

# Repeatability of Small Field Output Factor Measurements with Various Detectors

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## Abstract

There are well established dosimetry reference standards for broad beams; however, there are no reference standards that can be used for both broad and small fields. The variation of the equivalent square fields and field output factors in small static photon fields when using a synthetic diamond, an electron diode, and ionization chambers (pin point, semiflex, and liquid filled) was investigated over time. Data from this study were compared to the data from other hospitals in the country and standard data sets, i.e., the British Journal of Radiology Supplement No. 25 of 1996 (BJR25) and the Radiological Physics Centre (RPC) 2012 data. The results showed that reliance on one detector and one measurement session, could yield incorrect field output factors (FOFs) for small fields. At least one of the detectors should be a solid state type with published field output correction factors and at least three measurement sessions should be performed for each FOF data point. Comparing measured data with published datasets, like RPC, will assist in verifying data. BJR25 datasets should not be used for  $S_{\text{clin}} \leq 4$  cm.

**Keywords:** Accurate, equivalent square field, field output factor, reference dosimetry

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## INTRODUCTION

There are three conditions that characterize a small field. Two of these are related to the beam and the third to the detector used.<sup>[1]</sup> One or more of these must be fulfilled for a field to be classified as a small field. These are: Loss of lateral charged particle equilibrium; partial occlusion of the primary photon source on the beam axis by the collimating devices; and volume averaging of the detector.<sup>[2]</sup>

Small fields were implemented in radiotherapy for many years before there was an international code of practice published. There was no coordinated guidance and medical physicists, therefore, relied on manufacturers' recommendations and published data. As a result, data showed significant differences, for example, Das, *et al.* reported differences of up to 12% for output factors measured in collimated photon beams for field diameters of 20 mm,<sup>[3]</sup> Derreumaux, *et al.* reported variations of 5% to 10% in output factors for field sizes  $\geq 12$  mm  $\times$  12 mm and around 30% for the smallest field size of 6 mm  $\times$  6 mm,<sup>[4,5]</sup> and Li, *et al.* reported differences in measured percentage depth dose for 6 mm  $\times$  6 mm fields  $>5\%$ .<sup>[6]</sup> The differences observed could have been due to the lack of harmonized dosimetry for small fields and

to the use of detectors that might not have been suitable for small fields.<sup>[4,5]</sup>

The International Atomic Energy Agency (IAEA) in collaboration with the American Association of Physicists in Medicine (AAPM) published a dosimetry Code of Practice for small static fields in 2017,<sup>[7]</sup> referred to as the IAEA TRS 483 in this paper. With this publication, more consistency in the implementation of the dosimetry for small static fields is expected. Furthermore, guidance is available for centers to accurately determine the dosimetry in small fields.

There are well-established reference standards for broad beams, however, there is no reference standard that can be used for broad and small fields. EBT3 film may be ideal, but considerable expertise and time is needed for accurate and reproducible results.<sup>[8]</sup> The variation in the field output factor (FOF) data from several independent measurement

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sessions using different detectors (two solid-state, one liquid-filled ionization chamber and one air ionization chamber), was investigated.

## MATERIALS AND METHODS

FOFs are defined as the detector response at a reference depth in a nonreference field divided by the detector response in a reference field at the same reference depth.<sup>[7,9,10]</sup> This only holds true when the detector response is independent of the dosimetric quantities like for broad beams. In small fields, the dosimetric quantities such as perturbation factors, have a field size and energy dependency. A field output correction factor (FOCF),  $k_{Q_{clin}, Q_{ref}}^{f_{clin}, f_{ref}}$ , is therefore needed to correct for the detector response in small field and this is shown in equation 1:<sup>[7,10]</sup>

$$\Omega_{Q_{clin}, Q_{ref}}^{f_{clin}, f_{ref}} = \frac{M_{Q_{clin}}^{f_{clin}}}{M_{ref}^{f_{ref}}} k_{Q_{clin}, Q_{ref}}^{f_{clin}, f_{ref}} \quad 1$$

Where:

