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Can Gafchromic EBT3 films effectively characterize small fields of 6 MV unflattened photon beams of Cyberknife system?

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Abstract

Shielded silicon diodes are commonly employed in commissioning of Cyberknife 6 MV photon beams. This study aims to measure output factors, off centered ratio (OCR), percentage depth dose (PDD) of 6 MV photons using shielded and unshielded diodes and to compare with Gafchromic EBT3 film measurements to investigate whether EBT3 could effectively characterize small 6 MV photon beams. Output factors, OCR and PDD were measured with shielded and unshielded silicon detectors in a radiation field analyzer system at reference condition. Water equivalent solid phantom were used while irradiating EBT3 films. From multiuser data, diodes underestimated output factor by 3% for collimator fields ≤ 10 mm, while EBT3 underestimated the output factor by 3.9% for 5 mm collimator. 1D Gamma analysis of OCR between diode and film, results in gamma ≤ 1 for all measured points with 1 mm distance to agreement (DTA) and 1% relative dose difference (DD). Dose at surface is overestimated with diodes compared to EBT3. PDD results were within 2% relative dose values between diode and EBT3 except for 5 mm collimator. Except for small collimator fields of up to 10 mm, results of output factor, OCR, PDD of all detectors used in this study exhibited similar results. Relative dose measurements with Gafchromic EBT3 in this work show that EBT3 films can be used effectively as an independent tool to verify commissioning beam data of small fields only after careful verification of methodology for any systematic errors with appropriate readout procedure.

Key words: diode detectors; GafChromic EBT3; small fields; output factor; off centered ratio; percentage depth dose.

Introduction

With the advent of new technologies in radiotherapy, the complexity of treatment and uncertainties associated with it are on the rise. Cyberknife robotic radiosurgery unit (Accuray Inc, USA) uses multiple small pencil beams to treat tumors with high doses and can deliver greater conformal treatment with minimal normal tissue damage [1]. This system is used for stereotactic radiosurgery (SRS) and stereotactic body radiotherapy (SBRT) applications. The efficacy of SRS [2,3] and SBRT [4-6] applications were demonstrated by large body of literature. In recent years, small field dosimetry gain increased attention and several investigations are going on, to address the issues associated with small fields [7-11]. Absence of lateral electronic equilibrium and steep dose gradients of small-field photon beams require special attention as against broad beam characteristics to accurately determine the dose. Many criteria should be met for ideal dosimetry conditions for small fields say detector resolution, minimum radiation field perturbation etc. Volume of detector plays a major role in accurate determination of small field dose. The diode detectors are characterized by its high sensitivity to ionizing radiation and thus can be made with small sensitive volumes. Several diode models are available commercially. One of the main concerns is the choice of detector in measuring accurate dose. In this work, shielded (Diode P), unshielded (Diode E) silicon diode detectors and Gafchromic EBT3 films were used to measure beam data for Cyberknife fixed conical collimators. Further, the effectiveness of Gafchromic EBT3 films as an independent tool to check the beam commissioning data was analyzed.

Materials and methods

Cyberknife G4 system uses 6 MV unflattened photon beam energy with maximum dose rate of 600 MU/min. Linear accelerator (linac) is mounted on a robot and has 6 degrees of freedom to deliver non-coplanar, non isocentric treatment beams. Treatment fields are defined by fixed secondary collimators, which are circular cones of diameter 5, 7.5, 10, 12.5, 15, 20, 25, 30, 35, 40, 50, 60 mm and projected at source to detector plane of 800 mm. The detectors used in this study are two silicon diodes with disk shaped sensitive volume perpendicular to detector axis and Gafchromic EBT3 films (Ashland Specialty ingredients, NJ, US). Both diode detectors are PTW Freiburg make with model 60016 Shielded (Diode P) and 60017 unshielded (Diode E). Both detectors have the sensitive volume of 0.03 mm^3. The output factor, off centered ratio (OCR) and PDD measurements were carried out using these detectors. The output factor is the ratio of the absorbed dose at a particular field size relative to the dose at a reference field size. The OCR is the ratio of absorbed dose at a point at a known distance from central axis of beam relative to the dose at central axis at a reference depth. PDD profiles are normalized to dose maximum of each collimator fields respectively.

