Original Article

Analysis of small field percent depth dose and profiles: Comparison of measurements with various detectors and effects of detector orientation with different jaw settings

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ABSTRACT

The advent of modern technologies in radiotherapy poses an increased challenge in the determination of dosimetric parameters of small fields that exhibit a high degree of uncertainty. Percent depth dose and beam profiles were acquired using different detectors in two different orientations. The parameters such as relative surface dose (D_S), depth of dose maximum (D_{max}), percentage dose at 10 cm (D_{10}), penumbral width, flatness, and symmetry were evaluated with different detectors. The dosimetric data were acquired for fields defined by jaws alone, multileaf collimator (MLC) alone, and by MLC while the jaws were positioned at 0, 0.25, 0.5, and 1.0 cm away from MLC leaf-end using a Varian linear accelerator with 6 MV photon beam. The accuracy in the measurement of dosimetric parameters with various detectors for three different field definitions was evaluated. The relative D_S (38.1%) with photon field diode in parallel orientation was higher than electron field diode (EFD) (27.9%) values for 1 cm × 1 cm field. An overestimation of 5.7% and 8.6% in D_{10} depth were observed for 1 cm × 1 cm field with RK ion chamber in parallel and perpendicular orientation, respectively, for the fields defined by MLC while jaw positioned at the edge of the field when compared to EFD values in parallel orientation. For this field definition, the in-plane penumbral widths obtained with ion chamber in parallel and perpendicular orientation were 3.9 mm, 5.6 mm for 1 cm × 1 cm field, respectively. Among all detectors used in the study, the unshielded diodes were found to be an appropriate choice of detector for the measurement of beam parameters in small fields.

Key words: Beam profile; detector orientation; penumbra; percent depth dose; small field dosimetry

Introduction

With the adoption of advanced technologies in modern radiotherapy such as stereotactic radiosurgery, stereotactic body radiation therapy, and intensity-modulated radiation therapy, there is an increased interest in the small field dosimetry of photon beams. The accurate dosimetry of small fields in subcentimeter range used in modern treatment techniques makes the measurement difficult due to steep dose gradient, lack of charge particle equilibrium, detector size as well as the partial occlusion of radiation source.[1,2] Furthermore, the directional and energy response of detectors influence the measurements in small field dosimetry.[3,4] In addition, the volume averaging and perturbation are caused due to the finite size of the active volume of the detector and nonwater equivalence

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materials.[5,6] No detector is said to be ideal in radiation dosimetry as they perturb the radiation field and introduce systematic errors during measurements.

The experimental determination of dosimetric parameters is challenging, especially in small fields that exhibit a high degree of uncertainty. Commonly used detectors in the dosimetry of photon fields are ionization chambers, solid state diodes, thermoluminescent and film dosimeters. An accurate characterization at edges of the beam is challenging with ion chamber as it leads to broadening of beam edges due to its finite size.[7,8] In particular, diodes are frequently used to measure beam profiles and verify dose distributions for the very small fields.[9,10] Diodes have been recommended for small field dosimetry due to its small active dimensions.[11,12] The directional response of the detector during beam characteristics measurement is vital as the angular distribution of electrons and scattered photon changes with depth and distance from the beam center.[13]

The exactness of dose calculation in modern radiotherapy techniques requires accurate acquisition of dosimetric parameters such as percent depth dose (PDD), profile, and output factor. Significant discrepancies (∼10%) have been observed by several authors in small field measurement with various detectors. The American Association of Physicists in Medicine's Task Group 106 report explains that the acquired PDD may vary depending on the type of detector used.[14] Apipunyasopon *et al*. have observed a rapid change in the build-up region and an increased surface dose (D_S) of approximately 10–30% with field size.[15] The accuracy in aligning the detector with central axis (CAX) is vital as 1 mm of CAX deviation leads to an error of 2% in PDD for 1 cm × 1 cm field.[16] Few studies have shown a substantial broadening of penumbra during beam profile measurement using different detectors.[17,18] Change in the measured profile broadens the penumbra due to different sources of perturbation that includes electron transport alteration and volume averaging.[19] The configuration as well as the position of jaws above multileaf collimator (MLC) would change the dose characteristics on central and off axis of the beam.[20] Monte Carlo calculations demonstrated that the jaw openings affect the particle fluence strongly, particularly in small field as the radiation source is finite in size.[6]

The aforementioned effects instigated an emphasis on the accurate acquisition of CAX PDD and profile with different detectors in parallel and perpendicular orientation for small fields. The fields were defined by jaws (MLC in park position), MLC (jaws fixed at 40 cm × 40 cm), and by MLC whereas the jaws were positioned at 0, 0.25, 0.5, and 1.0 cm away from MLC leaf-end. The parameters such as relative surface dose D_S, the depth of dose maximum (D_{max}), percentage dose at 10 cm (D_{10}), cross-plane and in-plane penumbral width, flatness, and symmetry were evaluated from the acquired PDD and profile with different detectors. The aim of this work is to evaluate the accuracy in the measurement of aforesaid dosimetric parameters with four detectors for different field definitions in two orientations.

