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A multi-detector comparison to determine convergence of measured relative output factors for small field dosimetry

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Abstract

Purpose: Good clinical practice in small field dosimetry relies on using multiple detectors for the determination of relative output factors (ROFs). The TRS-483 Code of Practice (CoP) provides recommended output correction factors, k, for a range of detectors and beam energies as used in small field dosimetry. In this work, the convergence of the ROFs for 6MV x-ray beams with and without flattening-filters were investigated under a different combinations of beam collimation and published detector correction factors.

Method: Three IBA detectors SFD, PFD and CC04 were used to measure ROFs on a TrueBeam STx linear accelerator with small fields collimated by the high definition MLC which has 2.5 mm and 5.0 mm wide leaves. Two configurations were used for the collimators being 1) fixed-jaws at 10×10 cm^2 and 2) with a 2 mm offset from the MLC edge, in line with the recommended geometry from IROC-H as part of their auditing program and published dataset. The k factors for the three detectors were taken from the TRS483 CoP and other published works.

Results: The standard deviation in measured ROFs between detectors under 6MV-WFF beam are 1.4% and 1.9% while these under 6MV-FFF beam are 2.3% and 2.4% in MLC field with fixed-jaw and with 2 mm jaws-offset, respectively. The relative difference in averaged ROFs of three reference detectors from corresponding IROC-H dataset are 2.0% and 3.1% under 6MV-WFF beam while they are 2.4% and 3.2% under 6MV-FFF beam at the smallest available field size 2×2 cm^2. For smaller field sizes, the uncertainty in averaged ROFs of three reference detectors from corresponding results of from 2 mm jaws-offset setting by Akino and Dufreneix showed the largest difference are 6.6% and 6.2% under 6MV-WFF beam while they are 3.4% and 3.6% under 6MV-WFF beam at smallest field size 0.5 × 0.5 cm^2.

Conclusion: The corresponding datasets provided by TRS-483 and IROC-H are generic and may not statistically large enough with 6MV-FFF and also MLC field with 2 mm jaws-offset setting, so that clinical users should use at least three different types of small field detector in measurements. The IROC-H dataset is not available for field size smaller than 2 × 2 cm^2 so that user should carefully check with other publications with the same setting.

Introduction

In recent years, radiotherapy techniques have advanced in complexity with examples such as intensity modulated radiation therapy (IMRT), volumetric modulated arc therapy (VMAT), stereotactic radiosurgery (SRS) and stereotactic body radiation therapy (SBRT) [1]–[4]. These techniques make use of the multi-leaf collimators (MLC) in shaping small photon fields with backup collimation using the jaws which either fixed or moving relative to the MLC jaws or jaws moving. Therefore, the relative output factors (ROFs) for an x-ray field depends how radiation fields are all components of beam collimation whether using the MLC, jaws or a combination of both.

Small field dosimetry presents a number of challenges due to the a number of factors including a loss or lack of lateral charged particle equilibrium (LCPE), partial occlusion of the primary radiation source by the beam collimation, when the size of the detector is similar to the minimum field dimension and the non-water equivalence of the detector [5]–[7]. Most of these will be impacted by the beam collimation for the particular field and therefore the measured ROFs are a factor of both the MLC and jaw settings. As a consequence, the uncertainty in small field dosimetry is generally large as indicated by multi-center studies [8]–[13], even in multi-national study [14].

The Imaging and Radiation Oncology Core-Houston (IROC-H) Quality Assurance Center, formerly named the Radiological Physics Center, was established to ensure that radiation therapy for institutions participating in the National Cancer Institute’s clinical trials is delivered in a comparable, consistent, and accurate manner. IROC-H has examined the dosimetric properties of linear accelerators through on-site dosimetry review visits by an IROC-H physicist to participating institutions. The IROC-H has measured the dosimetric characteristics of more than 500 Varian machines for analysis. These photon data are can be used as a secondary check of acquired values, as a means to verify commissioning a new machine, especially, a new small beam model [12][16].

There are published codes of practice (CoP) on the dosimetry of small fields from the International Atomic Energy Agency (IAEA) TRS-483 (2017) and the American Association of Physicists in Medicine (AAPM) and TG-155 (2021), which generally consider field size equal or less than 3 × 3 cm^2 as small field for most common photon beam energies [6][8].

