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Penumbra Measurements and Comparison of In-House and Standard Circular Cones by the Gafchoromic Film, Pinpoint Ion Chamber, and MCNPX Monte Carlo Simulation

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ABSTRACT

Introduction: Penumbra is an important property of the radiation beam to obtain a suitable margin surrounding the target volume. Therefore, the precise penumbra width determination in stereotactic radiotherapy is necessary for treatment planning. This study aimed to compare the obtained results of penumbra width by in-house and standard circular cones by different dosimeters, as well as evaluating the function of EBT3 for dosimetric properties of the small field radiation.
Material and Methods: Different circular cones were mounted on the head of the accelerator to produce 12, 20, and 40 mm field sizes at isocenter. Dosimetric measurements were performed with the EBT3 film, PinPoint ion chamber. Afterwards, MCNPX Monte Carlo simulation was used to evaluate the dosimetric parameters.
Results: According to the obtained results, the penumbra width was increased by larger diameters of circular cones. The obtained measured data by PinPoint ion chamber showed a larger penumbra width compared to those calculated by Monte Carlo at all field sizes. The gamma index analysis revealed distance-to-agreement and dose-difference of 2 mm /2%/ at all points. The results of this study showed that source to diaphragm distance had a major role in penumbra size determination of small field dosimetry with PinPoint ion chamber, EBT3 film, and Monte Carlo simulation.
Conclusion: As findings of this study reported, EBT3 films are reliable detectors for relative dosimetry due to high spatial resolution for small field sizes. Furthermore, they can be used for measuring beam profile and percentage depth dose curves.

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Introduction

The aim of radiotherapy is to deliver a lethal dose to the tumor and reduce normal tissue complications as much as possible. Stereotactic radiotherapy is one of the cancer treatment modalities, in which small target volume receives high doses of ionizing radiation with a positional accuracy of ±1 mm and dose accuracy of ±5% in multi fraction [1]. This technique requires a high standard of equipment and methods for accurate dosimetry. Stereotactic radiosurgery (SRS) can be performed in one fraction or more by a variety of techniques, including the Gamma knife radiosurgery, Cyber knife, linac-based SRS with circular cones, and Multileaf Collimators (MLCs).

The linear accelerator (linac) is frequently used for conventional radiotherapy and SRS. It was first proposed theoretically by Larson et al. in 1974, and the first clinical use of this technique with circular collimators was reported by Betti and Derechinsky in 1984 [2]. Linac-based SRS treatment consists of different arcs using couch and gantry rotations with circular cones or MLCs. In linac-based radiosurgery, a greater number of collimator sizes are used compared to the Gamma Knife. Therefore, it takes longer setup and delivery time, especially in multiple isocenters techniques.

A micro multileaf collimator (mMLCs) is a kind of MLC with leaf width below about 2 mm. The advantage of using mMLCs in comparison with circular collimators refers to the possibility of choosing multiple isocenters in treatment. The utilization of multiple overlapping spherical treatments results in good field shaping for larger tumours. However, the disadvantages of this multiple

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isocenter techniques include the increase in the treatment time and the dose inhomogeneity [3]. Accordingly, it is important to choose a reliable detector to measure dosimetric parameters in stereotactic fields. The accuracy of the detector at the high gradient dose region, such as penumbra region, is of utmost importance due to the lack of lateral electronic equilibrium and steep dose gradients.

Penumbra is divided into two groups, namely geometric penumbra and physical penumbra/radiological penumbra. The former depends on the size of the source and some parameters, such as source to diaphragm distance (SDD), source to skin distance (SSD), source size, whereas, the latter depends on the lateral scatter and the energy of the beam. Physical penumbra is an important parameter of a beam in small field irradiation which is caused by geometric penumbra and radiation penumbra. The geometric penumbra dependents on the collimator properties, and radiation source size. On the other hand, the radiation penumbra dependents on the energy and field size [4]. Different dosimeters have been used for measuring radiation in small fields, such as EBT3 Gafchromic film, ion chamber, diamond, and diodes.

