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Research Paper

Calibration of Various Detectors for Commissioning of Total Body Irradiation for a New Installation in Maggiore Hospital, Trieste-Italy

Festo Kiragga [1,✉], Rosella Vidimari [2]

1. University of Trieste/The Abdus Salam International Center for Theoretical Physics, 34100 Italy.
2. Department of Medical Physics, Ospedale Maggiore, A.O.U. Ospedali Riuniti di Trieste, Italy.

✉ Corresponding author: Mr. Festo Kiragga, University of Trieste/The Abdus Salam International Center for Theoretical Physics, 34100 Italy, Tel: +256 752141331 Email: jireh4festo@gmail.com

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Abstract

Calibration of detectors: Gafchromic EBT3(GAF) and Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) was done under reference conditions for use in Total Body Irradiation (TBI) conditions. Three Source Axis Distances (SAD) were chosen: 5m, 4.5 m, and 4m with minimal or no backscatter from the wall. Lateral-Lateral (LL), gantry angle 90°, collimator angle 0°, and 6 MV energy were chosen with respect to the nature of the bunker. Percentage Depth Doses (PDDs) were evaluated, first with a big water phantom using calibrated dosimetry diode, P and then also with RW3 slab phantom (30 x 30 x 30 cm^3) at the three positions using GAF. Afterwards, the PDDs were then compared allowing the beam to be characterized in different setups. MOSFETs calibration factors corresponding to each channel were also obtained by first measuring the average dose with a Farmer chamber under reference conditions in the same position. Then the MOSFETs were cross-calibrated against the Farmer chamber. A length of 140 cm (pediatric) was found to be in the flatness region with a dose variation of 3%. GAF, and MOSFETs were calibrated and a calibration curve was plotted for GAF while a table of calibration factors was made for the MOSFETs to be used in TBI conditions. A dose variation of less than 2% was achieved between the Farmer chamber and GAF readings at similar points in the RW3 phantom. The beam characteristics were important parameters to understand the behavior of the beam in non-reference conditions (TBI conditions). These were within the tolerance range as dose variations of up to ± 10% are allowed in TBI conditions. The doses measured with the calibrated Farmer chamber and GAF were compared with less than 2% difference and this meant that the GAF can be used in any TBI setup. Therefore, the bunker was found fit for carrying out the TBI technique, particularly for pediatrics.

Keywords: Total Body Irradiation; beam; MOSFETs; Gafchromic; Ionisation chamber.

Introduction

Any quality Bone Marrow Transplant (BMT) requires Total Body Irradiation (TBI) as part of the preparatory conditioning regimen (Podgorsak, 2005). A BMT replaces the patient's diseased bone marrow with stem cells from a healthy donor (allogenic transplant) or from the patient himself (autologous transplant). These cells reconstitute the recipient's hematopoietic and immune systems, thus providing a cure. The main action of TBI is undoubtedly total (by means of supra-lethal doses) or partial (with sub-myeloablative doses) eradication of radiosensitive hematological malignancies (ISTISAN, 2005).

TBI is a special radiotherapeutic technique that delivers to a patient's whole body a dose uniform to within ± 10%

of the prescribed dose. It is primarily used for suppressing the immune system before a BMT but can also be used as a means of eradicating malignant cells (e.g., leukemias, lymphomas, and certain solid tumors) or cell populations with genetic disorders.

TBI can be applied in one of these three ways in hematology and oncology: *myeloablative TBI*, i.e., supra-lethal doses of radiotherapy (7-15.75 Gy) is administered in association with one or more chemotherapy drugs, *non-myeloablative TBI*, i.e., low-dose TBI (≤ 2 Gy) is administered in one session and *low dose cytoablative TBI*, i.e., low-dose (1-1.5 Gy) TBI fractionated into 10 - 15 cGy/day. This depends on the nature and history of the patient (ISITSAN, 2005).

A study by Mikell *et al.* (2014) on the significant difference between patients that underwent myeloablative TBI and reduced intensity TBI revealed that there were no significant differences between the two.

TBI requires many specialists to establish individual parameters for each patient (energy, fractionation, dose rate, single dose, total dose, dose to the lung, etc.) and this implies the need for a multi-disciplinary team, with each member having a clearly delineated sphere of action. The roles of the interdisciplinary team are well defined: the hematologist proposes treatment; the radiation oncologist discusses it with him, accepts it as suitable for a given clinical condition and selects the TBI schedule, the medical physicist establishes the dosimetry and actively works with the radiation oncologist who is ultimately responsible for therapy.