One of the important tasks in small field dosimetry is the determination of ROFs. It has been shown that detector-specific output correction factors $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ depend on many factors such as the perturbation of particle fluence and volume averaging effects, in particular, on the field size, detector type, and the design, size, and non-water equivalency of most of the detectors [16]–[18].

Noticeably, TRS-483 has provided "global" output correction factor table for various detector type but still recommends to use at least two and preferably three different detector types for the calculation of ROFs in small fields [6], so that the convergence of ROFs between detectors should be investigated. The mean ROFs from detectors at a certain field size should be compared to the IROC-H collected dataset for the same machine type and beam energy for quality assurance purpose.

Materials and Methods

In this study, three IBA detectors (unshielded SFD, shielded PFD-3G and CC04 IC) with well published $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ in the TRS-483 CoP were used to observe the convergence of ROF under 6MV-WFF and 6MV-FFF beam and collimated by MLC. We also investigate the convergence in ROFs between detectors when applying specific output correction factor from a known publication by Casar et al [19][20].

The SFD is an unshielded and stereotactic diode with high sensitivity and high spatial resolution, which is suitable for measurement in small field size down to 0.5×0.5 cm^2. For field size equal or larger than 2×2 cm^2, the shielded diode PFD shows a larger perturbation but high sensitivity while the CC04 shows a lowest sensitivity, biggest volume averaging but highest stability [6][7]. Brief summary of properties of these detectors is shown in Table 1.

Table 1 - Properties of the three IBA detectors in this study [21]

Detector	**Type**	**Orientation (beam axis)**	**Active diameter (mm)**	**Effective point of measurement (mm)**	**Polarity (VDC)**
IBA SFD	Unshielded diode	Parallel	0.6	0.47 from surface	0
IBA PFD 3G-pSi	Shielded diode	Parallel	1.6	1.0 ± 0.2 from surface	0
IBA CC04	Ionization chamber	Perpendicular	4.0	1.9 upstream from central electrode	+300

The 6MV-WFF and 6MV-FFF photon beams from a Truebeam STx linear accelerator (Varian Medical System, Palo Alto, CA, USA) were collimated by the high definition 120 multi-leaf collimator (HD120-MLC). This MLC system including 40 central leaves and 60 peripheral leaves with projected thickness at isocenter of 2.5 mm and 5.0 mm, respectively. The beam dose rate of 600 MU/min was selected for both 6MV-WFF and 6MV-FFF beams in order to provide consistency in detector response without any dose rate effects impacting on the results in terms of dose rates.

As recommended by the IROC-H, two sets of small field output factors were measured, both measured at 10 cm depth and a Source-Surface-Distance (SSD) of 100 cm and were normalized to a 10×10 cm^2 field in two different forms which they refer to as “IMRT-style” and “SBRT-style” fields [12], which is not mentioned in the TRS483 CoP. The IMRT-style fields have the jaws fixed at 10×10 cm^2 and the MLC moved to the nominal field sizes 0.5 × 0.5, 1.0 × 1.0, 1.5 × 1.5, 2 × 2, 3 × 3, 4 × 4, 6 × 6, 10 × 10 cm^2. In comparison, the SBRT-style fields had the same MLC field sizes as previously stated but the jaw positions were set to 2 mm beyond the MLC edge in both the cross-plane and in-plane directions. The same issues with 6MV-FFF beam were also investigated because of the increasing use of this beam type, but output correction factor under 6MV-WFF beam and 6MV-FFF beam were not separated in tabulated table in the TRS-483 CoP.

The only difference in comparison with the IROC-H setting above is the use of the HD120-MLC, so field size smaller than 2 × 2 cm^2 could be measured. The published IROC-H dataset are not available for field sizes smaller than 2 × 2 cm^2, so that some other works with the same linear accelerator type, MLC type and measurement setting were got involved for the comparison [13][22].