High spatial resolution and accuracy are two main properties of small field detectors. Determination of the accurate size of the penumbra in the small field is crucial for treatment planning purposes. A large number of studies addressed small field dosimetry with different detectors [4-11]. Pappas et al. measured the profiles of different small fields irradiating 6MV photon beams with ion chamber, a diamond detector (type 60003 by PTW Freiburg, Germany), silicon-diode array (DOSI), and vinyl-pyrrolidone-based polymer gel dosimeter. According to their study, ion chamber was not suitable for small photon field dosimetry. Diamond had high resolution; however, it needed position and dose rate correction factors. Moreover, the findings of the study showed that DOSI and polymer gels were adequate for small field measurements without any positioning problems [6]. According to the International Atomic Energy Agency, ionization chambers have sensitive volume of 0.3–0.6 cm3, meaning that they are not suitable for small field dosimetry due to their volume and their unreliable readings in water phantom, percentage depth dose, and profile measurements [12].

Heydarian et al. measured dosimetric parameters of small fields. They employed diode, film, diamond detectors, and EGS4 Monte Carlo (MC) simulation in their study. The obtained results showed that diamond detectors were more suitable for SRS than other traditional types of dosimeters [4]. Moreover, MC simulation could be considered as a reliable reference for dose calculation of small fields. Many investigations have been devoted to MC calculations [13-15]. Scott AJ et al. calculated the dosimetry properties of the small field by MC simulation method and measured them by a shielded diode, unshielded diode, diamond detector, PinPoint ion chamber, and RK chamber. They suggested that the unshielded diode was a good choice for the measurements in small fields and MC simulation could correctly predict dosimetric parameters for field sizes below15 mm [15]. The current study aimed to compare the obtained results of penumbra (geometric and physical penumbra) width by in-house and standard circular cones by different dosimeters, as well as evaluating the function of EBT3 film for measuring the dosimetric properties of the small field radiation.

Materials and Methods

Circular Cones

This study investigated two types of circular cones. The circular cones included a collimator housing fixed to the base plate of linac head in order to produce small field sizes at the isocenter. As shown in Table 1, there were different commercial circular cones, including 12, 20, and 40 mm diameters (3-dimensional Line Medical Systems, USA), as well as one in-house cone. The diameter of the holes at isocenter was the nominal name of the circular cone. The aperture size determined the shape of the beam rays. The aperture size varied for different cones. The upper and lower aperture sizes were measured 7.5 and 9 mm for 12-mm circular cone, 12 and 15 mm for 20-mm circular cone and 27 and 30 mm for 40-mm circular cone, respectively. Figure 1 illustrates in-house cone which consists of a base plate and a divergent cylindrical cone with an outer diameter of 80 mm, isocenter of 20 mm, and height of 100 mm, which results in a radiation field with a diameter of 20 mm at the isocenter [16].

Measurements

Percentage depth dose (PDD) and beam profiles of two types of circular cones were measured in a PTW water tank with an exterior dimensions of 50×50×70 cm^3 using PinPoint ion chamber (PTW, Freiburg, Germany). All dosimetry measurements were performed at SSD of 100 cm and depth of 5cm. The PinPoint ion chamber with a sensitive volume of 0.3 cm^3 was used as a standard dosimeter. The secondary collimators of linac were 3×3 cm^2 at isocenter for 12 and 20 mm circular fields and 5×5cm^2 at isocenter for 40 mm circular field. In order to obtain the experimental measurements, the effective point of chamber was adjusted precisely on the isocenter point [17]. All readings by the PinPoint chamber were repeated three times.