Diode measurements

Measurement of output factors, OCR scans and PDD were made using diode E and diode P detectors for all 12 fixed collimators of Cyberknife systems. Output factors are measured at 15 mm depth in water with the source to axis distance (SAD) of 800 mm. All dose output for fixed collimators are normalized to 60 mm fixed collimator output reading. Diode detector was mounted on motorized MP3 water phantom (PTW Freiburg) of radiation field analyzer (RFA) system at a depth of 15 mm of water with an source to surface distance (SSD) in water 785 mm. Laser pinpoint tool provided in Cyberknife system was used for initial setup to align the detector at the center of collimated beam axis. Before performing actual measurements, alignments were verified with radiation beam center by lateral profile scans in two directions at two different depths. Ideally, for the purpose of commissioning of Cyberknife, OCR scans are performed at recommended depths for all fixed collimators. For this work, a depth of 5 cm in water at constant SAD 800 mm was taken. The Cyberknife robotic system is aligned in such a way that the radiation beams incident the water surface at perpendicular direction. This was achieved by programming the Cyberknife system in world coordinate mode and adjusting the z-axis in vertical direction. OCR scans were measured using diode P and diode E detectors in MP3 phantom. The measurements steps were fixed at 1 mm resolution for all collimators. A set of orthogonal scans were taken across the radiation fields. The scanned OCR profiles are then normalized to central axis maximum for each collimators. Central axis measurements of PDD were carried out in water with source to surface of water distance (SSD) at 800 mm. To avoid scan hysteresis, the scanning direction along central beam axis was made from depth of 250 mm in water to -0.5 mm beyond surface of water. The measurements steps for PDD were fixed at 2 mm resolution for all collimators.

Gafchromic EBT3 film measurements

Before measuring profiles and output factors, film dose calibration was done with a strip of 18 precut EBT3 film by irradiating each film with known dose ranging from 5 cGy to 800 cGy. For dose calibration, precut films were sandwiched between Virtual Water (VW) Phantom (Standard Imaging, USA) with density 1.03 g/cc at a reference plane of 5 cm depth in VW phantom with surface of phantom at 750 mm from source. For output factor measurements, films were irradiated for 350 monitor units (MUs) in all fixed collimators with phantom at SSD 785 mm and the film placed at 15 mm below VW phantom perpendicular to incident radiation beam. Similarly, for OCR measurements the films were kept in between VW phantom slabs layered at 50 mm depth from surface of Phantom. Linac was aligned in such a way that source to surface distance in phantom is at 750 mm so that a SAD of 800 mm is ensured between source to film. Films were then irradiated for a known dose of 400 cGy for all fixed collimators. For PDD measurements, precut EBT3 films are stacked in between phantom slabs at specified depths say surface (SSD 800 mm), 15 mm, 50 mm, 100 mm, 150 mm, 200 mm and aligned perpendicular to beam axis for irradiation. All films used for this study were scanned after a post irradiation time period of 72 hrs. Film directions are labeled during irradiation so that the film scanning direction remains same in landscape orientation for all precut films. Films are scanned using Epson Expression 10000XL flatbed scanner (Epson America Inc., CA, USA) using transmission mode and 48 bit RGB with no color correction. The resolution of film scanning was kept at 150 dpi and saved in tagged image file format (tiff) for analysis. PTW Verisoft film analysis (PTW Frieburg) software was used for analyzing the film data and only red channel of the images was analyzed. To minimize the uncertainty associated with single point measurement, mean dose value over a 2.5 mm diameter was measured from the centroid of irradiated circular region to determine relative dose values for collimators >10 mm and for collimators 5 mm, 7.5 mm and 10 mm mean dose value over 1 mm diameter was measured.

