Influence of Jaw Setting in the Determination of Stereotactic Small-Field Output Factors with Different Detectors

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Abstract

Background: The experimental determination of relative output factors presents the greatest challenge, especially for small fields with different detectors. The aim of this study is to evaluate the influence of jaw positions on small-field output factors for the fields defined by micro-multileaf collimator and circular cones with different detectors. **Materials and Methods:** The stereotactic output factors were measured on Primus linear accelerator with BrainLab micro-multileaf collimator (mMLC) and circular cones as add-on tertiary collimators. Square field sizes ranging from 0.6 cm × 0.6 cm to 9.8 cm × 9.8 cm and circular fields of diameter ranging from 1.0 cm to 4.0 cm were defined by mMLC and circular cones, respectively. The influence of jaw position on output factor was assessed for different geometric configurations with three different detectors. **Results:** The values obtained with PinPoint ion chamber were consistent with microDiamond detector for fields greater than 24 mm × 24 mm, but an underestimation of 23.9% was noticed in 6 mm x 6 mm field size. For the mMLC defined field size of 6 mm × 6 mm, when the X-Y jaw was moved from 8 mm × 8 mm to 80 mm × 80 mm, an increase in the output by a factor of 1.7 was observed with both microDiamond and stereotactic radiosurgery diode, whereas an increase in output by a factor of 1.9 was noticed with PinPoint ion chamber. **Conclusion:** Output factors obtained with different detectors show high differences in the smallest field size for all collimating systems. This study confirms that the position of X and Y jaw above the tertiary collimator significantly influences the small-field output factor.

Keywords: Detectors, jaw effect, output factor, small-field dosimetry

INTRODUCTION

With the introduction of advanced techniques such as stereotactic radiosurgery (SRS) and intensity modulated radiotherapy, small radiation fields have become an essential part of radiotherapy despite the fact that the dosimetry of small beam presents many challenges that are not encountered in standard field photon dosimetry.[1] The accurate dosimetry of small-field output factors is challenging due to charged-particle disequilibrium, finite size of the detector as well as the partial occlusion of the source.[2,3]

The experimental determination of relative output factor presents the greatest challenge in small fields with different detectors that exhibits high degree of uncertainty.[4,5] The TRS-483 Code of Practice, jointly published by the International Atomic Energy Agency (IAEA) and American Association of Physicists in Medicine, provides an extensive data set for detector-specific output correction factors to determine small-field output factors.[6] Several studies recommend using more than one detector to measure small-field output factors

for clinical use. Although a significant amount of data on small-field output factors and output correction factors for a spectrum of detectors are published in the literature, there is a substantial scatter in the data of output factors for the smallest field sizes.[7] Moreover, the dosimetric characteristics of a beam would also be changed due to the configuration and position of the jaws.[8] The positions of X and Y jaw setting from the tertiary field edge significantly affect the smaller field output due to the increased multileaf collimator (MLC) transmission.

These challenging effects instigated an emphasis on the acquisition of small-field output factor with various detectors. Hence, an attempt has been made to measure the influence

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of jaw position on small-field output factors using three different detectors on Primus linear accelerator with BrainLab micro-MLC (mMLC) and BrainLab circular cones as tertiary add-on collimators.

MATERIALS AND METHODS

Linear accelerator

A dual energy Primus linear accelerator (Siemens, Germany) capable of producing 6 MV and 15 MV photon beams was used in this study. Stereotactic irradiations were performed with BrainLab mMLC and BrainLab circular cones as an add-on tertiary collimator to the Primus linear accelerator with 6 MV photon beams. The BrainLab mMLC has 26 pairs of tungsten leaves that generate variable small square fields ranging from 6 mm × 6 mm to 98 mm × 98 mm. The BrainLab circular cones are made up of lead embedded in a brass shell of 11.5 cm length and an outer diameter of 10.8 cm. The inner diameter of circular cones varies from 10 mm to 40 mm at isocenter in steps of 5 mm.

Dosimeters

The detectors used in this study were PTW microDiamond, PTW SRS diode, and PTW PinPoint ionization chamber. The tissue equivalent microDiamond (60019) detector has an active area of 1.1 mm radius and 1 μm thick disc with a sensitive volume of 0.004 mm^3. The waterproof SRS diode (60018) has a sensitive volume of 0.3 mm^3 with an active area of 1.2 mm diameter and 0.25 mm thick circular silicon disk. The PinPoint (31014) ionization chamber has a sensitive volume of 0.015 cm^3 and 2 mm in diameter. The response of the aforementioned detectors was obtained with PTW UnidosE electrometer. The microDiamond and SRS diode were operated at 0 V whereas PinPoint ionization chamber was operated at +400 V. The microDiamond and SRS diode detectors were positioned with its axis parallel to the central axis (CAX) of the beam, whereas the ionization chamber was positioned perpendicular to the CAX of the beam in MP3 radiation field analyzer (PTW, Germany). Accurate positioning of the detector at the center of the radiation field was confirmed with the dose profiles acquired at 10 cm depth.