Materials and Methods

Treatment unit

Photon beam of energy 6 MV was used to obtain PDD and profiles of small fields in Clinac DHX linear accelerator (Varian Medical Systems, Palo Alto, CA, USA). This accelerator features a single-focused millennium MLC below the secondary jaws as tertiary collimator. The millennium MLC consists of tungsten leaves of 60 pairs with central 40 leaf pairs of 5 mm projected leaf width at isocenter and 10 leaf pairs of 10 mm projected leaf width on either side of isocenter. The leaf movements are controlled by the stepper motors through MLC controller workstation. A nominal dose rate of 400 MU/min was used during the acquisition of dosimetric parameters.

Dosimetric measurement tools

Beam data were acquired using a computer-controlled radiation field analyzer (RFA-300, Scanditronix Wellhofer AB, Sweden), a water phantom having the scanning area of dimensions 495 mm × 495 mm × 495 mm (*X*/*Y*/*Z*) and positional accuracy of ±0.5 mm. The detectors used in this study were IBA photon field diode (PFD) and electron field diode (EFD), Nordic Association of Clinical Physicists (NACP) parallel plate, and RK cylindrical ion chamber. The recommended orientation for measurements with PFD and EFD diodes is parallel to CAX with 0.6 and 0.4 mm from the surface as the effective point of measurement. The diodes oriented parallel to CAX of the beam have the sensitive volume (silicon chip) facing the beam. It is recommended to position NACP and RK ion chambers perpendicular to CAX of the beam with 0.6 mm below the outer surface and 6.5 mm from the top surface along the chamber axis as the effective point of measurement. Table 1 tabulates the characteristics of detectors used in this study. OmniPro Accept (Version 7.4c) software (Scanditronix Wellhofer AB, Sweden) was used to control the movement of detectors in water phantom and to analyze the acquired PDD and beam profiles.

Experimental setup

PDD and beam profiles were acquired using different detectors oriented both in parallel and perpendicular direction to CAX of the beam for square fields varying from 1 cm × 1 cm to 10 cm × 10 cm with an increment of 1.0 cm defined at 100 cm source to surface distance (SSD). At the nominal depth of zero, the effective point of measurement of detectors was positioned parallel to the water surface. The placement of the detector in two different orientations with respect to CAX of the beam during the acquisition of dosimetric data in RFA has been depicted in Figure 1.

Table 1: Characteristics of various detectors used in this study

Trade mark and model	Detector type	Material	Density (g/cm^3)	Volume (cm^3)	Dimensions	Package material
RK 8304	Cylindrical ion chamber	Air	0.001	0.12	4 mm inner diameter, 10 mm active length	Perspex/epoxy resin and graphite
IBA PFD	Shielded diode	Silicon	2.33	29×10^{-5}	2 mm diameter, 0.06 mm thick	Epoxy resin + tungsten
IBA EFD	Unshielded diode	Silicon	2.33	29×10^{-5}	2 mm diameter, 0.06 mm thick	Epoxy resin
NACP	Parallel plate ion chamber	Air	0.001	0.16	10 mm diameter, 2 mm electrode spacing	Mylar foil and graphite window/PMMA

PFD: Photon field diode, EFD: Electron field diode, NACP: Nordic Association of Clinical Physicists, PMMA: Polymethyl methacrylate

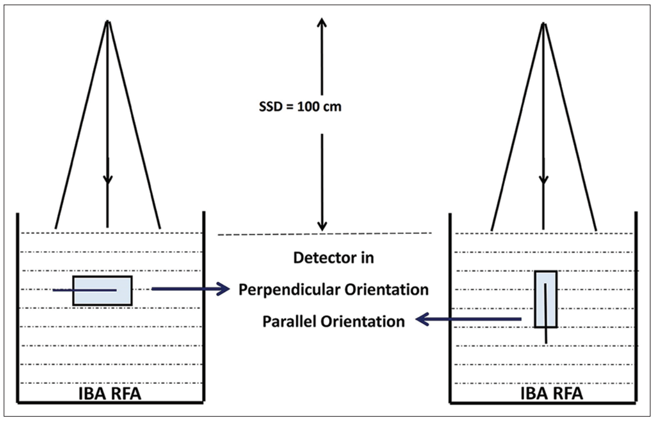

Figure 1: The schematic representation of detector orientations for the measurement of small field percent depth dose and profile in radiation field analyzer

Following are the three different sets of measurements that have been performed to acquire the dosimetric parameters.

