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FULL PAPER

Experimental determination of stereotactic cone size and detector specific output correction factor

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Objective: To investigate the effect of intermediate field size (f_{int}), volume of reference ionization chamber (IC) and normalization conditions on output factor ($OF_{\text{det}}^{f_{\text{clin}}}$) measurement using small field detectors (SDs) and derive $OF_{\text{det}}^{f_{\text{clin}}}$ correction factors $k_{Q_{\text{clin}}, Q_{\text{int}}}^{f_{\text{clin}}, f_{\text{int}}}$ (SD) for active and passive detectors.

Methods: Measurements were made on Novalis-Tx accelerator for 6 MV photon at 1000 MU min⁻¹. Six active SDs, high resolution diodes (SFD, EDGE, PTW 60008), CC01 IC, PTW 60003 natural diamond, Exradin W1 plastic scintillator and two passive detectors (Al₂O₃:C nanoDot-OSLD and Gafchromic EBT3 films) were used for measurement from small circular cones having 4 to 15 mm diameter. Effect of the choice of f_{int} ranging from 20 × 20 mm² to 40 × 40 mm² and reference ICs (FC65, PPC40, CC13) volume on $OF_{\text{det}}^{f_{\text{clin}}}$ was investigated for all active SDs. Influence of direct normalization at reference field of 40 × 40 mm² or 100 × 100 mm² and indirect normalization at 100 × 100 mm² through f_{int} using Daisy-chain strategy on $OF_{\text{det}}^{f_{\text{clin}}}$ was also investigated. $k_{Q_{\text{clin}}, Q_{\text{int}}}^{f_{\text{clin}}, f_{\text{int}}}$ (SD) was calculated as ratio of the $OF_{\text{det}}^{f_{\text{clin}}}$ of each SDs relative to Gafchromic EBT3.

Results: For any combination of SDs and reference ICs, selection of f_{int} of 40 × 40 mm² will result in $OF_{\text{det}}^{f_{\text{clin}}}$ variation to within ±1.8%. Indirect normalization at

100 × 100 mm² through f_{int} of 40 × 40 mm² and direct normalization at 40 × 40 mm² showed comparable (≤2%) results for EDGE, PTW 60008 and CC01. Whereas, for PTW 60003 and Exradin W1 direct and indirect normalization at 100 × 100 mm² agrees within −2%. $OF_{\text{det}}^{f_{\text{clin}}}$ measurement by SDs following Daisy-chain strategy shows deviation as large as 23% for 4 mm cone which reduces to <2% for cone size >10 mm except for nanoDot. The calculated $k_{Q_{\text{clin}}, Q_{\text{int}}}^{f_{\text{clin}}, f_{\text{int}}}$ (SD) is least for SFD (0.992–1.013) and largest for nanoDot (1.047–1.294) which reduces to 0.99–1.023 after correcting for volume averaging effect. The long-term standard uncertainty ($k = 2$, 95% CI) was largest for nanoDot (2.93%) and least for PTW60003 (0.11%).

Conclusion: Medium size IC is less sensitive to f_{int} and could be a better alternative to standard volume ICs. Minimum f_{int} of 40 × 40 mm² is suggested in Daisy-chain strategy. Different normalization conditions could lead to $OF_{\text{det}}^{f_{\text{clin}}}$ variation measured by same SD up to ±5%. $k_{Q_{\text{clin}}, Q_{\text{int}}}^{f_{\text{clin}}, f_{\text{int}}}$ (SD) varies largely with cone size and detector volume.

Advances in knowledge: Comprehensive study of the influencing parameters and conditions on $OF_{\text{det}}^{f_{\text{clin}}}$ measurement from single data set and estimation of $k_{Q_{\text{clin}}, Q_{\text{int}}}^{f_{\text{clin}}, f_{\text{int}}}$ (SD) for newly emerging detectors.

INTRODUCTION

The use of small photon fields in radiotherapy techniques has increased substantially due to the wider clinical implementation of stereotactic radiosurgery (SRS), stereotactic body radiotherapy and intensity modulated radiotherapy. Accuracy of dose delivery from such special techniques is largely dependent on the accuracy of beam data commissioned in the treatment planning system (TPS). The commissioning of TPS with incorrectly

measured or extrapolated beam data, specially nominal output and field output factor, can result in systematic error in dose delivery which subsequently may lead to erroneous patient treatments and radiation incidents or accidents.¹

The measurement of accurate beam data from small photon fields still remains challenging mainly due to source occlusion, lack of lateral electronic equilibrium,

volume averaging and dose perturbation by the detector.^{2–4} So far, there is no ideal commercial detector available for small field dosimetry.^{3,4} Besides the limitations in the inherent characteristics of detector design, the methodology of output factor measurement, adopted formalism and their reporting also varies widely.^{4–10}

In an attempt to establish a standard protocol on small and non-standard beam, an IAEA/AAPM working group³ has introduced a new formalism. As per this new formalism, the absorbed dose to water $D_{w,Q_{clin}}^{f_{clin}}$ for a clinical field size, f_{clin} of beam quality Q_{clin} is given by

$$D_{w,Q_{clin}}^{f_{clin}} = D_{w,Q_{msr}}^{f_{msr}} \cdot \Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} \quad (1)$$

where Q_{msr} is the beam quality of the machine specific reference field f_{msr} and $\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ is the field output factor given by

$$\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = OF_{det}^{f_{clin}} \cdot k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} \quad (2)$$

The output factor, $OF_{det}^{f_{clin}}$, is the ratio of the detector readings for the clinical field and beam quality ($M_{Q_{clin}}^{f_{clin}}$) to that from machine specific reference field and beam quality ($M_{Q_{msr}}^{f_{msr}}$).

$$OF_{det}^{f_{clin}} = \frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{msr}}^{f_{msr}}} \quad (3)$$

$k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ is a correction factor which accounts for the difference between the detector response in the fields f_{clin} and f_{msr} and includes contribution from volume averaging effect and charge particle fluence perturbation. In the case of a conventional linear accelerator (Linac), f_{msr} is equal to reference field size of $100 \times 100 \text{ mm}^2$.