At the next step, EBT3 Gafchromic films (Ashland ISP Advanced Materials, NJ, USA) were used to measure dosimetric parameters. The calibration curve was based on the obtained results of the previous study [18]. The EBT3 films were irradiated in a solid water phantom. All films were sandwiched between phantom layers at a depth of 50 mm, and were cut into 5×20, 7×20, and 13×20 cm^2 pieces for field sizes of 12, 20, and 40 mm 24 h before irradiation, respectively. The gantry angel for PDD and beam profile measurements was set to 90̊. In order to extract the optical density of the irradiated pieces of films, the scanner (9800XL, Microtek International Inc., USA) was used in landscape orientation to have less side artifacts and more dynamic range. All scanned EBT3 films were saved in image file format (.tiff) and imported to the Image J software (Wayne Rasband, NIH, USA) and FilmQApro software (Ashland ISP AdvancedMaterials, NJ, USA) to evaluate dosimetric measurements.

Monte Carlo simulation

The MC simulation was applied to evaluate the dosimetric parameters of small photon fields. The MCNPX (Los Alamos, USA, Version 2.6) has been used in different investigations to model the Varian Clinac 2100C linear accelerator (Varian, Palo Alto, California, USA) in 6MV photon mode and circular cones [13-15],[19]. Figure 2 shows the simulated components, including a target, primary collimator, flattening filter, ionization chamber, mirror, secondary collimators, a circular collimator with a diameter of 20 mm, and water phantom. All applied dimensions and materials of the linear accelerator were based on the technical data provided by the manufacturer. The energy distribution of incident electrons on the tungsten target was Gaussian with full width at half maximum of 1.1 MeV.

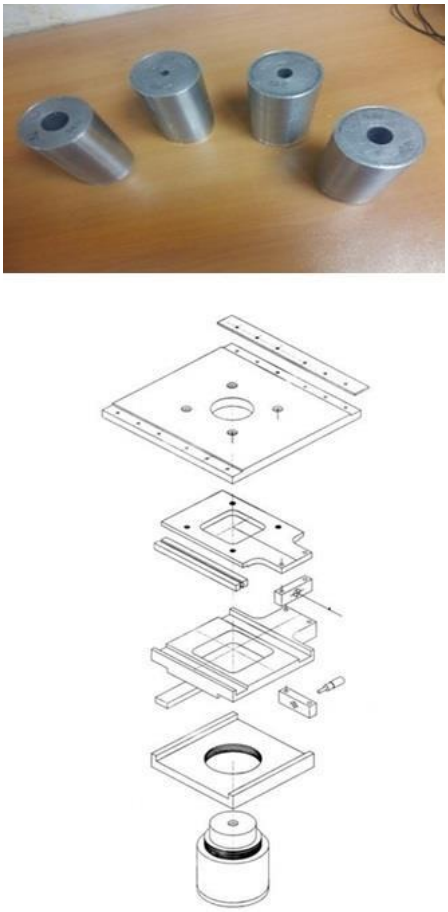


Figure 1. Components of in-house circular cone

Table 1. Characteristics of standard and in-house circular cones

	Height (mm)	Diameter(mm)	Material
Commercial circular cones	128	12, 20, 40	Lead
In-house circular cones	100	20	Lead

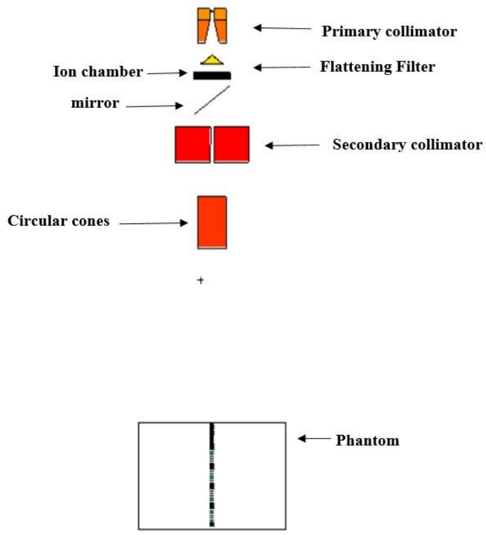


Figure 2. Simulated components of linear accelerator along with commercial circular cone

