DOSE MAP BLOOD IRRADIATOR DOSIMETRY SYSTEM: CUSTOMIZED BLOOD EQUIVALENT PHANTOM AND GAFCHROMIC EBT-XD FILM

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ABSTRACT: Blood irradiation is done to sterilize and cease donor T-lymphocytes functionality to avoid Transfusion Associated-Graft Versus Host Disease (TA-GVHD). Dose mapping is the primary means of ensuring that the irradiation process is being conducted correctly. The aim of this study is to measure the minimum, maximum and central absorbed gamma radiation dose delivered at the newly customized blood equivalent phantom using a Gafchromic EBT-XD film. A Gammacell 3000 Elan Blood Irradiator with Cesium-137 source was used. To obtain the dose calibration curves, the films were placed at the center of a phantom and irradiated with the dose range from 5 Gy to 35 Gy with one unirradiated film as a control. The dose calibration curve was plotted using red, green and blue channels. For the dose mapping measurement, the irradiation exposure of 9.03 minutes was used to deliver a central dose of 25 Gy to the film. The response of the film will be compared with the GC Dose Mapping Report 2022 which used a water equivalent medium as a phantom. For the calibration curve, the red channel of the film was utilized in this study as it had a higher signal than the other channel. The doses obtained at central, minimum and maximum using EBT-XD film with customized blood equivalent phantom were in agreement with that obtained from GC Dose Mapping Report 2022 to be within ±7.6%, ±8.51% and ±9.95% respectively. We concluded that the customized blood equivalent phantom together with EBT-XD film has a potential to map the dose in blood irradiator accurately. The doses obtained from EBT-XD film were in the range of doses needed to inhibit the proliferation of the T-lymphocytes with central, minimum and maximum doses (26.9 Gy, 17.2 Gy, 35.7 Gy).

***KEYWORDS**: Blood Irradiator, Cesium-137, Gafchromic EBT-XD Film, Dose Map, Blood Equivalent Phantom*

1.0 INTRODUCTION

Blood transfusion is a vital component of every country's health service. It can be a life-saving intervention for severe, acute anemia, but mistakes in the transfusion process can be life-threatening, either immediately or years later through transmission of infectious agents [1]. For example, transfusion associated-graft versus host disease (TA-GVHD) which is identifies as an uncommon disease that could occur after an unirradiated blood transfusion to immunocompromised recipient such as bone marrow transplant patients, patients with malignancies receiving aggressive chemotherapy and persons with congenital immune deficiency syndromes, where the recipient's immune responses are incapable of effectively eliminating donor leukocytes, permitting unabated responses of the donor T-lymphocytes [2].

Blood irradiation is done to sterilize and cease donor T-lymphocytes functionality to avoid immunological reaction where it triggers hostile reaction due to presence of foreign cells from the recipient's body. This disease is known as TA-GVHD) and is treated by utilizing of at least 25 Gy to 50 Gy gamma irradiation from either Cs-137 or Co-60 using a specialized irradiation machine called blood irradiator, enough even for use towards pediatrics and transplant patients [3]. Sterilization of T-lymphocytes is done by damaging its Deoxyribonucleic Acid (DNA) and arrest responses to allogeneic cells [4]. Utilization other than gamma sources for T-cells sterilization are also viable for X-rays that includes self-constrained X-ray (bremsstrahlung), medical linear X-ray (bremsstrahlung), and electron accelerators used primarily for radiotherapy [4,5].

Dose mapping is the primary means to ensure that the irradiation process is being conducted correctly by measuring the maximum and minimum delivery of radiation within a simulated blood component over an area in which a blood component is placed. To achieve this, dose mapping should be performed with sensitive dosimetry techniques [6].

Film dosimeters are often used to map dose in blood irradiators and EBT-XD film is the most appropriate dosimeter for dose verification [3]. Radiochromic film approach, radiation sensitive film is embedded between two halves of a circular-fitting polystyrene plastic phantom [5].

Moroff et al 1997 [6] reported that in practical terms, attenuation is caused when the irradiation enters a liquid, such as water or blood, and will increase as the irradiation transverses to the center point. The edges of the canister are exposed to a greater dose of irradiation compared with the center line because the attenuation is less in the periphery. The generated dose map describes the distribution of the dose, and it is commonly observed in actual practice that the minimum dose is located at the central bottom of the canister.

The dose delivery in irradiation processes is influenced by various physical factors, such as the geometry of the source and sample, the uniformity of the dose distribution within the irradiation volume, and the dose absorption in the sample. Fearon et al 2005 [7] reported that the greatest influence on the dose delivered to the blood product is the source and sample geometry. Therefore, it is importance to perform routine dose validation as recommended by Department of Health and Human Services (1993).