Dieterich and Sherouse⁶ demonstrated that the use of intermediate field size to link the output measure from the reference field of $100 \times 100 \text{ mm}^2$ to small field through an intermediate field in the so-called “Daisy chaining” method eliminates the biasing effects resulting from the spectral differences between reference and smaller field sizes and reduce potentially significant errors. The IAEA/AAPM new formalism applied to Daisy-chaining (hereafter refer as extended new formalism) can be expressed by extending Equation (1) as

$$D_{w,Q_{clin}}^{f_{clin}} = D_{w,Q_{msr}}^{f_{msr}} \cdot \frac{M_{Q_{clin}}^{f_{clin}}(SD)}{M_{Q_{int}}^{f_{int}}(SD)} \cdot \frac{M_{Q_{int}}^{f_{int}}(IC)}{M_{Q_{msr}}^{f_{msr}}(IC)} \cdot k_{Q_{clin},Q_{int}}^{f_{clin},f_{int}}(SD) \cdot k_{Q_{int},Q_{msr}}^{f_{int},f_{msr}}(IC) \quad (4)$$

with field output factor represented by

$$\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = \frac{M_{Q_{clin}}^{f_{clin}}(SD)}{M_{Q_{msr}}^{f_{msr}}(SD)} \cdot \frac{M_{Q_{int}}^{f_{int}}(IC)}{M_{Q_{msr}}^{f_{msr}}(IC)} \cdot k_{Q_{int},Q_{msr}}^{f_{int},f_{msr}}(SD) \cdot k_{Q_{clin},Q_{int}}^{f_{clin},f_{int}}(IC) \quad (5)$$

where “SD” refers to small field detectors, “IC” refers to an ionization chamber suitable for the broad beam dosimetry and the index “int” refers to the intermediate field. For the intermediate field size, which can establish lateral charged particle equilibrium, the correction factor $k_{Q_{int},Q_{msr}}^{f_{int},f_{msr}}(IC)$ can be considered

as unity. Therefore, under this condition the field output factor can be written as

$$\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = \frac{M_{Q_{int}}^{f_{int}}(SD)}{M_{Q_{msr}}^{f_{msr}}(SD)} \cdot \frac{M_{Q_{int}}^{f_{int}}(IC)}{M_{Q_{msr}}^{f_{msr}}(IC)} \cdot k_{Q_{clin},Q_{int}}^{f_{clin},f_{int}}(SD) \quad (6)$$

$$OF_{det}^{f_{clin}} = \frac{M_{Q_{clin}}^{f_{clin}}(SD)}{M_{Q_{int}}^{f_{int}}(SD)} \cdot \frac{M_{Q_{int}}^{f_{int}}(IC)}{M_{Q_{msr}}^{f_{msr}}(IC)} \quad (7)$$

Several studies^{5–10} have reported significantly large variation in the output factor, particularly for the smaller fields, when measurement was performed using different dedicated detectors and formalism. Various detectors with or without correction have been recommended and correction factors for the detectors have been derived primarily by Monte Carlo calculation or measurement with a suitable active/passive detectors.^{7,8,11–14} However, the correction factors are reported to be dependent on detector type, Linac head design, beam shaping device and measurement conditions.^{8,13} Overall, there seemed to be no general agreement on the output factor, metrological dosimetric reference and correction factor.¹⁰ Therefore choosing the appropriate detector, measurement of accurate output factor and determination of the correction factors continue to be an area of active research.

In this study we have systematically investigated the influence of various parameters and conditions on accurate measurement of output factor using dedicated and newly emerging detectors. A recently available plastic scintillator (Exradin W1), $\text{Al}_2\text{O}_3:\text{C}$ based optically simulated luminescent dosimeter (OSLD, nanoDot) and Gafchromic EBT3 film, was investigated for $OF_{det}^{f_{clin}}$ measurement from small diameter circular cones ($\leq 15 \text{ mm}$) used in SRS. Measurements were also carried out using other dedicated active detectors designed for small field dosimetry, following the new formalism (Equation 3) and extended new formalism (Equation 7) for reference dosimetry of small and non-standard photon fields. Effect of the choice of reference detector volume and intermediate field sizes f_{int} on $OF_{det}^{f_{clin}}$ was also investigated. Correction factors $k_{Q_{clin},Q_{int}}^{f_{clin},f_{int}}(SD)$ were derived for the entire detector based on measurement with respect to Gafchromic EBT3 film. The study also investigates uncertainties involved in various measurement conditions.

METHODS AND MATERIALS

Stereotactic radiosurgery system

Novalis Tx (Varian Medical System, Palo Alto, CA) Linac equipped with high definition multileaf collimator as tertiary collimator and stereotactic cones as add-on accessory were used in this study. The $OF_{det}^{f_{clin}}$ of circular cones (BrainLAB, Munich, Germany) having diameter of 4, 6, 7.5, 10, 12.5 and 15 mm were measured for SRS 6 MV X-rays ($TPR_{10}^{20} = 0.66$) at 1000 MU min^{-1} dose rate using both active and passive detectors. For Novalis Tx, the machine specific reference field f_{msr} is the same as the reference field of $100 \times 100 \text{ mm}^2$.

Measurement with active detectors

The characteristics of the active small field detectors (SDs), namely (a) high-resolution diodes (IBA SFD, IBA Dosimetry, Nuremberg, Germany; Sun Nuclear EDGE, Sun Nuclear Cooperation, SunTree

Table 1. Characteristics of the active and passive detectors investigated in the study

Trademark and model	Material	Density (gm/cm ³)	Z _{eff}	Volume (mm ³)	Diameter or side (mm)	Thickness or length (mm)	Package material
Sun Nuclear EDGE	Silicon	2.33	14	0.0019	0.8	0.03	Brass
IBA SFD	Silicon	2.33	14	0.017	0.6	0.06	Plastic ABS + epoxy resin
PTW 60008	Silicon	2.33	14	0.0025	1.13	0.0025	
PTW 60003 Diamond	Carbon	3.5	6	1–6	2.0–4.4	0.1–0.4	Polystyrene
Standard Imaging Exradin w1	Polystyrene	1.05		2.4	1	3	Plastic ABS + polyimide stem
IBA CC01	Air	0.001225	7	10	2	3.6	C-552
Landauer nanoDot OSLD	Al ₂ O ₃ :C	3.97	10.6	0.039	0.5	0.2	Plastic cassette

Blvd, Melbourne; PTW 60008, PTW Freiburg, Germany;), (b) small ionization chamber (IBA CC01), (c) small natural diamond (PTW 60003) and (d) small plastic scintillator (Standard Imaging Exradin W1), investigated for small field $OF_{det}^{f_{clin}}$ measurement in this study are summarized in Table 1. One mini (CC13) and two standard (FC65 and PPC40) volume ionization chambers (ICs), all from IBA (IBA Dosimetry, Nuremberg, Germany) were used for ionization measurement in intermediate and reference field sizes. The ICs CC13, FC65 and PPC40 have calibration factor traceable to our national standard dosimetry laboratory.