- The fields were defined by X and Y jaws while MLC were retracted to the extreme edges
- The fields were defined by MLC while jaws were fully retracted
- The fields were defined by MLC while jaws were positioned at distances 0, 0.25, 0.5, and 1.0 cm away from the edges of MLC.

The geometric configuration of the field defined by millennium MLC and the different jaw position above MLC are shown in Figure 2.

Percentage depth dose

PDD was acquired along the CAX of the beam at a SSD of 100 cm for field sizes ranging from 1 cm × 1 cm to 10 cm × 10 cm with an increment of 1 cm. All PDDs were normalized at the D_{max} with 10 cm × 10 cm field after measurement with each detector. The detectors were positioned accurately in the detector holder and PDDs were obtained by scanning each detector from a depth of 30 cm to the surface of water tank in discrete of 0.5 mm steps for all field settings as mentioned in the previous section. The relative D_S, percentage D_{10}, and the value of D_{max} in water were analyzed for all detectors.

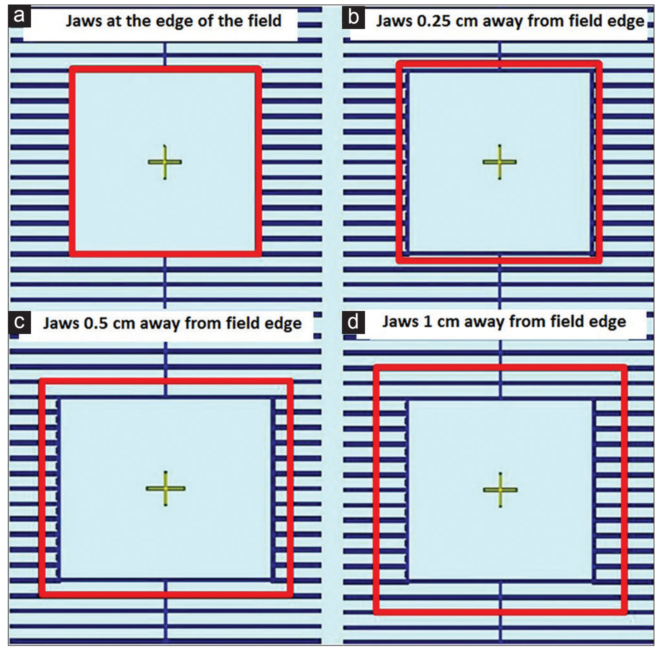

Figure 2: The configuration of multileaf collimator-defined fields when jaws are positioned (a) close to the edge of multileaf collimator (b) 0.25 cm away (c) 0.5 cm away, and (d) 1.0 cm away from the fields defined by multileaf collimator

Beam profile

Beam profiles for different field settings mentioned in experimental setup were measured across the center of the field using various detectors in two different orientations with a target-to-surface distance of 100 cm. The acquired profiles were normalized at 100% on the CAX of the beam. Cross- and in-plane profiles for each field along the center of the beam were acquired at D_{max} and 10 cm for 6 MV photon beam. The cross- and in-plane profiles acquired using various detectors for small fields were analyzed to find the variation in flatness, symmetry, and penumbral width (20–80%).

Results and Discussion

Analysis of relative surface dose

D_S gives an indication of the energy spectra as it is mostly due to low energy components of the radiation beam.[21] A large variation was observed in the relative D_S

that is obtained from PDD data acquired performed with various detectors for all fields with three different field definitions. Nevertheless, irrespective of field definition, the performance of various detectors followed a similar pattern for all field sizes. In accordance with the known fact, an increase in D_S with field size was noticed regardless of the type of detector used in measurement. Apipunyasopon *et al.*[15] have reported an increase in D_S from 10% to 28% with increase in field size using Monte Carlo simulation. The increase in D_S could be due to extra electron contamination and scattered photons arising from various components in treatment head and the intervening air column.[15,22,23]

