyzed in terms of image distortion.

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