Blue Phantom radiation field analyser (RFA, IBA Dosimetry, Nuremberg, Germany) was used for precise positioning of the detector and ionization measurement in water. The detectors were oriented with their stem parallel (SFD, PTW 60008 and PTW 60003) and perpendicular (Edge, CC01 and Exradin W1) to the beam axis. All the active detectors except Exradin W1 were connected to Dose 1 electrometer (IBA Dosimetry, Nuremberg, Germany) for ionization measurement. Measurements with the Exradin W1 were obtained using a timed collection method using a two-channel SuperMAX electrometer (Standard Imaging) set to low range. Background Cherenkov radiation was automatically corrected by the system software using a prior calibration file based on two-channel method described by Guillot et al.¹⁵

Influence of the intermediate field size (f_{int}) and volume of ICs on output factor ($OF_{det}^{f_{clin}}$) measurement for small fields:

Prior to $OF_{det}^{f_{clin}}$ measurement from circular cones, intermediate field size (f_{int}) require to establish lateral electronic equilibrium was calculated by fitting the measured TPR_{10}^{20} values of various circular cone and Jaws defined small fields in the relations proposed by Li et al.¹⁶

$$r_{lee} \left(\frac{gm}{cm^2} \right) = 5.973(TPR_{10}^{20}) - 2.688 \quad (8)$$

Then the effect of the choice and volume of IC in extended new formalism (Equation 7) was investigated for two representative SD, namely SFD and CC01. In the first case, $20 \times 20 \text{ mm}^2$ and

$100 \times 100 \text{ mm}^2$ fields were selected as f_{int} and f_{msr} field sizes while SFD and FC65 were chosen as SD and reference IC, respectively. From the mean ionization readings, multiplication factor (MF), an arbitrary factor defined for this study was estimated.

$$MF = \frac{1}{M_{Q_{int}}^{f_{int}}(SD)} \cdot \frac{M_{Q_{int}}^{f_{int}}(IC)}{M_{Q_{msr}}^{f_{msr}}(IC)} \quad (9)$$

where $M_{Q_{int}}^{f_{int}}(SD)$ and $M_{Q_{int}}^{f_{int}}(IC)$ are the mean ionization readings measured for f_{int} (e.g. $20 \times 20 \text{ mm}^2$) using SD (e.g. SFD) and IC (e.g. FC65) while $M_{Q_{msr}}^{f_{msr}}(IC)$ is the mean ionization readings measured from the f_{msr} ($100 \times 100 \text{ mm}^2$) using IC (FC65). The product of this MF and mean reading from a circular cone measured with the same small field detector ($M_{Q_{clin}}^{f_{clin}}(SD)$) gives the $OF_{det}^{f_{clin}}$ represented by the above equation.⁷ Similarly, MF was estimated for other f_{int} of $25 \times 25 \text{ mm}^2$, $30 \times 30 \text{ mm}^2$ and $40 \times 40 \text{ mm}^2$, respectively. The same set of measurement was repeated for SD of CC01 and FC65 IC combination. To investigate the effect of the choice of volume of reference IC on $OF_{det}^{f_{clin}}$, the complete set of measurement with FC65 was repeated using PPC40 and CC13 IC.

Output factor ($OF_{det}^{f_{clin}}$) measurement with active SDs

Output factor ($OF_{det}^{f_{clin}}$) measurement of circular cones begins with the accurate centring of each active SD by means of in-line and cross-line profile measurements using 4-mm circular cone. The $OF_{det}^{f_{clin}}$ measurement was carried out in isocentric setup of irradiation, with the effective point of measurement of each detector positioned at 15-mm depth following recommendation of TPS beam data generation guide.¹⁷ For every set of measurement, five meter readings were taken for each cone size and every active SD. Then the output factor $OF_{det}^{f_{clin}}$ were calculated by directly normalizing the mean ionization reading of each cone to that from reference field sizes of (a) $40 \times 40 \text{ mm}^2$, (b) $100 \times 100 \text{ mm}^2$ in Equation.³ The reference field size of $40 \times 40 \text{ mm}^2$ was chosen for the purpose of inter- and intra-institutional comparison. In case of extended new formalism using Daisy-chaining method (Equation 7), ionization measurement

from intermediate ($40 \times 40 \text{ mm}^2$) and reference ($100 \times 100 \text{ mm}^2$) field sizes were carried out at 100 mm depth and 900 mm target to phantom surface distance using both active SD and FC65 reference IC.¹⁷ However the ionization measured for reference condition (FC65 ionization chamber and $100 \times 100 \text{ mm}^2$) was scaled up to the depth of dose maximum. We have chosen $40 \times 40 \text{ mm}^2$ and FC65 as f_{int} and reference IC for $OF_{\text{det}}^{\text{clin}}$ measurement based on the results of our investigation on the influence of f_{int} and reference detector on $OF_{\text{det}}^{\text{clin}}$.

Measurement with passive dosimeters

Two passive detectors used in this study were InLight nanoDots (Landauer, Inc., Glenwood, IL) optically simulated luminescent dosimeter (OSLD) and Gafchromic EBT3 film (International Specialty Products, Wayne, NJ).

Measurement with nanoDots OSLD

The sensitive material of nanoDot, $\text{Al}_2\text{O}_3:\text{C}$, is a 5 mm diameter disk approximately 0.2 mm thick, but thin polyester films on either side of the disc, used for binding, making the total disc thickness of about 0.3 mm.¹⁸ It is housed in a plastic (mass density 1.03 g cm^{-3}) light-tight casing, measuring $10 \times 10 \times 2 \text{ mm}^3$. Only previously unexposed screened nanoDots having predetermined sensitivity calibration value ranging from 0.80 to 0.86 were used in this study.

Output factor measurement with nanoDot OSLD was performed in a solid plastic slab (SP34; IBA Dosimetry, Nuremberg, Germany) phantom (density: 1.03 g cm^{-2}). A square hole of $10 \times 10 \text{ mm}^2$ was drilled at the centre of a 2-mm thick solid plastic slab just to accommodate the nanoDot. This not only fills the air gap between the slabs created by the nanoDot but also allows the precise alignment and positioning of the sensitive material of nanoDot at the centre of the radiation field. The physical centre of the 5-mm circle appearing on both the surface of the light-tight plastic casing (representative of $\text{Al}_2\text{O}_3:\text{C}$ disc position inside) was carefully aligned with the Linac isocentre using the calibrated optical field cross-wire. The congruence of optical and radiation field centres were within $\pm 0.2 \text{ mm}$ as determined from multiple profile measurement in RFA using 4-mm SRS circular cone and SFD. Irradiation from the different SRS circular cones was performed by keeping the centre of the sensitive disc of nanoDot at isocentric distance of 1000 mm and at the depth of 15 mm from the surface of the phantom.

