Small photon field dosimetry using EBT2 Gafchromic film and Monte Carlo simulation

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► ***Original article***

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ABSTRACT

Background: Small photon fields are increasingly used in modern radiotherapy especially in intensity modulated radiation therapy (IMRT) and stereotactic radiosurgery (SRS) treatments. Accurate beam profile and central axis depth doses measurements of such beams are complicated due to the electron disequilibrium. Hence the EBT2 (external beam therapy) Gafchromic film was used for dosimetry of small circular photon beams because of its high spatial resolution. The results of EBT2 film were compared with PinPoint measurements and Monte Carlo calculations. ***Materials and Methods***: Four small field sizes (5, 10, 20 and 30 mm diameters) were produced by circular cones coupled to a Varian Clinac-2100 linear accelerator at 6MV photon beam energy. Experimental measurements were carried out using two dosimeters: The Gafchromic EBT2 film and the 0.015 cm^3 PinPoint ionization chamber (PTW, type 31006). The EGSnrc/BEAMnrc code was used to calculate dosimetric parameters for the above small fields. ***Results***: The results showed that the PDD values measured by EBT2 film had maximum local differences 4% and 3% with PinPoint measurements and MC calculations respectively. The measurements of penumbra (80-20%) at 5 cm depth in a water phantom and SSD=100 cm by EBT2 film were up to 0.8 and 0.4 mm smaller than PinPoint measurements and MC calculation respectively. Our results show good agreement between EBT2 film measurements and MC calculation for small field output factors but PinPoint measurements need correction factors. ***Conclusion***: This study showed that the Gafchromic EBT2 film is suitable detector for small field dosimetry especially for penumbra and output factor measurements.

Keywords: *: Small field, dosimetry, Gafchromic EBT2 film, Monte Carlo.*

INTRODUCTION

Small photon fields are increasingly used in modern radiotherapy especially in intensity modulated radiation therapy (IMRT) and stereotactic radiosurgery (SRS) treatments. It is difficult to measure beam profiles, central axis depth doses and output factors in small fields accurately. That is related to the electron disequilibrium [(1)], partial blocking of the beam source [(2, 3)], steep dose gradients and perturbation due to different density of the detector and the medium [(4, 5)]. Due to these challenges, the suitable detector for small field dosimetry should have some properties such as high spatial resolution, small volume, energy, and dose rate independent, linearity, reproducibility and stability [1, 6]. The most common detectors for small field dosimetry are ionization chambers [7, 8], silicon diodes [8, 9], diamond detectors [10], radiographic [11] and radiochromic films [12, 13]. Other detectors used for the dosimetry of small fields are thermoluminescent dosimeters (TLDs), polymer gels, plastic scintillators, metal oxide semiconductor field effect transistors (MOSFETs) and alanine dosimeters [14-17].

All of these detectors have some advantages and disadvantages. Ionization chambers may be too large for the small beams used in SRS. Micro-chambers with detection dimension of 3 mm or less can measure fields' ≥12.5 mm but are too large for smaller fields [13, 18].

For diodes, despite having very small active volume dimensions, dose rate, temperature, energy and angular dependency are its disadvantages [18-20]. The diamond detector has the advantages of being tissue equivalent, relatively high spatial resolution and high sensitivity for small field dosimetry. These detectors have disadvantages too. The dimensions of the detector (including the active volume and materials around it) are relatively large for very small fields. Diamond detectors are expensive and dose rate dependent [10, 21].

Radiographic film, such as EDR2 (Extended Dose Range) has been widely used in two-dimensional small field dosimetry. They have high spatial resolution which is suitable for beam profile measurements as well as output factors for small field. Energy dependent response and difficulties in uniform and reproducible development of EDR2 are its disadvantages [22, 23]. This problem was solved by introducing radiochromic film as a self-developing dosimetry film [24]. External beam therapy (EBT) Gafchromic film (International Specialty Products, Wayne, NJ) is an appropriate dosimeter for using in small radiation fields or regions of high dose gradient because of low energy dependence and high spatial resolution. EBT film has been studied and accepted as a two-dimensional detector especially for small field dosimetry [13, 25-26].

