Original Article

Effect of Detector Orientation and Influence of Jaw Position in the Determination of Small-field Output Factor with Various Detectors for High-energy Photon Beams

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Abstract

Background: Accurate dose measurements are difficult in small fields due to charge particle disequilibrium, partial source occlusion, steep dose gradient, and the finite size of the detector. **Aim:** The study aims to determine the output factor using various detectors oriented in parallel and perpendicular orientations for three different tertiary collimating systems using 15 MV photon beams. In addition, this study analyzes how the output factor could be affected by different configurations of X and Y jaws above the tertiary collimators. **Materials and Methods:** Small field output factor measurements were carried out with three detectors for different tertiary collimating systems such as BrainLab stereotactic cones, BrainLab mMLC and Millennium MLC namely. To analyze the effect of jaw position on output factor, measurements have been carried out by positioning the jaws at the edge, 0.25, 0.5, and 1.0 cm away from the tertiary collimated field. **Results:** The data acquired with 15 MV photon beams show significant differences in output factor obtained with different detectors for all collimating systems. For smaller fields when compared to microDiamond, the SRS diode underestimates the output by up to -1.7% ± 0.8% and -2.1% ± 0.3%, and the pinpoint ion chamber underestimates the output by up to -8.1% ± 1.4% and -11.9% ± 1.9% in their parallel and perpendicular orientation respectively. A large increase in output factor was observed in the small field when the jaw was moved 0.25 cm symmetrically away from the tertiary collimated field. **Conclusion:** The investigated data on the effect of jaw position inferred that the position of the X and Y jaw highly influences the output factors of the small field. It also confirms that the output factor highly depends on the configuration of X and Y jaw settings, the tertiary collimating system as well as the orientation of the detectors in small fields.

Keywords: Detector orientation, jaw effect, output factor, small field

Received on: 03-11-2023 **Review completed on:** 13-02-2024 **Accepted on:** 13-02-2024 **Published on:** 30-03-2024

Introduction

The accurate dose measurements are difficult due to charge particle disequilibrium, partial occlusion of the source, steep dose gradient, and the finite size of the detector where the small field is involved.[1,2] Accurate determination of small-field output factor is limited by systematic errors caused by volume averaging, lack of lateral charged particle equilibrium, non-tissue equivalency of detectors, and positional uncertainty of the detector.[3] The position and configuration of secondary jaws above tertiary collimators could considerably alter the fluence of the incident beam, the dose distribution, and the output of small fields.[4]

No ideal detector is available to determine the small-field output factors accurately without incorporating appropriate correction factors that indicate the necessity to find a suitable detector. Modern radiation techniques demand high-resolution and tissue-equivalent detectors in order to perform dose measurements in the regions of lateral electronic disequilibrium and steep dose gradients.[5] Although there are numerous studies on output factor measurements with different detectors for 6 MV photon beams, very few studies have been performed

Access this article online	
Quick Response Code:	**Website:** www.jmp.org.in
	DOI: 10.4103/jmp.jmp_148_23

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How to cite this article: Godson HF, Manickam R, Ponmalar YR, Ganesh KM, Saminathan S, Chandraraj C, *et al*. Effect of detector orientation and influence of jaw position in the determination of small-field output factor with various detectors for high-energy photon beams. J Med Phys 2024;49:73-83.

on output factors with 15 MV photon beams using various detectors for the different collimating systems. The lack of dosimetric data instigated an emphasis on the determination of the output factor for 15 MV photon beams with three different detectors in parallel and perpendicular orientations for small fields. These fields are defined by different tertiary collimating systems such as BrainLab stereotactic cones, BrainLab micro multileaf collimator (mMLC), and Millennium multileaf collimator (MLC). In addition, this study highlights the variation in output factor due to different configurations of X and Y jaws above the tertiary collimator.

Materials and Methods

Treatment unit

Dosimetric measurements were performed on Primus (Siemens, Germany) and Clinac 2100CD (Varian Medical Systems, Palo Alto, CA) linear accelerators. Primus and Clinac 2100CD linear accelerators are capable of producing 6 MV and 15 MV photon beams as well as five electron beams. The Clinac 2100CD linear accelerator incorporates a MLC that consists of 60 pairs of tungsten leaves as a tertiary collimating system. The Primus linear accelerator has been used for stereotactic irradiation with BrainLab micro-multileaf collimator or circular cones as an add-on tertiary collimating system. The add-on mMLC consists of 26 pairs of tungsten leaves over a field size of 9.8 cm × 9.8 cm with variable width. This design has 14 pairs at the center with a 3 mm projected width, 3 adjacent pairs of leaves with a 4.5 mm projected width, and 3 adjoining pairs of leaves with a projected width of 5.5 mm at the isocenter. BrainLab circular cones are made up of lead that is embedded in a brass shell having an outer diameter of 10.8 cm and a length of 11.5 cm. The inner diameter of circular cones ranges from 10 mm to 40 mm in steps of 5 mm.

Detectors

The detectors used in this study were PTW 60019 microDiamond, PTW 60018 stereotactic radiosurgery (SRS) diode, and PTW 31014 PinPoint ion chamber. The readings were obtained using a PTW UnidosE electrometer with microDiamond and diode operated at 0 V and a PinPoint ionization chamber at + 400 V. The characteristics of detectors used in this study are tabulated in Table 1. The data acquisition was carried out using PTW MP3 radiation field analyzer that has a positional accuracy ± 0.1 mm.

Output factor measurement

Three different tertiary collimators, including BrainLab mMLC, BrainLab stereotactic circular cones, and Millennium MLCs, were used to measure the small-field output factors of 15 MV photon beams. The BrainLab mMLC and circular cones were attached as tertiary collimators in Primus linear accelerator, whereas Millennium MLC was used as tertiary collimators in Clinac 2100CD linear accelerator. Square fields ranging from 1.2 cm × 1.2 cm to 9.8 cm × 9.8 cm were defined by mMLC, and stereotactic cones were used to define the circular fields ranging from 1.0 cm to 4.0 cm with an increment of 0.5 cm. Furthermore, Millennium MLCs were used to define square fields varying from 1 cm × 1 cm to 10 cm × 10 cm in steps of 1.0 cm. During the measurements, the X-Y jaws were positioned at the edges of the tertiary collimated fields. All measurements were performed with a source-to-detector distance of 100 cm at 10 cm depth using different detectors positioned in parallel and perpendicular orientations to the central axis (CAX) of the beam. The precise positioning of detectors at the center of the radiation field was confirmed with relative dose profiles at 10 cm. Each measurement was repeated four times by delivering 100 MU for all field sizes, and the average value was used in the study. Before every session, output measurements were performed under reference conditions to confirm the linear accelerator's output constancy. Ensuring consistent output on different days helps to validate consistency in comparison of output factors with different detectors. The PTW microDiamond detector oriented parallel to the CAX of the beam has been considered as the reference detector to compare the response of other detectors. Figure 1 depicts the schematic representation of small-field output factor measurement with various detectors in two different orientations.