$\Omega_{Q_{clin}, Q_{ref}}^{f_{clin}, f_{ref}}$  is the FOF;

$M_{Q_{clin}}^{f_{clin}}$  is the electrometer reading in the clinical small field corrected for all relevant influence quantities (temperature, pressure, humidity, polarity, ion collection efficiency, etc);

$M_{ref}^{f_{ref}}$  is the electrometer reading in the reference field corrected for all relevant influence quantities (temperature, pressure, humidity, polarity, ion collection efficiency, etc); and

$k_{Q_{clin}, Q_{ref}}^{f_{clin}, f_{ref}}$  is a correction factor for the variation in the response of the detector in a reference field,  $f_{ref}$ , with beam quality  $Q_{ref}$ , compared with that in the clinical small field with beam quality  $Q_{clin}$ .

A Siemens Primus with a multileaf collimator (MLC) of 82 leaves of 1 cm projection width at the isocentric plane in the X-axis (cross-plane) direction, and a conventional asymmetric collimator in the Y-axis (in plane) direction, was used. The central leaf pair was centered on the cross-plane major axis. Small photon fields were produced using the MLC and jaw in a 6 MV flattened photon beam. The settings of the gantry and the collimator were verified using a spirit level and confirmed with cross-plane profile measurements. Measurements were performed in set field sizes of 10 cm × 10 cm, 6 cm × 6 cm, 4 cm × 4 cm, 3 cm × 3 cm, 2 cm × 2 cm, 1 cm × 1 cm and 0.6 cm × 0.6 cm.

A motorized PTW MP3 water phantom with a moving mechanism driven by three high-speed stepper motors was used for data acquisition. The precision stepper motors allowed for movement of the detector with a speed of 50 mm/s and positioning accuracy of ± 0.1 mm. The water tank was visually aligned with the gantry and the alignment of the scanning arm was confirmed using a spirit level when the tank was filled with water.

The details on the detectors that were used are given in Tables 1 and 2. All the detectors used in the study were mounted in the water phantom with the chamber stem parallel to the beam axis. The effective point of measurement was positioned in the water phantom using the engineering diagrams provided by the manufacturer. An isocentric technique, at a source axis distance of 100 cm, and a depth of 10 cm in water, was used with the gantry and collimator at 0° for all measurements in this study.

The full width half maximum was determined from the cross- and in-plane beam profiles and the equivalent square field size ( $S_{clin}$ ), was calculated.  $S_{clin}$  was calculated using the method suggested by Cranmer-Sargison<sup>[11]</sup> which was adopted by the IAEA TRS 483.<sup>[7]</sup>  $S_{clin}$  was determined using all detectors in three measurement sessions over a period of 3 months, and FOF data were also collected. The FOFs were calculated using equation 1 and the FOCFs that are published in the IAEA TRS 483.<sup>[7]</sup>

A desktop audit was performed of measured and calculated small field FOFs for 6 MV (with flattening filter) MLC beams, obtained from two hospitals in the country. The data were compared to standard data sets, i.e., British Journal of Radiology Supplement No. 25 of 1996 (BJR25)<sup>[12]</sup> and Radiological Physics Centre (RPC).<sup>[13]</sup>

Associated measurement uncertainties were estimated following the Guide to the Expression of Uncertainty in Measurement, JCGM 100:2008 BIPM JCGM.<sup>[14,15]</sup> All the measurement uncertainties quoted are for  $k = 2$ , equal to a confidence level of 95%.

## RESULTS

$S_{clin}$  were measured using different detector types in three different sessions over a period of 3 months. The water phantom was set up once for each session. Session one measurements were performed 3 days after MLC recalibration using the PTW 60012, 60019, and 31021 detectors. The PTW 60012, 31018, and 31021 detectors were used in the second session, which was 66 days after MLC recalibration. The third session was 84 days after MLC recalibration and the PTW 60012, 60019, 31016, 31018, and 31021 detectors were used. The results using each detector are shown in Table 3 including the session associated standard deviation. The session standard deviation was determined from measurements obtained using the detectors in that session.