In February 2009 ISP stopped production of EBT film and replaced it by a similar radiochromic film under the name Gafchromic EBT2 film. According to the manufacturer notes, they have decreased post-exposure development time, sensitivity to UV light and the changes in the thickness of the film's sensitive layer. The Gafchromic EBT2 film has no film saturation until 40 Gy too [24, 27].

The aim of this study is to investigate the capability of this Gafchromic EBT2 film for dosimetry of small circular photon beams produced by the Varian Clinac 2100 linac equipped with circular collimators. Beam profiles (BP), percentage depth doses (PDD) and output factors (OF) were measured by this film. The results of EBT2 film have been compared with those obtained by the PinPoint chamber and Monte Carlo calculations.

MATERIALS AND METHODS

Measurements

The 6MV photon beam, by energy index ($TPR_{20,10}$) of 0.667 was applied. The linac was equipped with an in-house designed radiosurgical collimator consisting of collimator housing and divergent cylindrical treatment cones that produce fields of 5, 10, 20 and 30 mm diameter at the isocentre. The output factor, profiles and central axis depth doses were measured for different circular fields at source to surface distance (SSD) of 100 cm.

In this work the output factor was defined as D_{coll} /D_{30}, where D_{coll} represents the measured dose with each collimator and D_{30} is the reference dose measured with the 30 mm collimator. The cone with diameter of 30 mm was used here as machine specific reference field size instead of the standard 10 cm field as it is closer to the small fields whilst there is still sufficient electronic equilibrium and good agreement between measurements made with various types of detectors [28].

Films were irradiated in a solid water phantom with dimensions of 30 cm × 30 cm × 30 cm. PDD was measured with the film sandwiched tightly between slabs and irradiated in parallel orientation to the beam. The dimension of the film pieces were 6 × 25 cm^2. Beam profiles and OF were measured by the 6 × 6 cm^2 film pieces at depth of 5 cm in the solid water. 200 Monitor Units (MU) were delivered in each irradiation step. To obtain dose calibration curve, EBT2 films were cut 2 × 2 cm^2 and were irradiated at SSD=100 cm and field size= 10×10 cm^2 field size. The dose values between 0 to 300 cGy were delivered in 25 cGy steps. The calibration curve was used to convert optical density of film to dose.

All films were scanned 24 hours after irradiation in a same orientation using a flatbed scanner (9800XL, Microtek, CA). The scanner was used in transmission mode. EBT2 films were scanned in the 48-bit red-green-blue (RGB) mode (16 bits per color) and resolution 75 dpi (0.3387 mm per pixel). The red channel has a greater response up to 10 Gy [(24)]. Therefore only the red color channel image was used and saved in tagged image file format (TIFF).The Image J software was used to analyze the EBT2 films.

All EBT2 film dose measurements were repeated at least three times and three scans of the same film were obtained. The protocol suggested by Devic *et al.* was used [(29)].

The OF, BP and PDD were measured for different circular field sizes using PinPoint chamber in a water tank (50×50×70 cm^3) (PTW, Freiburg, Germany). The PinPoint chamber (PTW-Freiburg, Germany, type 31006) is a waterproof 0.015 cm^3 cylindrical air chamber with a central electrode made of steel. The sensitive volume is 2mm in diameter and 5mm in length and it can be used for relative and absolute dose measurements. It has been especially designed for beam profile measurements where high spatial resolution is desired e.g. in IMRT and stereotactic beams [(30)]. For each measurement the detector was centered on the horizontal plane. Scans were performed to verify that the detector was located in center. Repeated readings displaced by 0.5 mm were taken to ensure that the maximum signal intensity (and therefore central axis) had been found. All measurements were made with 100 MU and averaged over a series of four repeated runs.