The relative D_S obtained using EFD in parallel orientation is the lowest of all detectors for all field settings. For the lowest and the largest fields used in this study, the values obtained were 27.9% with 1 cm × 1 cm field and 39% with 10 cm × 10 cm field. As the unshielded silicon diode (EFD) has good spatial resolution and no metallic encapsulation, it gives better results in PDD measurements for photon beams.[17,11] The values obtained by PFD in parallel orientation and parallel plate ion chamber were higher than the values obtained by EFD. The relative D_S values obtained with PFD in parallel orientation were 38.1% and 47.3% for 1 cm × 1 cm and 10 cm × 10 cm field, respectively, whereas 37.8% and 43.7% were obtained with parallel plate ion chamber for 2 cm × 2 cm and 10 cm × 10 cm field, respectively. The over-response of the parallel plate ion chamber at the phantom surface could be due to the scattered electrons contributed from the side walls of the chamber and collected in its active volume.[24,25] The highest value (67.6% with 1 cm × 1 cm field and 78.9% with 10 cm × 10 cm field) was observed for all field sizes with PFD in perpendicular orientation. The large D_S values indicated in the shielded diode (PFD) are due to primary and secondary electrons backscattered from the metallic encapsulation present on the backside of the chip. In addition, due to the presence of high atomic metal, the emission of angular scattering of secondary electrons into the backward hemisphere is too strong that contributes additional signal to the diode.[11] A percentage increase in D_S was noticed for thermoluminescent dosimeter (4%) and Markus chamber (10%) in comparison with Monte Carlo for all square fields.[15]

On the analysis of D_S with the effect of jaw position, a maximum and minimum deviation of 1.4% and 0.8% was observed when the jaw was moved away by 0.25 cm from the field edge. With this jaw position setting, an increase in D_S of ∼ 1% was noticed in most of the detectors which could be due to the scattering from the jaw and the leakage/transmission of radiation through MLC leaf as well.[20] While comparing the D_S values, a maximum increase of 2.5% was observed for fields defined by MLC alone rather defined by jaw alone. This variation is attributed to the difference in the origin of scattered photons and electrons from MLC which is proximally located with the detector position compared to jaw position. When the field is set by MLC, the placement of leaves would expose larger area of flattening filter in the primary beam compared to the area of flattening filter exposed when the field is set using jaws. As a result, the detector would detect enhanced number of scatter photons and electrons originating from the larger area of flattening filter.[23]

Table 2 depicts the D_S enhancement factor in comparison with EFD positioned parallel to CAX for fields defined by MLC while jaw was positioned at the edge of MLC with all detectors. The D_S enhancement factor is the ratio of relative D_S obtained with any detector to the relative D_S obtained with EFD in parallel orientation. Similar behavior in enhancement factor was observed for all three field settings with every detector. Among the various detectors in different orientations, the PFD, EFD diodes in perpendicular orientation, and RK ion chamber in parallel orientation had shown the maximum enhancement factor for all fields. This variation could be due to the difference in interface geometry caused by the nonuniform configuration of diode towards the incident photons. Moreover, certain part of detectors closer to the surface of phantom was above the water level at some points of measurement that causes nonequilibrium.[15] The greater cross section of the sensitive volume of ion chamber contained in smaller fields attribute to volume averaging and lateral electronic disequilibrium.[5,26] Further, the over-response in D_S is due to the nonwater equivalency of the detectors in steep dose gradient region.[15]

Analysis of percent dose at 10 cm depth

PDD data analyzed at 10 cm depth with different detectors and the percentage variation of each detector with EFD reference values are shown in Figure 3a-c for different field settings. The detector-to-detector variation was observed for the smallest field (1 cm × 1 cm) whereas negligible deviations were found for large fields with different field settings. Irrespective of different field definition, the observed variation between detectors in the descending part of PDD curve was better than 1% for fields >1 cm × 1 cm; however, a maximum variation of 1.9% was observed with parallel plate ion chamber for 2 cm × 2 cm field. This is consistent with the recommendations of Aspradakis *et al.* and it is evident in the measurement that the PDD values decrease with field sizes.[27,28] These changes in PDD values are due to the variation in scattering of electrons and photons from collimator and phantom, respectively.[29]

An overestimation of 5.7% and 8.6% was observed in 1 cm × 1 cm field with RK ion chamber in parallel and perpendicular orientation respectively, for the fields defined by MLC while jaw was positioned at the edge of the field. Similarly, an overestimation of 3.5% and 4.4% was observed with RK ion chamber in parallel and

Table 2: Surface dose enhancement factor in comparison with electron field diode values

Field size (cm²)	*RK (parallel)*	*RK (perpendicular)*	*PFD (parallel)*	*PFD (perpendicular)*	*EFD (parallel)*	*EFD (perpendicular)*	*NACP*
1×1	2.1	1.5	1.4	2.4	1	2.0	-
2×2	2.1	1.8	1.3	2.4	1	2.0	1.3
3×3	1.9	1.7	1.2	2.2	1	1.8	1.2
5×5	1.8	1.6	1.2	2.1	1	1.7	1.1
10×10	1.8	1.5	1.2	2.0	1	1.7	1.1