Data analysis

Output factors measured with diodes and film were compared against reported Accuray multiuser data [12]. Full width half maximum defined by each OCR lateral profile was compared with reference to the set collimator field size. To analyze OCR profiles, 1-Dimensional gamma analysis as proposed by Low *et al* [13] were used to compare the results of diode and gafchromic film. Gamma approach was made to account for inaccuracies that arise from alignment of compared scans and high gradient dose regions of small fields. Thus this approach of gamma analysis is a fair compromise between difference in relative dose (DD) and distance to agreement (DTA).

Results

Output factor

Measured output factors were plotted against field size for all detectors as shown in **Figure 1**. The results of output factor are given in **Table 1**. It was noted that the results of diode E and diode P agrees with Accuray's multiuser average data within 2% difference except 5 mm, 7.5 mm, 10 mm and 12.5 mm collimators. EBT3 film results also agree with average multiuser data except for 5 mm, 7.5 mm, 10 mm collimators for which the percent difference were 3.9%, 2.7% and 2.2% respectively.

All the detectors used in this study under estimated output factor for 5 mm, 7.5 mm and 10 mm collimators above 2% when compared with Accuray's multiuser data. The percentage disagreement in output factor with multiuser data between diode P, diode E and EBT3 film are given in **Table 2**.

Output factor measurements for small field sizes especially for field size < 10 mm, it is reported that measurement with silicone diodes are shown to over respond and output correction factors are needed [14]. Field output correction factors for Cyberknife machines, as a function of the diameter of circular fields for diode E detector are given in IAEA TRS 483 [14]. These correction values were applied to diode E results and the percentage difference of EBT3 results against uncorrected and corrected output factors are given in **Table 3**.

It was observed that output factors with EBT3 film agrees with diode E uncorrected output factor values within 1% except for 5 mm collimator where the EBT3 results underestimate the output factor by 1.7%. However with applied correction to diode E output factor values, the percentage difference of EBT3 values are overestimated by ≥ 2% for collimators ≤ 10 mm.

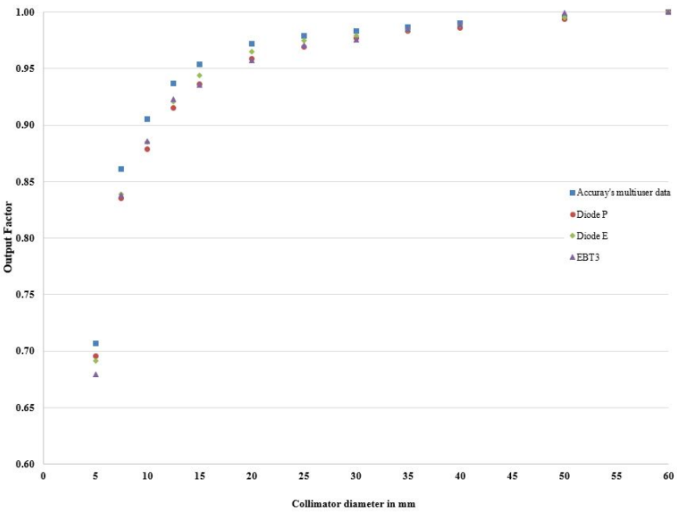

Figure 1. Comparison of output factors measured by diode P, diode E, EBT3 film detectors and Accuray multiuser data.

Table 1. Output factors measured using diode P, diode E detectors and EBT3 film.

Collimator diameter in mm	Output factors		
	Diode P	Diode E	EBT3
5	0.695	0.691	0.679
7.5	0.836	0.839	0.838
10	0.879	0.885	0.885
12.5	0.915	0.921	0.923
15	0.936	0.944	0.935
20	0.958	0.965	0.958
25	0.969	0.975	0.971
30	0.977	0.979	0.975
35	0.983	0.984	0.985
40	0.986	0.988	0.989
50	0.994	0.995	0.999
60	1.000	1.000	1.000

Table 2. Percentage disagreement of output factor by Diode P, Diode E and EBT3 film data from multiuser data.