The PDD curves and beam profiles were obtained in a simulated water phantom with dimensions of 30×30 ×30 cm^3 at SSD of 100 cm. In order to determine the PDD values, the sizes of the voxels were considered as a disk with a radius of 5 mm and a height of 1 mm across the central axis. The profile depth was 5 cm, and the dimension of the voxels was 1×0.5×0.5 cm^3 perpendicular to the central axis of the beam. Finally, the *F8 tally was used to calculate the energy deposition in voxels. The numbers of generated histories were 2e9. Moreover, energy cut off for photon and electron were selected as 0.01 MeV and 0.5 MeV, respectively.

The ScanDoseMatch software [20] was used to plot gamma index and the evaluation of the agreement between calculated values with measured ones [21]. The acceptable gamma index criteria was set to distance-to-agreement of 2 mm and dose-difference of 2% [22]. Finally, the penumbra width measured with in-house and commercial circular cones (20-mm diameter) by ion chamber, EBT3 Gafchromic film, and MC simulation were compared.

Results

Validating MC simulation

To evaluate the accuracy of MC simulation, the PDDs and beam profiles of 3×3 cm^2 and 5×5 cm^2 field sizes were measured with a PinPoint ion chamber and the obtained results were compared. Figures 3 and 4 illustrate a good agreement between the calculated and measured data. The gamma index analysis showed the differences of 2%/2 mm at all points.

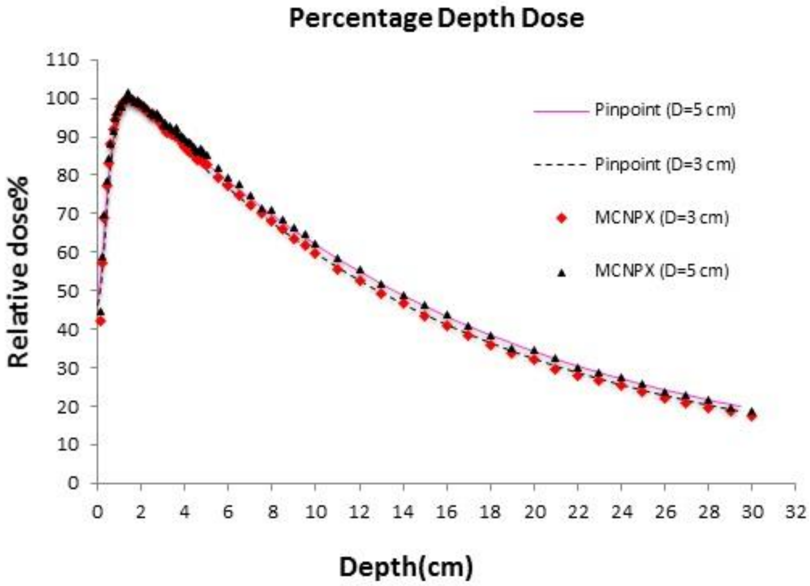


Figure 3. Comparison of the calculated and the measured PDD at 3×3 cm^2 and 5×5cm^2 field sizes