Each of the exposed OSLD was read after 10 min and before 1 h after the exposure on InLight microStar reader (Landauer, Inc., Glenwood, IL). This read-out schedule for the OSLD was required to stabilize the low-level, non-dosimetric electron traps ($\sim 0.7 \text{ eV}$). Each OSLD was read six times consecutively of which the first reading was always avoided for $OF_{\text{det}}^{\text{clin}}$ measurement. This reader operates in continuous wave (CW) mode with a 7 s illumination-read period. The reader was operated in its "Hardware Test" modality, using the low intensity LED beam for pre- and post-irradiation measurements. The OSLD signal after correcting individual sensitivity factor was converted to dose by applying a non-linear calibration curve generated during the commissioning of the OSLD system.

Measurement with gafchromic EBT3 film

Gafchromic EBT3 is a nearly tissue equivalent ($Z_{\text{eff}} = 6.84$) new generation film dosimetry having same composition and thickness of the sensitive layer as that of EBT2 film. The most important change in Gafchromic EBT3 is the symmetric layer configuration which eliminated side orientation dependence reported for EBT2 film.¹⁹ The Gafchromic EBT3 films measurements were performed in a solid plastic slab (SP34; IBA Dosimetry, Nuremberg, Germany) phantom (density: 1.03 g cm^{-2}) following general recommendations outlined in the AAPM TG-55 report²⁰ and by other authors.^{9,19} Gafchromic EBT3 films cut into $30 \times 30 \text{ mm}^2$ square pieces were placed between slabs of SP34 solid plastic slab in an orientation perpendicular to the beam central axis. Gafchromic EBT3 films were irradiated isocentrically at a depth of 15 mm from different cones. Each exposed film was positioned at the centre of the Epson 10000XL flatbed scanner (SEIKO Epson Co, Suwa, Nagano, Japan) and scanned in transmission mode using 48 bit RGB with a scanner resolution of 400 dpi. Optical density (OD) was measured prior to exposure to quantify the background image and 48 h following the exposure, after which the latent image had stabilized. ImageJ software 1.48r (National Institutes of Health, Bethesda, MD) was used to analyse the films and measure the pixel values in a small region of interest for each piece of film for the pre-irradiation and post-irradiation scans. The ROI was chosen in such a way that it was centred on the central axis of the beam, enclosing an area having $\geq 97\%$ of the dose. Similar to the method describe by Taylor et al⁹ the pixel values measured for the red channel of the scanner were used to calculate the net OD for each film piece and these were converted to absorbed dose (in cGy) using a pre-measured net OD-to-dose calibration curve.

Estimation of measurement uncertainty

The estimation of total uncertainty, expressed as standard uncertainty, associated with the measurement of output factor using different detector was carried out following a similar method described elsewhere.^{12,21} Briefly, five sessions, one session for every 2 weeks, of measurements were performed for each field detector. Each session consists of three subsessions. For every subsession, four sets of $OF_{\text{det}}^{\text{clin}}$ measurements were performed at isocentre using two six active (SFD, Edge, Exradin W1, PTW 60003 natural diamond, PTW60008 and CC01) and two passive (Gafchromic EBT3 films and nanoDot OSLDs) detectors. Thus, for each detector, there were 15 complete sets of $OF_{\text{det}}^{\text{clin}}$ measurement over a period of around 4 months. In each set and for every detector cone combination, 5-m reading in case of active detector and five times read-out in case of passive detectors were taken. For every set of measurement with active detectors, detector position was recalibrated based on profile measurement from 4-mm SRS circular cone. In between consecutive subsessions, the position of the RFA and solid phantom was disturbed and re-setup as if it is a new day for measurement. This method allows the estimation of overall uncertainty associated with the measurement of $OF_{\text{det}}^{\text{clin}}$ mainly due to detector positioning error, misalignment of detector centre with the centre of the circular cone, misalignment of phantom, uncertainty in setting the source-surface distance with the optical distance indicator, output fluctuation of the accelerator and dosimeter reproducibility. The combined standard uncertainty was estimated following the

Figure 1. Variation in multiplication factor with intermediate field size (f_{int}) of different reference ionization chambers (FC65, PPC40 and CC13) for the small field detector of SFD (Figure 1a) and CC01 (Figure 1b).

methodology described in IAEA TECDOC 1585.²¹ The reported uncertainty is based on the combined standard uncertainty multiplied by a coverage factor of 2 ($k = 2$), providing a level of CI of approximately 95%.²¹

Estimation of correction factor

The correction factor due to finite size, non-water equivalence and dose perturbation of the field detectors were estimated directly as a ratio of the OF_{det}^{clin} of a particular cone measured with Gafchromic EBT3 film to that from the SDs. An independent correction factor was derived for nanoDot OSLD based on volume averaging effect. For this, the active size (5-mm diameter) of the nanoDot OSLD disc was considered to be made up of various subdiscs having radius 0.25 mm and thickness of 0.2 mm.

The relative dose to each subdiscs was obtained by multiplying it by the known relative dose at that point in the field determined from the film profiles. Then the dose integral over the detector sensitive volume was simplified to one-dimensional integration. The ratio of the dose integral to the detector sensitive volume provides the ratio of the averaging value to the peak value of the field. This when normalized to the peak dose of the central pixel gives the volume averaging correction factor.

RESULTS

Influence of the intermediate field size (f_{int}) and volume of IC on output factor measurement for small fields

The minimum diameter/side of radiation field required to establish lateral electronic equilibrium was calculated to be 20 mm. Figure 1 shows the variation in the MF of active small field detectors (Figure 1a for SFD and Figure 1b for CC01) with respect to intermediate field sizes (f_{int}) for FC65, PPC40 and CC13 ICs, respectively. The relatively large volume ICs (FC65 and PPC40) show high sensitivity of MF to intermediate field sizes especially for $20 \times 20 \text{ mm}^2$ and $25 \times 25 \text{ mm}^2$, but become comparable for $30 \times 30 \text{ mm}^2$ and $40 \times 40 \text{ mm}^2$. However, medium size IC (CC13) shows less dependency of MF with f_{int} .

For the range of f_{int} ($20 \times 20 \text{ mm}^2$ to $40 \times 40 \text{ mm}^2$) studied, the MF estimated using CC13 as reference IC, remains almost 0.22 for SFD and ranged from 3.91 to 3.80 for CC01 field detector, respectively. For any combination of SD and IC, the selection of either $30 \times 30 \text{ mm}^2$ or $40 \times 40 \text{ mm}^2$ will result output factor measurement variation to within $\pm 1.8\%$ (Table 2). However, this variation could reach as high as $-16.115.9\%$ if f_{int} of $20 \times 20 \text{ mm}^2$ is selected instead of $30 \times 30 \text{ mm}^2$ or $40 \times 40 \text{ mm}^2$. Based on these findings and ready availability of calibrated cylindrical ionization chamber in all radiotherapy facilities, a field size of $40 \times 40 \text{ mm}^2$ and $100 \times 100 \text{ mm}^2$ was chosen as f_{int} and f_{msr} and FC65 as reference IC for all subsequent measurements. All the data presented hereafter are subjected to these conditions except OF_{det}^{clin} data for passive dosimeter wherein the dose measured by the dosimeter for every cone sizes are directly normalized to that of $100 \times 100 \text{ mm}^2$.