PFD: Photon field diode, EFD: Electron field diode, NACP: Nordic Association of Clinical Physicists

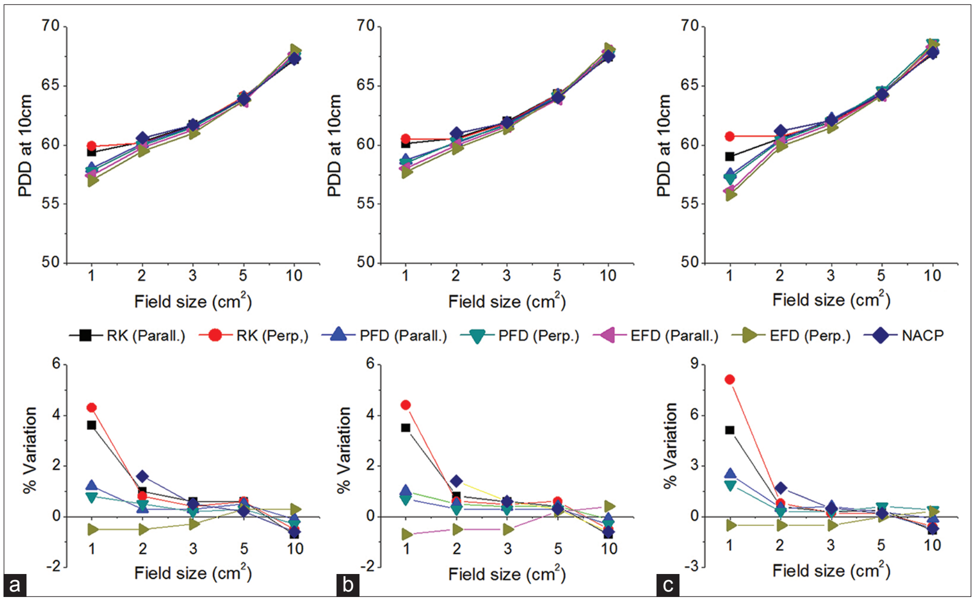

Figure 3: The variation in dose at 10 cm depth acquired with different detectors for fields defined by (a) jaw alone (b) multileaf collimator alone (c) multileaf collimator when jaw was positioned 0.25 cm away from the field edge

perpendicular orientation for the smallest field defined by MLC and jaw independently. Bucciolini *et al*. have reported an overestimation of dose in ion chamber with depth up to 4% with respect to diode detectors. This discrepancy could be due to the averaging of ion chamber response in an area where the profile is not flat which is more prominent at shallow depths.[17] The over-response of mini ion chambers that attributes to volume averaging effect has been reported by several authors.[30,31] When the smallest field is used, only a portion of the sensitive volume gets irradiated at shallow depth compared to the volume irradiated at deeper depth due to the divergence of the beam. This irradiation condition results in higher PDD that has been observed in this study.[30] In addition, a small positioning error in detector could lead to few percent of error in depth dose measurement of small beams.[32]

The response of shielded and unshielded diodes in PDD measurements agrees well with each other irrespective of their orientation. With an MLC field of 1 cm × 1 cm, an overestimation of 2.5% and 1.8% was observed as the jaw was positioned at the edge of the field in parallel and perpendicular orientation of PFD when compared to EFD value. For fields defined by MLC alone and jaw alone, about 1% increase was observed in both orientations of PFD as compared to EFD.[17] The contribution of backscatter in shielded diodes is twice compared to unshielded diodes that causes higher dose response in small fields due to the presence of high-density shielding material.[5] The diode response also increases due to the decrease in low-energy photons fluence as field size decreases.[6] The over-response of diodes in PDD measurement as a function of depth is not as noticeable as in output ratio. This result is consistent with the results published in literatures.[33]

On comparison of PDD values between the respective detectors for fields defined by jaw alone and MLC alone, an increase of 1.2% was observed for 1 cm × 1 cm field defined by MLC alone, while for fields between 2 cm × 2 cm and 10 cm × 10 cm, no more than 0.5% increase in PDD values was noticed. This small variation could be due to the differential scattering from jaws and MLC. Nevertheless, a negligible increase in PDD values (<0.5%) was observed when the jaws were moved away from the edge of the MLC-defined field. This is because the scattered photons and electrons from the jaw get attenuated by the intervening MLC system.[20] The results obtained are consistent for all three field definitions and the values are in good agreement with the results reported by Kehwar *et al*.[34]

