Original paper

Evaluation of Acuros® XB accuracy for static small fields dose calculations based on the IAEA/AAPM TRS-483 recommendation

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ABSTRACT

Purpose: Evaluate Acuros® XB dose calculation accuracy following TRS-483 recommendations in small static fields for flattened and un-flattened 6 MV X-ray beams.

Methods: Field output factors were measured following TRS-483 recommendations using four radiation detectors. Two sets of field output factors were measured. One set was used to configure the beam model into Acuros® XB down to a jaw-defined field size of 1.0 cm × 1.0 cm. The second set was used to evaluate the differences between calculated and measured field output factors for MLC-fields down to a field size of 0.5 cm × 0.5 cm.

Results: Acuros® XB showed an accuracy within 1.5% down to an MLC-field of 1.0 cm × 1.0 cm, for a focal spot size of 1.0 and 0.0 mm in the cross and in-plane directions. For an MLC-field of 0.5 cm × 0.5 cm, an agreement was found within 3% between calculated and measured field output factors. These results were addressed by optimizing the focal spot size to minimize the differences between calculated and measured dose profiles.

Conclusions: By optimizing the focal spot size, Acuros® XB showed an acceptable agreement within 3% down to an MLC-field of 0.5 cm × 0.5 cm. The results of this work suggest that if static and modulated delivery of very small targets is planned, then a field output factor table down to a field size of 1.0 cm is required in the beam configuration model.

1. Introduction

In the last decades, photon radiotherapy systems integrate complex dose calculation algorithms for treatment planning. The introduction of Monte Carlo, Boltzmann, and model-based convolution methods has considerably improved dose calculation accuracy in homogeneous and inhomogeneous media and replace those algorithms based on correction methods [1,2]. The aforementioned modern algorithms need detailed information on the radiation source characteristics (parameters), such as focal spot size, X-ray spectrum, beam fluence, electron contamination, and backscatter to monitor chamber, among others [3]. Radiation source parameters are determined from a set of experimental measurements through optimization methods. Commonly, total scatter factors (output factors), percentage depth dose, and off-axis profiles constitute the set of measurements required by current treatment planning systems

(TPS) to derive beam parameters and verify the beam model's dose calculation [4].

Contrary to correction-based algorithms, it is not straightforward to understand the influence and impact of the measurements' quality for TPS commissioning on the accuracy of modern dose calculation algorithms. More challenging for the TPS is the modeling of small beams, where the loss of lateral electronic equilibrium, among other effects, compromises the accuracy of the calculated dose. Several authors have evaluated the performance of advanced dose calculation algorithms for conventional radiotherapy applications down to 3 cm × 3 cm field sizes. Nevertheless, few reports in the literature evaluate algorithms' performance in small fields [5,6]. A standard methodology to evaluate the accuracy of TPS dose calculations, is to compare the calculated dose against Monte Carlo simulations or high-quality experimental measurements. However, this methodology may not be helpful for small

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fields because even the Monte Carlo simulation requires accurate measurements for its validation.

The employed detector strongly impacts the accuracy and quality of the measurements in small fields. The detector's density and volume influence the accuracy of output factors measurement. An inadequate detector leads to errors in dose prediction, compromising the accuracy and quality of treatment delivery. Recently, the International Atomic Energy Agency (IAEA) and the American Association of Physicists in Medicine (AAPM) have published the code of practice (CoP) TRS-483. The CoP has the goal to standardize the dosimetry of non-conventional and small fields worldwide [7]. The TRS-483 CoP establishes procedures to measure the absorbed dose to water in non-reference conditions for modern radiotherapy equipment (such as Tomotherapy® and CyberKnife®) and to measure relative dosimetry in small static radiation beams collimated by multileaf and circular cone collimators. For relative dosimetry, the CoP is based on the use of Monte Carlo calculated correction factors ($k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$), which are used to correct for the differences in the detector's response between the machine reference field (f_{msr}) and the clinical small field (f_{clin}). The $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ allows the measurement of absorbed dose to water ratio (field output factors) between the small field and the machine-specific reference field from the ratio of the detector signals.

This work aimed to evaluate the Acuros® XB algorithm's accuracy for dose calculation in small static fields for flattened and un-flattened beams at 6 MV shaped by the MLC. For that, TRS-483 recommendations were followed to measure field output factors for beam configuration and TPS evaluation.