Because of the effect of steel central electrode, the output measured by PinPoint needs to be corrected. To correct this effect, signal correction factors were calculated applying the data reported by Ding et al [(31)] and the method reported by Sauer and Wilbert [(18)]. Ding et al have reported output factors for several field sizes at 5 cm depth and 6 MV photon beam by two types of chambers with aluminum and steel central electrode (Wellhofer CC01 and CC04). Ratio of output factors of these chambers were calculated and plotted against the field size. By linearly extrapolating to small fields, Signal correction factors for studied field sizes were calculated as Sauer and Wilbert have suggested.

Monte Carlo simulation

The BEAMnrc Monte Carlo code [(32, 33)] has been used for simulation of the radiation transport through the Varian Clinac 2100 treatment head. The components were modeled using detailed geometry and material composition provided by the manufacturer. The component modules that were used in BEAMnrc for modeling different sections of the linac head were SLABS for the target, CONS3R for the primary collimator, FLATFILT for the flattening filter, CHAMBER for the monitor chamber, MIRROR for the mirror, JAWS for the fixed outer diaphragm, and CONESTAK for the circular cones and their aluminum covers. The procedure suggested by Sheikh-Bagheri *et al.* was used to determine the energy and spatial spread of the electron beam [(34)]. Photon and electron cut off values, PCUT and ECUT, were set to 0.01 and 0.521 MeV, respectively. To increase the speed of the calculation, directional bremsstrahlung splitting (DBS) has been used at the level of the flattening filter. The smallest radius that completely enclosed the entire treatment field with some overlap was chosen as the splitting radius therefore contribution to central axis dose from fat photons was negligible

[35]. The bremsstrahlung splitting number (NBRSPL) was set to 1000 for the simulated 6 MV photon beam because it gives maximum photon fluence efficiency [36]. The number of histories was adjusted for each field size so that the achieved uncertainty was below 0.2%.
The Monte Carlo simulation of the linac produces a phase-space file which acts as a source of particles for the DOSXYZnrc program to model the water phantom in which dose measurements were done.

The simulation phantom was a 50×50×50 cm^3 tank and the medium was set to water. Phase space data scored at SSD=100 cm were used as an input source to obtain off axis dose profiles in water at depth of 5 cm. Voxel dimensions of 0.5 mm lateral and 2 mm height were used within the fields including their penumbral regions and appropriate margins. Because of using circular cones, the profiles along the X and Y axes are identical. Therefore the profiles were calculated on the X axis only. Although the calculation resolution was 0.5 mm, the results were interpolated and the penumbra results were reported with 0.1 mm resolution. To calculate percent depth dose on central axis, lateral voxel dimensions of 2 mm were used for all field sizes while a voxel height (z) of 1 mm was used in the build up region down to a depth of 3 cm and of 4 mm beyond that depth. The voxel dimension of 2×2×5 mm^3 was used to calculate output factors for various field sizes. The spatial distance between 80-20% and 90-10% off-axis dose values was used for calculation beams penumbra.

The MATLAB and EXCEL software were used to extract, analyze and compare data (percent depth dose, dose profile, output factor and penumbra) from measurement and simulation.

To compare measured and calculated data in regions with a small dose gradient, local dose differences between two points were calculated as a percentage by equation 1:

$$\text{Local dose difference} = 100 \times (|Dose_{meas} - Dose_{calcu}|) / Dose_{mea} \qquad (1)$$

For the large dose gradient region a tolerance expressed in mm by calculation of distance to agreement (DTA).

To validate Monte Carlo model, MC calculated percentage depth doses, beam profiles and output factors were compared with experimental measurements. The values for the energy and spatial spread of a Gaussian electron pencil beam incident on the target were chosen as 6.2 MeV monoenergetic and 1.5 mm FWHM. The best agreement for PDD, off-axis profile and penumbra measurements was found with this energy and spot size for fields of 3 cm to 10 cm. 3 cm is the smallest field size that there is good agreement between measurements made with various types of detectors.