Effect of jaw position on output factor

To analyze the effect of jaw position on output factor, measurements have been carried out by positioning the jaws at the edge, 0.25, 0.5, and 1.0 cm away from the tertiary collimated field. Figure 2 depicts the geometrical configuration of fields defined by MLC (tertiary collimator) for different X and Y jaw openings. The effect of jaw position on output factors was performed with BrainLab mMLC and stereotactic cones in Primus linear accelerator and with Millennium MLC in Clinac 2100CD linear accelerator as tertiary collimators for 15 MV photon beams. The measurements were performed with a source-to-detector distance of 100 cm at 10 cm depth using different detectors in parallel and perpendicular orientations.

The relative increase in output factor for different jaw positions was estimated as the ratio of output factor when the jaws are positioned at 0.25 cm away from the field edge to

Table 1: Summary of the detectors used and their characteristics

Make and model	Detector type	Sensitive material	Density (g/cm^3)	Volume	Dimensions	Encapsulation material
PTW 60019 micro-diamond	Micro diamond	Diamond	3.53	0.004 mm^3	2.2 mm diameter, 1 µm thick	RW3 + Epoxy resin
PTW 60018 SRS diode	Mini unshielded diode	Silicon	2.33	0.3 mm^3	1 mm diameter, 0.25 mm thick	RW3 + Epoxy resin
PTW 31014 PinPoint	Ionization chamber	Air	0.001	0.015 cm^3	2 mm diameter, 5 mm length	PMMA + Graphite

SRS: Stereotactic radiosurgery, PMMA: Polymethylmethacrylate

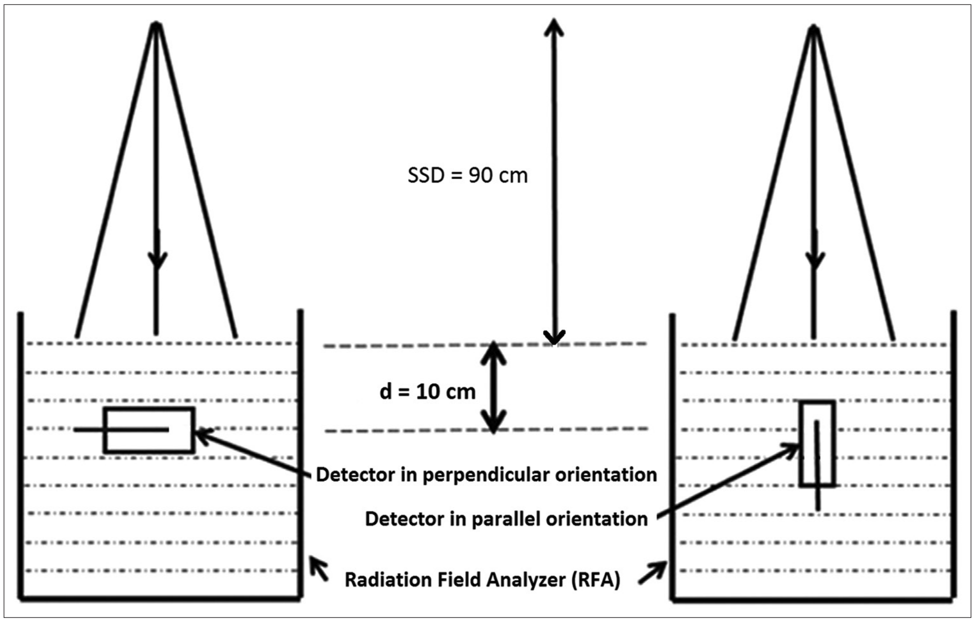

Figure 1: Schematic representation of small-field output factor measurement with various detectors in two different orientations

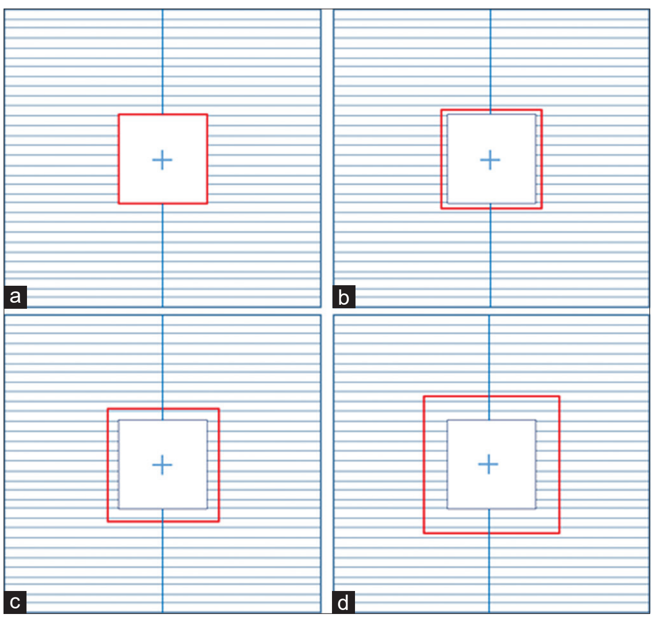

Figure 2: The geometrical configuration of fields defined by MLC for different X and Y jaw (highlighted in red color) settings (a) close to the edge of MLC, (b) 0.25 cm away, (c) 0.5 cm away, (d) 1.0 cm away from the fields defined by MLC

that of the output factor when the jaws are positioned at the edge of the tertiary collimated field. The relative increase in the output factor for any jaw position is defined as the ratio of the output factor for that particular jaw position to that of the output factor in the previous jaw position. The effect of detector orientation in the determination of the output factor was also analyzed by finding the ratio of the output factor obtained with a particular detector in parallel orientation to that of the output factor in perpendicular orientation for different jaw settings.