Influence of jaw position on output factor

The influence of jaw position on the stereotactic output factor for the fields defined by tertiary collimators with different detectors was analyzed. Stereotactic output factors were measured for the square fields defined by BrainLab mMLC ranging from 0.6 cm × 0.6 cm to 9.8 cm × 9.8 cm with various jaw positions and for circular fields defined by BrainLab cones ranging from 1.0 cm to 4.0 cm diameter with an increment of 0.5 cm using 6 MV photon beams. The geometric configuration of mMLC and the jaw defined fields for which measurements were carried out are highlighted in Table 1. All measurements were carried out by positioning the detectors at a depth of 10 cm with a source-to-surface distance of 100 cm. Each measurement was repeated three times by delivering 100 MU for all field sizes, and the average value was used in the study. Figure 1 depicts the placement of

Table 1: The geometric configuration of the fields defined by micro-multileaf collimator and the secondary jaws

mMLC field (mm×mm)	Jaw field (mm×mm)	mMLC field (mm×mm)	Jaw field (mm×mm)
6×6	8×8	12×12	14×14
	10×10		20×20
	20×20		44×44
	44×44		80×80
	80×80		98×98
	98×98		
18×18	20×20	24×24	44×44
	44×44		60×60
	80×80		80×80
	98×98		98×98
30×30	44×44	36×36	44×44
	60×60		60×60
	80×80		80×80
	98×98		98×98
42×42	44×44	60×60	60×60
	60×60		80×80
	80×80		98×98
	98×98		
80×80	80×80	98×98	98×98
	98×98		

mMLC: micro-multileaf collimator

detectors with respect to CAX of the beam in radiation field analyzer during measurement. The detector-specific output correction factors ($k_{Q_{clin}Q_{msr}}^{f_{clin}f_{msr}}$) published in IAEA TRS 483 protocol for different detectors have been used to account for the under-response and over-response of the detectors in the determination of output factors.

RESULTS

BrainLab micro-multileaf collimator output factors

The influence in small-field output factors due to the presence of an add-on BrainLab mMLC attached to the Primus linear accelerator with different detectors was analyzed. A good agreement (<1%) was obtained with microDiamond detector and SRS diode for fields greater than 12 mm × 12 mm, however a high estimation of 2% was seen in SRS diode for 6 mm × 6 mm field. The values obtained with PinPoint ion chamber were consistent with microDiamond detector for fields >24 mm × 24 mm, but a downgrade of 23.9% was noticed for the smallest field size (6 mm × 6 mm). The PinPoint ion chamber underestimated the output factor for the field size of 12 mm × 12 mm by 6.3%. Measurements performed for larger fields greater than 24 mm × 24 mm were found to be consistent for all detectors. Figure 2 represents the output factors obtained with various detectors for the fields defined by mMLC for the minimum and maximum jaw setting. Table 2 represents the output factors obtained with three detectors for the fields defined by BrainLab mMLC for various jaw settings and the percentage deviation of each detector with respect to the microDiamond reference detector.
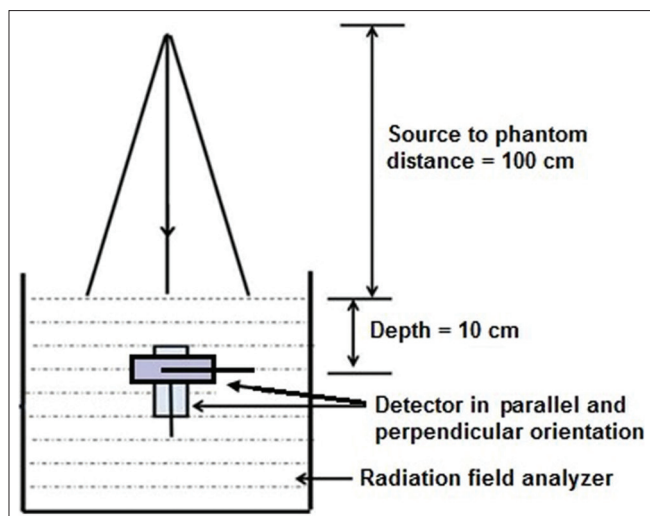
Figure 1: Experimental setup for the output factor measurements