FOF data were also measured and the results including the associated session standard deviation, are shown in Table 4. The session standard deviation was determined from measurements obtained using the detectors in that session. In the first session the PTW 60012, 60019, and 31021 were used, in the second session the PTW 60012 and 31018 were used and in the third session, the PTW 60012, 60019, 31016, 31018, and 31021 were used. The session dates coincided with those of the  $S_{clin}$  measurements.

Figure 1 shows the FOF plotted against  $S_{clin}$  for session three. An analytical method suggested by Sauer and adopted in

**Table 1: Specifications of the ionization chambers used during the study as provided by the manufacturer**

Ionisation chamber type	Central electrode	Nominal sensitive volume	Dimensions of sensitive volume	Wall material and thickness	Reference point
PTW 31016	Aluminum	0.016 cm <sup>3</sup>	Radius 1.45 mm, length 2.9 mm	PMMA + graphite, 85 mg/cm <sup>2</sup>	2.4 mm from chamber tip, on chamber axis
PTW 31018	Graphite	0.0017 cm <sup>3</sup>	Radius 1.25 mm, depth 0.35 mm	Polystyrene + graphite + varnish, 107 mg/cm <sup>2</sup>	0.975 mm from the entrance window, on chamber axis
PTW 31021	Aluminum	0.07 cm <sup>3</sup>	Radius 2.4 mm, length 4.8 mm	PMMA + graphite, 84 mg/cm <sup>2</sup>	3.45 mm from the chamber tip, on chamber axis

**Table 2: Specifications of the solid-state detectors used during the study as provided by the manufacturer**

Solid-state detector description	Dimensions of a detectors	Nominal sensitive volume	Dimensions of sensitive volume	Reference point
PTW 60012 unshielded diode E with a p-type silicone diode	Diameter of 7 mm, length 45.5 mm	0.0025 mm <sup>3</sup>	Radius 0.56 mm and a depth of 2.5 μm	0.6 mm from the detector tip
PTW 60019 microDiamond	Diameter of 7 mm, length 45.5 mm	0.004 mm <sup>3</sup>	Radius of 1.1 mm and thickness of 1 μm	1 mm from the detector tip

**Table 3:  $S_{clin}$  measured in three measurement sessions using PTW 60012, 60019, 31016, 31018, and 31021 detectors**

Set field size (cm)	$S_{clin}$ (cm)														
	Session 1				Session 2				Session 3						
	PTW 60012	PTW 60019	PTW 31021	Std DEV	PTW 60012	PTW 31018	PTW 31021	Std DEV	PTW 60012	PTW 60019	PTW 31016	PTW 31018	PTW 31021	Std DEV	
10 × 10	10.01	10.03	10.26	0.14	9.75	9.73	9.67	0.04	9.84	9.84	9.83	9.84	9.79	0.02	
6 × 6	5.99	5.97	6.19	0.12	5.78	5.77	5.71	0.04	5.86	5.86	5.83	5.85	5.79	0.03	
4 × 4	3.94	3.96	4.14	0.11	3.78	3.76	3.70	0.04	3.85	3.85	3.82	3.85	3.79	0.03	
3 × 3	2.95	2.92	3.11	0.10	2.78	2.77	2.70	0.04	2.85	2.85	2.84	2.86	2.80	0.02	
2 × 2	1.93	1.92	2.12	0.11	1.79	1.77	1.72	0.03	1.86	1.86	1.85	1.86	1.81	0.02	
1 × 1	0.98	0.96	1.18	0.12	0.84	0.84	0.85	0.01	0.91	0.91	0.91	0.92	0.91	0.004	
0.6 × 0.6	0.61	0.65	0.84	0.12	0.51	0.54	0.64	0.07	0.59	0.59		0.60	0.93	0.17	

Std DEV: Standard deviation

**Table 4: Field output factor derived from three measurement sessions using PTW 60012, 60019, 31016, 31018, and 31021 detectors, as a function of set field size**