Analysis of depth of dose maximum

The D_{max} position depends on energy and field size. Generally, the depth of maximum dose changes slightly with field size for a particular beam quality from a given machine.[35] The variation in D_{max} measured with various detectors in two orientations for three different field definitions is shown in Figure 4. The D_{max} values observed for all detectors were ranging from a minimum value of 1.25 cm to a maximum of 1.7 cm. Among all detectors, PFD and EFD in perpendicular orientation showed minimum D_{max} values in small fields. In the design of shielded diode, due to the presence of high atomic material, low-energy scatter can be absorbed and it may lead to the under-response of the detector.[12] The small difference observed between PFD and EFD at D_{max} is due to the differences in response to contaminant electrons and was also noticed by Dasu *et al*.[36]

With increase in field size, the D_{max} position shifted towards the phantom surface irrespective of field definition.[34] A small differential component of electron scatter also shifts the depth of maximum towards the phantom surface with increasing field size.[29] The D_{max} value gradually increases from 1 cm × 1 cm field till it attains maximum value at 3 cm × 3 cm field and then is found to be gradually decreasing as field size increases. This descending zone for larger and smaller fields on either side of 3 cm × 3 cm was found to be similar in all detectors with each field settings. The decrease in D_{max} values is due to collimator and flattening filter scatter effects in larger fields and reduced phantom scatter effects in smaller fields.[35]

Analysis of beam profile and penumbra

The profiles acquired at the depth of D_{max} and 10 cm using three detectors were analyzed to find the variation in penumbra. The penumbra is characterized by the beam edge of a profile, where there is lack of lateral electron equilibrium that leads to steep dose gradients and it depends on field size, depth, collimator scatter, and phantom scatter. Penumbral width is measured as the lateral distance between 80% and 20% isodose lines. During the analysis of cross-plane profiles acquired using different detectors, a substantial difference in penumbral width was observed and that has also been reported by several authors.[12,13,17,18,37] Moreover, broadening of penumbra in the cross- and in-plane beam profiles was found to be different with various detectors in parallel and perpendicular orientations. For small fields, profiles were found to be dependent on both sensitive volume and type of the detectors.[6] The cross-plane and in-plane penumbral width obtained at the depth of dose maximum with various detectors for different field definitions are tabulated in Tables 3 and 4.

During the analysis of penumbra, it was observed that the penumbral width obtained by RK ion chamber was found to be broadened by 1 mm for all field sizes with three field definitions. The broadened penumbra observed with ion chamber was due to higher electron range in air than in water and the signal was averaged across its sensitive volume.[30,31] The two main causes for the penumbra broadening are the alteration in electron transport if the detector is nonwater equivalent and the volume averaging effect.[19] Among various detectors used in this study, RK ion chamber produced the widest penumbra. RK ion chamber was found to have higher uncertainty with other detectors indicating nonsuitability for penumbra measurements. Estimation of penumbral width with silicon diode had shown promising results as it has better spatial resolution capable of resolving steep dose gradients.[5,17,38] While profiles measured with PFD and EFD diodes were found to agree with a negligible difference, which could be due to the difference in design of these diodes, it is reasonable to assume that the results obtained by EFD are more accurate than PFD because the design includes an additional nonwater equivalent tungsten epoxy backing in the PFD diodes.[2]

The shape of profile and penumbral width is influenced not only by detector orientation but also by the scan direction. A difference in penumbral width was substantial for both cross- and in-plane profiles in two different orientations with ion chamber measurements than other detectors used in the study. Nevertheless, the penumbral width obtained from in-plane profile has shown larger deviation within their orientations of ion chamber. While in cross-plane profile for the fields defined by MLC when jaws were positioned at the edge of MLC field, the penumbral widths obtained with diodes and ion chamber were 3, 4 mm for the smallest field of 1 cm × 1 cm and 3.2, 4.6