Table 2. Percentage variation in the output factor estimation while selecting different and combination of different f_{int} small field detectors and reference ionization chambers

Small field detector	mm ²	% Variation wrt of $30 \times 30 \text{ mm}^2$			% Variation wrt of $40 \times 40 \text{ mm}^2$		
		FC65	PPC40	CC13	FC65	PPC40	CC13
SFD	20×20	-15.2	-12.1	1.5	-15.9	-13.0	3.3
	25×25	-4.7	-3.6	0.9	-5.6	-4.5	2.7
	30×30	0.0	0.0	0.0	-0.9	-1.0	1.7
	40×40	0.9	1.0	-1.7	0.00	0.00	0.00
CC01	20×20	-15.3	-12.4	1.2	-16.1	-13.4	2.8
	25×25	-4.6	-3.6	0.9	-5.5	-4.6	2.5
	30×30	0.00	0.00	0.00	-1.0	-1.2	1.6
	40×40	1.0	1.2	-1.5	0.00	0.00	0.00

SFD, standard field detector.

Table 3. Percentage variation in the output factor of different active detectors resulted from direct normalization methods as compared to indirect normalization at $100 \times 100 \text{ mm}^2$ through intermediate field size of $40 \times 40 \text{ mm}^2$ (extended new formalism)

Small field detector	% Variation in the $OF_{\text{det}}^{\text{clin}}$ of direct normalization approach as compared to indirect normalization at $100 \times 100 \text{ mm}^2$ through intermediate field size of $40 \times 40 \text{ mm}^2$ (extended new formalism/Daisy chain)	
	Direct normalization at $40 \times 40 \text{ mm}^2$	Direct normalization at $100 \times 100 \text{ mm}^2$ (New formalism)
SFD	2.6	-4.1
Edge	0.0	-5.0
PTW 60008	2.1	-2.6
Extradin W1	3.4	-1.8
PTW 60003	3.7	-1.3
CC01	2.0	-3.6

Variation in the $OF_{\text{det}}^{\text{clin}}$ measured using active small field detectors (SD) following different formalism

The percentage deviation in the $OF_{\text{det}}^{\text{clin}}$ of different active SD resulted from direct normalization methods (new formalism) as compared to indirect normalization at $100 \times 100 \text{ mm}^2$ through intermediate field size of $40 \times 40 \text{ mm}^2$ (extended new formalism) are presented in Table 3. In comparison to the indirect normalization at $100 \times 100 \text{ mm}^2$ through an f_{int} of $40 \times 40 \text{ mm}^2$ (extended new formalism), direct normalization at $OF_{\text{det}}^{\text{clin}}$ of $100 \times 100 \text{ mm}^2$ (new formalism) underestimates the $OF_{\text{det}}^{\text{clin}}$ measured by all active SD ranging from 1.3% (PTW 60003, natural diamond) up to 5.0% (Edge). When the f_{msr} was reduced to $40 \times 40 \text{ mm}^2$, all active SD excepting Edge resulted in overestimation of $OF_{\text{det}}^{\text{clin}}$ ranging from 2% (CC01) to 3.7% (PTW 60003, natural diamond). Only Edge shows similar $OF_{\text{det}}^{\text{clin}}$ when normalized

directly to $40 \times 40 \text{ mm}^2$ and indirectly to $100 \times 100 \text{ mm}^2$ through $40 \times 40 \text{ mm}^2$.

Output factor of small circular cones measured using different active and passive dosimeters

Table 4 summarizes the mean $OF_{\text{det}}^{\text{clin}}$ of SRS circular cones measured isocentrically at d_{max} (15 mm depth) using the combination of SDs and FC65 IC, following the extension of new formalism for 6 MV SRS beam from Novalis Tx. This table also includes the $OF_{\text{det}}^{\text{clin}}$ measured using Gafchromic EBT3 and OSLD passive dosimeters. The $OF_{\text{det}}^{\text{clin}}$ measured using different detectors showed large deviation especially for the smallest cone size. Of the three diodes used in this study, the $OF_{\text{det}}^{\text{clin}}$ measured using the two shielded diodes (Edge and PTW 60008) showed excellent agreement, better than 1% and was higher than those measured with other detectors. In comparison to the unshielded diode (SFD), Edge and PTW 60008 showed larger $OF_{\text{det}}^{\text{clin}}$ of up to 4.0%. The agreement in the $OF_{\text{det}}^{\text{clin}}$ measured using Extradin W1, PTW 60003 and CC01 was better than 1% for all cone sizes except for 4-mm cone for which Extradin W1 estimated around 11.1% more than the other two detectors. Among all the detectors, the nanoDot OSLD measured the least $OF_{\text{det}}^{\text{clin}}$ ranging from 0.514 for 4 mm cone to 0.880 for 15 mm cone, respectively.

The $OF_{\text{det}}^{\text{clin}}$ measured at d_{max} using Gafchromic EBT3 film varies from 0.665 for 4 mm cone to 0.921 for 15 mm cone. The $OF_{\text{det}}^{\text{clin}}$ measured using SFD and Gafchromic EBT3 agree within $\pm 1.3\%$. In comparison with Gafchromic EBT3 measurement, both the shielded diodes showed $OF_{\text{det}}^{\text{clin}}$ higher by up to 3.5% (Edge) and 4% (PTW 60008), respectively. All other detectors, Extradin W1, PTW 60003, CC01 and nanoDot showed consistently lower $OF_{\text{det}}^{\text{clin}}$ as low as 23% for the smallest 4 mm cone which gradually improves with increase in cone size. For cone size $>10 \text{ mm}$ the variation in $OF_{\text{det}}^{\text{clin}}$ becomes within -2% except for nanoDot for which the variation was -5.7% for 12.5 mm and -4.5% for 15 mm cone.

Table 4. Output factor ($OF_{\text{det}}^{\text{clin}}$) of SRS circular cones measured by active small field detectors (SFD, Edge, Extradin W1, PTW60008 diode, PTW60003 diamond and CC01) and passive dosimeters (EBT3 and nanoDot OSLD) for 6 MV SRS beam from Novalis Tx linear accelerator following extended new formalism/Daisy-chain strategy

Cone diameter (mm)	EBT3	SFD	Edge	PTW60008	ExtradinW1	PTW60003	CC01	nanoDot OSLD
4	0.665	0.668	0.671	0.677	0.584	0.521	0.519	0.514
6	0.781	0.771	0.796	0.802	0.725	0.723	0.719	0.681
7.5	0.818	0.824	0.847	0.851	0.782	0.785	0.777	0.744
10	0.880	0.878	0.896	0.895	0.847	0.850	0.849	0.819
12.5	0.906	0.911	0.923	0.916	0.888	0.891	0.889	0.854
15	0.921	0.929	0.938	0.929	0.906	0.909	0.909	0.880

SRS, stereotactic radiosurgery.