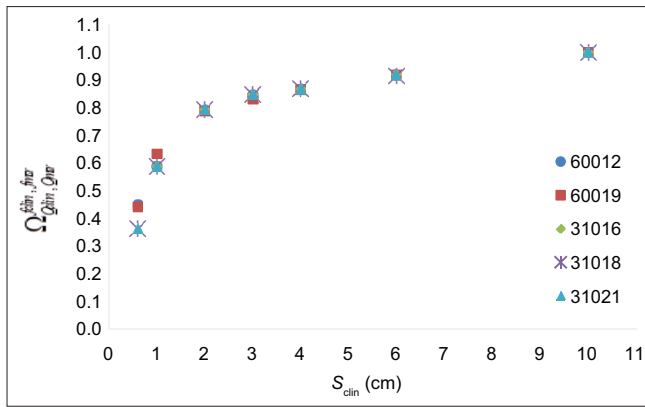
Set field size (cm)	FOF													
	Session 1				Session 2				Session 3					
	PTW 60012	PTW 60019	PTW 31021	Std DEV	PTW 60012	PTW 31018	Std DEV	PTW 60012	PTW 60019	PTW 31016	PTW 31018	PTW 31021	Std DEV	
10 × 10	1.000	1.000	1.000		1.000	1.000		1.000	1.000	1.000	1.000	1.000		
6 × 6	0.917	0.918	0.917	0.001	0.918	0.919	0.001	0.918	0.918	0.919	0.914	0.918	0.002	
4 × 4	0.862	0.862	0.862	0.0002	0.862	0.863	0.001	0.862	0.863	0.863	0.859	0.863	0.002	
3 × 3	0.827	0.830	0.827	0.002	0.831	0.832	0.001	0.831	0.831	0.833	0.830	0.832	0.001	
2 × 2	0.782	0.785	0.781	0.002	0.785	0.786	0.001	0.784	0.786	0.788	0.788	0.786	0.002	
1 × 1	0.636	0.645	0.628	0.009	0.619	0.625	0.005	0.634	0.633	0.648	0.646	0.633	0.01	
0.6 × 0.6	0.467	0.482	0.428	0.03	0.387	0.402	0.01	0.449	0.439		0.453	0.371	0.04	

FOF: Field output factor, Std DEV: Standard deviation

the IAEA TRS 483 was used to determine the FOF for the predetermined  $S_{clin}$ <sup>[7,16]</sup>

Figure 2 shows measured (E-M) and treatment planning system (TPS) (D and E) FOF data for 6 MV flattened beams from ELEKTA Synergy linacs obtained from two other

hospitals (D and E) in the country. Data from center D were measured before the publication of the IAEA TRS 483.<sup>[7]</sup> An average of the data measured in this study (A) was used for this comparison. Data from BJR25<sup>[12]</sup> and the RPC<sup>[13]</sup> are also shown in the figure. An analytical method suggested by Sauer



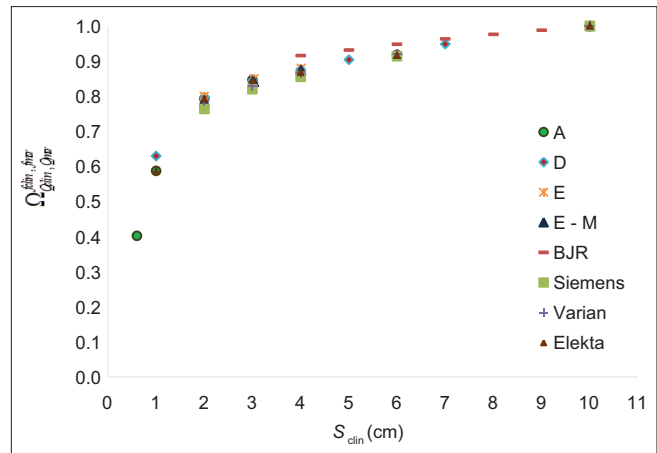
**Figure 1:** Field output factor versus  $S_{clin}$  for the third session

and adopted in the IAEA TRS 483 was also used to determine the FOF for the predetermined  $S_{clin}$ .<sup>[16]</sup> The FOF data submitted by center D were down to  $S_{clin}$  of 1 cm, whereas center E submitted data down to  $S_{clin}$  of 2 cm. Data from RPC were down to  $S_{clin}$  of 2 cm whereas the BJR data were down to 4 cm.