2. Materials and methods

A TrueBeam STx® linear accelerator (Varian Medical Systems, Palo Alto, CA, USA) was used for measurements and TPS dose calculations with photon beams at 6 MV with (WFF) and without flattening filter (FFF). The beams were shaped with the secondary jaw collimators (for commissioning) and a multileaf collimator (for TPS dose calculations), model HD120®. The multileaf collimator has 60 leaf pairs with widths down to 2.5 mm at the isocenter plane. Measurements and calculations were performed in liquid water at 10 cm depth with a source to surface distance (SSD) of 90 cm for TPS evaluation and 100 cm for commissioning. Eclipse v. 15.6 (Varian Medical Systems, Palo Alto, CA, USA) was used for dose calculations with the Acuros® XB algorithm. The reference field size (*machine-specific reference field*) was set to 10 cm × 10 cm shaped by the jaws or MLC when appropriate. Dosimetric measurements were carried out in a computerized beam scanner phantom MP3-M (PTW-Freiburg, Freiburg, Germany) filled with liquid water. The detectors used for small field dosimetry and their main characteristics are listed in Table 1.

2.1. Recommendations of TRS-483

The field output factors ($\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$) are defined as the ratio of absorbed doses in water between the clinical small field (f_{clin}) and the machine-specific reference field (f_{msr}) at a reference depth ($z_{ref} = 10\text{cm}^{-2}$) along the central beam axis [7],

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

where Q refers to the beam quality for f_{clin} and f_{msr} fields, respectively. Experimentally, field output factors are derived from the ratio of the detector's signal (M) between f_{clin} and f_{msr} by applying a correction factor or output correction factor ($k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$) as following,

Table 1

Main characteristics of detectors employed to measure field output factors.

	CC-01	PinPoint 3D	microDiamond	SFD
Sensitive material	Air	Air	Carbon	Silicon
Sensitive volume (mm ³)	10	16	0.004	0.017
Diameter and thickness	2.0 mm, 3.6 mm	2.90 mm, 1.45 mm	2.2 mm, 1.0 µm	0.60 mm, 60 µm
Density (g cm ⁻³)	0.0013	0.0013	3.52	2.33
Wall materials	C552 ^a	PMMA, Graphite	RW3 ^b , Epoxy resin	ABS, Epoxy resin
Minimum Field Size (cm) ^{cd}	0.6	1.0	0.4	0.4

^a C552 is an air-equivalent plastic with a density of 1.76 g cm⁻³.

^b RW3 is a composition of Polystyrene and TiO₂ manufactured by PTW-Freiburg.

^c Side length of the square field size.

^d Minimum field size with available output correction factors as listed in Table 26 from TRS-483.

$$\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} \frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{msr}}^{f_{msr}}} \quad (2)$$

The signal detector ratio is measured by carefully positioning the radiation detector on the central beam axis at 10 cm depth. Thus, the central beam axis must be located for each radiation field size by measuring in-plane and cross-plane profiles [7]. The output corrections factors are extensively reported in TRS-483 for several detectors commonly used in small beam dosimetry for external beam radiotherapy. The $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ shows a marked dependence on field size. For that reason, instead of using the nominal field size, the actual field size must be measured accurately as possible. In this work, the field size was measured in-line using each detector (Table 1). Cross-plane and in-plane profiles were measured for each nominal field size for SAD and SSD measurement set-up. Following TRS-483, the equivalent square field size (S_{clin}) is derived using

$$S_{clin} = \sqrt{AB} \quad (3)$$

where A and B are the full width at half maximum (FWHM) for the cross-plane and in-plane profiles, indistinctly. The Eq. (3) is valid if $0.7 \leq A/B \leq 1.4$ is true. The $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ were obtained from Tables 26 and 27 of TRS-483 by spline interpolation as a function of S_{clin} , and field output factors were calculated applying Eq. (2). This experimental procedure was followed for 6 WFF and FFF beams. The measured field output factors were averaged for each field size, and they were compared with those field output factors reported by other authors using the same experimental conditions [8–10]. The measured field output factors were used to evaluate Acuros® XB's accuracy to calculate the dose in small static fields (≤ 3 cm length size) at the central beam axis shaped by the MLC.