Table 5. Cone size specific field correction factors ($k_{Q_{int}, Q_{msr}}^{f_{int}, f_{msr}}(IC)$) of different detectors derived based on direct measurement with EBT3 film

Cone diameter (mm)	Calculated correction factor $k_{Q_{int}, Q_{msr}}^{f_{int}, f_{msr}}(IC)$ for different detectors							Volume averaging correction factor
	SFD	Edge	PTW60008	ExtradinW1	PTW60003	CC01	nanoDot OSLD	nanoDot OSLD
4	0.996	0.991	0.982	1.139	1.276	1.281	1.294	1.272
6	1.013	0.981	0.974	1.077	1.080	1.087	1.147	1.121
7.5	0.992	0.966	0.962	1.046	1.043	1.053	1.099	1.111
10	1.003	0.982	0.983	1.039	1.035	1.037	1.074	1.067
12.5	0.995	0.981	0.989	1.020	1.017	1.019	1.061	1.058
15	0.992	0.982	0.991	1.016	1.013	1.013	1.047	1.039

Note: This table also includes volume averaging correction factor for nanoDot OSLD.

Estimation of correction factor

The output factor correction factor $k_{Q_{clin}, Q_{int}}^{f_{clin}, f_{int}}(SD)$, calculated as a direct ratio of the $OF_{det}^{f_{clin}}$ of a particular cone measured using Gafchromic EBT3 film to that of the corresponding detector is shown in Table 5. Table 5 also includes the volume averaging correction factor of nanoDot OSLD. In general, for every small field detectors, the correction factor was larger for the smaller cone size which decreases with increase in cone diameter. The calculated $k_{Q_{clin}, Q_{int}}^{f_{clin}, f_{int}}(SD)$ was least for high-resolution SFD (range 0.992–1.013) and largest for relatively large detector, nanoDot OSLD (range 1.047–1.294). In case of OSLD, the $k_{Q_{clin}, Q_{int}}^{f_{clin}, f_{int}}(SD)$ derived based on Gafchromic EBT3 film is consistently larger than that of volume averaging method for all cone sizes. The calculated $k_{Q_{clin}, Q_{int}}^{f_{clin}, f_{int}}(SD)$ of nanoDot OSLD after correcting volume averaging effect reduces in the range of 0.990–1.023.

Estimation of measurement uncertainty

The overall long term measurement standard uncertainties associated with the different detectors are shown in Table 6. The reported uncertainty is based on the combined standard uncertainty multiplied by a coverage factor of 2 ($k = 2$), providing a

level of CI of approximately 95%. In general standard uncertainty was larger for the smaller cone and decreases with increase in cone size. The estimated overall long term standard uncertainty ($k = 2$, 95% CI) were highest for nanoDot with mean value for cone sizes at 2.9% and least (0.1%) for PTW 60003 natural diamond detector. Among the diodes, Edge showed the least uncertainty at 0.2%. The estimated standard uncertainty for Gafchromic EBT3 film passive detector was high with average for cone sizes estimated at 1.8%.

DISCUSSION

Influence of the intermediate field size and volume of ICs on $OF_{det}^{f_{clin}}$

The minimum radiation field size required for establishing lateral electronic equilibrium, calculated in our study, using the empirical relations proposed by Li et al¹⁶ was slightly lower than the Monte Carlo calculated value ($20 \times 20 \text{ mm}^2$ vs 26 mm diameter) for 6 MV reported by the same authors. This could be due to the differences in the beam quality (TPR_{10}^{20}). However, our calculated value is in agreement with other finding.²² This contradictory results lead to our investigation on the effect of intermediate field size on output factor for different combination of stereotactic and reference detectors. Based on the high sensitivity of

Table 6. Overall long-term measurement standard uncertainty ($k = 2$, 95% CI) estimated for different detectors

Cone diameter (mm)	EBT3	SFD	Edge	PTW60008	ExtradinW1	PTW60003	CC01	OSLD
4	2.6	1.3	0.3	0.3	0.9	0.2	0.6	4.2
6	3.2	1.4	0.1	0.3	0.6	0.0	0.1	3.7
7.5	2.8	1.0	0.2	0.5	0.6	0.2	0.1	2.5
10	0.7	0.9	0.2	0.5	0.4	0.1	0.8	2.1
12.5	0.8	0.8	0.1	0.5	0.4	0.1	0.6	3.3
15	0.7	0.7	0.1	0.5	0.1	0.0	0.2	1.8
Average	1.8%	1.0%	0.2%	0.4%	0.5%	0.1%	0.4%	2.9%

MF on intermediate field size and chamber volume observed in our study, we suggest a minimum intermediate field size of $30 \times 30 \text{ mm}^2$ to establish lateral electronic equilibrium and a medium size detector (CC13) having a valid dose calibration factor as an alternative to standard volume reference chamber (FC65/PPC40). We could not find any similar study for the purpose of comparison.

Influence of the choice of different formalism on

$$OF_{\text{det}}^{\text{clin}}$$

We have investigated the influence of different strategies/formalism using a single data set measured at the same setup and condition. In comparison to direct normalization at $100 \times 100 \text{ mm}^2$ (new formalism), the use of Daisy-chain strategy improves the standard deviation of the output factor of the three diodes (SFD, Edge and PTW60008) from 0.9 to 0.5% for 15-mm cone and 2.8 to 2.3% for 6-mm cone. This is in agreement with the finding of Dieterich and Sherouse.⁶ In our study output factor from all the three diodes comes closer while using Daisy-chain strategy. However it was not appreciable for Exradin W1 and PTW60003 natural diamond wherein the output factor remains within -1.8% . The excellent agreement (0.02%) of output factor measured using Edge under direct normalization at $40 \times 40 \text{ mm}^2$ and Daisy-chain strategy suggests that the previous simple method is a good alternative to the later. The same is true for CC01 ionization chamber with a slightly larger deviation of 2.0%.