MC modeling validation

Local dose differences between PinPoint Measured and MC calculated were less than 1% for PDD values in depths less than 30 cm, but increased up to 7% or 1 mm in the build up region for field sizes between 3 and 10 cm. Measured and MC calculated off-axis dose profiles for field sizes between 3 cm - 10 cm at 5cm depth and SSD=100 cm were compared. The agreement between measurements and calculation was within 1% or 1 mm.

Percentage depth doses

Figure 1 shows Monte Carlo calculated and measured percentage depth doses for the 5, 10, 20 and 30 mm collimator at several depths in water at SSD=100 cm. All measurements were normalized to maximum dose. The measurements uncertainty was less than 1% and 2% for PinPoint chamber and EBT2 film respectively. The maximum local dose difference between EBT2 film and PinPoint measurements was 4% for PDD values behind the build up region for field size 5 mm. These differences between EBT2 film measurements and MC calculation were less than 3%. The PDD values measured by EBT2 film had local differences 3% and 2% with PinPoint measurements and MC calculation respectively behind the build up region for field size 10 mm. These differences were less than 2% for field sizes 20 mm and 30 mm. Figure 2 shows ratio of PinPoint measurements and MC calculations over EBT2 film measurements versus distance for PDD and for various field sizes. The PDD measured by

EBT2 film was steeper than that measured with the PinPoint chamber and calculated. The same result has been reported by Wilcox and Daskalov for EBT film compared with the Wellhofer CC01 ion chamber and a PTW 60008 diode [13].

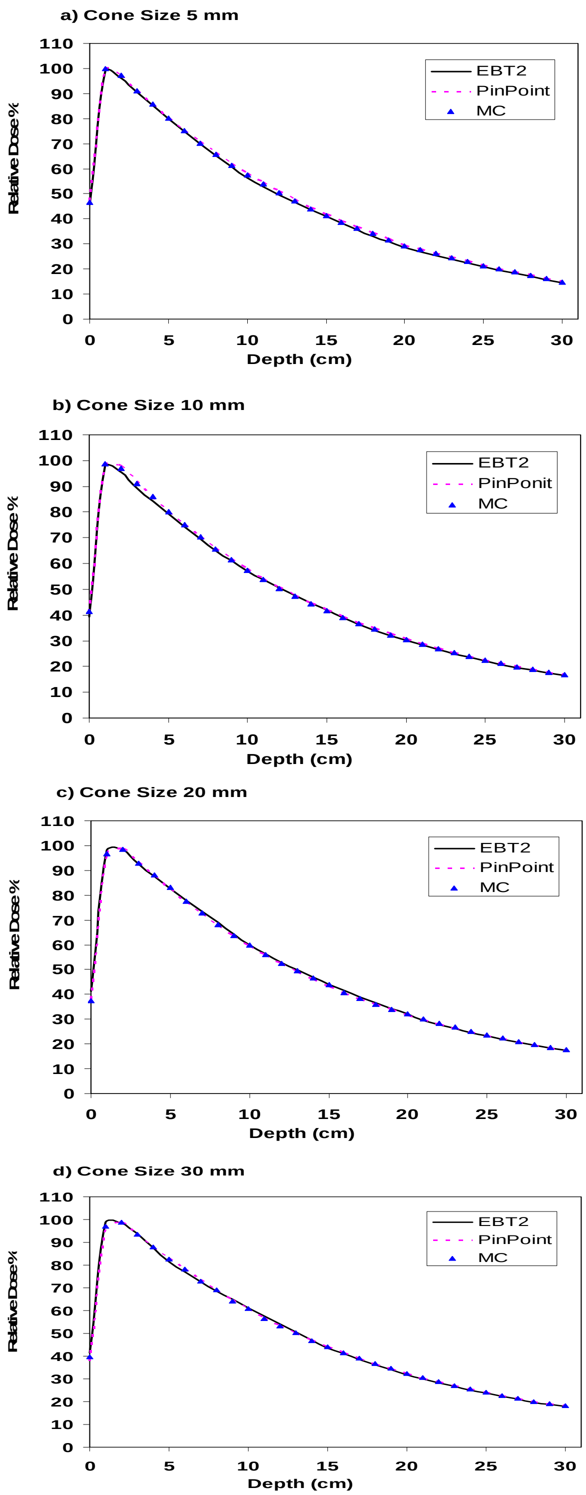

Figure 1. Measured and MC Percent Depth Dose for different circular field sizes at SSD=100 cm.