In-vivo dosimetry is of critical relevance before any TBI is carried out because of the complexity in calculation of the dose at different points in the patient and also due to the increased risk of patient movements due to the long duration of treatment. *In-vivo* dosimetry refers to measuring the dose received by the patient during treatment. Examples of *In-vivo* dosimeters include; Thermoluminiscent dosimeters (TLDs), diodes and Metal Oxide Semi-Conductor Field Effect Transistors (MOSFETs).

Studies by Oliveira *et al.* (2014) have been made on the application of TLDs and semi-conductor detectors for pre-treatment verification. This has shown the applicability of especially TLDs for quality control thus demonstrating the value of thermoluminescent dosimetry as a treatment verification system and its effectiveness as part of a program of quality assurance in radiotherapy. However, in this study, we opted for Gafchromic EBT^3 and MOSFETS for *In-vivo* dosimetry because of their availability in the Department.

The challenge for *In-vivo* dosimetry in TBI conditions is in three parts: to determine the dose at the desired point, that is, the mid-pelvis or mid-abdomen, to estimate the uniformity of the dose distribution at different locations in cranio-caudal direction and to monitor the dose distribution at the organs at risk (Van Dam, 1994).

The delivery of an accurate dose to the patient is dependent firstly on the accuracy to which a radiation beam can be calibrated in a uniform water-like medium and secondly, the dose at any point of interest within the patient must be calculated and correlated to this calibration dose. However, there are a number of physical parameters that should be considered and optimized for each institution implementing TBI. The most common parameters relate to: the energy of radiation, treatment distance, choice of Antero-Posterior (AP) treatments or lateral treatments or a combination of these and dose rate (Van Dyk, 1987).

Therefore, the choice of the technique is influenced by the size of the room and the source of radiation, whether cobalt-60 or linear accelerator (LINAC). For Maggiore Hospital, the room to be used is large enough (6 m from the isocenter to the wall). It’s to be used for pediatric patients to be treated in supine position. The project therefore aims at commissioning TBI in a new installation at Maggiore Hospital in Trieste for pediatric patients.

Material and Methods

Commissioning of TBI involves the use of various detectors to gain an understanding of the depth dose distribution, absorption through various attenuators, behavior of the beam at different distances from the source and other parameters which are critical before treatment commences. The following phantoms were used to characterize the beam and also to calibrate the detectors in TBI conditions.

The Water Phantom

The large MP3 water tank from PTW Freiburg is suitable for very large field measurements. Beam incidence may be vertical, horizontal or oblique. The horizontal detector moving range is 500 mm x 500 mm and the vertical range is 407.5 mm. The 20 mm thick acrylic walls and bottom do not bulge during prolonged period of use and feature etched lines for precise tank alignment. Precision stepper motors are mounted close above the tank making it possible to adjust distances between the LINAC head and the water surface as small as 120 mm. They provide for high detector moving speed of 50 mm/s and high positioning accuracy of ± 0.1 mm.

Plexiglas

Polymethyl methacrylate (PMMA) also known as acrylic or acrylic glass as well as by the trade names; Crylux, Plexiglas, Acrylite, Lucite and Perspex among others is a transparent thermoplastic often used in sheet form as a light weight or sharter-resistant alternative to glass.

RW3 slab phantom

The acrylic slab phantom is designed for the use with photon radiation in the range from 70 kV up to 50 MV and for electron radiation from 1 MeV up to 50 MeV. The RW3 phantom is water-equivalent in the energy ranges from ^{60}Co to 25 MV photons and from 4 MeV to 25 MeV electrons. The phantoms are used for monitor calibration and quality control measurements.

Depth dose measurements were made by varying the measuring depth. To provide for backscatter, slabs were placed below the radiation detector. The slab phantoms each consist of 1 plate of 1 mm thick, 2 plates each 2 mm thick, 1 plate 5 mm thick and 29 plates each 10 mm thick. This combination makes it possible to vary the measuring depth in increments of 1 mm. The size of the complete phantoms is 30 cm x 30 cm x 30 cm. Each plate is precisely machined for a thickness tolerance of only ± 0.1 mm.