Considering the output factor measured using diodes and Daisy-chain strategy is a very good approximation to the actual value,⁶ choice of direct normalization at $40 \times 40 \text{ mm}^2$ can be consider as a good strategy for other detectors (PTW 60003, Exradin W1 and CC01) due to their comparable results. Table 7 represents the overall standard deviation (in percent) of output factor of each cone size measured by several active detectors under different normalization conditions. It can be seen that choice of Daisy-chain for diodes and direct normalization at $40 \times 40 \text{ mm}^2$ strategy for other detectors provides the least standard deviation of 7.7% for 4-mm cone and 0.6% for 15-mm cone size, respectively. The larger standard deviation observed for smaller cones in all normalization conditions may be primary due to the small output factor measured from relatively large volume detectors (PTW 60003 and CC01) for which volume averaging effect is more pronounce. This also suggests the necessity of calculating a set of correction factors specific to cone size and detector type besides choosing the appropriate formalism. In this study, we have reported output factor calculated following Daisy-chain/extended new formalism.

Variation in $OF_{\text{det}}^{\text{clin}}$ measured by several active and passive detector

Although several authors have reported output factor, direct comparison is difficult due to variation in the beam shaping devices, Linac model, measurement conditions and adopted formalism. We have compared our data with the near similar studies reported in the literature that are summarized in Table 8. The large deviation observed in the output factor especially for smaller cones are in agreement with other report.^{2-5,7-10,23} The output factor measured with Gafchromic EBT3 is in good

Table 7. Comparison of output factor ($OF_{\text{det}}^{\text{clin}}$) measured using different stereotactic detectors in our study with published data

Detector	SFD	SFD	SFD	SFD	SFD	SFD	SFD	SFD	SFD	EBT3	EBT2	EBT2	EBT2	Edge	Edge	Edge	PTW 6008	PTW 6008	PTW 6008	PTW 6003	PTW 6,0003
Cone diameter																					
4	Present work ⁸	Bassinnet et al ⁸	Larraga Gutierrez et al ²⁴	Ralston et al ⁷	Dieterich et al ⁶	Present work	Bassinnet et al ⁸	Larraga Gutierrez et al ²⁴	Ralston et al ⁷	Morales et al ²⁴	Present work	Edge	Edge	Edge	Bassinnet et al	Dieterich et al	Present work	Bassinnet et al	Dieterich et al	Present work	Bassinnet et al
6	0.668	0.651	0.664	0.693	-----	0.665	0.632	0.615	0.649	0.651	0.671	0.672	0.672	0.671	0.672	0.672	0.677	0.532	-----	0.521	0.532
7.5	0.771	0.775	0.772	-----	-----	0.781	0.77	0.739	-----	-----	0.796	0.821	0.821	0.796	0.821	0.821	0.802	0.772	-----	0.723	0.772
10	0.824	0.827	0.83	0.842	-----	0.818	0.841	0.806	0.822	0.81	0.847	0.875	0.875	0.847	0.875	0.875	0.851	0.851	-----	0.785	0.851
12.5	0.878	0.882	0.885	0.902	0.815	0.88	0.875	0.871	0.891	0.87	0.896	0.926	0.926	0.896	0.926	0.926	0.895	0.901	0.840	0.850	0.901
15	0.911	0.914	0.915	0.937	0.86	0.906	0.945	0.912	----	0.903	0.923	0.952	0.952	0.885	0.952	0.952	0.916	0.935	0.875	0.891	0.935
	0.929	0.933	0.929	0.958	0.88	0.921	0.958	0.926	----	0.932	0.938	0.965	0.965	0.890	0.965	0.965	0.929	0.953	0.888	0.909	0.953

Table 8. Standard deviation (%) in output factor of same cone size measured using different detectors and calculated using different normalization condition

Cone diameter (mm)	Directly normalized at $10 \times 10 \text{ cm}^2$	Indirectly normalized at $10 \times 10 \text{ cm}^2$ through intermediate field size of $4 \times 4 \text{ cm}^2$ (Daisy-chain)	Daisy chain for diodes & direct normalization at $4 \times 4 \text{ cm}^2$ for other detectors
4	7.7	8.4	7.7
6	4.2	4.8	3.8
7.5	3.2	3.6	2.6
10	2.2	2.7	1.6
12.5	1.5	2.1	0.9
15	1.2	1.8	0.6

agreement ($<1.5\%$) with other studies^{7,24} for cone size ≥ 7.5 mm. However, for 4-mm cone our values are higher in the range of 2.1–7.5%. In comparison to data from Bassinet et al⁸ our Gafchromic EBT3 film measured output factor varies within $\pm 5\%$. In all the above cited studies Gafchromic EBT2 film was used. Very recently Morales et al²⁴ have investigated Gafchromic EBT3 film for small field output factor measurement using similar Linac model, beam quality, cones and measurement conditions as reported in our study. Our measured output factor is in good agreement ($\leq \pm 1.2\%$) with the value reported by Morales et al²⁴ for all cones except 4 mm wherein the variation is 2.1%.

Output factor measured with unshielded SFD is in very good agreement ($\leq 1.3\%$) with that of Gafchromic EBT3 and comparable ($<1\%$) with other published data^{8,24} except for 4-mm cone for which our value is 2.5% more than that of Bassinet et al⁸ but comparable ($<1\%$) to the values reported by Larraga-Gutierrez et al²⁴. On the contrary, our SFD output factor is lower by up to 3.8% compared to Ralston A et al⁷ and higher by up to 7.2% compared to Dieterich and Sherouse.⁶ The agreement between shielded diodes (PTW60008 and Edge) is within 1% for all cone sizes. The over-response of the shielded diodes (up to 4.0%) as compared to unshielded diode (SFD) is in agreement with earlier studies.^{6–8,11} The over-response of the diodes is reported to be due to the relatively high atomic number of the active layer and the surrounding silicon substrate of the diode.^{11,13,25} In case of Edge diode, our value is around 3% lesser than that of Bassinet et al⁸ except for 4-mm cone which remains comparable (0.1%). However, for the similar diodes (SFD, Edge and PTW60008) and cone size, our output factor is 4–7% more than that reported by Dieterich S and Sherouse.⁶ Contrarily to other findings^{7,8} we did not notice over-response of SFD compared to Gafchromic EBT3 film.