2.2. Uncertainty budget

The experimental uncertainties were estimated for field output factor measurements. It was followed the procedure reported by Lechner et al. [11] and Huq et al. [9]. The sources of uncertainties considered were:

- Uncertainty of the output correction factor ($k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$)
- Detector positioning to the beam center
- Collimator field size setting and resetting
- Electrometer reading

The uncertainty associated with the output correction factors was taken from Table 37 of TRS-483 [7]. Detector positioning uncertainty and collimator field size setting and resetting were estimated according to Lechner et al. [11] by measuring dose profiles for each field size. The uncertainty associated with the electrometer reading was estimated by using repeated measurements. Each detectors' output signal was measured at least 3 times per field size.

Unless otherwise is stated, the uncertainties were combining by quadrature. The uncertainty of the average field output factor was calculated as follows,

$$\sigma_{\Omega} = \frac{\sqrt{\sum_{i=1}^n \sigma_i^2}}{\sqrt{n}} \quad (4)$$

where σ_i was the uncertainty associated with the field factor measured by detector i , and n was the total number of detectors used to measure the field factor. For field sizes ≥ 1.0 cm length side, $n = 4$. For the 0.5 cm $\times$ 0.5 cm field, $n = 2$. These uncertainties were used for 6 WFF, and FFF beams indistinctly as a function of field size.

2.3. Commissioning of Acuros® XB

The TPS was commissioned according to the manufacturer's specifications. The secondary jaws were used to shape 6 MV WFF and FFF beams. Data for commissioning consisted of measurements of dosimetric curves and output factors for symmetric and asymmetric radiation fields.

2.3.1. Dosimetric curves

Depth dose and off-axis profiles for TPS commissioning were measured using the microDiamond detector with a source to surface distance (SSD) of 100 cm for field sizes from 40 cm $\times$ 40 cm to 2 cm $\times$ 2 cm. The TPS configuration ignores dosimetric curves for field sizes < 2.0 cm length side. A detector with high spatial resolution and water-equivalence, such as the microDiamond, is recommended to commission and configure modulated techniques [12]. Also, the dosimetric leaf gap (DLG) was measured accordingly to the manufacturer's guidelines. The measured DLG values were 0.43 mm and 0.26 for 6 MV WFF and FFF, respectively.

2.3.2. Field output factors table

Field output factors were measured at 10 cm depth down to a field size of 1.0 cm $\times$ 1.0 cm with an SSD = 100 cm, for 6 MV WFF and FFF beams. The measurements were divided in two groups. The first group of measurement consisted of field output factors for conventional field sizes, from 40 cm $\times$ 40 cm to 8 cm $\times$ 8 cm. For these measurements, it was chosen a 0.125 cm³ semiflex ionization chamber (PTW-31010, PTW-Freiburg, Germany). According to TRS-483, the semiflex ionization chamber has output correction factors close to unity (within 0.1%) for field sizes down to 3 cm $\times$ 3 cm [7]. Therefore, only the semiflex ionization chamber was used for this group of measurements.

The second group of measurements consisted of field output factors for jaw-shaped field sizes ≤ 6 cm length side. For these fields, the measurements were performed with the detectors listed in Table 1 and following the recommendations of TRS-483 (see Section 2.1). The configuration of Acuros® XB requires the measurement of output factors for symmetrical and asymmetrical field sizes. The TRS-483 did not consider asymmetrical field sizes with A/B out of the interval of 0.7 to 1.4. For that reason, asymmetrical field sizes (such 1 cm $\times$ 40 cm) were out of this work scope and limited to square fields. The measured field output factors were compared with data available in the literature for this group of measurements.

2.3.3. Field size at phantom surface and nominal field size

When it is performed SSD measurements, the actual field size at the measurement depth is larger than the nominal field size at the phantom

surface; the field size is reported and configured into the TPS at the phantom's surface, not at the measurement depth. For example, a 10 cm $\times$ 10 cm nominal field size is about 11 cm $\times$ 11 cm at 10 cm depth using an SSD of 100 cm. It is common to consider a factor of 1.1 between the field size at surface and measurement depth [10]. This factor was validated to apply in small fields (see Supplement material).

On the other hand, TRS-483 recommends the determination of the actual field size (S_{clin}) at the measurement depth. However, the TPS only can be configured with the nominal field sizes. The TPS does not allow the introduction of non-integer field size values into the beam configuration modeling. For that reason, it is necessary to perform an interpolation of the experimental field output factors (Ω) as a function of the nominal field size. The interpolation was performed following the formula [13,9],

$$\Omega(S_{clin}) = P_{\infty} \frac{S_{clin}^n}{l^n + S_{clin}^n} + S_{\infty} (1 - e^{-b \cdot S_{clin}}) \quad (5)$$

where P_{∞} , l , S_{clin} , b and n are fitting parameters. The resulting interpolated field output factors were used to configure the TPS as a function of the nominal field size.