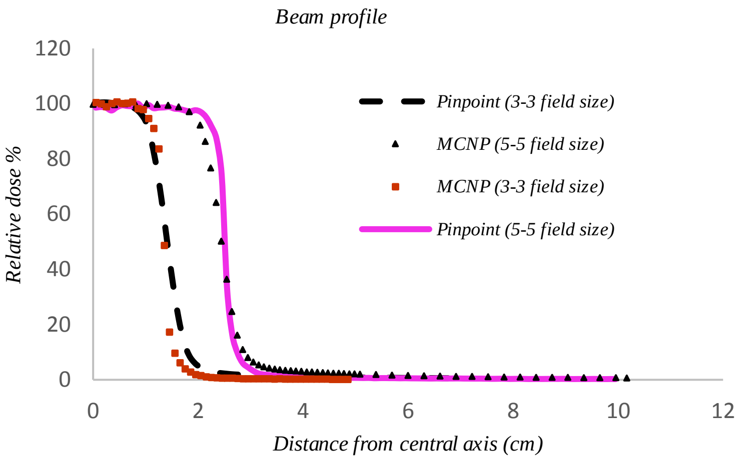
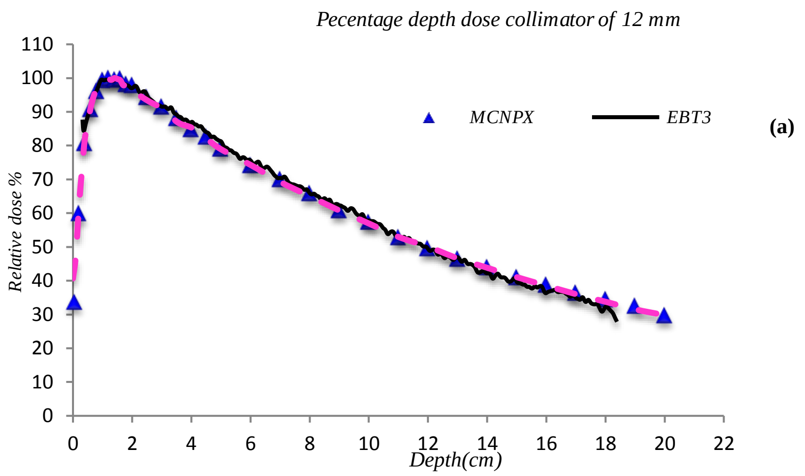
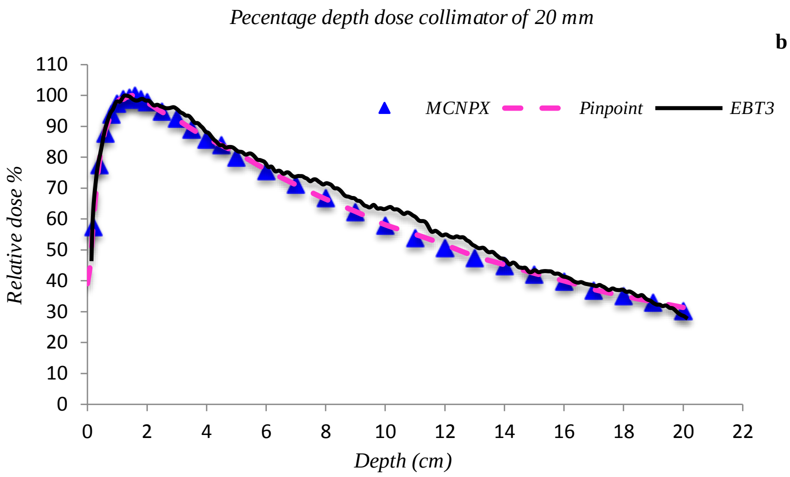


Figure 4. Comparison of the calculated and measured dose profile at 3×3 cm^2 and 5×5cm^2 field sizes