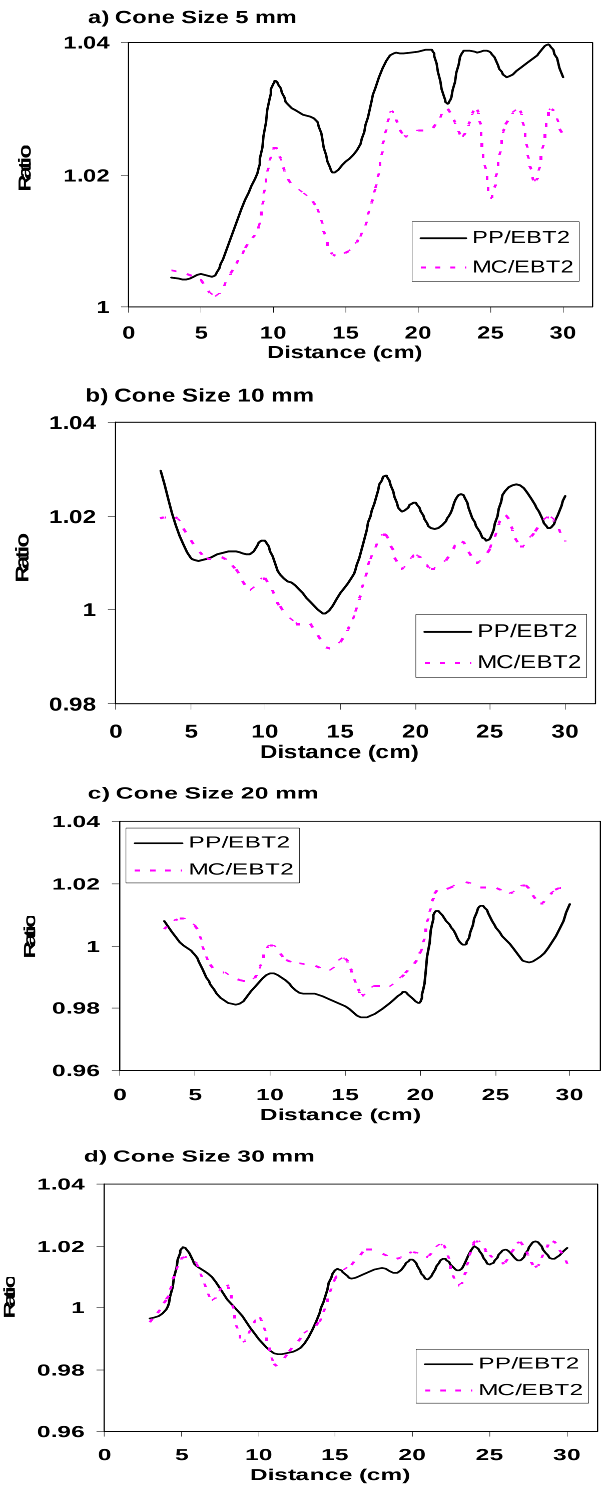

Figure 2. Ratios of PinPoint and MC over EBT2 versus distance for PDD and for various field sizes.

Beam profiles

Measured and MC calculated beam profiles for 5, 10, 20 and 30 mm diameter field sizes at 5cm depth and SSD=100 cm are shown in figure 3.

The voxel resolution in the penumbra region was 0.5 mm for MC calculations while Pin Point measurements were performed in 1 mm steps. The profiles are symmetric therefore only half-profiles are shown. All profiles are normalized to 100% on the central axis for each separate beam.