Collimator diameter in mm	Accuray average output factor	Percentage difference with reference data		
		Diode P	Diode E	EBT3
5	0.707	-1.6	-2.3	-3.9
7.5	0.861	-3.0	-2.6	-2.7
10	0.905	-2.9	-2.2	-2.2
12.5	0.937	-2.3	-1.7	-1.5
15	0.954	-1.9	-1.0	-1.9
20	0.972	-1.4	-0.7	-1.5
25	0.979	-1.0	-0.4	-0.8
30	0.983	-0.6	-0.4	-0.8
35	0.987	-0.4	-0.3	-0.3
40	0.99	-0.4	-0.2	-0.1
50	0.995	-0.1	0.0	0.4
60	1.000	0.0	0.0	0.0

Table 3. Percentage disagreement of output factor by EBT3 film data from uncorrected and corrected output factors of diode E.

Collimator diameter in mm	Percentage difference of EBT3	
	vs Diode E (uncorrected)	vs Diode E (corrected)
5	-1.7	2.3
7.5	-0.1	2.6
10	0.0	1.9
12.5	0.2	1.5
15	-0.9	-0.1
20	-0.8	-0.5
25	-0.4	-0.3
30	-0.4	-0.4
35	0.1	0.0
40	0.1	0.0
50	0.4	0.4
60	0.0	0.0

Off centered ratio

Measured OCR scans were normalized to 100% at central axis of the radiation beam. There were no significant difference between the measurement data acquired by diode P and diode E detectors and the results of OCR scans were well within ±0.5% difference between them. The comparison result of normalized OCR measured with diode P and EBT3 films for 5 mm collimator is shown in **Figure 2**. The maximum difference in relative dose was found to be 4.5%. Similarly, for 7.5 mm collimator the maximum difference was found to be 4% and for 10 mm collimator, the maximum difference was found to be 3.7% and was shown in **Figure 3** and **4** respectively.

For collimators 12.5 mm, 15 mm and 20 mm, the maximum difference in relative dose between diode and EBT3 gradually decreased to 2.7%, 1.6%, 1.5% respectively as shown in **Figure 5**. For rest of the collimators from 25 mm to 60 mm, the maximum relative dose difference between diode P and EBT3 film were within 1% as shown in **Figure 6**.

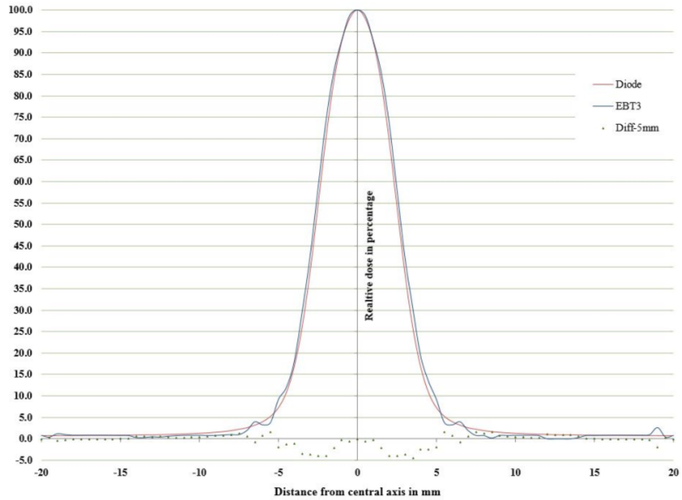

Figure 2. Diode P versus EBT3 film OCR profile with relative dose difference in percentage for 5 mm collimator.

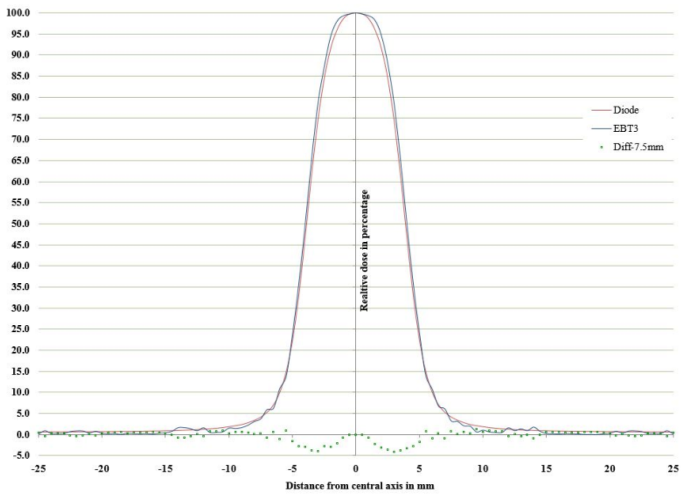

Figure 3. Diode P versus EBT3 film OCR profile with relative dose difference in percentage for 7.5 mm collimator.