Alderson Radiotherapy Phantom

The Alderson Radiation Therapy phantom (ART) has been in use for over 30 years. It has been refined and improved in both design and materials. ART phantoms are molded of tissue-equivalent material; they are designed within highly sophisticated technological constraints and follow "ICRU-44 Report -Tissue Substitutes in Radiation Dosimetry and Measurement" (Allisy, 1989). They are also designed for accuracy and ease of use.

Gafchromic EBT^3 films

Gafchromic EBT^3 is designed for the measurement of absorbed doses of ionizing radiation. It is particularly suited for high-energy photons. The dynamic range of this film is designed for best performance in the dose range from 0.2 to 10 Gy making it suitable for many applications. The film is comprised of an active layer, nominally 28 μm thick, sandwiched between two 125 μm matte-polyester substrates.

Metal Oxide Semiconductor Field Effect Transistors (MOSFETs)

MOSFETs can be used in radiation therapy applications. The main characteristics of MOSFETs as shown in Figure 2.0 are: small size, permanent storage of dose, dose rate independence, instant readout, portability, requirement of low power, detector irradiation without the need of cables, and negligible attenuation of the radiation. These characteristics make them particularly suitable for *In-vivo* dosimetry, dosimetry of small beams, and of brachytherapy (Scalchi and Francescon, 1998).

Ionisation chambers (IC)

Now two ionisation chambers were also used but for purposes of cross-calibration and PDD measurements: The Farmer chamber (30013) which is a standard ionization chamber for absolute dosimetry was used to cross-calibrate the GAF and MOSFETs in reference conditions. The procedure is explained in the next sections – "Calibration of dosimeters". The second was the dosimetry diode P, a p-type Silicon diode designed for dose distribution measurements in high energy photons with a range of applications. This was used for PDD measurements in the water tank and the procedure is explained under the section - "PDD measurements in the water tank". Table 1 contains some of the ionisation chambers' specifications.

Table 1 . Specifications for the ionisation chambers

Chamber type	Manufacturer/Model number	Sensitive volume (cc)	Ion collection time (μs)	Nominal response (nC/Gy)	Water proof
Farmer	PTW 30013	0.6	140	0.2	Yes
Dosimetry Diode P	Team Best (Type 60016)	0.03	Not applicable	9	Yes

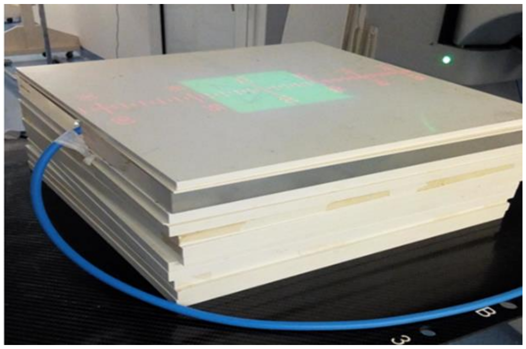

Figure 1. Set up of the phantom for dose calibration with ionization chamber and Gafchromic.

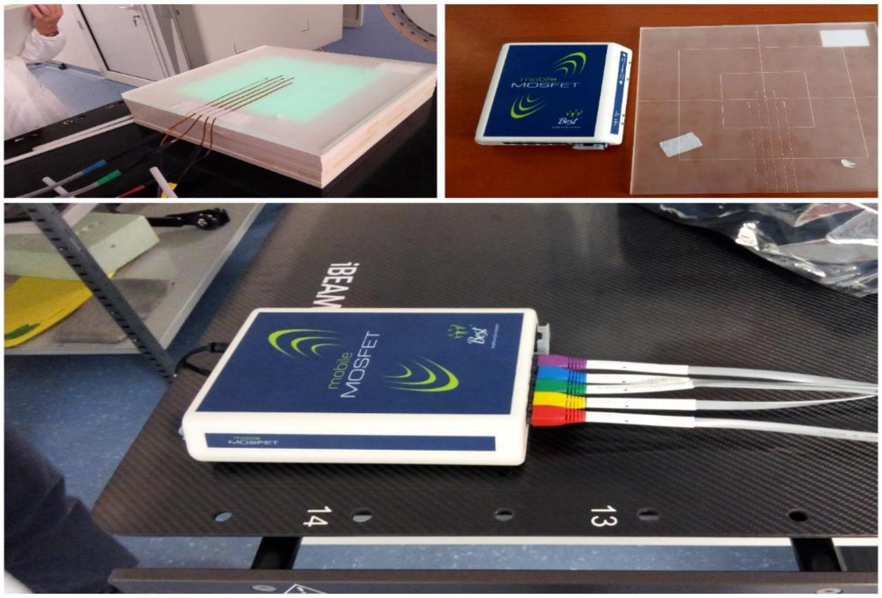

Figure 2. The mobile MOSFET (bottom) and the calibration jig (top-left and right).