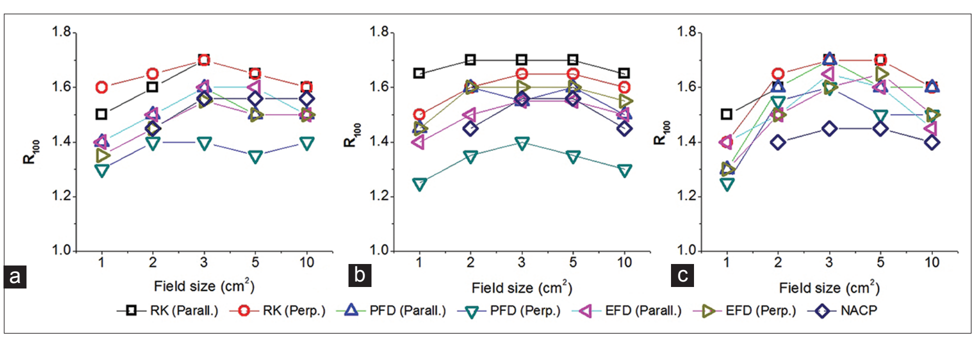

Figure 4: The variation in depth of dose maximum acquired with different detectors in parallel and perpendicular orientations for different jaw settings: (a) Jaw alone (b) multileaf collimator alone (c) multileaf collimator when jaw was positioned 0.25 cm away from the field edge

Table 3: The cross-plane penumbral width acquired with different detectors at dose maximum depth for different field definitions

Jaw position	*Field size (cm²)*	*RK (parallel)*	*RK (perpendicular)*	*PFD (parallel)*	*PFD (perpendicular)*	*EFD (parallel)*	*EFD (perpendicular)*
At edge of MLC	1×1	4.0	4.0	3.2	3.0	3.1	3.0
	2×2	4.1	4.1	2.8	2.7	3.0	3.1
	3×3	4.2	3.9	2.9	2.7	2.9	2.9
	5×5	4.3	4.3	3.1	2.9	3.0	3.0
	10×10	4.8	4.5	3.2	3.1	3.2	3.2
0.25 cm away from MLC	1×1	4.3	4.1	3.4	3.2	3.3	3.0
	2×2	4.4	4.2	3.1	3.1	3.1	3.1
	3×3	4.5	4.3	3.1	3.0	3.2	3.1
	5×5	4.5	4.6	3.3	3.2	3.3	3.0
	10×10	4.9	4.7	3.4	3.3	3.4	3.3
0.5 cm away from MLC	1×1	4.5	4.4	3.7	3.5	3.5	3.5
	2×2	4.4	4.5	3.4	3.4	3.5	3.5
	3×3	4.8	4.6	3.5	3.3	3.5	3.4
	5×5	4.7	4.9	3.7	3.5	3.7	3.7
	10×10	5.4	5.1	3.8	3.6	4.0	4.0
1.0 cm away from MLC	1×1	4.6	4.7	3.7	3.6	3.6	3.7
	2×2	4.6	4.7	3.4	3.4	3.5	3.6
	3×3	4.7	5.1	3.5	3.4	3.8	3.8
	5×5	4.8	5.2	3.7	3.6	3.8	3.9
	10×10	5.2	5.3	3.8	3.7	4.0	4.1
MLC alone	1×1	3.3	3.3	2.3	2.6	2.4	2.3
	2×2	3.6	3.6	2.5	2.4	2.4	2.3
	3×3	3.7	3.6	2.6	2.5	2.7	2.5
	5×5	3.8	3.7	2.7	2.6	2.7	2.6
	10×10	4.0	3.9	2.8	2.7	2.8	2.7
Jaw alone	1×1	3.1	3.2	2.2	2.0	1.9	1.9
	2×2	3.2	3.1	2.1	2.1	2.0	1.9
	3×3	3.5	3.4	2.1	2.20	2.2	2.1
	5×5	3.4	3.2	2.3	2.1	2.2	2.1
	10×10	3.6	3.5	2.4	2.3	2.3	2.3

MLC: Multileaf collimator, PFD: Photon field diode, EFD: Electron field diode

mm for the largest field of 10 cm × 10 cm in both orientations. With the aforementioned field definition, the widths of 3.9 and 5.6 mm for smallest field and 4.7 and 8 mm for largest field were obtained with in-plane profile using ion chambers in parallel and perpendicular orientation, respectively. The large variation between two different orientations with ion chamber could be due to the change in fluence experienced across the field by the chamber and the asymmetry of the chamber volume at the beam edges.[12] No noteworthy difference was noticed in the values of penumbral width measurements carried out by diodes in both orientations. However, diodes in perpendicular orientation showed a little lower value (~0.3 mm) than parallel orientation. Though the diodes positioned with its axis perpendicular to the CAX of the beam offer good spatial resolution,[39] this would underestimate the penumbral width because of reduced electron range in the diode and the housing.[13]