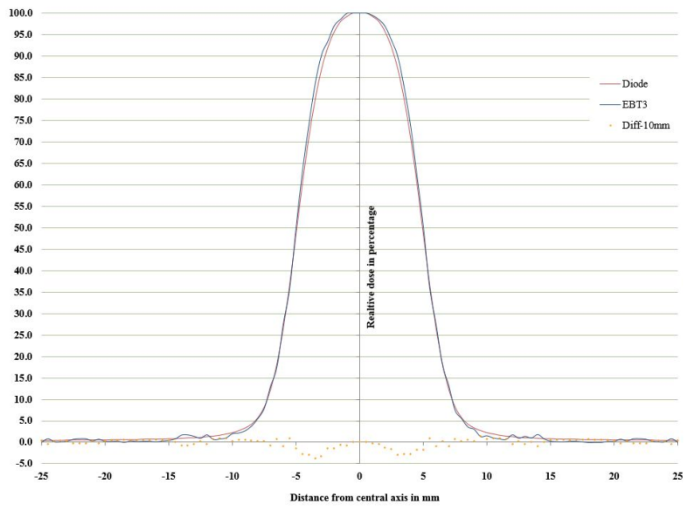

Figure 4. Diode P versus EBT3 film OCR profile with relative dose difference in percentage for 10 mm collimator.

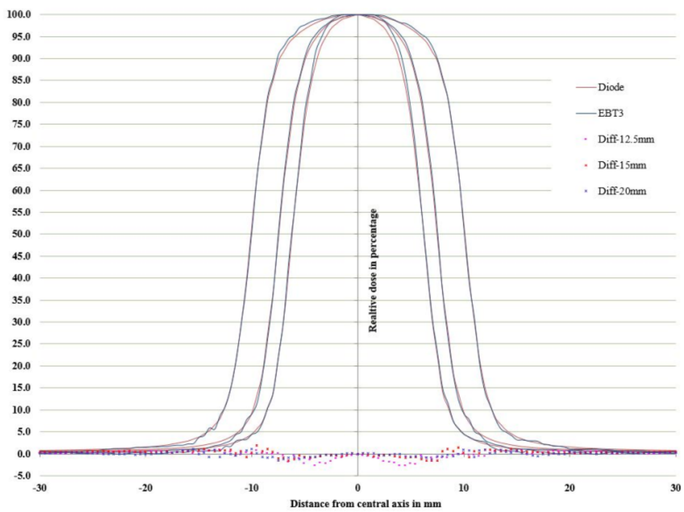

Figure 5. Diode P versus EBT3 film OCR profile with relative dose difference in percentage for 12.5 mm, 15 mm, 20 mm collimators.

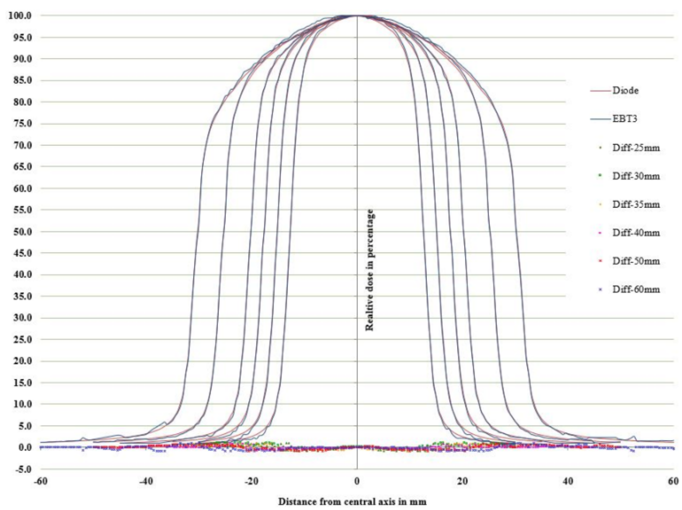

Figure 6. Diode P versus EBT3 film OCR profile with relative dose difference in percentage for 25 mm, 30 mm, 35 mm, 40 mm, 50 mm, 60 mm collimators.