In this study the main objective is to investigate the uniformity of the dosage of radiation delivered to the blood using Caesium-137 (Cs-137) gamma source blood irradiator with newly customized blood equivalent phantom using Gafchromic EBT-XD by examining the integrity of central, minimum, and maximum doses. It is important to ensure that the given doses are sufficient to prevent graft-versus-host disease in both pediatric and transplant patients. The dose differences is compared to the irradiation results from the previous GC Dose Mapping Report 2022 by using water equivalent phantom [8]. The final results shall conclude the suitable phantom to be utilized when undergoing a clinical experiment or routine dose validation of blood irradiator quality control activities.

2.0 METHODOLOGY

2.1 SAMPLE PREPARATION AND IRRADIATION

For this study the Gammacell 3000 Elan Blood Irradiator located at the Department of Pathology, Hospital Sultan Abdul Aziz Shah (HSAAS) was used. The Gamma irradiation chamber (GIC) components included are a metal canister that is positioned on a rotating turntable with pre-fixed rotational speed, and a free standing pencil-shaped Cs-137 irradiator as gamma source positioned vertically and is operating at 30.9 Terabecquerel (TBq) equivalent to 8.35 Curie (Ci).

The customized blood-equivalent phantom (CIRS Inc, USA) shown in Figure 1, with a density of 1.06 g/cm^3, was used to closely mimic real-life clinical irradiation conditions and act as a substitute for blood. This phantom allows for the calibration of photon and electron beams within 0.5% of true water dose, making it ideal for routine beam constancy inspection.

To create two hemispheric-shaped phantoms of identical size and dimensions, a cylindrical phantom with a diameter of 12 cm and a height of 18 cm was vertically cut from top to bottom. This cutting process allowed for the insertion of Gafchromic EBT-XD films for further evaluation.

Figure 1: Customized blood equivalent phantom

2.2 FILM DOSE CALIBRATION

The EBT-XD Gafchromic films were cut into eight small cuts of 2 cm × 2 cm square and three large cuts of 8 cm × 18 cm rectangle. The films are prepared for calibration curve and dose mapping purposes respectively, where each part has one unirradiated film to act as a control. The films are suitable for absorbed dose measurement of high energy photons. The films are composed of a nominally 25 μm thick active layer sandwiched in between two 125 μm matte-polyester substrates which are unneeded for post-exposure treatment. The active layer contains the active component, a marker dye, stabilizers, and other components giving the film its near energy-independent response [9]. The thickness of the active layer will vary slightly between different production lots. The EBT-XD film has a functional dynamic dose range of 0.1 Gy to 60 Gy, and an efficient optimum dose range of 0.4 Gy to 40 Gy. A highly efficient and effective radiochromic dosimetry system as it has more decreased UV/light sensitivity than its predecessors and unnecessary for non-uniformity correction due to addition of marker dye in the film active layer.

The EBT-XD film dose calibration curve technique implemented was, by irradiating seven out of eight small 2 cm × 2 cm Gafchromic EBT-XD films inside the free-standing Cs-137 sourced blood irradiator. The films were sandwiched in between the hemispheric blood equivalent phantom and positioned at the center of the phantom. Each film was irradiated once at doses of 5 Gy, 10 Gy, 15 Gy, 20 Gy, 25 Gy, 30 Gy, and, 35 Gy. One film is left unirradiated to provide comparison as a control sample during measurement.

The films were placed at the centre inside the blood equivalent phantom then they were sealed from the outside using thin micropore tape to avoid being dislodged during irradiation. After irradiation, the topside of the films is labeled for reference and left for cooling.

The small films are scanned in transmission mode, with no color or sharpness corrections and consistent orientation using a light emitting diode (LED) based flatbed with 48-bit (16-bit per channel) color Microtek ScanMaker 1000 XL (Taiwan) scanner that have three color modes consisting of red, green, and blue color with a resolution of 75 dots per inch (dpi). Scanning was done on the small films with fixed position and saved as tiff. image. The pixel values of the images were then analyzed using ImageJ by draw the ROI with five 0.52 cm × 0.52 cm squares.

The pixel values are translated into net optical density (OD) using Equation 1 and are used to plot the dose calibration graph.

$$\text{Net OD} = OD_{exposed} - OD_{unexposed} = \log 10 \left(\frac{I_{unexposed}}{I_{exposed}}\right) \ldots (1)$$

where $I_{unexposed}$ and $I_{exposed}$ are the readings for unexposed and exposed film pieces, respectively [10].