The effective field size S_{clin} at the depth of measurement was determined by Gafchromic RTQA2 film and ImageJ software (NIH, USA) for small fields (less than 4 × 4 cm^2) after scanning by Epson Expression 11000XL Pro Scanner in reflective mode 24 hours after irradiation. It is the field used to determine output correction factor. It is not as perfectly square as geometric field, especially at small size, so its shape is rectangular and its squared equivalence is defined by the in-plane (A) and cross-plane (B) dosimetric full width at half maximum (FWHM) of the lateral beam profiles, as defined by Cranmer-Sargison [6][13][23]:

$$S_{clin} = \sqrt{A.B} \quad (1)$$

All measurements were performed in the Blue Phantom 2 (IBA Dosimetry, Schwarzenbruck, Germany) with a positioning accuracy of 0.1 mm. Accurate positioning of the detector in the IBA water phantom was made by moving detector in 0.5 mm steps forward and 0.1 mm steps backward (in-line and cross-line) to find the maximum reading of the same monitor unit delivery with an MLC field size 1.0 × 1.0 cm^2.

Prior to any measurements, a pre-irradiation dose of 10 Gy was given for each detector. The measurement with each detector were repeated in three separate sections all other field sizes as recommended by the TRS-483 CoP [6] and other authors [9][24].

Multi-detector output factor determination

For a particular clinical field f_{clin} and machine-specific reference field f_{msr}, the relative output factor $\Omega^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$ is given by

$$\Omega^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}} = \frac{M^{f_{clin}}_{Q_{clin}}}{M^{f_{msr}}_{Q_{msr}}} k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}} \tag{2}$$

where Q_{clin} and Q_{msr} denote the beam quality in the clinical and machine-specific reference fields, while $M^{f_{clin}}_{Q_{clin}}$ and $M^{f_{msr}}_{Q_{msr}}$ are detector readings, respectively. The relative output factor $\Omega_{clin,msr}$ obtained from each detector were calculated from reading ratios in combination with detector's correction output factor $k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$ which is taken from tabulated tables in the TRS-483 CoP. Separated $k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$ data between 6MV-WFF beam and 6MV-FFF beam could be utilized from Casar's published work.

One of crucial points in the TRS-483 CoP is that $k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$ should not vary by more than ±5%. For this reason, tables 23–27 do not include $k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$ values for field sizes or beam energies that exceed this interval.

The PFD and CC04 detectors are valid to be used in field size down to 1 × 1 cm^2. Output factors at each field size could be defined as an average from three reference detectors:

$$\bar{\Omega}_{clin,msr} = \frac{1}{3}\left(\Omega_{clin,msr(SFD)} + \Omega_{clin,msr(PFD)} + \Omega_{clin,msr(CC04)}\right) \tag{3}$$

Divergence in output factor determination between detectors

Uncertainties in the measured and calculated relative correction factor in this study were evaluated according to the use of uncertainty budget from the IAEA TRS-398 CoP [25][26]. The total uncertainty of output correction factor (denoted as Beam quality correction factor) is 1% for the experimental values with fields larger than 1 × 1 cm^2, and 2% for the experimental values with fields smaller than 1 × 1 cm^2 as recommended from the Table 15 of the IAEA TRS-483 CoP [6]. Therefore, the combined standard uncertainties in determination of output factor are estimated about 2.1% for field size larger than 1 × 1 cm^2 and 2.7% for field size smaller than 1 × 1 cm^2, as an average for all valid detectors, and could be considered as Type B uncertainty (μ_B) for each detector.

The divergence between calculated $\Omega_{clin,msr}$ from each detector is a measure of scatter level of these values at a certain field size, hence could be considered as the Type A uncertainty (μ_A) of $\Omega_{clin,msr}$ determination between detectors (except at field size 0.5 × 0.5 cm^2 because at this field size, the PFD and CC04 were not valid to be used):

$$\mu_B^2\left(\bar{\Omega}_{clin,msr}\right) = \frac{1}{n}\sum_{i=1}^{n}\left(\Omega_{clin,msr(i)} - \bar{\Omega}_{clin,msr}\right)^2 \tag{4}$$

The total uncertainties in determination of $\bar{\Omega}_{clin,msr}$ from all detectors then could be calculated as:

$$\sigma_{\bar{\Omega}_{clin,msr}} = \sqrt{\mu_A^2 + \mu_B^2} \quad (5)$$

The total uncertainties in determination of $\bar{\Omega}_{clin,msr}$ at the field size 0.5 × 0.5 cm^2 could be approximately estimated from its μ_B and field size 1 × 1 cm^2 measured μ_A.