Calibration of dosimeters

The procedure to calibrate the Gafchromic EBT^3 followed the steps proposed by Casanova Borca et al. (2013). The marked pieces of Gafchromic paper of about 5 x 5 cm^2 were marked, cut and kept from ambient conditions. They were scanned with a normal EPSON scanner switched on 30 minutes earlier for warm up to read the background dose using *ImageJ*. *ImageJ* is an Open-Source public domain image processing software with power and flexibility allow it to be used as a research tool in many disciplines. It can be used to display, annotate, edit, calibrate, measure, analyze, process and save raster (row and column) image data and other purposes (https://serc.carleton.edu, 2023). Then the films were cross-calibrated against the Farmer chamber in reference conditions (Source Surface Distance (SSD) - 100 cm, field size 10 x 10 cm^2, 6 MV photon beam in a PTW RW3 slab phantom with a build-up of 16 mm) with each piece of film irradiated in the same position. The range of Monitor Units (MUs) covered a dose range of 0 – 3 Gy. The irradiated films were also scanned and the dose read out. The dose and optical density were then calculated. A curve of dose versus optical density was then plotted and a polynomial fitting to the data was then extracted for the red channel. Using this calibration curve, the dose for any optical density can be easily computed.

The calibration of the MOSFET was done using the MOSFET Calibration Jig (TN-RD-57-30) in conjunction with the mobile MOSFET Dose Verification system (TN-RD-16).

The system was connected 20 minutes before irradiation for warm-up. The MOSFETs were connected to the reader (mobile MOSFET) using the default color setting in the software with Red coming first and purple last as shown in Figure 2.0 above. Then using the Farmer chamber set-up in standard conditions (100 cm SSD, gantry 0^o, 10 x 10 cm^2 field size, build-up 15 mm, RW3 as phantom material and 100 MUs), an average dose of irradiations was got from the electrometer. The measurement was repeated under similar conditions except for the field size of 20 x 20 cm^2 and the dose recorded for the following MOSFETs calibration.

A dose that was read by the Farmer chamber was used in the operational software on a computer and a correction factor was then derived by the software. This was repeated three (3) times until the average correction factor (calibration factor) was accepted. By this, the MOSFETs had been calibrated. The set of calibration factors for each single MOSFET was then stored for later use in TBI dose measurements.

Set up of measurements in TBI conditions

Three kinds of setups were considered depending on the height of patients to be treated. For ease of measurements and repeatability of the setup of the treatment, distances were measured from the wall. The largest field size of 35 x 35 cm^2 was used with the gantry at 90^o.

SET-UP 1: *Maximum patient height 170 cm*

SAD = 5.0 m, patient axis and wall distance equal to 2.0m

Dose rate = 12.5 cGy/min for nominal dose rate of 400

SET-UP 2: *Maximum patient height 150 cm*

SAD = 4.5 m, patient axis to wall distance equal to 2.5 m

Dose rate = 15.5 cGy/min for nominal dose rate of 400

SET-UP 3: <u>*Maximum patient height 130 cm*</u>

SAD = 4.0 m, patient axis to wall distance equal to 3.0 m

Dose rate = 24.2 cGy/min for nominal dose rate of 400.

Measurements in TBI conditions: Percentage Depth Dose (PDD) measurements in a water phantom

PDD measurements were done using the Photon diode P and the following setup was followed: Gantry 90°, Field size: 35 x 35 cm^2, phantom material: water, dose rate: max, reference positions: 2 m, 2.5 m and 3 m from the wall. The diode was able to measure at a distance 0.5 cm from the inner surface of the water phantom (or 2.5 cm from the surface) as this was the maximum it could go horizontally. The diode movement was parallel to the direction of the beam axis.