The dose calibration curves of the films (net OD versus absorbed dose) were plotted individually according to their respective color channels using the RGB channels scan modes to present and choose the best channel to obtain the optimum curves for the films.

2.3 FILM DOSE MAPPING

Absorbed dose mapping was conducted based on the net OD average from two 8 cm × 18 cm sized EBT-XD films. Extrapolation of net OD versus absorbed dose calibration graph is utilized to obtain the absorbed dose of each 1 cm × 1 cm region of the EBT-XD film. This method is done accurately by using the quadratic equation of the best polynomial curve that is close to unity.

3.0 RESULTS AND DISCUSSION

3.1 FILM DOSE CALIBRATION

"The calibration curves obtained for the red, green, and blue channels against an absorbed dose range from 0 to 35 Gy are shown in Figures 2. Based on Figure 2, at doses of 20 Gy and above, the green and yellow channels displayed decreasing OD values as the dose increased. This result contradicts the report written by Palmer et al. in 2015 [11], where the optical density increased with an increasing dose. Higher doses of optical density were applied gradually until saturation was reached. For the red channel, it showed sensitivity at higher dose levels compared to the green and yellow channels, with a net OD value higher than the other channels."

The red channel polynomial curve was found to be the most relevant to be used as net OD versus absorbed dose calibration curve as its goodness-of-fit measure of R^2 is 0.9971, the closest to unity, which is 1. This is followed by the green channel with an R^2 value of 0.9777, and finally the blue channel with an R^2 of 0.8150. The slopes of the response function for the EBT-XD film have shown that the red channel has a broader dynamic range than the other channels. This means that the red channel is significantly more sensitive than the others. Therefore, this study used the red channel of the EBT-XD film since it had a greater dynamic range.

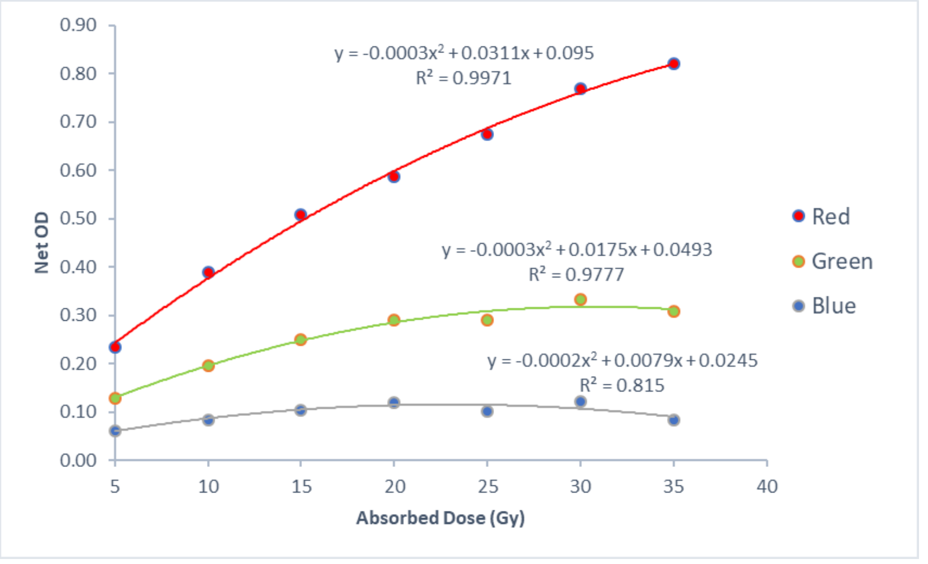

Figure 2: Calibration curve of red, green, and blue channels on Gafchromic EBT-XD films.

3.2 FILM DOSE MAPPING

Extrapolation of films absorbed dose through net OD relationship using red color channel polynomial curved calibration graph made the absorbed dose mapping of large films possible.

By utilizing the OriginPro 2022 software, both Figures 3 and 4 depict color and black-and-white contours. Figure 3 presents the outcomes of the Experimental: Dose mapping of Gafchromic EBT-XD film using the customized blood-equivalent phantom, while Figure 4 shows the results of the GC dose report 2022: Dose Mapping Gafchromic EBT-XD film using the water-equivalent phantom. The colored contour graph on the film is created using red, green, and blue color spectra, representing the absorbed dose of both films. This facilitates dose distribution analysis

From Figure 3, 25 Gy irradiation dose distribution on films were shown to be approximately 25 Gy or larger. In this experiment the absorbed dose at the center of the film is found to be 26.9 Gy, with a central absorbed dose rate of 2.99 Gy/min. The minimum and maximum doses for current study of Gafchromic EBT-XD film irradiation using customized blood equivalent phantom are found to be 17.2 Gy and 35.7 Gy respectively. On the other hand, the results using water equivalent phantom shows that the absorbed dose at the center of the film is 25 Gy with a central absorbed dose rate of 2.78

Gy/min. The minimum and maximum doses are found to be 19.1 Gy and 32.9 Gy respectively.