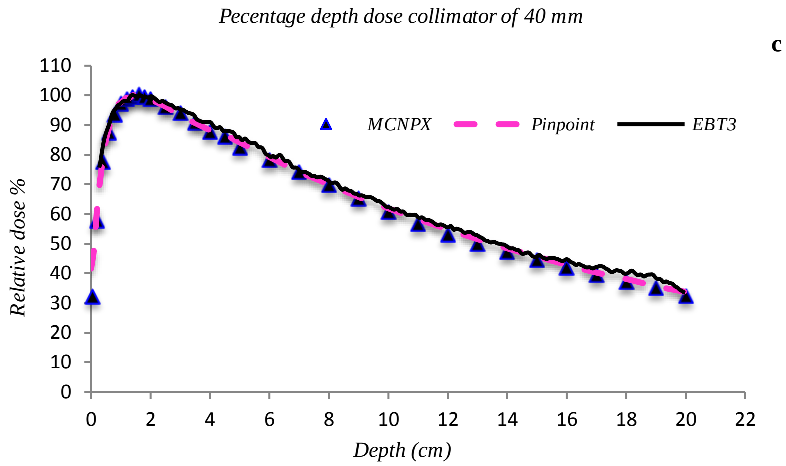
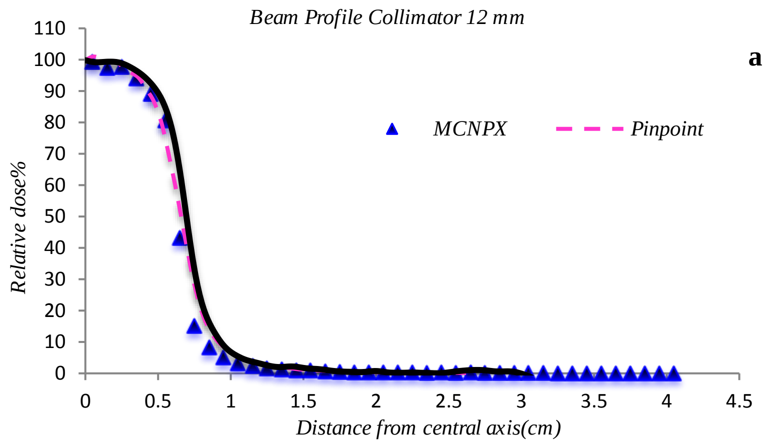
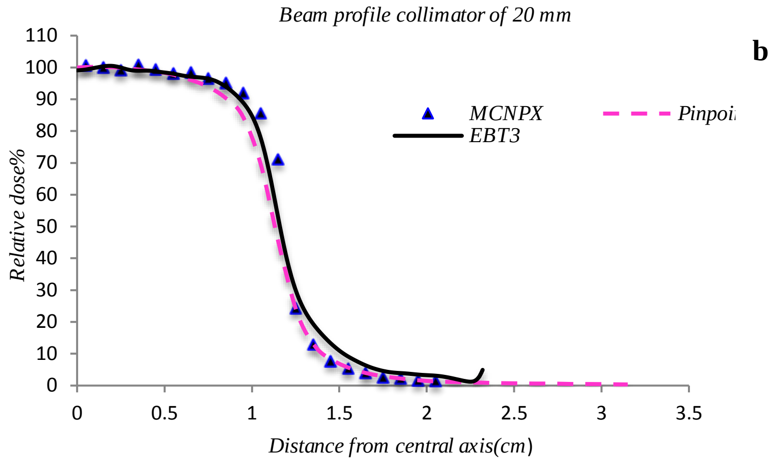


Figure 5. Comparison of the PDD obtained from MC simulation, PinPoint ion chamber, and EBT3 Gafchromic films for 6 MV photon beams at different diameters of (a) 12 (b) 20, and (c) 40 mm of cones