A noticeable increase in output factor was noticed in small fields when the jaws were moved away from the edges of the tertiary collimated field. For the mMLC defined field size of 6 mm × 6 mm, the increase in jaw position from 8 mm × 8 mm to 80 mm × 80 mm showed a significant increase in the output factor with different detectors. An increase in output by a factor of 1.7 was observed with microDiamond and SRS diode whereas an increase in output by a factor of 1.9 was noticed with PinPoint ion chamber. While for a field size of 12 mm × 12 mm, when the jaw was moved to 98 mm × 98 mm from 14 mm × 14 mm, the increase in output by a factor of 1.20 was observed with all detectors. For mMLC fields of 6 mm × 6 mm and 12 mm × 12 mm, when the jaws were moved to the maximum position of 98 mm × 98 mm from 60 mm × 60 mm, the output has been increased only by a factor of 1.008 and 1.009, respectively. No significant deviation in output factor was noticed for the fields greater than 24 mm × 24 mm for the minimum and maximum jaw opening. Table 3 shows the increase in output factor for fields defined by mMLC when the jaws were moved from the minimum jaw field to maximum jaw field setting. Figure 3 depicts the influence of jaw position on output factor for four different fields defined by mMLC.

The detector-specific output correction factors ($k_{Q_{clin}Q_{msr}}^{f_{clin}f_{msr}}$) account for the variation in response of solid-state detectors and ionization chamber when small fields are involved.[9] The detector specific output correction factors mentioned in TRS 483 report[6] for microDiamond and SRS diode are 0.968, 0.960 and 0.989, 0.990 for 6 mm × 6 mm and 12 mm × 12 mm fields, respectively. For the 6 mm × 6 mm field defined by mMLC with a X-Y jaw opening of 10 mm × 10 mm, the over-response of the microDiamond and the SRS diode was corrected and the output factor was reduced to 0.438 ± 0.03 and 0.443 ± 0.03, respectively. With 12 mm × 12 mm mMLC field for a jaw opening of 20 mm × 20 mm, the output factor obtained with microDiamond detector and SRS diode was reduced to 0.718 ± 0.03 and 0.716 ± 0.03, respectively. The
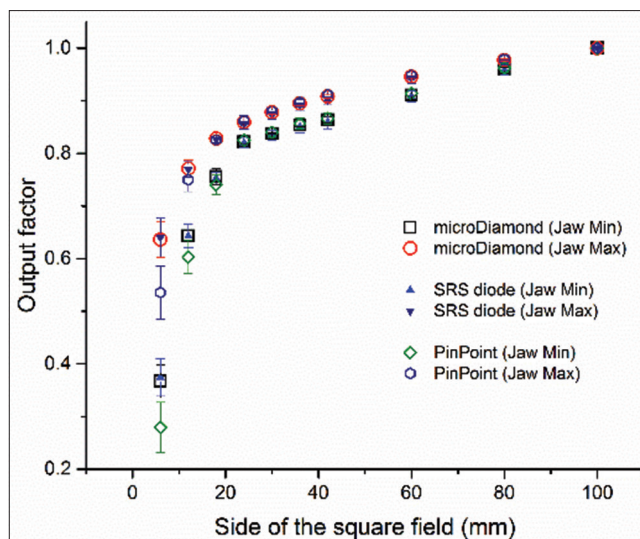

Figure 2: Comparison of output factors obtained with various detectors for the fields defined by BrainLab micro-multileaf collimator when X and Y jaws were positioned closer to the micro-multileaf collimator defined field and at the maximum jaw position (98 mm × 98 mm)

detector-specific output correction factor ($k_{Q_{clin}Q_{msr}}^{f_{clin}f_{msr}}$) for PTW PinPoint ionization chamber is 1.041 for 12 mm × 12 mm field. For the mMLC field opening of 12 mm × 12 mm with the jaw opening of 20 mm × 20 mm, the under-response of the ionization chamber was enhanced to 0.727 ± 0.04 from 0.699 ± 0.04.