The maximum dose is located on the most left bottom side of the film since the most affected areas should be on the periphery horizontal sides, while the minimum dose is located on the top side of the film as should on the vertical sides. This is due to the sided irradiation condition by the singular pencil vertically configured Cs-137 source in the blood irradiator [6]. As we can observe from Figure 3 and 4, it is in agreement with Moroff et al 1997 [6] that where areas affected more are at the periphery of the film compared to the center as it is less attenuated by the blood equivalent phantom.

The minimum and maximum absorbed dose range for both figures are different due to the slightly extended period of irradiation for the current study and difference in phantom handling. Overall, from both results, there is a susceptible amount of absorbed dose present at the center of the film to sterilize and halt t-lymphocytes functionality which is 25 Gy [12].

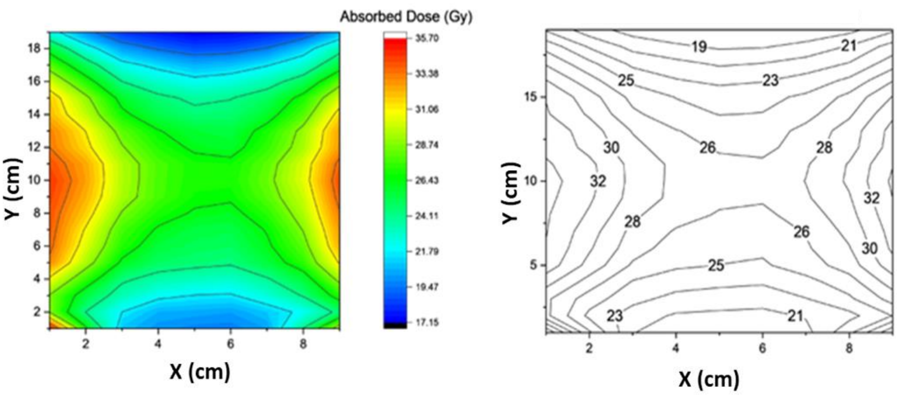

Figure 3: Experimental: Dose mapping of Gafchromic EBT-XD film using customized blood-equivalent phantom; (a) color contour and (b) black and white contour.

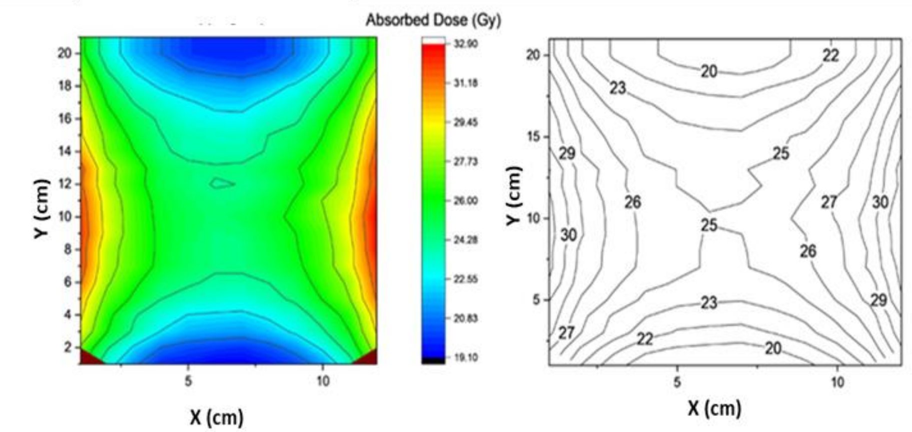

Figure 4: GC dose report 2022: Dose mapping of Gafchromic EBT-XD film using water-equivalent phantom; (a) color contour and (b) black and white contour.

Table 1 summarizes the central, minimum and maximum dose according to experimental using blood equivalent phantom and GC dose mapping report 2022 using water equivalent phantom. The doses obtained at central, minimum and maximum using EBT-XD film with customized blood equivalent phantom were in agreement with that obtained from GC Dose Mapping Report 2022 with water equivalent phantom [8, 13] where the deviations are ±7.6%, ±8.51% and ±9.95% respectively.