The agreement between film measurements and MC calculations was within 2% or 1 mm for BP values for field sizes of 5 and 10 mm. This agreement was within 1% or 0.7 mm for field sizes of 20 and 30 mm. Figure 4 shows ratio of PinPoint measurements and MC calculations over EBT2 film measurements versus distance for BP and for various field sizes.

Positional accuracy of ±1 mm is essential to deliver dose in radiosurgery therefore high accuracy in penumbra measurement is important [37]. The penumbra widths (80%-20%) and (90%-10%) measured with EBT2 film and PinPoint ion chamber for 5, 10, 20 and 30 mm diameter field sizes at 5cm depth are compared with MC calculated penumbra in table 1. The measurements with PinPoint ion chamber show the widest penumbra for all cones. The main reasons are the effect of volume averaging over the big sensitive region of PinPoint and over-response to low-energy Compton scatter because of photoelectric interactions in the steel central electrode [28, 38].

The effect of volume averaging is important in beam penumbra. The MC calculated results seems to be bigger than real penumbra because of relatively big voxel dimension size (0.5 mm). The EBT2 Gafchromic film results are close to real penumbra because of high spatial resolution and low energy dependence [12, 39].

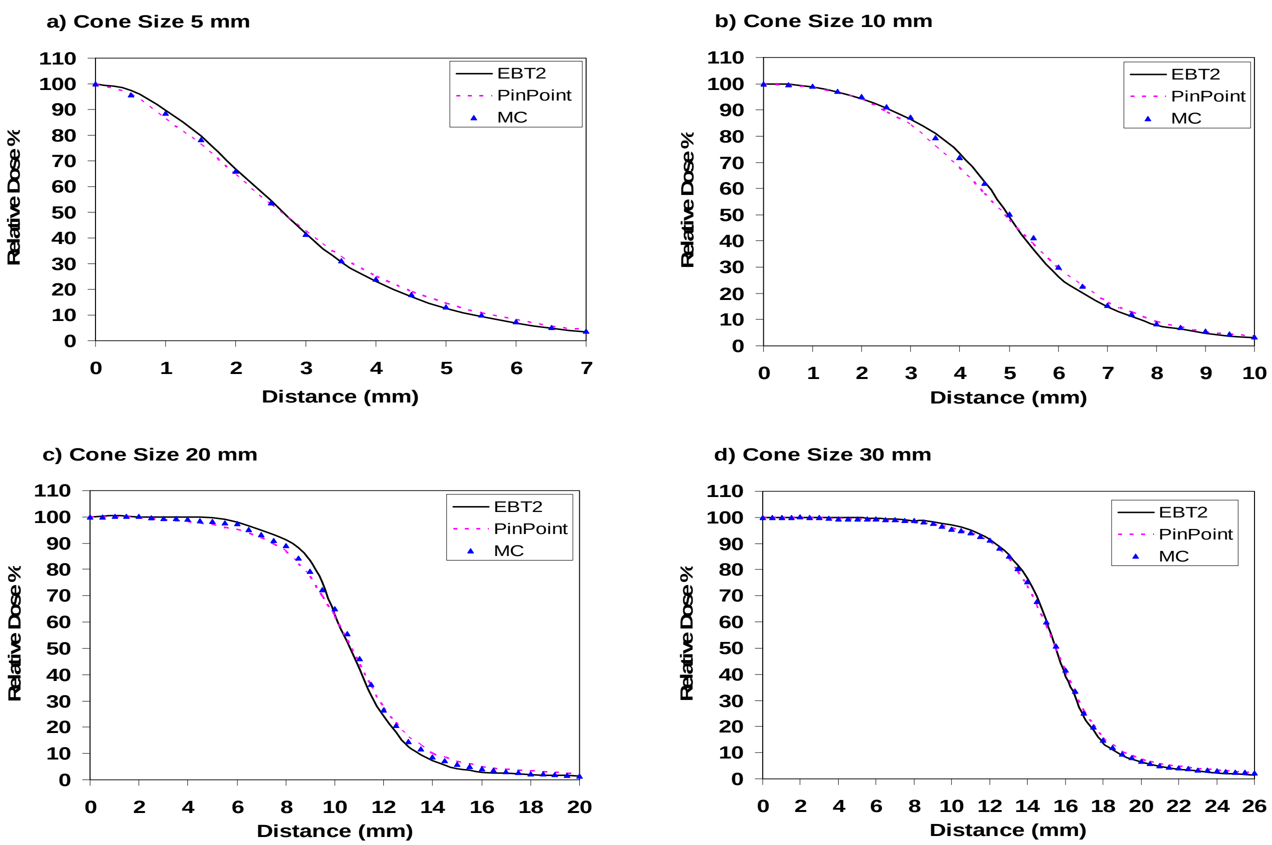

Figure 3. Measured and MC calculated relative beam profiles for different circular field sizes at 5cm depth and SSD=100 cm.