Results

Effective field size determination

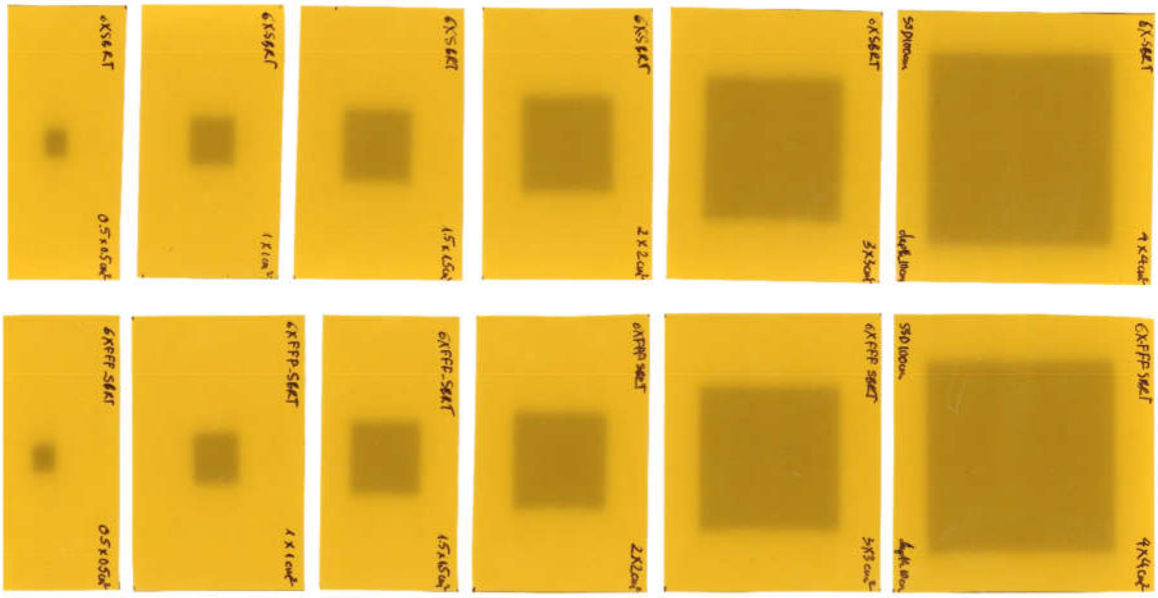


Figure 1: Effective field size determination using RTQA2 Gafchromic film.

As in the Fig.1, the dosimetric field is not square as geometric field toward the smallest field. The measured dosimetric field size under 6MV-WFF and 6MV-FFF beams were used to find corresponding output correction factor for reference detector as in the Table 2.

Table 2 – Nominal field size and dosimetric field size (Sclin) of 6MV-WFF and 6MV-FFF beams from Varian Truebeam at depth 10 cm in water and SSD 100 cm.

Nominal field size (cm)	Sclin (cm) MV-WFF	Sclin (cm) 6MV-FFF
10.0	NA	NA
6.0	NA	NA
4.0	4.4	4.4
3.0	3.25	3.25
2.0	2.15	2.15
1.5	1.65	1.65
1.0	1.05	1.05
0.5	0.55	0.55

Relative output factor evaluation

There is a good convergence in calculated relative output factor between reference detectors as shown in the Table 3, with a standard deviation between 0.6% – 1.9% under 6MV-WFF beam, between 0.8% – 2.4% under 6MV-FFF beam. Under each beam type, the better agreement is with IMRT-style compared to SBRT-style with equal or lower uncertainties at the same corresponding field size. The better agreement was observed for the 6MV-WFF beam compared to 6MV-FFF beam at all field sizes. The worst convergence observed by multi-detector is 2.4% at field size 1×1 cm^2. At the smallest field 0.5×0.5 cm^2, there is no measured data by the PFD and CC04 because their output correction factors are not existing.

Table 3 – Convergence in calculated ROF between the SFD, PFD and CC04 small field detectors with output correction factor taken from the TRS-483 CoP and from Casar's data.