BrainLab stereotactic cone factors

Output factors for all detectors were consistent with microDiamond detector values (< 1%) for cones of diameter ranging from 2.5 cm to 4.0 cm. The jaws were positioned at a fixed distance of 0.5 cm away from the tertiary collimated field. The values obtained for PinPoint ion chamber and SRS diode were in good agreement with microDiamond reference values for all circular fields greater than 2 cm diameter. For the smallest cone of diameter 1 cm, the output factors determined by microDiamond, SRS diode, and PinPoint ion chamber were 0.646 ± 0.03, 0.657 ± 0.04, and 0.615 ± 0.05, respectively. The SRS diode showed an overestimation of 1.7% and 1.1% for cones of diameter 1.0 cm and 1.5 cm, respectively, with respect to microDiamond detector, and a good agreement was noticed for larger cone sizes. An underestimation of 4.8%, 2.9%, and 1.9% was observed with PinPoint ion chamber for 1.0 cm, 1.5 cm, and 2.0 cm diameter cones, respectively. Table 4 represents the output factors obtained with three detectors for the fields defined by BrainLab stereotactic cones and the percentage deviation of each detector from the microDiamond reference detector.

The detector-specific output correction factors ($k_{Q_{clin}Q_{msr}}^{f_{clin}f_{msr}}$) for the fields defined by stereotactic cones have been incorporated to correct for the difference in response of the detectors in small fields. After applying the correction factors, the output factors observed with microDiamond and SRS diode were 0.636 ± 0.03 and 0.646 ± 0.04, respectively, for the smallest

Table 2: Output factors obtained with different detectors for the small fields defined by BrainLab micro-multileaf collimator and the percentage deviation from microDiamond reference detector

mMLC field (mm×mm)	Jaw field (mm×mm)	Output factor			Percentage deviation	
		microDiamond	SRS diode	PinPoint	Diode	PinPoint
6×6	8×8	0.367	0.374	0.279	1.9	−23.9
	10×10	0.453	0.462	0.368	2.0	−18.8
	20×20	0.615	0.619	0.511	0.5	−17.0
	44×44	0.631	0.634	0.527	0.5	−16.5
	80×80	0.635	0.638	0.532	0.5	−16.2
	98×98	0.636	0.640	0.536	0.6	−15.8
12×12	14×14	0.643	0.643	0.603	−0.1	−6.3
	20×20	0.726	0.723	0.699	−0.3	−3.7
	44×44	0.759	0.756	0.735	−0.3	−3.1
	80×80	0.767	0.766	0.746	−0.1	−2.8
	98×98	0.771	0.770	0.750	−0.2	−2.7
18×18	20×20	0.756	0.753	0.740	−0.4	−2.1
	44×44	0.801	0.798	0.798	−0.3	−0.4
	80×80	0.822	0.819	0.820	−0.4	−0.2
	98×98	0.828	0.826	0.826	−0.3	−0.3
24×24	44×44	0.822	0.820	0.825	−0.2	0.4
	60×60	0.834	0.832	0.838	−0.3	0.4
	80×80	0.848	0.845	0.851	−0.4	0.4
	98×98	0.859	0.856	0.862	−0.3	0.3
30×30	44×44	0.837	0.835	0.840	−0.3	0.3
	60×60	0.851	0.848	0.855	−0.4	0.4
	80×80	0.868	0.866	0.871	−0.3	0.3
	98×98	0.878	0.875	0.880	−0.4	0.2
36×36	44×44	0.854	0.850	0.857	−0.4	0.3
	60×60	0.866	0.864	0.869	−0.2	0.4
	80×80	0.884	0.882	0.886	−0.3	0.2
	98×98	0.895	0.892	0.897	−0.3	0.2
42×42	44×44	0.864	0.859	0.866	−0.5	0.3
	60×60	0.881	0.877	0.883	−0.5	0.2
	80×80	0.896	0.892	0.899	−0.4	0.3
	98×98	0.908	0.904	0.911	−0.4	0.3
60×60	60×60	0.911	0.908	0.914	−0.3	0.3
	80×80	0.932	0.929	0.935	−0.4	0.3
	98×98	0.946	0.943	0.948	−0.3	0.2
80×80	80×80	0.960	0.958	0.962	−0.2	0.2
	98×98	0.977	0.976	0.979	−0.1	0.2
98×98	98×98	1	1	1	-	-

SRS: Stereotactic radiosurgery

cone of diameter 1 cm. For the 1.5 cm diameter cone, the response of the PinPoint ionization chamber was corrected to 0.715 ± 0.005. The output factor values were found to be consistent for fields >2 cm diameter cone. Figure 4 represents the output factors obtained before and after applying the detector-specific output correction factor of various detectors for the stereotactic fields shaped by an add-on BrainLab circular cones in Primus linear accelerator.