Field size defined at 50% relative dose value (RDV) as full width half maximum (FWHM) for all fixed collimators measured from OCR profile at SAD 800 mm are shown in **Table 4**. The results of gamma analysis for $\gamma_{0.3\text{-}1\% / 0.3\text{-}1\ \text{mm}}$ were shown in **Table 5**.

Percentage depth dose

Percentage depth dose film measurement in VW phantom are corrected for depth in water by scaling of depths as recommended in IAEA TRS 398 [15]. PDD measurements at specified depths are then plotted against in-water PDD measurements by diode P and the results are shown in **Figure 7a** for collimators 5 mm, 12.5 mm, 25 mm, 40 mm. For collimators 7.5 mm, 15 mm, 30 mm and 50 mm, respective PDD curve are shown **Figure 7b** and for rest of all the collimators PDD curve are shown in **Figure 7c**.

Table 4. Field size measured from OCR profiles for Diode P and EBT3 film.

Collimator diameter in mm	Measured field size as FWHM in mm		Difference in mm from set field size	
	Diode P	EBT3	Diode P	EBT3
5	5.28	5.52	-0.28	-0.52
7.5	7.79	8.00	-0.29	-0.50
10	9.87	10.01	0.13	-0.01
12.5	12.42	12.48	0.08	0.02
15	14.94	15.04	0.06	-0.04
20	20.17	20.09	-0.17	-0.09
25	25.33	25.27	-0.33	-0.27
30	30.31	30.19	-0.31	-0.19
35	35.39	35.29	-0.39	-0.29
40	40.41	40.34	-0.41	-0.34
50	50.65	50.48	-0.65	-0.48
60	60.52	60.32	-0.52	-0.32

FWHM – Full width at half maximum

Table 5. 1D Gamma analysis result for range of gamma criteria for Diode vs. EBT3 profile.

Collimator diameter in mm	% Points with Gamma ≤ 1		
	$\gamma_{1\%/1\text{mm}}$	$\gamma_{0.5\%/0.5\text{mm}}$	$\gamma_{0.3\%/0.3\text{mm}}$
5	100	100	80
7.5	100	100	79
10	100	100	92
12.5	100	94	72
15	100	100	96
20	100	97	84
25	100	97	94
30	100	97	75
35	100	93	72
40	100	97	87
50	100	93	65
60	100	95	73

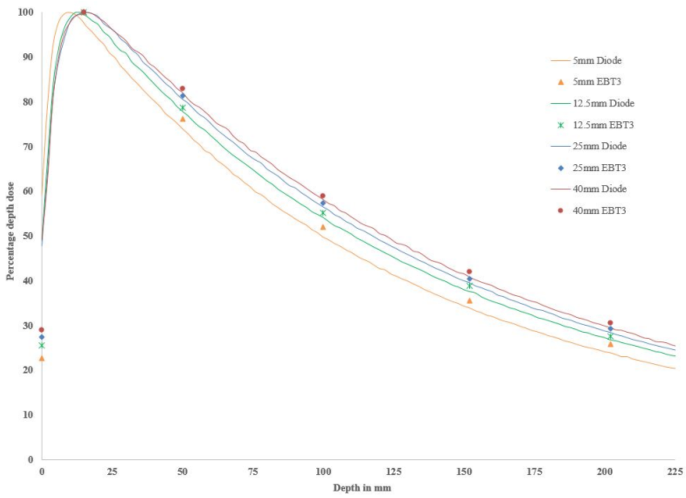

Figure 7a. PDD: Diode P versus EBT3 film for 5 mm, 12.5 mm, 25 mm, 40 mm collimators.