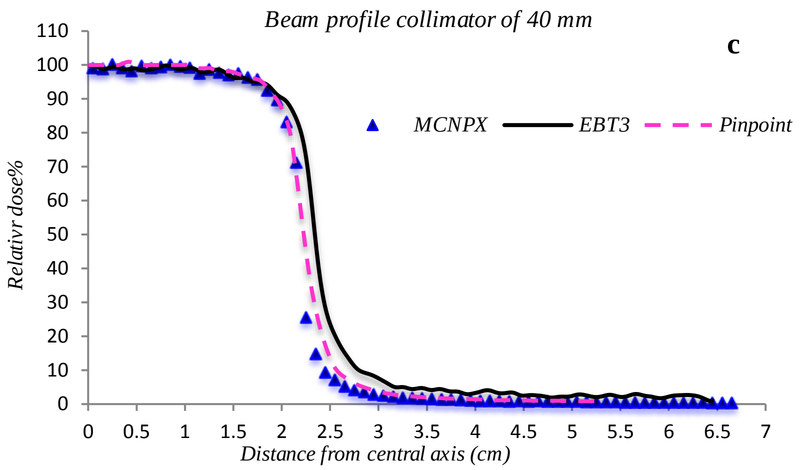
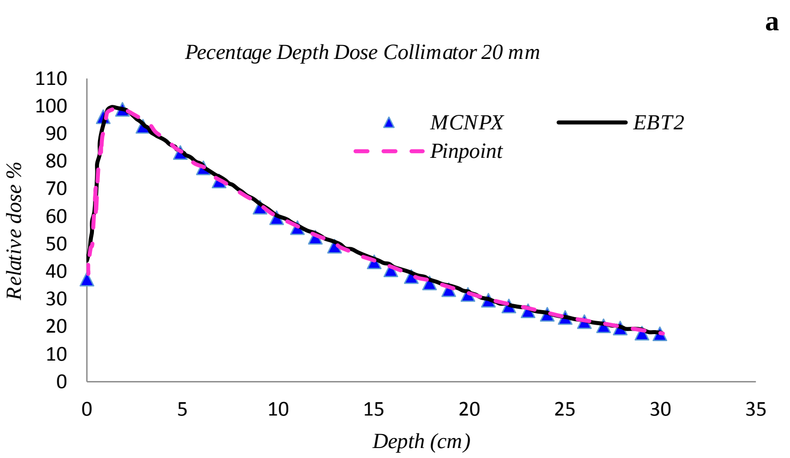


Figure 6. Comparison of beam profile obtained from the MC simulation, PinPoint ion chamber and EBT3 Gafchromic films for 6 MV photon beams at different diameters (a) 12, (b) 20, and (c) 40 mm of cones



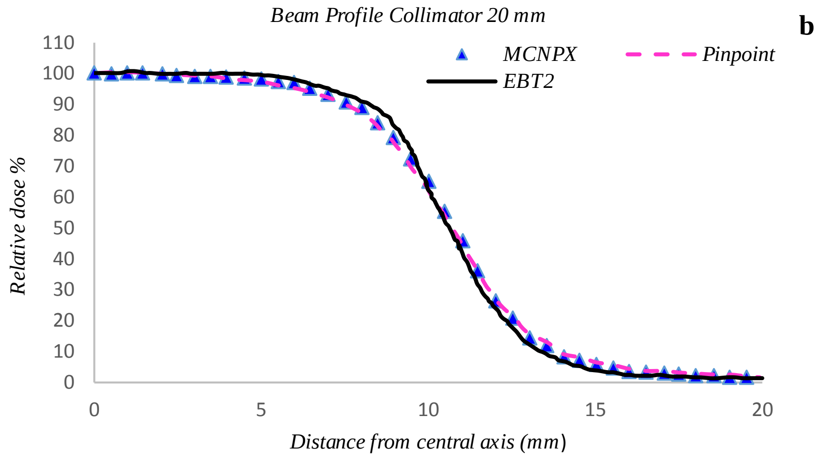


Figure7. Comparison of (a) PDD and (b) Beam profile obtained from MC simulation, ion chamber, and EBT3 Gafchromic film for in-house collimator (20-mm diameter)

Measured data

Figure 5 and 6 indicates the comparisons of PDD and beam profiles of commercial circular cones obtained from the MC simulation, PinPoint ion chamber, and EBT3 Gafchromic films for the circular fields of 12, 20 and 40 at SSD of 100 cm. The gamma index analysis showed the differences of 2%/2 mm at all points.

Figure 7 shows the obtained data by in-house collimator (20-mm diameter).

Penumbra

The penumbra region (geometric and physical) is usually defined as a part profile curve between 20% and 80% of the central axis dose.The Penumbra widths were measured for 6 MV photon beams at a depth of 5 cm for different circular cones (Table 2). According to the obtained results, the penumbra width increased by the elongation of the diameters of circular cones except for the obtained results of MC due to the volume effect. We had errors in right measured penumbra at depth of 5 cm and d $_{max}$, but the left measured penumbra in MC codes increased by the elongation of the diameters of circular cones. Finally, Table 3 indicates the comparison of penumbra width measured by in-house and commercial circular cones (20-mm diameter). The calculated penumbra obtained with MC simulation in the in-house circular collimator was larger than the EBT3 value due to the definition of voxel sizes in Monte Carlo codes. In addition, the SSD in measuring dosimetric parameters by in-house circular collimator which was more than SSD in considering parameters by the commercial circular collimator, meaning that the less the SSD, the less the penumbra width.