We observed a large variation in output factor (4 to 8%) measured with PTW 60003 natural diamond as compared to other publication.⁸ This could be due to the possible variation in the volume of natural diamond, for which the actual volume is not available with us and also the measurement conditions. Azangwe et al¹³ have demonstrated that for a $6 \times 6 \text{ mm}^2$ beam, the volume averaging effect for the PTW 60003 natural diamond detectors based on the manufacturer's specifications can range from just over 1% for a 2-mm diameter detector to nearly 8% for a rectangular

$5 \times 3 \text{ mm}^2$ detector. Recently, Tanny et al¹⁴ have reported that Exradin W1 produces accurate and consistent output factor for non-standard fields. Similar to our finding, they also reported that output factor of Exradin W1 is comparable to other small volume ($\leq 0.01 \text{ cc}$) ionization chambers and less than Edge shielded diode. Our result is not directly comparable as measurement and normalization conditions are different. The smaller output factor observed for CC01 ion chamber is in consistent with other publication for similar chamber.^{6,8,14}

We have investigated nanoDot OSLD available in the department for *in vivo* dosimetry as a passive detector for small field dosimetry. This initiative was taken up as a part of establishing *in vivo* dosimetry protocol for patient treated with SRS. As anticipated, the smallest output factor measured with nanoDot OSLD in our study as compared to other detectors is due to its unfavourable physical dimension (5-mm diameter). This can be explained by the significant improvement in the $OF_{\text{det}}^{\text{clin}}$ (0.654 to 0.914 for 4–15 mm cone) after correcting for the volume averaging effect, which subsequently brings the $OF_{\text{det}}^{\text{clin}}$ to within $\pm 2.3\%$ with that from Gafchromic EBT3 film measurement. We could not find any similar study for comparison. The wide variation in the measured output factor by the different stereotactic detectors clearly demonstrates the need of a correction factor.

Detector and cone size specific correction factor

In general, relatively large correction factor $k_{Q_{\text{clin}}, Q_{\text{int}}}^{\text{clin}, \text{int}} (SD)$ needed for smaller cone size and relatively large volume stereotactic detectors are consistent with other publication.^{7,8,13} For the similar diodes and cone sizes, the agreement between our calculated correction factor and other published data are within $\pm 2\%$ ⁷ and $\pm 3\%$,⁸ except in few occasions where the variation is up to 4.5%. This relatively large variation could be due to the variation in measurement setup, normalization conditions and adopted formalism in these studies. The close agreement ($<1.7\%$), except for 7.5-mm cone (-2.3%), between the calculated $k_{Q_{\text{clin}}, Q_{\text{int}}}^{\text{clin}, \text{int}} (SD)$ and volume averaging correction factor demonstrate the dominance of volume averaging factor in the total correction factor for nanoDot OSLD. The calculation of volume averaging effects of other detectors under different conditions will be reported separately.

Measurement uncertainty

The pattern of uncertainty observed for different cone sizes and detectors are similar to other publications^{5,7,8,12} although the values are different. Similar to our finding, Ralston et al⁷ and Cranmer-Sargison et al⁵ also reported decrease in measurement uncertainty with increase in radiation field size. The values are not directly comparable as the beam shaping device, field sizes and methodology of reporting uncertainties among the studies are different. In a similar study, Francescon et al¹² reported an uncertainty of 0.7% calculated as 1σ of the average of all the measurements carried out using PTW 60012 diode and for the smallest field of $5 \times 5 \text{ mm}^2$. This value is higher than our average standard uncertainty of 0.4% (0.3% for 6 mm cone) for PTW 60008 diode. This could be due to the larger uncertainty associated with mechanical tolerance of the MLC.¹² The mean of standard uncertainty of Gafchromic EBT3 film observed in our study (1.8%) is lesser than type A uncertainty of EBT2 film (2.5%) reported by Ralston et al.⁷ Bassinet et al⁸ and Larraga-Gutierrez et al²³ also reported uncertainty of 1.8 and 2.1% (1σ) for EBT2 films. The sources of the long term measurement uncertainty derived for the Gafchromic EBT3 could be film scanner reading reproducibility, interfilm reproducibility and whole-film uniformity.^{19,20} The apparent field size dependence of the magnitude of the uncertainty could be due to the presence of the lateral electronic disequilibrium which decreases with the increase in the field size.

CONCLUSION

The measurement of output factor ($OF_{\text{det}}^{\text{clin}}$) is influenced by the choice of normalization method/formalism, intermediate field size (f_{int}) and volume of reference detector. Medium size ionization chamber (IBA CC13) showed less sensitivity to f_{int} as compared to regular volume ionization chamber (IBA FC 65 and PPC40) and can be considered as a better alternative provided absolute dose calibration factor is available. In comparison to indirect normalization through f_{int} of $40 \times 40 \text{ mm}^2$ (extended

new formalism), direct normalization at reference field size of $40 \times 40 \text{ mm}^2$ showed similar ($\leq 2\%$) result for shielded diodes (Edge and PTW 60008) and small volume ionization chamber (CC01). Whereas for PTW 60003 natural diamond and Exradin W1 plastic scintillator, new (direct normalization at reference field size of $100 \times 100 \text{ mm}^2$) and extended new formalism agrees within -2% . Among all the active small field detectors studied, unshielded diode (IBA SFD) exhibits strong sensitivity to the spectral changes in field size. The variation in $OF_{\text{det}}^{\text{clin}}$ measured using various detectors following extended new formalism showed maximum variation of up to 23% for the smallest cone, which reduces with increase in cone size. For cone size $\geq 12.5 \text{ mm}$, all detectors except nanoDot OSLD measured $OF_{\text{det}}^{\text{clin}}$ within $\pm 2\%$. It is suggested to repeat small field $OF_{\text{det}}^{\text{clin}}$ measurement using different dedicated detector and appropriate formalism before clinical commissioning. The detector and cone size specific field correction factor ($k_{Q_{\text{clin}}, Q_{\text{int}}}^{\text{clin}/f_{\text{int}}}(\text{SD})$) calculated based on Gafchromic EBT3 measurement was least for the unshielded diode (IBA SFD) and largest for nanoDot OSLD. The $k_{Q_{\text{clin}}, Q_{\text{int}}}^{\text{clin}/f_{\text{int}}}(\text{SD})$ of the two shielded diodes are largely comparable and showed over response in comparison to Gafchromic EBT3 measurement. Whereas other detectors (Exradin W1, PTW60003, CC01, OSLD) showed under response and in general, $k_{Q_{\text{clin}}, Q_{\text{int}}}^{\text{clin}/f_{\text{int}}}(\text{SD})$ increases with increase in detector volume and decrease in cone size. Our measured $OF_{\text{det}}^{\text{clin}}$ and calculated $k_{Q_{\text{clin}}, Q_{\text{int}}}^{\text{clin}/f_{\text{int}}}(\text{SD})$ values contribute to the recent development in small and non-standard field dosimetry for inter- and intrainstitutional comparison. The large $k_{Q_{\text{clin}}, Q_{\text{int}}}^{\text{clin}/f_{\text{int}}}(\text{SD})$ requires for nanoDot OSLD is reduced substantially after correcting for volume averaging effect. Although NanoDot OSLD in its current form is not preferable for small field $OF_{\text{det}}^{\text{clin}}$ measurement requires for commissioning of TPS, it can be used for quick quality assurance of $OF_{\text{det}}^{\text{clin}}$ and *in vivo* dosimetry of patient undergoing SRS.

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