DISCUSSION

The influence of jaw position in the determination of output factors with different detectors for radiation fields defined by tertiary collimators such as BrainLab mMLC and cones is discussed. Noticeable difference in output factors measured with different detectors was observed for the smallest field size with all tertiary collimating systems as reported in the literature.[9-11] The rapid decrease in output factors observed for fields <2 cm × 2 cm could be primarily due to the loss of lateral charged-particle equilibrium and partial source occlusion by different collimating devices.[6] The dependence of field size observed on output factor could also be due to the rapid decrease in primary dose where no electronic equilibrium exists for fields smaller than the lateral electron range. These differences imply that the density of the detector is vital in small fields where lateral electronic disequilibrium breaks down significantly.[3,12]
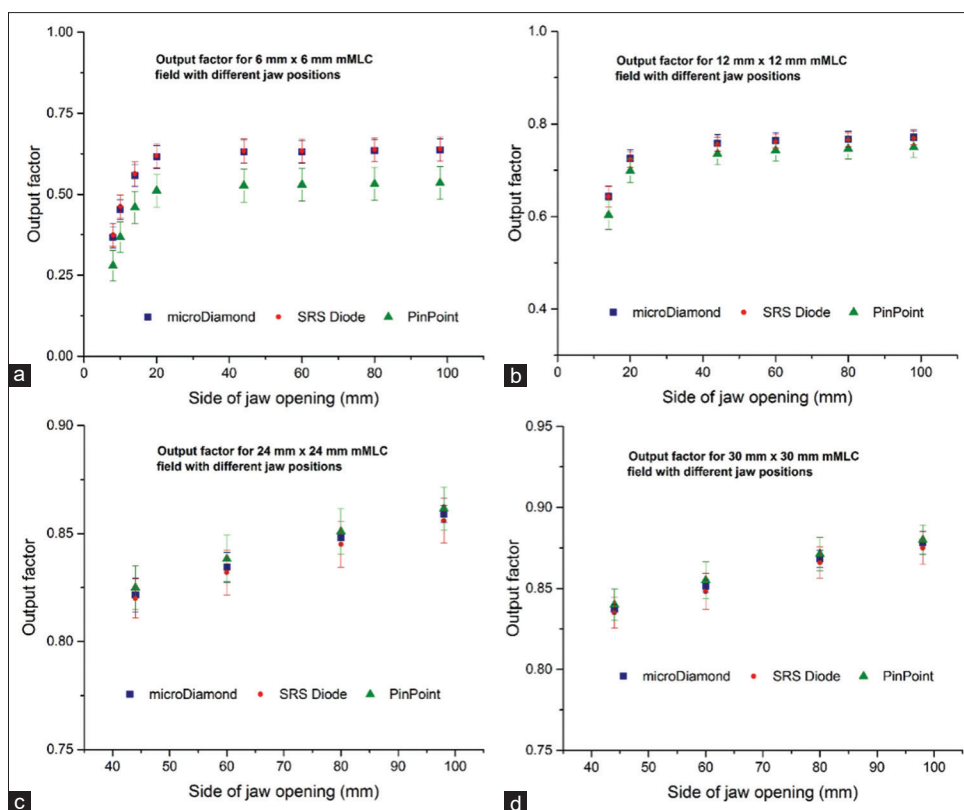
Figure 3: (a-d) Influence of jaw position on output factor for four different fields defined by micro-multileaf collimator
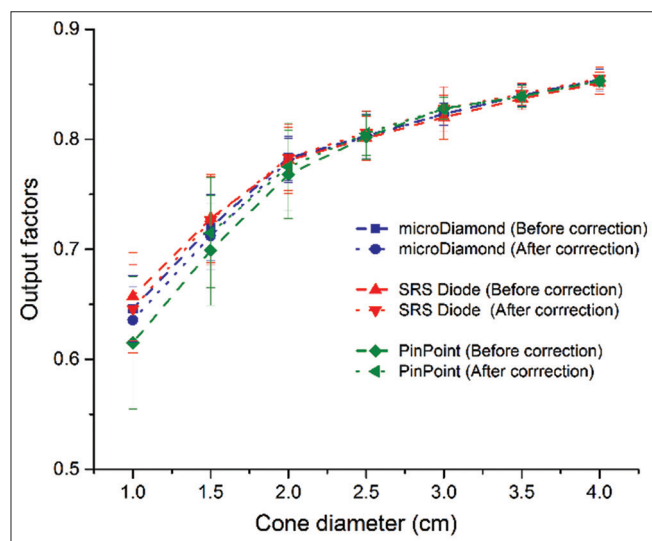

Figure 4: The output factors obtained before and after applying the detector-specific output correction factor of various detectors for the fields defined by stereotactic cones