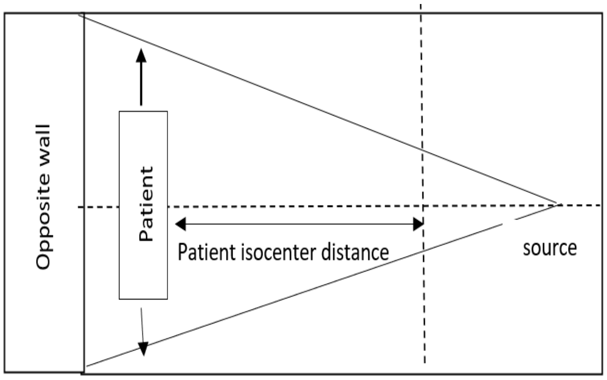

Figure 3. Image of CT ion chamber (A) and electrometer (B) (PTW chamber type 30009, Freiburg, Germany).

Results and Discussion

Gafchromic EBT^3 and Ionisation chamber

The Gafchromic EBT^3 film was calibrated following the protocol outlined in the section above and the results were obtained and analyzed as shown in Tables 2 and 3.

Table 2. Warm-up measurements of the Ionization chamber (IC) at 100 MU

Ionisation Chamber (IC) measurements	**L_1 (cGy)**	**L_2 (cGy)**	**L_3 (cGy)**	**L_4 (cGy)**	**Mean dose (cGy)**
	86.97	86.88	86.9	86.94	86.92 ± 0.04

Table 3. Comparison of doses from GAF and IC

GAF	**Mean background**	**Mean irradiated**	**Optical density**	**Monitor Units (MU)**	**GAF Dose (cGy)**	**IC dose (cGy)**	**Deviation (%)**
1	44565	39632	0.0509	50	43.5	42.9	1.4
2	44654	37541	0.0754	80	69.5	68.8	1.0
3	44452	35233	0.1009	115	100.0	99.7	0.3
4	44571	33882	0.1191	140	121.7	123.8	-1.7
5	44786	32258	0.1425	180	156.5	157.5	-0.7
6	44492	31301	0.1527	200	173.8	173.1	0.4
7	44067	29871	0.1689	230	199.9	199.0	0.5
8	43970	28151	0.1937	280	243.4	241.3	0.8
9	44147	27507	0.2054	300	260.8	262.5	-0.7
10	44233	26191	0.2276	350	304.2	304.3	0.0

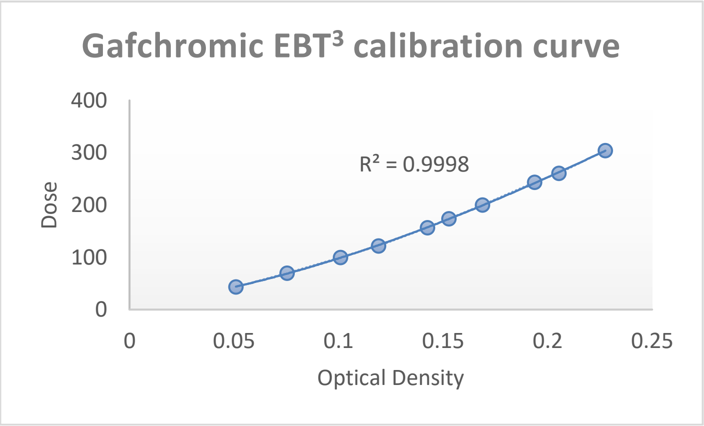

Figure 4. Calibration curve for Gafchromic EBT^3 film.

The results in Table 2 are warm-up measurements that the chamber read at 100 MU. Before any measurements are done, this process is necessary such that consistent and accurate results are obtained. Three to four results are necessary for this process. The results in Table 3 show measured values for Gafchromic EBT^3 films versus the ionization chamber (IC). The percentage deviation of doses in the two readings is less than 2% which is a good trend. This implies that GAF films can be used in TBI conditions where a dose variation of ±10% is allowed. A calibration curve of optical density vs dose was plotted for Gafchromic EBT^3 using data from Table 3.

From the calibration curve in Figure 4 above, a polynomial fitting the data was found (dotted), an equation: $y = -4047.1x^3 + 4438x^2 + 502.25x + 7.3887$. It was therefore possible to get the dose for any optical density by using the calibration equation. The data also shows an almost perfect linear correlation (R=0.9998) between the optical density and the dose which was read out from the films. Generally, since the doses in TBI conditions are low, we choose many points at low doses (0 – 300 cGy) or 0 – 350 MU.