Table2. Comparison of penumbra width obtained by MC simulation, PinPoint ion chamber and EBT3 Gafchromic films for 6 MV photon beams at different diameters of cones

Penumbra width (mm)			
Collimator size (mm)	MC	EBT3 Films	Pin Point Ion chamber
12	2.3	2.3	2.8
20	2	2.9	3
40	2.2	3.1	3.2

Table 3. Comparison of penumbra width of in-house and commercial circular collimator in 20-mm diameter

Penumbra width (mm)			
	Pin Point Ion chamber	Gafchromic film	MC
Commercial circular collimator	3	2.9	2
In-house circular collimator	3.9	3.1	3.4

Discussion

According to the problem of electronic disequilibrium, an appropriate detector choice could be helpful to achieve accurate dose at the high gradient dose region in small field dosimetry. The beam penumbra width has to be measured precisely to obtain a minimum PTV margin for SRS; therefore, detector selection is an important part of small field dosimetry. PinPoint with appropriate active volume is known as a golden standard dosimeter in small field dosimetry. Figure 4 shows that the reading of the PinPoint chamber overrates to low energy seceondry photons due to the central electrode and photoelectric interactions,[23].

As shown in Figures 5b and 6b, the measured dose of EBT3 was higher than the measured PinPoint chamber data, and calculated MC data. This effect was based on the EBT3-film experimental measurement noise. Moreover, it overrated the responses of the Gafchromic film due to low energy scattered photons as shown in Arnfield MR et al. study [24]. Beam profile curves depended on the circular field size and had a rapid dose reduction when the circular field sizes decreased**.** This dose reduction led to the maintenance of the normal tissue around the target volume.

According to Table 2, the obtained measured data by PinPoint chamber showed larger penumbra compared to those calculated by MC in all field sizes due to the central electrode in the PinPoint chamber. The penumbra width increased by enlarging the diameters of the circular cones. In other words, the less the diameter of the circular cones, the more the rate of fall off at penumbra. This finding was in line with the previous studies conducted by Abdullah et al study [17] and Mahmoudi et al study [25]**.**

Table 3 tabulates the obtained data by commercial circular collimator of 20 mm compared to in-house collimator of 20 mm. The effect of SDD on all measured data was significant. Our obtained data for in-house collimator was more than commercial collimator due to the effect of SDD. It was not possible to reduce SSD to less than 100 cm because the distance from the bottom of the circular collimator to the surface of the phantom in this situation was 28 cm. Distance less than 28 cm caused electron contamination at the surface of the phantom in 6 MV photon beams.

Conclusion

According to the obtained results, there is a need to choose a sensitive detector for low energy photons with high resolution. The reason for this is that detectors measure dosimetric parameters in high gradient dose regions, such as penumbra in modern cancer treatment techniques due to the high doses delivery in multi fractions. The EBT3 films are reliable detectors for relative dosimetry because of high spatial resolution for small field sizes, possibility of measuring two-dimensional dose distribution, and separation into different pieces to setup in a water phantom or a solid water phantom. On the other hand, our Monte Carlo data showed approximately constant radiation penumbra width for circular cones due to the errors and some limitations in defining voxels. The calculation of dose and determination of NPS in MCNP code is essential to have the less error in our data. Regarding these limitations, MCNP code would be a useful tool for evaluating dose distribution in terms of defining suitable NPS. Finally, PinPoint ion chamber with a proper active volume is known as one of the standard detector for dosimetry measurements in modern techniques, such as SRS and IMRT.

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