The positions of X and Y jaw setting from the tertiary field edge significantly affect the smaller field output and decrease with increase in field size. The deviation observed was found to be more prominent for smaller opening than larger opening of X and Y jaws from the tertiary collimator edge in smaller fields.[13] Generally, X and Y jaws are fixed 5 mm away from the mMLC field edge, and the jaws were fixed 5 cm × 5 cm for all conical

collimators during clinical treatment. A noticeable increase in small-field output with increasing jaw field size observed could be due to the increased MLC transmission. The partial occlusion of the X-ray target by the field boundaries could be the reason that lowers the output, and the effect of occlusion is prominently dependent on the design of the collimating system and the divergence of small fields.[14,15] The X-Y jaw settings greatly alter the incident fluence and the output of small fields due to the finite radiation source.[16] A finite error in jaw position could significantly alter the output in small fields. The multiple scatters within the tertiary collimator as well as the differential photon scatter angle from the X and Y jaws could significantly alter the output factor in small fields. Moreover, the reduction in photon fluence owing to the obscure of source periphery decreases the output factor. The proportion of the flattening filter and aperture of primary collimator viewed by the detector highly influences the output as the collimating setting is decreased.[15,17] The output characteristics of small fields depend not only on the type of collimating device but also on the configuration of jaw position.

The output factors measured with PinPoint ion chamber agree well with microDiamond detector (~0.5%) for all field sizes except with an underestimation in smaller fields. The under-response observed in ion chamber is due to the reduction in field width and greater cross-section of the sensitive volume faced by the beam that attributes to lateral electronic disequilibrium and volume averaging effect.[18-20] The response of SRS unshielded diode was comparable with microDiamond

Table 3: The increase in output factor for fields defined by micro-multileaf collimator when the jaws were moved from the minimum jaw field to maximum jaw field setting

mMLC field (mm×mm)	Jaw field (mm×mm)		Increase in output factor		
	Minimum	Maximum	microDiamond	SRS diode	PinPoint
6×6	8×8	98×98	1.73	1.71	1.92
12×12	14×14		1.20	1.20	1.24
18×18	20×20		1.10	1.10	1.12
24×24	44×44		1.05	1.04	1.04
30×30	44×44		1.05	1.05	1.05
36×36	44×44		1.05	1.05	1.05
42×42	44×44		1.05	1.05	1.05
60×60	60×60		1.04	1.04	1.04
80×80	80×80		1.02	1.02	1.02
98×98	98×98		1	1	1

SRS: Stereotactic radiosurgery, mMLC: micro-multileaf collimator

Table 4: Output factors obtained with different detectors for the small fields defined by BrainLab stereotactic cones and the percentage deviation from PTW microDiamond detector reference value

Cone size (cm)	Jaw size (cm)	Output factor			Percentage difference	
		microDiamond	SRS diode	PinPoint	Diode	PinPoint
1	1.5	0.646±0.03	0.657±0.04	0.615±0.06	1.7	−4.8
1.5	2	0.720±0.03	0.728±0.04	0.699±0.05	1.1	−2.9
2	2.5	0.783±0.03	0.781±0.03	0.768±0.04	−0.2	−1.9
2.5	3	0.803±0.02	0.801±0.02	0.802±0.02	−0.2	−0.1
3	3.5	0.823±0.01	0.820±0.01	0.821±0.01	−0.3	−0.2
3.5	4	0.840±0.01	0.837±0.01	0.839±0.01	−0.4	−0.1
4	4.5	0.854±0.01	0.851±0.01	0.853±0.01	−0.4	−0.1

detector, while for the smallest field configuration, an increase in detector response was observed for all collimator configurations. Although the unshielded diodes have shown to be the reliable detectors in the measurement of small-field output factors, it has been reported that the diodes over-respond in small fields.[21,22] The presence of a high-density silicon chip ($\rho Si = 2.33$ g cm^{-3}) and the nonwater equivalency of the dosimeter that causes a dose perturbation are the reasons for the increase in response of the detector in small fields.[3] Furthermore, the existence of charged-particle equilibrium with shorter lateral range of electrons in silicon than in water is another reason for this overestimation.[21,23]

The diamond detector has the advantage of approximate tissue equivalency over a wide range of photon energies and shows uniform radiation sensitivity with the incident photon beam direction. Chalkley and Heyes demonstrated that the new PTW 60019 microDiamond detector has shown dose-rate independence, water equivalence, and excellent spatial resolution for small fields ranging from 5 mm to 60 mm diameter cones.[24] It has been reported in the literature that microDiamond detector over-responds in smaller fields and yields $k_{Q_{clin}Q_{msr}}^{f_{clin}f_{msr}}$ values, a few percent below unity.[9,25] The diamond substrate behind the cavity attributes to electron backscattering which could be the cause for the over-response of the microDiamond detector in the smaller field. The

significant perturbations were due to the presence of the high-density diamond substrate and the finite size of the active volume.[26] As microDiamond detector has a relatively large sensitive volume when compared to SRS unshielded diode, it exhibits an increased volume averaging effect. This effect is partially compensated by the presence of a high-density chip surrounding the active volume.[27]