Results

Output factor

The measurement of small-field output factor with various detectors in parallel and perpendicular orientations for three different tertiary collimating systems such as BrainLab stereotactic cones, BrainLab mMLC, and Millennium MLC is described in this section.

BrainLab cone

The significant variation observed in small-field output factors due to the presence of add-on BrainLab stereotactic cones with different detectors for 15 MV photon beams is presented in this section. Figure 3 represents the spread in output factors of various detectors and the percentage variation with respect to the microDiamond reference values. Output factors obtained with the SRS diode are consistent with the microDiamond reference values (<1%) for cones of diameter ranging from 2.5 cm to 4.0 cm irrespective of detector orientation. A difference of −1.7% ± 0.8% and −1.2% ± 0.4% was observed with PTW SRS diode in parallel orientation for the cone diameters of 1.0 cm and 1.5 cm, respectively. An overestimation of 3.7% ± 1.6%, 2.8% ± 1.5%, and 1.5% ± 1.2% for cones of diameter 1.0 cm, 1.5 cm, and 2.0 cm, respectively, was seen in perpendicular orientation of microDiamond detector, and good agreement was noticed for larger cone sizes. PinPoint ion chamber of volume 0.015 cm^3 positioned parallel to CAX showed a deviation of −8.1% ± 1.4%, −5.2% ± 1.7%, and −3.4% ± 0.8% for the cone of diameter 1.0 cm, 1.5 cm, and 2.0 cm, respectively. An underestimation of 11.9% ± 1.9%, 7.5% ±1.6%, and 4.7% ± 0.5% was observed for the PinPoint ion chamber with the cone diameter of 1.0 cm, 1.5 cm, and 2.0 cm when positioned perpendicular to CAX of the beam. An underestimation of 2.1% ± 0.3%, 1.8% ± 0.4%, and 1.2% ± 0.3% was noticed in

1.0 cm, 1.5 cm, and 2 cm diameter cones, respectively, for PTW SRS diode in perpendicular orientation.

BrainLab mMLC

The output factors of stereotactic fields shaped by an add-on BrainLab mMLC were determined with various detectors for different orientations with 15 MV photon beams. Measurements performed for larger fields greater than 3.6 cm × 3.6 cm were found to be consistent for all detectors irrespective of their orientations. Output factors obtained with SRS diode in parallel and perpendicular orientations were consistent with the microDiamond reference values (<1%) for fields greater than 2.4 cm × 2.4 cm; nevertheless, a downgrade of 1.4% ± 0.9% (SE) and 1.8% ± 0.7% was noticed in parallel and perpendicular orientations, respectively, for the smallest field size. A variation of −1.07% ± 0.2% and −1.4% ± 0.3% was noticed with SRS diode in parallel and perpendicular orientations for a 1.8 cm × 1.8 cm field. For field sizes 1.2 cm × 1.2 cm and 1.8 cm × 1.8 cm, a high estimation of 3.4% ± 1.3% and 2.6% ± 0.9% was seen in perpendicular orientation of the microDiamond detector, respectively. The changes observed in parallel orientation of PinPoint ion chamber were −7.9% ± 0.6% and −4.5% ± 0.4% for the field sizes 1.2 cm × 1.2 cm and 1.8 cm × 1.8 cm, respectively. An underestimation of 10.4% ± 1.1%, 7.5% ± 0.5%, and 4.3% ± 0.3% was observed for PinPoint ion chamber in perpendicular orientation for the field sizes of 1.2 cm × 1.2 cm, 1.8 cm × 1.8 cm, and 2.4 cm × 2.4 cm, respectively. The variation in output factors for small fields due to the presence of mMLC as an add-on tertiary collimator to the linear accelerator is depicted in Figure 4.

Millennium MLC

The output factors of small fields with 15 MV photon beams were determined for the fields defined by Millennium MLC with various detectors in two different orientations, as represented in this section. A good agreement (<1%) with microDiamond was found when the measurements were performed for larger fields >3 cm × 3 cm irrespective of detector orientation. The SRS diode values obtained in parallel orientation were in good agreement with microDiamond for all field sizes, while differences show −1.05% ± 0.3% (SE) and −1.53% ± 0.2% in 1 cm × 1 cm and 2 cm × 2 cm

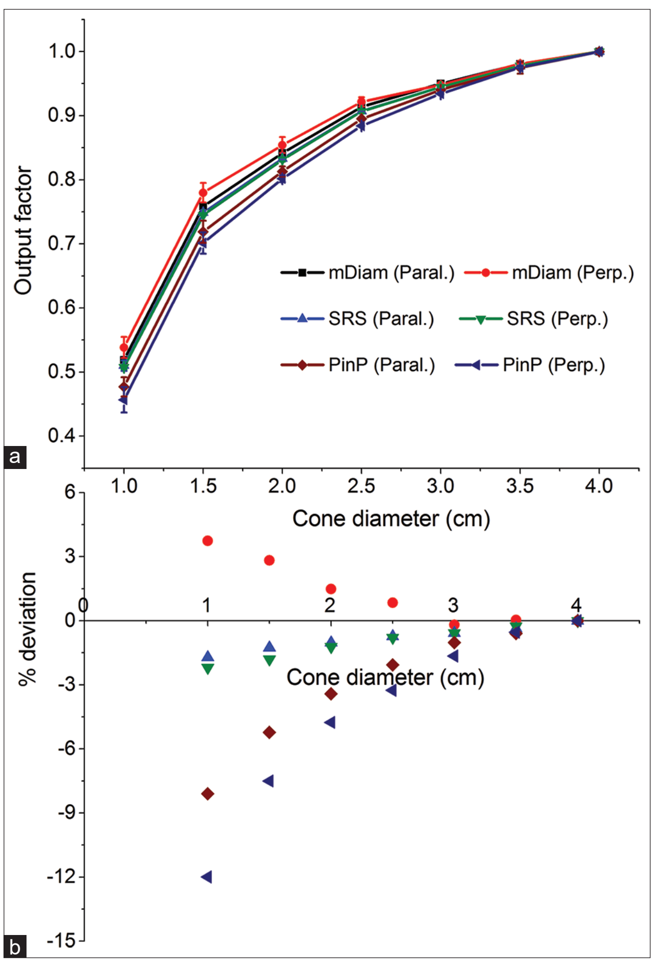

Figure 3: (a) Comparison of output factors with 15 MV photon beams for fields defined by circular cones using different detectors and (b) the percentage deviation of each detector with respect to the microDiamond detector for various cone diameters