Nominal Field size (cm)	Detector convergence (%) under 6MV-WFF				Detector convergence (%) under 6MV-FFF			
	IMRT-style		SBRT-style		IMRT-style		SBRT-style	
	TRS483	Casar	TRS483	Casar	TRS483	Casar	TRS483	Casar
10.0	NA	NA	NA	NA	NA	NA	NA	NA
6.0	0.6	0.08	0.8	0.07	0.8	0.04	0.9	0.06
4.0	0.8	0.03	1.0	0.03	1.4	0.10	1.4	0.13
3.0	1.0	0.01	1.3	0.11	1.5	0.14	1.5	0.18
2.0	0.7	0.11	1.1	0.00	1.4	0.51	1.5	0.14
1.5	0.7	0.07	1.2	0.13	1.6	0.17	1.6	0.18
1.0	1.4	0.52	1.9	0.60	2.3	0.58	2.4	0.64
0.5	NA	NA	NA	NA	NA	NA	NA	NA

A more visual comparison about the convergence between ROF curves measured by three reference detectors could be seen in the Figure 2.

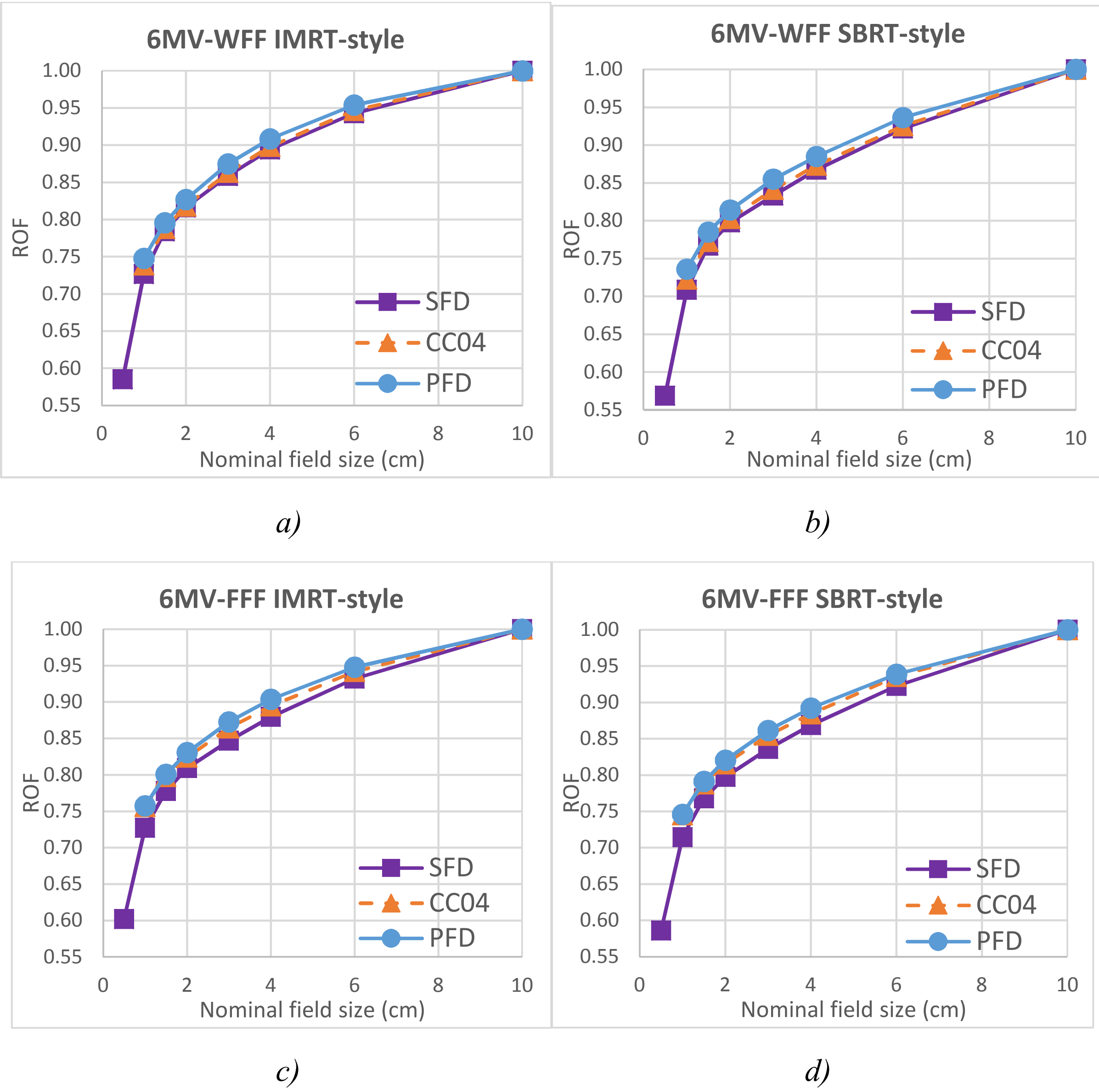
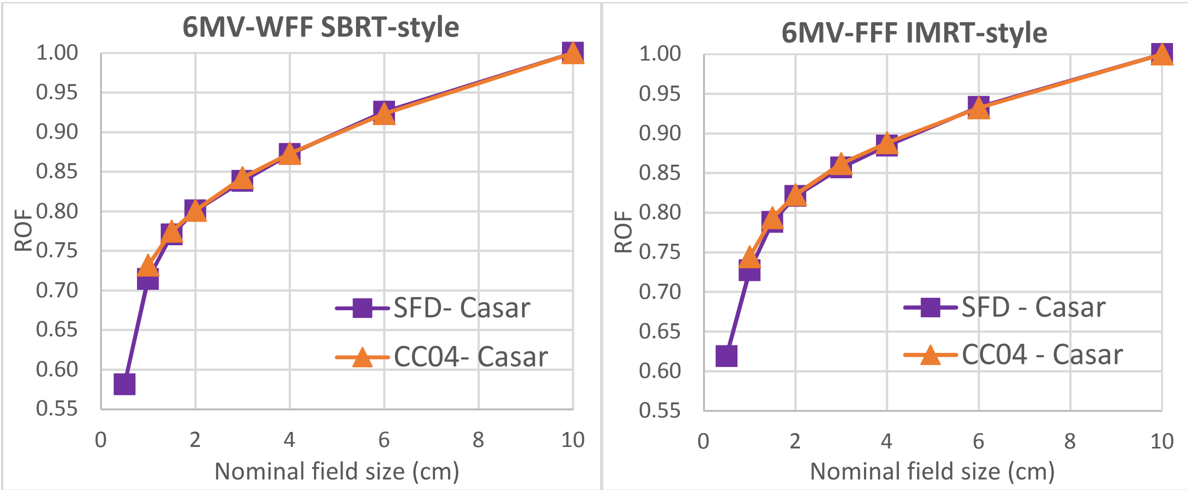
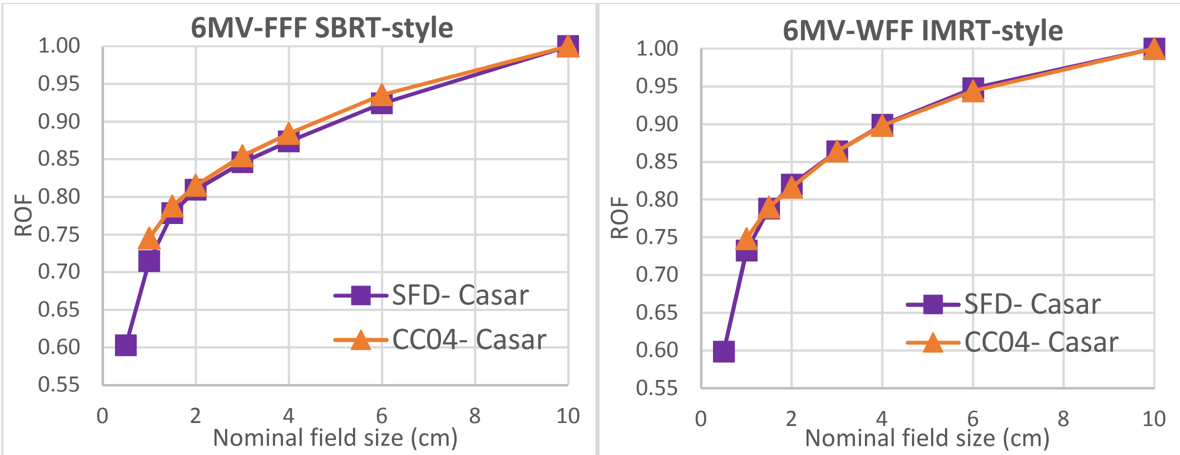


Figure 2: Relative output factors with correction factors from the TRS-483.