MOSFETs

The MOSFETs were also calibrated according to the procedure laid out in the section on "Calibration of dosimeters". A list of calibration factors for each single MOSFET was obtained according to the color code of the channel.

Table 4. Calibration factors for MOSFETs

S/N	Color code	Calibration factor (cGy/mV)
1	Red	1.10
2	Yellow	1.08
3	Green	1.07
4	Blue	1.09
5	purple	1.10

The calibration factors in Table 4 were to be used to find the doses at selected points in Gy for the patient during treatment. The measured dose was a small voltage (mV) or pulse such that the dose measured (cGy) at any point of the patient is obtained from a product of calibration factor (cGy/mV) and the measured voltage (mV).

PDD evaluation in different set-ups: PDD measured using the dosimetry diode P in a water phantom

PDD was evaluated using a diode with the water phantom. The measured profile was performed at gantry 90^o and the detector was aligned to the beam axis. The starting point of measurement was at 0.5 cm from the tank wall or from the internal surface to avoid a collision with the diode. After that, water profiles started from 2.5 cm and covered the entire phantom width.

As seen in Figure 5, the PDD distribution at all the setups was the same. Only small variations existed possibly due to movements of setups to various positions. This meant that any of the three positions from the wall was acceptable, save for other parameters.

PDD measured in RW3 using EBT^3

To study the behaviour of PDD in the build-up region, measurements were acquired with the calibrated Gafchromic in PTW RW3 slab phantom. The phantom size was 30x30x30 cm3 and Gafchromic film pieces were inserted almost every cm. The measurements were repeated for every TBI condition of SSD, with and without a spoiler. This data was subsequently compared with water PDD. 4000 MU was used in this case to give a substantial dose to the Gafchromic in TBI conditions. Figure 6 shows the results obtained.

From Figure 6, the PDD of 2m and 3m without a spoiler followed an expected trend except at a depth of 70 mm where they join and cross in unexpected directions. The same happened for the same depth for those with a spoiler. The meaning of this trend was not very clear and thus, a deeper study was needed.

Beam characteristics

The beam flatness and symmetry were investigated from the data acquired by the PTW MEPHYSTO software for the 6MV photon beam and a profile automatically generated. Field flatness for photon beams is traditionally the variation of dose relative to the central axis over the central 80% of the field size (flatness region) at a 10-cm depth in a plane perpendicular to the central axis. A dose variation of ±10% is considered acceptable in non-reference (TBI conditions). For symmetry, in the reference region, the dose should not differ more than 2% at any pair of points situated symmetrically with respect to the central ray. Therefore, from the data in the profile in Figure 7, dose variation in flatness region was 3% and symmetry <1%. These parameters are acceptable in TBI conditions.

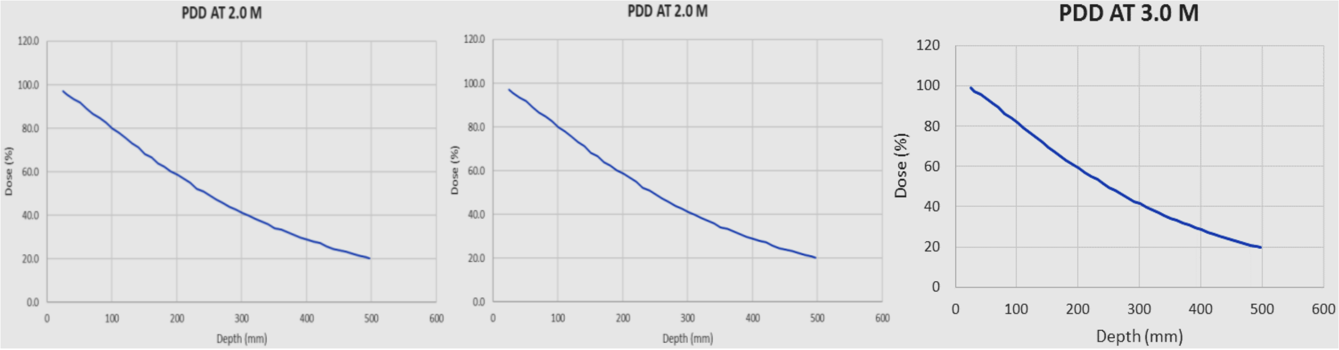

Figure 5. PDDs at 2, 2.5 and 3 m from the wall.