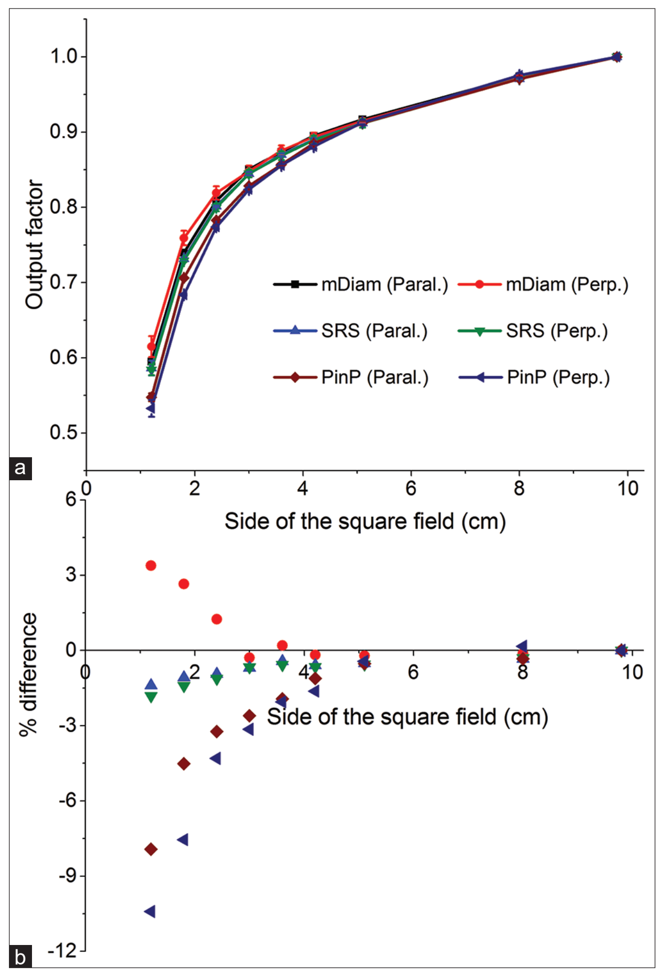

Figure 4: (a) Comparison of output factors with 15 MV photon beams for fields defined by mMLC using different detectors and (b) the percentage deviation of each detector with respect to the microDiamond detector for various field sizes

fields. Measurements using the SRS diode in perpendicular orientation showed an underestimation of up to −1.5% for fields smaller than 4 cm × 4 cm, and for larger fields, the deviations were <1%. An overestimation of 3.4% ± 0.7% was seen in the parallel orientation of microDiamond for 1 cm × 1 cm field, while an underestimation of ~0.4% was observed for fields >2 cm × 2 cm. In parallel orientation, the PinPoint ion chamber showed a deviation of −4.1% ± 0.5% and 1.6% ± 0.5% for 1 cm × 1 cm and 2 cm × 2 cm fields. A good agreement with microDiamond was found in the perpendicular orientation of the PinPoint ion chamber for field sizes greater than 2 cm × 2 cm, while an underestimation of 7.1% ± 1.5% was found for 1 cm × 1 cm field size. Figure 5 represents the spread in output factors observed with different detectors in parallel and perpendicular orientations for 15 MV photon beams.

Effect of jaw position on output factor

To investigate the influence of jaw position on output factors, the X and Y jaws have been moved 0.25 cm, 0.5 cm, and 1.0 cm symmetrically away from the edges of the tertiary collimated field. This section explains the output factor measurement

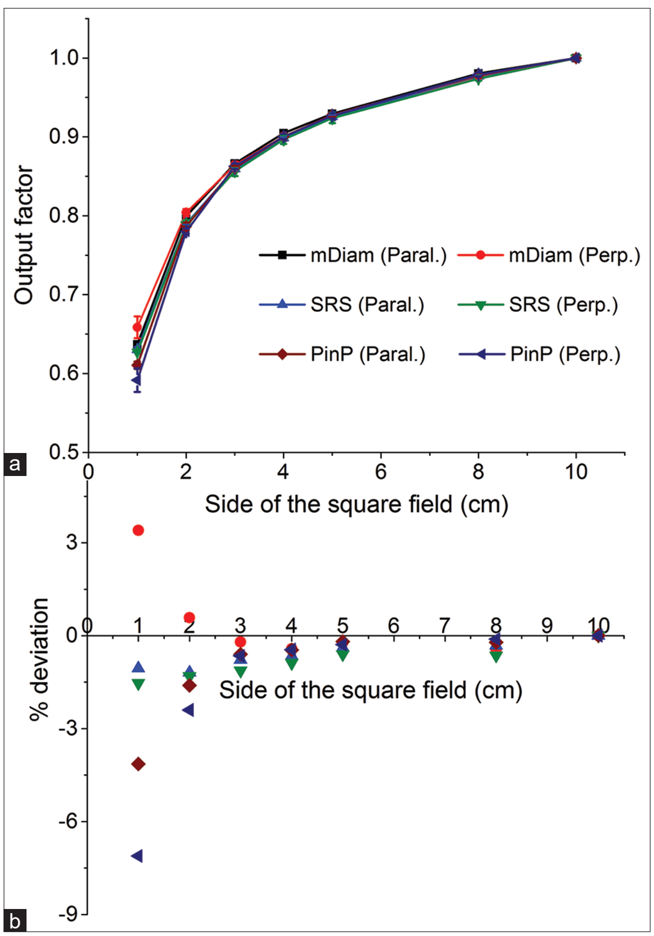

Figure 5: (a) Comparison of output factors with 15 MV photon beams for fields defined by Millennium MLC using different detectors and (b) the percentage deviation of each detector with respect to microDiamond detector for various field sizes

carried out with stereotactic cones, mMLC, and Millennium MLC for different jaw positions.