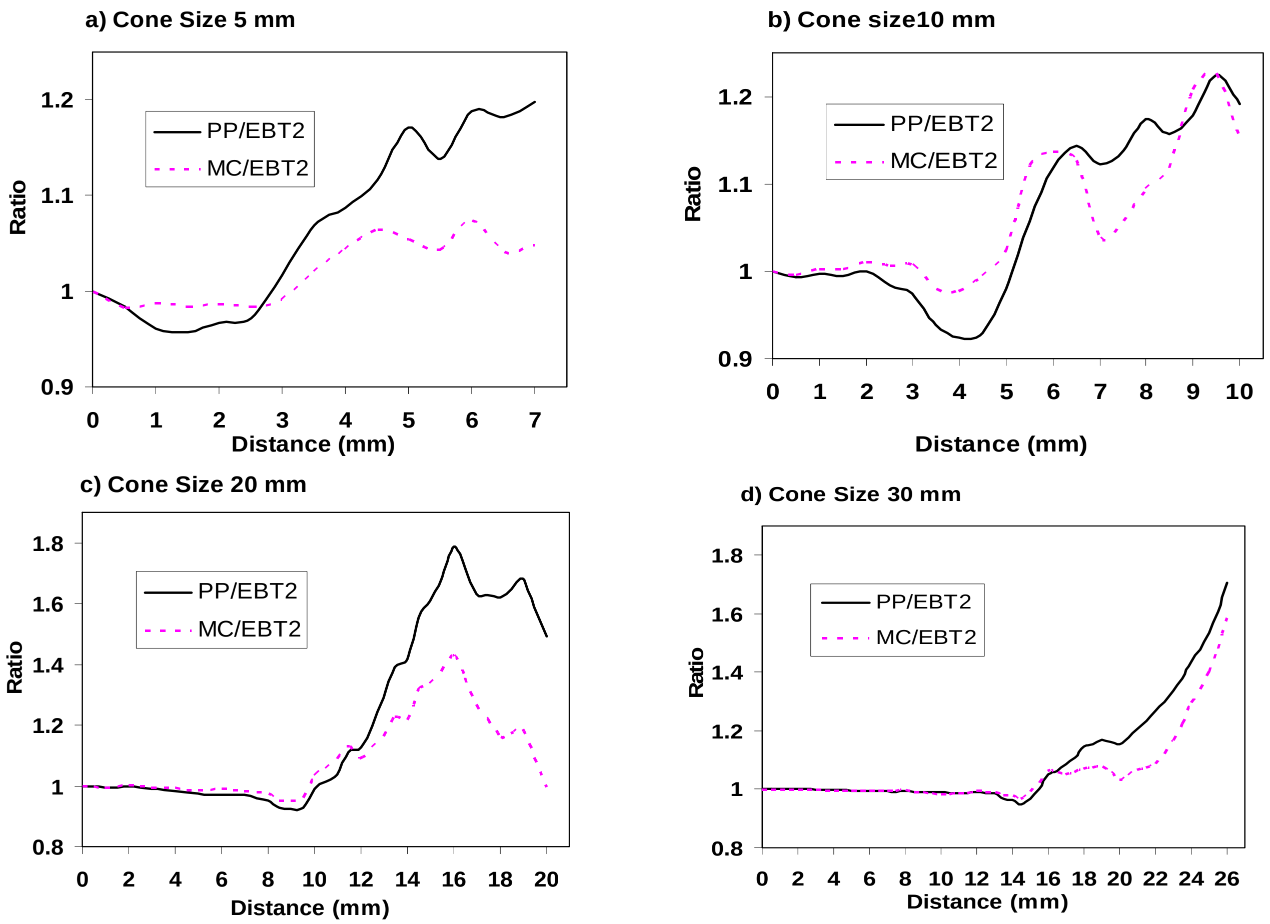

Figure 4. Ratios of PinPoint and MC over EBT2 versus distance for BP and for various field sizes.

Table 1. Measured and MC calculated penumbra widths (80%-20%) and (90%-10%) for different circular field sizes at 5cm depth.

Cone size (mm)	80%-20% (mm)			90%-10% (mm)		
	PinPoint	EBT2	MC	PinPoint	EBT2	MC
5	3.1	2.7	2.8	4.9	4.3	4.6
10	3.5	2.8	3.2	5.5	4.9	5.0
20	3.9	3.1	3.4	6.6	5.2	6.1
30	4.2	3.7	3.8	7.0	6.5	6.7

Output factors

Table 2 presents the measured output factors of Pinpoint, EBT2 and also calculated Monte Carlo for different circular cone sizes as well as 10 ×10 cm^2 square field. To avoid electron contamination originated from linac head, especially flattening filter, measured and calculated output factors was at 5 cm depth and SSD=100 cm in water phantom. Although ion chambers are the reference dosimeter in conventional radiotherapy but they need some correction for radiosurgery. The reason is that the plateau region of the dose profile is small or doesn't exist in small fields and the sensitive volume of ion chamber is bigger than the plateau region. Therefore the volume averaging correction factor is necessary for measured output factor by ion chambers. We calculated the PinPoint volume averaging correction factor for various field sizes from the MC generated dose distributions. Also the signal correction factors were calculated to correct the effect of steel electrode of the PinPoint chamber.

Corrected and uncorrected output factors measured by PinPoint for different circular cone sizes and 10 ×10 cm^2 square field are compared with EBT2 results and MC calculation in table 2.