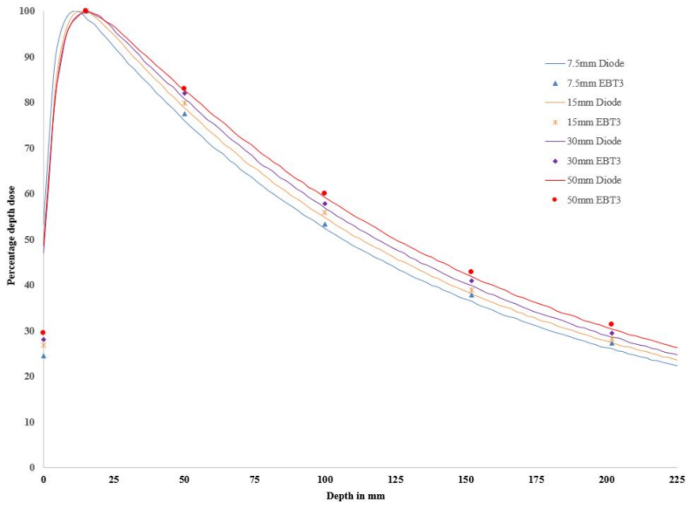

Figure 7b. PDD: Diode P versus EBT3 film for 7.5 mm, 15 mm, 30 mm, 50 mm collimators.

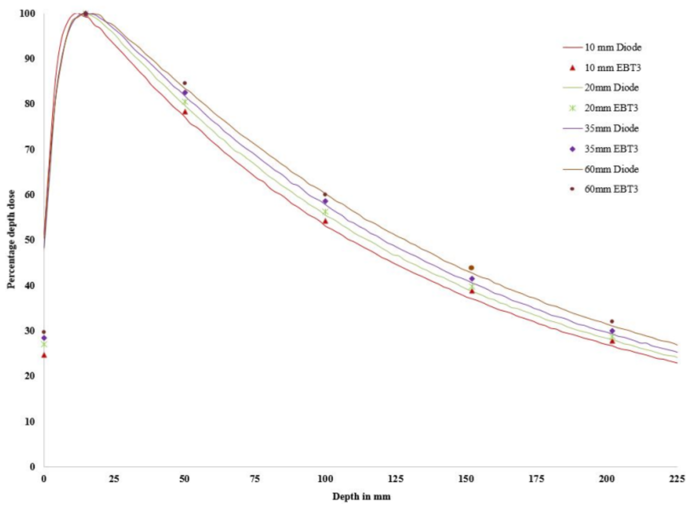

Figure 7c. PDD: Diode P versus EBT3 film for 10 mm, 20 mm, 35 mm, 60 mm collimators.

Diode P overestimates surface dose by more than 20% for all the collimator fields when compared to EBT3. At depths, except for 5 mm collimator, diode P and EBT3 PDD results agree within 2%. The difference in PDD values between diode P and EBT3 are given in **Table 6**.

Table 6. Difference in PDD for Diode P versus EBT3 at water equivalent depth.

Collimator diameter in mm	% difference in PDD					
	Water equivalent depth in mm					
	0	15	50	100	150	200
5	36.5	2.4	2.3	2.3	1.6	1.8
7.5	28.7	1.5	1.5	1.0	1.4	1.3
10	26.3	0.9	1.3	1.2	1.8	1.2
12.5	23.5	0.5	0.8	1.1	1.2	0.6
15	21.9	0.2	1.0	1.1	0.9	0.9
20	20.8	0.2	0.8	0.9	1.1	0.8
25	20.4	0.1	0.9	0.9	0.9	0.9
30	19.1	0.2	1.1	1.0	1.0	0.9
35	19.9	0.0	0.8	0.8	0.9	0.7
40	20.3	0.2	0.9	0.8	1.1	0.9
50	19.2	0.0	0.2	0.8	0.9	1.0
60	20.6	0.0	1.2	0.2	1.0	0.9