BrainLab cone

As the jaw was opened 0.25 cm symmetrically away from the field edge of the stereotactic cone, a large increase in output factor was observed up to 2 cm diameter cone and above which the increase in output was found to be negligible for the same jaw opening. Under this condition, an increase in output by a factor of 1.37, 1.39, and 1.40 was noticed with microDiamond, SRS diode, and PinPoint ion chamber in parallel orientation, respectively, for a 1.0 cm diameter cone. In perpendicular orientation, an increase in response by a factor of 1.41 has been observed with a PinPoint ion chamber for a 1.0 cm cone whereas, in microDiamond and SRS diode, the increase in output by a factor of 1.37 and 1.39 was observed. As the jaw was moved 0.5 and 1.0 cm away from the field edge, a maximum increase in output by a factor of 1.05 and 1.006 was observed in the smallest cone. Figure 6a-c illustrates the relative increase in output factor when the jaw was opened (a) 0–0.25 cm, (b) 0.25 cm–0.5 cm, and (c) 0.5 cm–1.0 cm away from the edge of the field defined by stereotactic cones and Figure 6d shows the variation in output factors with microDiamond detector for different jaw positions and the error bar indicates the standard uncertainty.

BrainLab mMLC

The influence of jaw position on output factors for the fields defined by BrainLab mMLC with various detectors for different jaw openings was measured and presented in this section. A noticeable increase in output factor was observed for fields up to 3 cm × 3 cm; nevertheless, a negligible deviation was seen in other fields as the jaw was moved 0.25 cm away from the field edge of the mMLC. For the PinPoint ion chamber in parallel orientation, the increase in response by a factor of 1.16 was observed with a 1.2 cm × 1.2 cm field, whereas an increase in response by a factor of 1.15 was observed with microDiamond and SRS diode in parallel orientation for 1.2 cm × 1.2 cm field with X and Y jaws positioned 0.25 cm away from the field edge. Under this condition, the increase in response by a factor of 1.15 was observed with PinPoint ion chamber in perpendicular orientation for 1.2 cm × 1.2 cm field whereas, with microDiamond and SRS diode in perpendicular orientation, an increase in output by a factor of 1.14 and 1.15 was observed. A maximum increase in output was observed by a factor of 1.03 and 1.008 for the smallest field as the jaw is moved 0.5 and 1.0 cm away from the field edge. Figure 7a-c illustrates the relative increase in output factor when the jaw was opened (a) 0–0.25 cm, (b) 0.25 cm–0.5 cm, and (c) 0.5 cm–1.0 cm away from the edge of the field defined by mMLC and Figure 7d shows the variation in output factors with microDiamond detector for different jaw positions and the error bar indicates the standard uncertainty.

Millennium MLC

The output factors were measured for the small fields defined by Millennium MLC with various detectors for the different

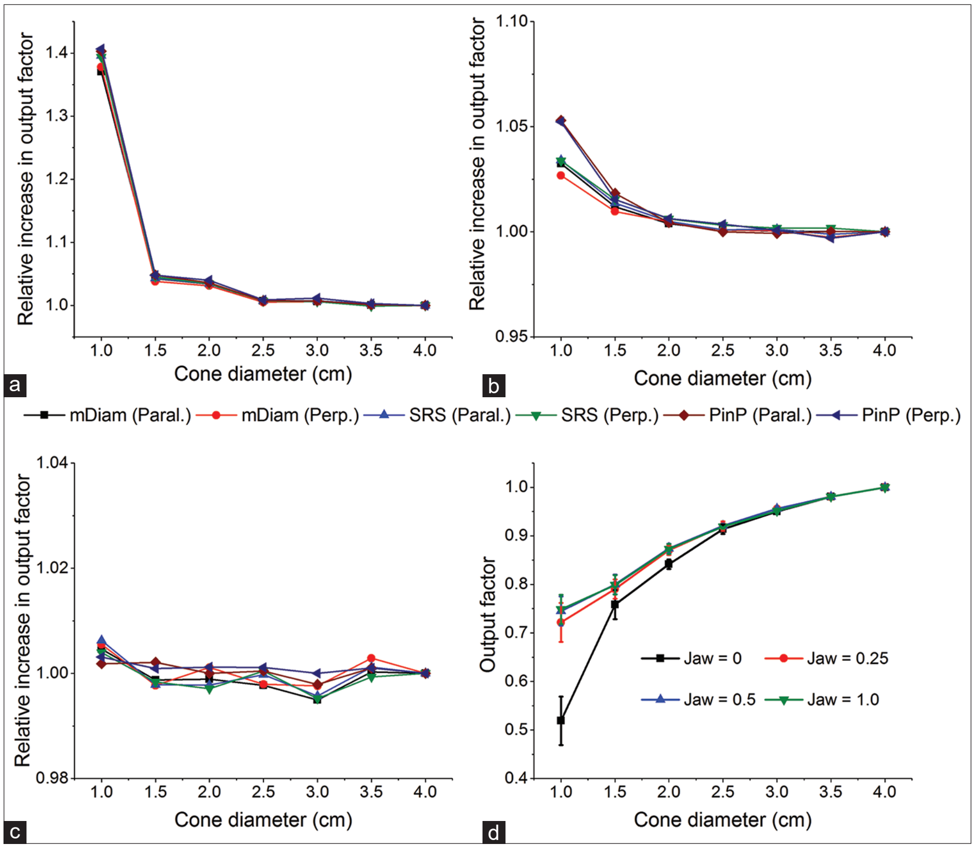

Figure 6: The relative enhancement in output factor with 15 MV when the jaw was opened (a) 0 to 0.25 cm, (b) 0.25 cm to 0.5 cm, (c) 0.5 cm to 1.0 cm away from the edge of the field defined by stereotactic cones and (d) Output factor measured with microDiamond detector for different jaw opening

openings of X and Y jaws using 15 MV photon beams. For a jaw opening of 0.25 cm symmetrically away from the MLC-defined field, a marginal increase in factor was noticed for field sizes above 2 cm × 2 cm; however, a noticeable increase was noted in the smallest field. Under this condition, the increase in the response of the PinPoint ion chamber was 1.05 in parallel orientation for a 1 cm × 1 cm field. The observed deviations for microDiamond and SRS diode were found to be 1.05 and 1.05 in parallel and 1.04 and 1.05 in perpendicular orientations. For the PinPoint ion chamber in perpendicular orientation, the increase in response was observed to be 1.06 for a 1 cm × 1 cm field. A maximum increase in output was found by a factor of 1.019 and 1.008 for the smallest field as the jaw is moved 0.5 cm and 1.0 cm away from the field edge. Figure 8a-c illustrates the relative increase in output factor when the jaw was opened (a) 0–0.25 cm, (b) 0.25 cm–0.5 cm, and (c) 0.5 cm–1.0 cm away from the edge of the field defined by Millennium MLC and Figure 8d shows the variation in output factors with microDiamond detector for different jaw positions and the error bar indicates the standard uncertainty.