Despite the sensitive volume of the microDiamond detector, it seems to be a good choice for measurement of output factors in small fields. However, the output factors obtained with different detectors were similar for the larger fields used in this study. This could be due to the existence of lateral charged-particle equilibrium and almost no corrections are required for the volume averaging effect and the variation between the mass density of a particular detector and the medium.

The detector-specific output correction factors $k_{Q_{clin}Q_{msr}}^{f_{clin}f_{msr}}$ for different types of detectors have been investigated by several research groups, and these correction factors were generally determined by comparing the measured uncorrected detector's response to the Monte Carlo calculated field output factors.[28,29] The detector-specific output correction factors depend on the type of detector, its volume averaging effect, and the perturbation of particle fluence.[7,30] The detector-specific output correction factors ($k_{Q_{clin}Q_{msr}}^{f_{clin}f_{msr}}$) published in IAEA TRS

483 protocol for different detectors have been used in this study to account for the over-response and under-response of the detectors. However, attention must be taken when using correction factors for very small fields where the width of the collimator aperture is similar to that of the electron source, and therefore, differences in source occlusion may change the beam output and potentially affect the correction factor.[31] Different collimation systems could influence the output correction factors significantly in the smallest field size of 0.5 cm × 0.5 cm for the 6 MV photon beams regardless of the detector used.

Conclusion

The dependence of the secondary and tertiary collimator configuration with output factor and the influence in output factor with different dosimeters have been investigated. The differential part of the flattening filter viewed by the detector with different jaw settings would result in the variation of output factor. The observed differences in output factors were evident in the smallest field size with various detectors. The noticeable increase in small-field output with increasing jaw field size observed could be due to the increased MLC transmission. This study confirms that the position of X and Y jaw above the tertiary collimator significantly influences the small-field output factor.

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Conflicts of interest

There are no conflicts of interest.