Our results show good agreement between EBT2 measurements and MC calculation as well as corrected PinPoint measurements for small field output factors. The agreement was within 0.5% for circular cone sizes 5, 10, 20, 30 mm and the 10 ×10 cm^2 square field.

Table 2. Corrected and uncorrected output factors measured by PinPoint, EBT2 results and MC calculation for different circular cone sizes and 10 ×10 cm^2 square field.

Cone size (mm)	Output factor			
	Uncorrected PinPoint	Corrected PinPoint	EBT2 Film	Monte Carlo
5	0.491	0.519	0.521	0.519
10	0.743	0.757	0.760	0.758
20	0.913	0.917	0.920	0.921
30	1.000	1.000	1.000	1.000
10×10 cm^2 Square field	1.133	1.122	1.125	1.126

CONCLUSION

Ionisation chambers are usually used for calibration and beam measurements in conventional radiotherapy because of their high sensitivity, accuracy and reproducibility and easy of use. There are special conditions in small field sizes such as the absence of lateral electron equilibrium, steep dose gradients and the lack of plateau region in beam profile. Because of these even the microionization chambers such as PinPoint with small sensitive volume (2 mm diameter and 0.015 cm^3 volume) are too large for small field dosimetry and they need some corrections factors. The EBT2 film has properties such as good spatial resolution, water equivalent material, linear response, energy independent and dose-rate independent. These properties make the EBT2 film suitable detector for small field dosimetry especially for penumbra and output factor measurements.

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