Parallel versus perpendicular orientation of the detector

To determine the response of each detector in two different orientations, the ratio of the output factor obtained with a detector in parallel orientation to the perpendicular orientation was calculated for two different jaw openings such as the jaw positioned at the edge and the jaw positioned at 0.25 cm away from the edge of the tertiary collimator. A noticeable variation in the response of the detector in two different orientations was observed in small fields for different jaw openings. For the smallest field defined by all tertiary collimating systems, namely circular cones, mMLC, and MLC, a noticeable variation (~ 3%) was noticed with the microDiamond detector for 15 MV photon beams; however, no noteworthy change in response was observed with SRS diode using 15 MV photon beams. A factor of 1.056, 1.031, and 1.032 was obtained with a PinPoint ion chamber for the smallest field defined by circular cones, mMLC, and MLC, respectively, using 15 MV beams. When the jaws were moved symmetrically away from the edge of the tertiary collimated field by 0.25 cm, the PinPoint ion chamber showed an enhanced response of 1.025, 1.028, and 1.026 in parallel orientation for the smallest field defined by circular cones, mMLC, and MLC, respectively. No considerable difference in output was observed with all detectors in two different orientations for fields greater than 2 cm × 2 cm with 15 MV photon beams for all three tertiary collimating systems used in this study. Tables 2-4 represent the ratio of output factor between parallel and perpendicular orientations with different detectors for two different jaw openings: (a) jaw positioned at the field edge and (b) jaw positioned 0.25 cm away from the edge of the tertiary collimator.

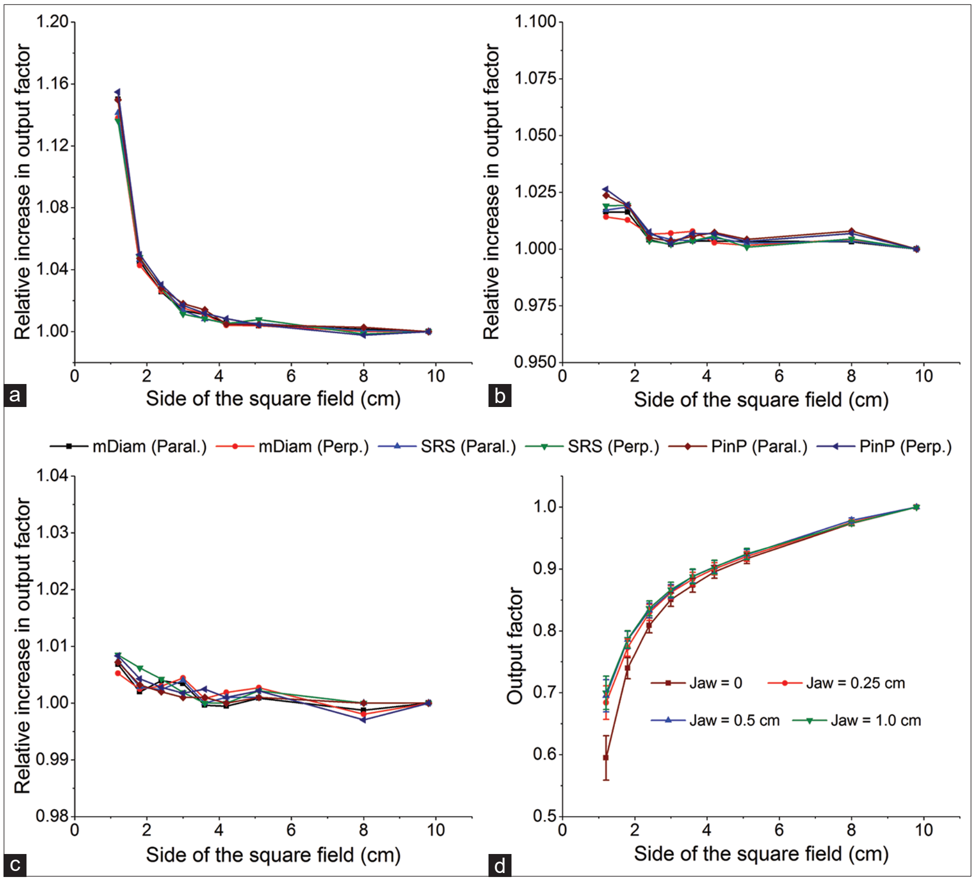

Figure 7: The relative enhancement in output factor with 15 MV when the jaw was opened (a) 0 to 0.25 cm, (b) 0.25 cm to 0.5 cm, (c) 0.5 cm to 1.0 cm away from the edge of the field defined by mMLC and (d) Output factor measured with microDiamond detector for different jaw opening

Table 2: The ratio of output factor between the parallel and perpendicular orientations of various detectors for different cone diameters with 15 MV

Cone diameter (cm)	Jaw positioned at field edge			Jaw positioned 0.25 cm away from field edge		
	MicroDiamond	SRS diode	PinPoint	MicroDiamond	SRS diode	PinPoint
1.0	0.977	0.996	1.056	0.985	0.995	1.025
1.5	0.983	0.996	1.023	0.995	1.005	1.017
2.0	0.993	0.998	1.016	0.997	1.005	1.006
2.5	0.998	0.999	1.010	0.998	1.003	0.997
3.0	1.002	0.999	1.001	1.002	1.002	1.000
3.5	1.000	0.998	0.999	1.000	1.002	0.998
4.0	1.000	1.000	1.000	1.000	1.000	1.000