Discussion

An ideal dosimeter for small field measurements should have good spatial resolution and have linearity and reproducibility characteristics and all of ideal characteristics for dosimetry in small fields are not met with any commercially available detectors. Das *et al*. [16, 17] discussed the merits and demerits of various detectors in small field dosimetry application. Further, use of various detectors for commissioning of linear accelerators were reported by Das *et al*. [18]. Radiographic films are ideal detector for relative dose measurement and are well suited for planar dose measurements. It has unrivaled spatial distribution of dose compared to solid detectors. However it has several limitation and dependent on type, batch, exposure condition, processor condition etc. Over the years, radiochromic films were developed and effectively replaced radiographic films as dosimetric tool in radiotherapy [19]. Gafchromic EBT3 film has advantage over radiographic films since no developing process is required. In addition, EBT3 film dosimetry protocols are well established and studied widely by several authors [20-22]. The main advantage of using EBT3 films is that it has high spatial resolution than any solid-state detectors and is tissue equivalent. Use of diode detectors for relative measurements in small fields are promising due to their small sensitive volume and diode P detector is employed widely for commissioning of Cyberknife photon beams [23]. Both diode detectors used in this study have common specification except that diode P has additional shielding in order to eliminate the issue of high response to low energy photon ranges [24]. However in our study, the measurements between diode P and diode E did not show significant difference when pitted against each other. The percent difference in output factor, OCR and PDD measured between diode E and diode P were less than 1% for all collimator fields. EBT3 underestimated output factors for collimators ≤ 10 mm and the largest difference of 3.9% was found for 5 mm collimator from Accuray multiuser data. However when compared with our test condition, the results of EBT3 agreed with diode detector results within < 2% difference. When IAEA TRS 483 recommended correction for output factors were applied to diode results, then EBT3 values overestimated the results for field size ≤ 10 mm up to 2.4%. OCR scans of diode P and EBT3 films were compared using 1D gamma analysis method with gamma criteria of 1% DD and 1% DTA ($\gamma_{1\%/1mm}$). All compared relative dose points were with gamma less than 1. This was due to the fact that comparing field sizes were too small. Few points in out of field regions i.e. lesser than 2% of relative dose value regions, had few points with gamma more than 1 and these points were ignored due to the reason that such low dose regions had high noise resulting from scanning EBT3 films. 1D gamma analysis were further done with more stringent gamma criteria of 0.3% DD and 0.3% DTA ($\gamma_{0.3\%/0.3mm}$) and 0.5% DD and 0.5% DTA ($\gamma_{0.5\%/0.5mm}$). Indeed few points were failed with such stringent criteria in the penumbral region. Even for $\gamma_{0.5\%/0.5mm}$, the confidence rate of ≥ 93 percentage of relative dose points shows that EBT3 film results are comparable to diode. 1D Gamma results thus proves the reliability of EBT3 measurements for lateral profiles. Statistically, at significance level of $p < 0.05$, there is no significant difference between diode and EBT3 results for output factors and FWHM values. Percentage depth dose at specified depths between diode P and EBT3 are in good agreement except for 5 mm collimator. Diode P overestimate the surface dose when compared to EBT3 due to the fact that diode P has inherent water equivalent thickness (WET) from sensitive volume of 2.33 mm which act as buildup whereas EBT3 has 0.1 mm WET from its active layer. This could be the reason for the large difference in estimation of surface dose.

Measurement of output factor, OCR and PDD for both shielded diode P and unshielded diode E were consistent for all Cyberknife fields and EBT3 film results were also consistent with diode measurements except for ≤ 10 mm collimators. At collimators ≤ 10 mm, an uncertainty exist for all detectors used in this study and thus requires correction factors for such small fields. More over repeated measurements over a particular period are in need to overcome human errors. Further extensive quality control measures and quality assurance procedures must be followed to minimize adverse results [25]. Care should be taken for EBT3 analysis, as any protocol violations will give rise to serious systematic errors.

Overall results promote diodes for beam data acquisition but it is always recommended to have multiple independent dosimeters to cross check and compare the acquired beam data. This study demonstrated that Gafchromic EBT3 films could be employed effectively for Cyberknife beam data measurements for routine quality assurance tests and as quick beam characteristic check after major component replacement if user follows appropriate methodology and scan readout procedures are well conducted.

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