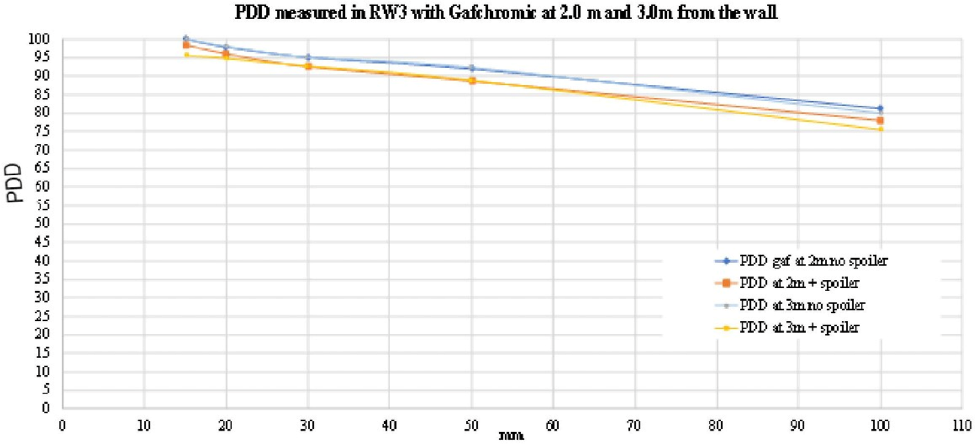

Figure 6. Comparison of PDD at different depth.

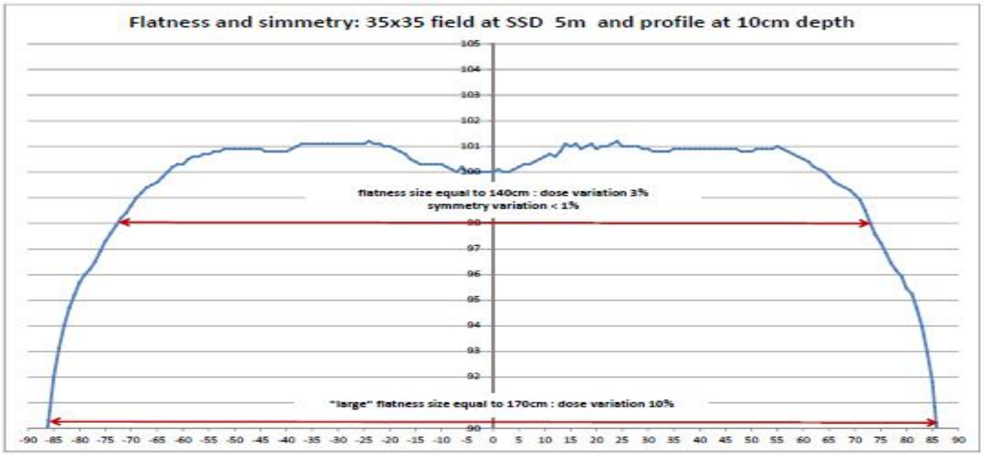

Figure 7. Comparison of PDD at different depth.

Conclusion

The detectors: EBT^3 Gafchromic (GAF) and MOSFETs were calibrated for measurement in TBI conditions and a calibration curve was plotted for GAF while a table of calibration factors was made for the MOSFETs. A dose variation of less than 2% was achieved between Farmer chamber and GAF readings at similar points in the RW3 phantom. Additionally, the dose distribution characteristics (PDD) were also investigated using a dosimetry diode, P in a water tank. They were found to follow a similar trend at 2, 2.5 and 3m. This indicated that other factors kept constant, a uniform dose distribution can be achieved at all the three distances. The beam characteristics were also acceptable as a dose variation of 3% in the flatness region was within the acceptable range of ±10%. Therefore, this data gave a good background for understanding the dose and beam characteristics as well as the dosimeters in non-reference conditions. The study also confirms that the bunker can be used for TBI for paediatric patients.

Abbreviations

GAF: Gafchromic EBT^3; IC: Ionisation Chamber; MOSFET: Metal Oxide Semi-conductor Field Effect Transistor; PDD: Percentage Depth Dose (PDD); RW3: PTW slab phantom; TBI: Total Body Irradiation.

Author Contributions

All authors contributed to this study. All authors gave their final approval.

Competing Interests

We declare no competing interests.

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