SRS: Stereotactic radiosurgery

Discussion

The variation in the response of the detector in the determination of small-field output factors due to parallel and perpendicular orientations for radiation fields generated by different tertiary collimating systems such as cone, mMLC, and MLC has been discussed in this section. The differences in output factor observed with various detectors were found to be high for the smallest field size with every collimating system used in this study. This variation highlights that the density of the detector material is vital as lateral electronic disequilibrium breaks down significantly in very small fields.[6,7] The dependency of field size on output factor could be due to a rapid reduction in primary dose where electronic equilibrium does not exist for field sizes smaller than its lateral electron range.[8,9]

An underestimation in output factors was noticed with a PinPoint ion chamber for smaller fields in both orientations. The main reason for the underestimation in output factor value is due to the increase in lateral electronic disequilibrium with an increase in the measuring volume of the detectors.[10] Moreover, the nonwater equivalence of the detector introduces significant beam perturbation.[11] The measured dose at the center of the beam can be perturbed by the volume averaging

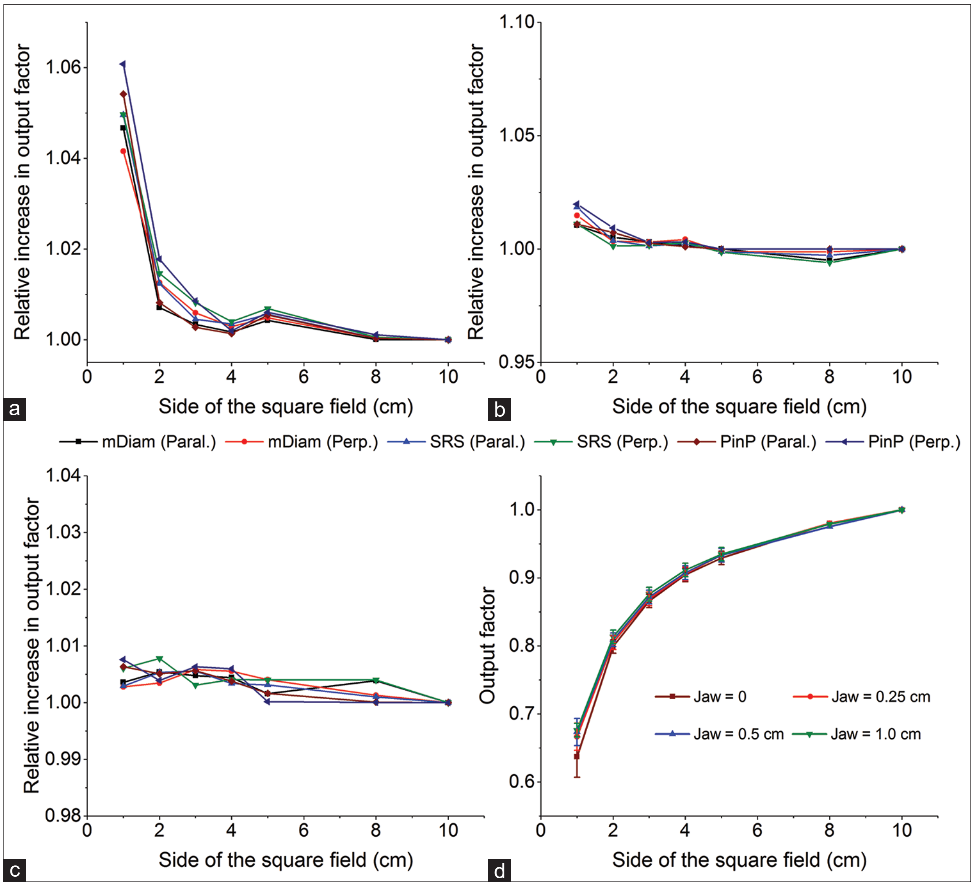

Figure 8: The relative enhancement in output factor with 15 MV when the jaw was opened (a) 0 to 0.25 cm, (b) 0.25 cm to 0.5 cm, (c) 0.5 cm to 1.0 cm away from the edge of the field defined by Millennium MLC and (d) Output factor measured with microDiamond detector for different jaw opening

Table 3: The ratio of output factor between the parallel and perpendicular orientations of various detectors for different fields defined by micro-multileaf collimator with 15 MV

Field size (cm^2)	Jaw positioned at field edge			Jaw positioned 0.25 cm away from field edge		
	MicroDiamond	SRS diode	PinPoint	MicroDiamond	SRS diode	PinPoint
1.2×1.2	0.967	1.004	1.031	0.969	1.004	1.028
1.8×1.8	0.974	1.003	1.033	0.976	1.002	1.030
2.4×2.4	0.988	1.002	1.011	0.987	1.003	1.009
3.0×3.0	1.003	1.000	1.006	1.001	1.002	1.007
3.6×3.6	0.998	1.001	1.001	0.998	1.001	1.004
4.2×4.2	1.002	1.001	1.005	1.003	1.001	1.002
5.1×5.1	1.002	1.000	0.999	1.002	0.998	0.999
8.0×8.0	1.001	1.000	0.995	1.003	1.000	1.000
9.8×9.8	1.000	1.000	1.000	1.000	1.000	1.000

SRS: Stereotactic radiosurgery

effect if the chamber size is relatively larger than the uniform region in the profile[12,13] Azangwe *et al*. reported corrections on the order of 20%–30% for ionization chambers of volume larger than 0.1 cm^3 due to the existence of relatively large air volume that disturbs the fluence in a water medium.[14] The measurements with PinPoint ion chamber show a reduced detector response for perpendicular orientation as compared to parallel orientation for smaller field sizes of each collimator configuration. This is because the entire volume of the chamber is not contained within the uniform dose region as well as the variation in fluence experienced by the ionization chamber across the field.[15]

Several authors suggested that unshielded diodes are a good choice for measuring small-field output factors.[14,16] The unshielded diodes are useful in the measurement of output factors due to their small sensitive cross-sectional area with the limited deviation in calculated dose-to-water and

Table 4: The ratio of output factor between the parallel and perpendicular orientations of various detectors for different fields defined by multileaf collimator with 15 MV