## DISCUSSION

The  $S_{clin}$  data, given in Table 3, for all the three sessions were in agreement to within the measurement uncertainty of 0.06 cm except for the data collected using the PTW 31021, which varied significantly with those using other detectors, especially for  $S_{clin}$  of 0.6 cm. Comparing data without the PTW 31021 for different sessions, a standard deviation  $\leq 0.03$  cm was calculated. The difference in the data collected using all detectors in session one is attributed to an error in the positioning of the 31021 during the setup, as the result was not reproducible. This highlights the importance of doing more than one measurement session and using more than one detector to collect small field data. The highest variation in FOF data given in Table 4 and in Figure 1 was for  $S_{clin} \leq 1$  cm. For  $S_{clin}$  of 0.6 cm, comparing the data collected using each detector showed that the highest variation was up to 12% for the PTW 31021. Similarly, in session three a difference of up to 22% was observed. When comparing all other detectors used here, the variation was  $\leq 3\%$ . The highest variation is therefore attributed to the size and perturbation effect produced by the PTW 31021 at this  $S_{clin}$ . The PTW 31021 is therefore not recommended for use at  $S_{clin} \leq 1$  cm.

From the data shown in Figure 2, the percentage standard deviation was 0.7% when comparing data from the three hospitals for  $S_{clin} \geq 2$  cm. Variations of more than 6% were observed at the  $S_{clin}$  of 4 cm when comparing data from this study to that of the BJR25.<sup>[12]</sup> Therefore, the BJR25 dataset for 6 MV should not be used for small FOFs. Comparing the data from each hospital to the data published by RPC,<sup>[13]</sup> the differences observed for the Siemens machine were 3% and 4% for  $S_{clin}$  of 3 cm and 2 cm respectively. For the Elekta machine at hospital D, the difference in the FOF was 0.3% and 1% for the  $S_{clin}$  of 3 cm and 2 cm, respectively and at hospital E, the difference was 1.0% for the measured data and



**Figure 2:** Field output factor versus equivalent square field ( $S_{clin}$ ), from this study (a), other centres (D, E and E-M), and published data from British Journal of Radiology Supplement No. 25 of 1996<sup>[12]</sup> and Radiological Physics Centre (Siemens, Varian and Elekta)<sup>[13]</sup>

0.1% and 0.04% for the TPS data for  $S_{clin}$  of 3 cm and 2 cm, respectively. A 7% difference was observed at  $S_{clin}$  of 1 cm when comparing data from centers A and D. This is indicative of the use of a solid-state detector by center D which may explain the overestimation in the FOF. FOCF were not applied by center D as data were collected before the publication of the IAEA TRS 483. The differences observed between centers A, D, and E could also be due to the differences attributed to the collimator design as also observed by Godson *et al.*<sup>[17]</sup> Locally measured data should be checked against the RPC dataset or similar datasets for the specific machine model from the same manufacturer.<sup>[13]</sup> The AAPM TG 142 recommends that the machine FOF tolerance be 2% for field size  $< 4$  cm  $\times$  4 cm.<sup>[18]</sup>

## CONCLUSION

Reliance on one detector and one session for performing measurements in small fields could yield incorrect FOFs, especially for  $S_{clin} \leq 1$  cm. One of the detectors should be a solid-state type with already published FOCF. At least three measurement sessions should be performed for each FOF data point. Comparing measured data with published datasets, for example, RPC, will assist in verification. BJR25 data sets should not be used for  $S_{clin} \leq 4$  cm. Centers that collected small fields FOF data before the publication of the IAEA TRS 483 and are using them for treatment, need to remeasure their data, particularly for  $S_{clin} < 2$  cm.

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### Conflicts of interest

PTW for the loan of several detectors.

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