References

1. Alfonso R, Andreo P, Capote R, Huq MS, Kilby W, Kjäll P, *et al*. A new formalism for reference dosimetry of small and nonstandard fields. Med Phys 2008;35:5179-86.
2. Das IJ, Ding GX, Ahnesjö A. Small fields: Nonequilibrium radiation dosimetry. Med Phys 2008;35:206-15.
3. Scott AJ, Kumar S, Nahum AE, Fenwick JD. Characterizing the influence of detector density on dosimeter response in non-equilibrium small photon fields. Phys Med Biol 2012;57:4461-76.
4. Haryanto F, Fippel M, Laub W, Dohm O, Nüsslin F. Investigation of photon beam output factors for conformal radiation therapy Monte Carlo simulations and measurements. Phys Med Biol 2002;47:N133-43.
5. Westermark M, Arndt J, Nilsson B, Brahme A. Comparative dosimetry in narrow high-energy photon beams. Phys Med Biol 2000;45:685-702.
6. Palmans H, Andreo P, Huq MS, Seuntjens J, Christaki K. Dosimetry of Small Static Fields used in External Beam Radiotherapy: An IAEA-AAPM International Code of Practice for Reference and Relative Dose Determination. Technical Report Series No. 483. Vienna: International Atomic Energy Agency; 2017.
7. Casar B, Gershkevitsh E, Mendez I, Jurković S, Huq MS. A novel method for the determination of field output factors and output correction factors for small static fields for six diodes and a microdiamond detector in megavoltage photon beams. Med Phys 2019;46:944-63.
8. Chow JCL, Seguin M, Alexander A. Dosimetric effect of collimating jaws for small multileaf collimated fields. Med Phys 2005;32:759-65.
9. Bassinet C, Huet C, Derreumaux S, Brunet G, Chéa M, Baumann M, *et al*. Small fields output factors measurements and correction factors determination for several detectors for a CyberKnife® and linear accelerators equipped with microMLC and circular cones. Med Phys 2013;40:071725.
10. Francescon P, Kilby W, Satariano N. Monte Carlo simulated correction factors for output factor measurement with the CyberKnife system results for new detectors and correction factor dependence on measurement distance and detector orientation. Phys Med Biol 2014;59:N11-7.
11. Klein DM, Tailor RC, Archambault L, Wang L, Therriault-Proulx F, Beddar AS. Measuring output factors of small fields formed by collimator jaws and multileaf collimator using plastic scintillation detectors. Med Phys 2010;37:5541-9.
12. Fenwick JD, Kumar S, Scott AJD, Nahum AE. Using cavity theory to describe the dependence on detector density of dosimeter response in non-equilibrium small fields. Phys Med Biol 2013;58:2901-23.
13. Godson HF, Ravikumar M, Ganesh KM, Sathiyan S, Ponmalar YR. Small field output factors: Comparison of measurements with various detectors and effects of detector orientation with primary jaw setting. Radiat Meas 2016;85:99-110.
14. Khelashvili G, Chu J, Diaz A, Turian J. Dosimetric characteristics of the small diameter brainLAB™ cones used for stereotactic radiosurgery. J Appl Clin Med Phys 2012;13:4-13.
15. Scott AJ, Nahum AE, Fenwick JD. Monte Carlo modeling of small photon fields: Quantifying the impact of focal spot size on source occlusion and output factors, and exploring miniphantom design for small-field measurements. Med Phys 2009;36:3132-44.
16. Ding GX, Duggan DM, Coffey CW. Commissioning stereotactic radiosurgery beams using both experimental and theoretical methods. Phys Med Biol 2006;51:2549-66.
17. McKerracher C, Thwaites DI. Head scatter factors for small MV photon fields. Part I: A comparison of phantom types and methodologies. Radiother Oncol 2007;85:277-85.
18. Lechner W, Palmans H, Sölkner L, Grochowska P, Georg D. Detector comparison for small field output factor measurements in flattening filter free photon beams. Radiother Oncol 2013;109:356-60.
19. Tyler M, Liu PZY, Chan KW, Ralston A, McKenzie DR, Downes S, *et al*. Characterization of small-field stereotactic radiosurgery beams with modern detectors. Phys Med Biol 2013;58:7595-608.
20. Lauba WU, Wong T. The volume effect of detectors in the dosimetry of small fields used in IMRT. Med Phys 2003;30:341-7.
21. Ralston A, Liu P, Warrener K, McKenzie D, Suchowerska N. Small field diode correction factors derived using an air core fibre optic scintillation dosimeter and EBT2 film. Phys Med Biol 2012;57:2587-602.
22. Morin J, Béliveau-Nadeau D, Chung E, Seuntjens J, Thériault D, Archambault L, *et al*. A comparative study of small field total scatter factors and dose profiles using plastic scintillation detectors and other stereotactic dosimeters: The case of the CyberKnife. Med Phys 2013;40:011719.
23. Gagnon JC, Thériault D, Guillot M, Archambault L, Beddar S, Gingras L, *et al*. Dosimetric performance and array assessment of plastic scintillation detectors for stereotactic radiosurgery quality assurance. Med Phys 2012;39:429-36.
24. Chalkley A, Heyes G. Evaluation of a synthetic single-crystal diamond detector for relative dosimetry measurements on a CyberKnife™. Br J Radiol 2014;7:20130768.
25. Ralston A, Tyler M, Liu P, McKenzie D, Suchowerska N. Over-response of synthetic microDiamond detectors in small radiation fields. Phys Med Biol 2014;59:5873-81.
26. Hartmann GH, Zink K. A monte carlo study on the PTW 60019 microDiamond detector. Med Phys 2019;46:5159-72.
27. Russo S, Masi L, Francescon P, Frassanito MC, Fumagalli ML, Marinelli M, *et al*. Multicenter evaluation of a synthetic single-crystal diamond detector for CyberKnife small field size output factors. Phys Med 2016;32:575-81.
28. Azangwe G, Grochowska P, Georg D, Izewska J, Hopfgartner J,

Lechner W, *et al*. Detector to detector corrections: A comprehensive experimental study of detector specific correction factors for beam output measurements for small radiotherapy beams. Med Phys 2014;1:072103.

29. Papaconstadopoulos P, Tessier F, Seuntjens J. On the correction, perturbation and modification of small field detectors in relative dosimetry. Phys Med Biol 2014;59:5937-52.

30. Manavalan M, Durai M, Narayanasamy G, Stathakis S, Godson HF, Subramani V. Output factor measurements with multiple detectors in CyberKnife® robotic radiosurgery system. J Can Res Ther 2021;17:870-4.

31. O'Brien DJ, León-Vintró L, McClean B. Small field detector correction factors k Q clin, Q msrf clin, f msr for silicon-diode and diamond detectors with circular 6 MV fields derived using both empirical and numerical methods. Med Phys 2016;43:411.