Field size (cm^2)	Jaw positioned at field edge			Jaw positioned 0.25 cm away from field edge		
	MicroDiamond	SRS diode	PinPoint	MicroDiamond	SRS diode	PinPoint
1×1	0.967	1.005	1.032	0.972	1.005	1.026
2×2	0.988	1.001	1.017	0.989	0.999	1.007
3×3	1.002	1.004	1.011	1.000	1.000	1.006
4×4	1.004	1.002	1.002	1.003	1.000	1.001
5×5	1.002	1.002	0.999	1.001	0.999	0.998
8×8	1.004	1.003	0.999	1.001	0.998	0.999
10×10	1.000	1.000	1.000	1.000	1.000	1.000

SRS: Stereotactic radiosurgery

dose-to-silicon ratio with field size.[2] It has been reported in the literature that the diodes over-respond in small fields, which could be due to the nonexistence of charged particle equilibrium for small fields as the lateral range of electrons is shorter in silicon than in water.[17,18] Several authors have reported the over-response of diodes in small fields based on Monte Carlo simulation[19,20] and experimental determination.[21,22] Furthermore, the over-response of the diode could be due to the increased electron-stopping power ratio of silicon to water with an increase in electron energy. The over-response of the unshielded diode due to the presence of high-density materials cannot be compensated by the volume averaging effect since the radius of the mini diode is too small.[11] The measurements carried out with an unshielded diode need to be corrected for the nonwater equivalence of the detector as well as its density effects.[23,24] Although diodes over-respond in small fields, the output factor measured with the sap flux density was systematically lower than that of the CVD (Chemical Vapor Deposited) diamond detector for 6 MV and 15 MV beam energies.[25] In accordance with the results reported in the literature, it has been observed that the output factors measured with the SRS diode were lower than the microDiamond detector in small fields for all beam energies. The behavior of the SRS diode was comparable with the microDiamond detector for all tertiary collimator configurations.

The microDiamond detector has been considered a promising detector in the measurements of relative output factors for small fields. However, the sensitive volume of the microDiamond detector is relatively large, hence it exhibits a volume-averaging effect. However, this effect is partially compensated by the over-response of the detectors due to the presence of high-density material surrounding the active volume.[11,26] The over-response of the high-density detector in small fields is expected due to the increase in electron fluence by the lateral shielding in the active volume by the diamond substrate. The over-response of the diamond detector has been found to agree with the results of Monte Carlo modelling, where a voxel of diamond over response by approximately 9% in a 5 mm field with 15 MV photon beam.[8] Chalkley and Heyes have reported that the water equivalence of the microDiamond was within 1% for the smallest field of ~5 mm at 6 MV, suggesting that the mass-density effect of the detector is well balanced by its volume averaging effect.[27] The over-response of the diamond detector increases with the thickness of the active layer of the detector in small fields has been reported in the literature.[8,28] On this basis, it is expected that the very small thickness of the active layer (1 μm) of the microDiamond detector would result in minimal over-response. In accordance with the results reported in the literature, an over-response of 1.5% has been observed in a 1 cm × 1 cm field with a microDiamond detector for 15 MV photon beams when compared with an SRS diode. Underwood *et al.* have reported that the microDiamond and electron field diode agree to be within 1.5% for all field sizes and all energies.[29]

The microDiamond detector in parallel orientation under-responds in a small field because the active dimension of the chip facing the beam is larger than the uniform dose region of the field, which results in volume averaging.[28] The effect of volume averaging is less pronounced in perpendicular orientation than that of parallel orientation which could be due to the larger proportion of the active volume of the detector in perpendicular orientation being well contained within the central high-dose region of the field. As the spatial resolution of the detector is high in perpendicular orientation, an enhanced over-response was noticed with the microDiamond detector, which could be due to the change in electron transport and the reduced electron range in the high-density crystal.[30] The response of the SRS diode in parallel orientation has shown a similar response in perpendicular orientation for smaller fields of each collimator configuration. The SRS diode showed a minimal dependence on detector stem orientation due to the finite size of the active area of the detector facing the beam.[18] A noticeable variation in the small-field output factor measurement with the PinPoint ion chamber was observed due to the cross-sectional dimension of the PinPoint ion chamber concerning radiation field size, the dose perturbation due to the effect of volume averaging, and nonuniform fluence along the entire volume of the cavity of the detector.[31] The reduced detector response observed with a PinPoint ion chamber in a perpendicular orientation with all tertiary collimating systems for smaller fields could be due to the noncontainment of the entire volume of the detector within the uniform dose region.[15]

The relative position of jaws above the tertiary collimated field substantially affects the output of smaller fields. A sharp increase in output factor was noticed when the jaw is moved away from 0 to 0.25 cm from the edge of the tertiary collimated field, while the increase is not prominently shown as the jaw position is shifted from 0.25 cm to 0.5 cm and 0.5 cm to 1 cm. This could be due to the partial occlusion of the source by the field boundaries that lower the output. The effect of occlusion strongly depends on the divergence of small fields as well as the design of the collimating system.[32] The jaw settings could alter the fluence of the incident beam and the output of small fields as the radiation source is finite in size.[33] Furthermore, the decrease in photon fluence due to the obscure of source at periphery reduces the output factor. As the field size is reduced, the proportion of the flattening filter and aperture of the primary collimator viewed by the detector is small that highly influences the output at the CAX of the beam.[34] An optimum jaw opening of 0.25 mm from the edge of the tertiary collimated field is preferable during the measurement. The difference in output factor for various tertiary collimators could be due to the difference in distance between the distal ends of the collimating system and the measurement plane as well as the differential photon scatter angle from the secondary jaws and the multiple scatter within the tertiary collimator.[35] The output characteristics of small fields depend not only on the type of collimating device but also on the configuration of jaw position.[36]

Conclusion

The experimental determination of output factor for small fields poses a great challenge as no detector is said to be ideal. For the smallest field size, a high difference in output factor was observed with all detectors for different collimating systems. With the enhanced response observed with the microDiamond detector due to the change in electron transport and the reduced electron range in the high-density crystal, the SRS diode could be the better choice in the measurement of output factor with 15 MV photon beams. This study confirms that the output factor highly depends on the configuration of X and Y jaw settings and the tertiary collimating system as well. However, appropriate Monte Carlo simulations would improve the accuracy in determining the small-field output factors by reducing the experimental uncertainties.

Acknowledgment

The research group would like to express their gratitude for the valuable support rendered by Dr. Paul Ravindran and Dr. Subhashini John.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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