The shape of small field profiles in the penumbral region also depends on the geometry of the collimator. The tertiary collimating system in Varian linear accelerator influences the dosimetric parameters in a way different from other collimating systems as MLCs are placed below the collimating jaw. The fields defined by MLC alone have higher values of penumbral width than for the fields defined by jaw alone. Similar results have been noticed by Kehwar *et al*.[34] However, the penumbral value for the fields defined by MLC combined with different jaw openings is higher than the other two field definitions. Though MLC leaf end is designed to have rounded edge to reduce penumbra, the obtained values are higher than the field defined by jaw alone due to the increased transmission through rounded edge. The increase in broadening of penumbra due to the effect of jaw position is noticeable when jaw is moved 0.25 cm away, whereas it is not substantial when jaw is positioned 0.5 and 1 cm away from the MLC field edge for all detectors. The enhanced behavior is due to the additional contribution of jaw scattering, intra- and inter-leaf leakage and transmission through rounded edge of MLC as well.[20]

The flatness and symmetry were also analyzed from beam profile data at D_{max} depth and 10 cm depth with various

Table 4: The in-plane penumbral width acquired with different detectors at dose maximum depth for different field definitions

Jaw position	*Field size (cm^2)*	*RK (parallel)*	*RK (perpendicular)*	*PFD (parallel)*	*PFD (perpendicular)*	*EFD (parallel)*	*EFD (perpendicular)*
At edge of MLC	1×1	3.9	5.6	3.1	2.9	3.1	3.1
	2×2	4.3	7.3	3.0	2.7	3.2	3.0
	3×3	4.1	7.2	3.1	2.7	3.1	2.9
	5×5	4.3	7.6	3.1	2.8	3.1	3.1
	10×10	4.8	8.0	3.3	3.0	3.4	3.1
0.25 cm away from MLC	1×1	4.1	6.0	3.1	2.8	3.0	3.1
	2×2	4.4	7.3	3.0	2.8	3.1	3.0
	3×3	4.1	7.2	3.0	2.6	2.7	2.9
	5×5	4.4	7.6	3.0	2.7	3.0	3.1
	10×10	4.6	7.9	3.2	2.9	3.3	3.2
0.5 cm away from MLC	1×1	4.4	6.4	3.2	2.9	3.0	3.2
	2×2	4.3	7.2	3.1	2.8	3.1	2.9
	3×3	4.0	7.3	3.0	2.6	3.0	2.9
	5×5	4.4	7.6	3.1	2.7	3.1	3.0
	10×10	4.9	7.9	3.2	2.9	3.3	3.2
1.0 cm away from MLC	1×1	4.7	6.7	3.3	3.1	3.1	3.3
	2×2	4.4	7.5	3.1	2.7	3.2	3.0
	3×3	4.3	7.4	3.1	2.7	3.1	2.9
	5×5	4.5	7.8	3.2	2.8	3.2	3.1
	10×10	4.8	8.1	3.3	3.0	3.4	3.3
MLC alone	1×1	3.1	6.0	2.3	1.6	1.9	1.8
	2×2	3.2	6.3	2.1	1.7	2.1	1.8
	3×3	3.3	6.3	2.1	1.9	2.1	1.8
	5×5	3.4	6.5	2.0	1.8	2.0	1.6
	10×10	3.5	6.8	2.3	1.8	2.2	2.0
Jaw alone	1×1	3.1	4.9	2.2	2.0	2.1	1.8
	2×2	3.2	6.1	2.3	2.1	2.3	2.1
	3×3	3.3	6.2	2.3	2.1	2.2	2.1
	5×5	3.6	6.0	2.4	2.3	2.5	2.2
	10×10	3.6	6.2	2.5	2.4	2.6	2.2

MLC: Multileaf collimator, PFD: Photon field diode, EFD: Electron field diode

detectors. The analyzed results for flatness and symmetry were found to have no variation for all three field definitions. Similar results have also been reported in the literature.[34]

Conclusion

The uncertainty in measurement of small field dosimetric parameters contributes directly to the treatment outcome. An extensive study with various detectors has been carried out to investigate the efficacy of detectors in small field dosimetric measurements. The beam characteristics with fields defined by jaw alone, MLC alone, and MLC combined with different jaw openings have been measured and a change has been observed in PDD and beam profile in smaller fields. The position of jaw above MLC should be considered during small field measurements as it influences the basic dosimetric parameters. This study concludes that appropriate detectors should be used to acquire data for small fields and detector must be considerably smaller than the beam axis where there is lack of lateral electronic equilibrium. This study suggests that the percentage depth dose measurement is reliable with any of the three detectors beyond build-up region. The overestimation of penumbral width observed with RK ion chamber in both orientations indicated the nonsuitability of the detector for profile measurements. Among all detectors used in the study, the unshielded diodes were found to be an appropriate choice of detector for the measurement of beam parameters in small fields as it closely matches with Monte Carlo simulated values.

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Conflicts of interest

There are no conflicts of interest.

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