In the application of specific correction factors given by Casar's publication [19][20], there is a better convergence between detectors. The maximum difference between ROF curves is just 0.64% at field size 1 × 1 cm^2 under 6MV-FFF beam, in SBRT-style (Fig.3).



a) *b)*



c) *d)*

Figure 3: Relative output factors with correction factors from Casar's data.

Because of IROC-H dataset is not available for field size smaller than 2 × 2 cm^2, additional published data from Akino [22][27] and Dufreneix [13] for the same linear accelerator type were included for comparison as in the Table 4 and 5 for 6MV-WFF and 6MV-FFF beams, respectively.

Table 4 –Relative Output Factor (mean and total uncertainty) under 6MV-WFF beam (with correction factors from the TRS-483).

Nominal Field size (cm)	This study		IROC-H		Akino	Dufreneix
	IMRT-style	SBRT-style	IMRT-style	SBRT-style	SBRT-style	SBRT-style
10.0	1.00	1.00	1.00	1.00	1.00	1.00
6.0	0.95 (2.2%)	0.93 (2.2%)	0.94	0.92	0.92	NA
4.0	0.90 (2.2%)	0.89 (2.3%)	0.89	0.86	0.87	NA

3.0	0.87 (2.3%)	0.84 (2.4%)	0.85	0.83	0.84	0.84
2.0	0.82 (2.2%)	0.81 (2.4%)	0.80	0.78	0.80	0.80
1.5	0.79 (2.2%)	0.78 (2.4%)	NA	NA	NA	NA
1.0	0.74 (2.5%)	0.72 (2.8%)	NA	NA	0.71	0.71
0.5	0.60 (3.0%)	0.58 (3.3%)	NA	NA	0.55	0.56

Table 5 –Relative Output factor (mean and total uncertainty) under 6MV-FFF beam (with correction factors from the TRS-483).

Nominal Field size (cm)	**This study**		**IROC-H**		**Akino**	**Dufreneix**
	IMRT-style	**SBRT-style**	**IMRT-style**	**SBRT-style**	**SBRT-style**	**SBRT-style**
10.0	1.00	1.00	1.00	1.00	1.00	1.00
6.0	0.94 (2.2%)	0.93 (2.3%)	0.93	0.92	0.93	NA
4.0	0.89 (2.5%)	0.88 (2.5%)	0.88	0.86	0.88	NA
3.0	0.86 (2.5%)	0.85 (2.6%)	0.84	0.83	0.84	0.84
2.0	0.82 (2.5%)	0.81 (2.6%)	0.80	0.79	0.81	0.81
1.5	0.79 (2.6%)	0.78 (2.6%)	NA	NA	NA	NA
1.0	0.75 (3.1%)	0.74 (3.2%)	NA	NA	0.72	0.72
0.5	0.62 (3.5%)	0.60 (3.6%)	NA	NA	0.57	0.58

The relative difference in averaged ROFs from this study with corresponding IROC-H dataset are 2.0% and 3.1% under 6MV-WFF beam while they are 2.4% and 3.2% under 6MV-FFF beam at the smallest available field size 2 × 2 cm^2 (Table 6 and Table 7). At smaller field sizes, the relative difference in average ROFs from this study and corresponding results of in SBRT-style by Akino and Dufreneix showed the largest difference are 6.6% and 6.2% under 6MV-WFF beam while they are 3.4% and 3.6% under 6MV-WFF beam at smallest field size 0.5 × 0.5 cm^2.

Table 6 –Relative differences between the mean output factor of 6MV-WFF beam with correction factors from the TRS-483 (compared to other datasets).

Nominal Field size (cm)	**IROC-H (%)**		**Akino (%)**	**Dufreneix (%)**
	IMRT-style	**SBRT-style**	**SBRT-style**	**SBRT-style**
10.0	NA	NA	NA	NA
6.0	1.2	1.5	0.8	NA
4.0	1.7	2.2	0.8	NA
3.0	2.0	2.2	1.0	0.8
2.0	2.0	3.1	0.8	0.9

1.5	NA	NA	NA	NA
1.0	NA	NA	2.0	2.1
0.5	NA	NA	6.6	3.4

Table 7 –Relative differences between the mean output factor of 6MV-FFF beam with correction factors from the TRS-483 (compared to other datasets).