Type	Central Dose (Gy)	Central Dose Rate (Gy/ minute)	Maximum Dose (Gy)	Minimum Dose (Gy)
Gafchromic EBT-XD Films (Blood Equivalent Phantom)	26.9	2.99	35.7	17.2
GC Dose Mapping Report, 2022 Gafchromic EBT-XD Films	25.0	2.78	32.9	19.1

(Water Equivalent Phantom)				
Deviation (%)	±7.6	±7.55	±8.51	±9.95

Table 1: Dose for central and dose rate, maximum and minimum dose

4.0 CONCLUSION

The experimental Gafchromic EBT-XD film showed central, minimum, and maximum doses of 26.9 Gy, 17.2 Gy, and 35.7 Gy, respectively. These doses fall within the acceptable range for blood irradiation, which is typically 15 Gy to 50 Gy. The doses obtained at the central, minimum, and maximum positions using the EBT-XD film with the customized blood-equivalent phantom were in agreement with those obtained from the GC Dose Mapping Report 2022, with deviations of ±7.6%, ±8.51%, and ±9.95%, respectively.

Based on the current findings, the customized blood-equivalent phantom offers a highly accurate method for mapping the absorbed dose in a blood irradiator. The use of EBT-XD film for dose mapping with the blood-equivalent phantom is justified by the fact that the measured doses on the film fall within the range necessary to inhibit T-lymphocyte proliferation.

5.0 REFERENCES

[1] Bates, I., & Owusu-ofori, S. (2020). Blood Transfusion. In System-oriented Disease, 229–234.

[2] Fast, L. D. (2015). Preventing transfusion-Associated graft-versus-host disease : state of the art. International Journal of Clinical Transfusion Medicine, (2), 1–6.

[3] Syafinaz, N, Mohd Roslee, A. Nur Amalina, & M. N. Noramaliza. (2020.) Dose Mapping of Gamma Irradiation Chamber (GIC). Asian Journal of Medical Technology (AJMedTech) 2(1): 49-57.

[4] Gòes, E. G., Borges, J. C., Covas, D. T., Orellana, M. D., Palma, P. V. B., Morais, F. R., & Pelá, C. A. (2006). Quality Control of Blood Irradiation: Determination T Cells Radiosensitivity To Cobalt-60 Gamma Rays.

[5] Saglam, S., Cakir, A., & Seyfettin, K. (2011). Blood Irradiation. In Modern Approaches To Quality Control (pp. 335–347). Retrieved from http://www.intechopen.com/books/modern-approaches-to-quality-control/blood-irradiation

[6] Moroff, G., & Luban, N. L. . (1997). The Irradiation of Blood and Blood Components to Prevent Graft-Versus-Host Disease: Technical Issues and Guidelines. Transfusion Medicine Reviews, 11(1), 15–26

[7] T. Fearon, V. R. Criss, and N. L. C. Luban, "Blood irradiator dosimetry with BANG polymer gels," vol. 45, pp. 1658–1662, 2005.

[8] Best Theratronics Dosimetry Laboratory. (2022). GC 3000 Dose Mapping Report, Best Theratronics Ltd., Canada, 1-3.

[9] Ashland. Gafchromic™ EBT-XD films. https://www.ashland.com/industries/medical/radiotherapy-films/ebtxd

[10] Dreindl, R., Georg, D., & Stock, M. (2014). Radiochromic film dosimetry: considerations on precision and accuracy for EBT2 and EBT3 type films. Zeitschrift für Medizinische Physik, 24(2), 153-163.

[11] Palmer, A. L., Dimitriadis, A., Nisbet, A., & Clark, C. H. (2015). Evaluation of Gafchromic EBT-XD film, with comparison to EBT3 film, and application in high dose radiotherapy verification. Physics in Medicine & Biology, 60(22), 8741.

[12] Olivo, R. A., Silva, M. V. D., Garcia, F. B., Soares, S., Rodrigues, V., & Moraes-Souza, H. (2015). Evaluation of the effectiveness of packed red blood cell irradiation by a linear accelerator. Revista brasileira de hematologia e hemoterapia, 37, 153-159.

[13] K.S.A.K. Bakar, N.M. Noor, M.F. Hassan, F. Idris, D.A. Bradley. (2023). Dose mapping in Cesium-137 blood irradiator using novel Ge-doped silica optical fibres in comparison with gafchromic EBT-XD film: A preliminary study, Radiation Physics and Chemistry, 209, 111010