Nominal Field size (cm)	IROC-H (%)		Akino (%)	Dufreneix (%)
	IMRT-style	SBRT-style	SBRT-style	SBRT-style
10.0	NA	NA	NA	NA
6.0	1.3	1.3	0.3	NA
4.0	1.9	2.6	0.3	NA
3.0	2.3	3.0	1.1	0.8
2.0	2.4	3.2	0.6	0.7
1.5	NA	NA	NA	NA
1.0	NA	NA	2.4	2.4
0.5	NA	NA	6.2	3.6

Discussion

The TRS-483 CoP collected data from published papers spanning a decade, some of which could be outdated due to advances in detector manufacturing or data based on older prototype devices. Additionally, the assumptions made by TRS-483 regarding choice of techniques, including phantom size and detector orientation, are not always clear and applicable, which could produce discrepancies between measured clinical data and data in the CoP [28].

As expected, the application of the same output correction factor provided by the TRS-483 CoP for 6MV-WFF and 6MV-FFF photon beams gives some divergences in calculated ROF from reference detectors. The divergence of ROF curves is smaller with 6MV-WFF beam compared to 6MV-FFF beam. This divergence could be explained by this CoP does not provide separated output correction factors between these beams. The availability of relevant publications with 6MV-FFF beam type at that time may not much enough. Furthermore, for each beam type, the convergence of ROF curves is better with IMRT-style in comparison with SBRT-style. This issue could be explained as the CoP does not provide separated output correction factors for detector to be used under different combinations of jaws and MLCs. Furthermore, the dataset of output correction factor may come mainly from MLC-based IMRT-style setting and cone-based SBRT-style setting, not MLC-based SBRT-style setting, as noted from the Introduction section. These results suggest that if the linear accelerator is expected to work clinically in SBRT-style (in respect of the combination between jaws and MLCs positioning), it should be commissioned more carefully with at least three different types of small field detectors.

In the comparison of averaged ROF values from this study with corresponding values from IROC-H dataset, the differences with IMRT-style are a little bit lower than that with SBRT-style. The ROFs in SBRT-style are smaller than the corresponding IMRT-style ROFs, both in this study and IROC-H report. The same observation was reported by Casar et al. As showed by IROC-H report, the number of Varian Truebeam machines in this dataset were nearly 20 units. Some parameters, like SBRT-style ROF, have relatively being collected at the end of the period [12]. HD120-MLC model may not popular in Truebeam systems at that time because the IROC-H dataset is not available for field sizes smaller than 2×2 cm^2. This might lead to some discrepancies in the ROF between this study and IROC-H.

For smaller fields that are not listed in IROC-H dataset (smaller than 2×2 cm^2), a comparison with results from other authors (Akino, Dufreneix) was made but the same setting is only available for SBRT-style. By that, the difference in averaged ROF values are very small (0.3% - 1.1%) with field size equal to 2×2 cm^2 or larger. However, the difference is largest at smallest field size of 0.5×0.5 cm^2, 6.2% and 3.6% in comparison with Akino and Dufreneix respectively.

As from Casar's work, the present results suggest that in general, for a given linear accelerator, small field output factors will need to be determined individually for every combination of beam energy and filtration (WFF or FFF) and field size as the differences from each other may be statistically significant [19]. In his work, the ROF for 6MV-FFF beam is always larger than the ROF for the corresponding ROF for 6MV-WFF beams for all investigated fields. Even more, output correction factor for reference detectors such as SFD was found to be statistically different between 6MV-WFF and 6MV-FFF beams.

The positioning accuracy of detector under small field is also very crucial [6]. One millimeter error of collimator aperture at field size 1×1 cm^2 may lead to 2-4% in dosage or output factor error [5][29]. The field size reproducibility is more accurate for the MLC due to stricter mechanical tolerances [30]. Therefore, at least three measurement sessions should be performed for each ROF data point as recommended by some authors [9].

Conclusion

The dataset provided by TRS-483 and IROC-H are generic and may not statistically large enough with 6MV-FFF and also SBRT-style. Specific measurements of relative output factor for this beam type and collimator setting on each machine with specific collimation system should be made with at least three different types of detector in at least three measurement sections. This study may make a small contribution to these datasets. Further work should be done to make comparison between calculation and measurement for these styles.

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