2.4. Measurement of field output factors for MLC shaped beams

The field output factors were measured for the following square MLC-fields: 0.5, 1.0, 1.5, 2.5, 3.0, 4.0, 6.0 and 10.0 cm. The backup jaws were set 0.5 cm larger than the MLC shaped field. The measurements were carried out at 10 cm depth with an SSD of 90 cm. The S_{clin} values differ from the nominal field sizes, then as in the previous section, Eq. (5) was used to interpolate the measured field output factors as a function of the nominal field size. The data interpolation facilitates comparison with data available in the literature and evaluating TPS calculated field output factors.

2.5. Calculation of field output factors with Acuros® XB

2.5.1. Briefly description of Acuros® XB algorithm

Acuros® XB is a deterministic algorithm for dose calculation in external beam photon radiotherapy. Acuros® XB solves the linear Boltzmann transport equations to calculate the dose, and it is based on Vassiliev et al. [14]. The algorithm uses a photon source model with previously calculated physical parameters, such as photon spectral, mean energy, and fluence distributions. The TPS uses the measured field output factors for jaw collimated beams to calculate collimator backscatter factors (CBSF). The CBSF accounts for the differences between calculated and measured output factors assumed to be caused by collimator backscatter to linac's monitor chamber [15]. The TPS uses the CBSF of the minimum configured field size for smaller jaw-field sizes. For MLC shaped beams, Acuros® XB calculates the dose delivered by the MLC-field and corrects the backscatter contribution defined by the backup jaw collimators. The TPS assumes that the backscatter contribution of the MLC collimator is negligible.

2.5.2. Calculation of field output factors for HDMLC® shaped beams

A cubic virtual phantom of 30 cm length side was defined using Eclipse TPS. The virtual phantom was filled with a homogeneous media with a density equal to liquid water. The calculation reference point was set to 10 cm depth with an SSD of 90 cm. The fields were shaped using the HDMLC®, and their dimensions were according to the field sizes used in the experiments (see Section 2.4). The static MLC-fields were configured to deliver 100 UM to the reference point for each field size. The calculated absorbed dose to water at the reference point was registered ($D_{w,TPS}$) and the field output factors were calculated as the ratio of calculated doses,

$$\Omega_{TPS}^{fclin,fmsr} = \frac{D_{w,TPS}^{fclin}}{D_{w,TPS}^{fmsr}} \quad (6)$$

The $\Omega_{TPS}^{fclin,fmsr}$ were calculated for small static fields ($0.5 \leq S_{clin} \leq 3$ cm) as a function of,

- The focal spot size.* The TPS was configured using the measured field output factors down to a field size of $1 \text{ cm} \times 1 \text{ cm}$. The $\Omega_{TPS}^{fclin,fmsr}$ were calculated for FSS of 0.0, 0.5, 1.0 and 1.5 mm in size in symmetrical and asymmetrical configurations. The backup jaws were set to a field size 0.5 cm larger than the MLC-field. Also, profiles for the smallest field (0.5 cm length side) were calculated as a function of the FSS. The calculated profiles were compared with measurements performed with the stereotactic diode (IBA-SFD). The comparison was evaluated using the root mean square error (RMS) for profiles and field output factors.
- The maximum jaw opening.* The backup jaws were set to 4.0, 3.0 and 2.0 cm field size. Field output factors for MLC-fields were calculated for each backup jaw configuration. Experimental field output factors were re-measured using backup jaws consistent with calculations.
- The minimum field size used to configure Acuros® XB.* The minimum field size was set to 3.0, and 2.0 to configure the beam model. The backup jaws were set as in a).
- The value of $\Omega(1 \times 1)$ in beam configuration.* This point aimed to explore the impact of the jaw-field output factor of the $1 \text{ cm} \times 1 \text{ cm}$ field in beam modeling on calculating the field output factor of the MLC-defined $0.5 \text{ cm} \times 0.5 \text{ cm}$ field.

For points a) to d), the accuracy of Acuros® XB was evaluated by comparing $\Omega_{TPS}^{fclin,fmsr}$ with those measured following TRS-483 ($\Omega_{Qclin,Qmsr}^{fclin,fmsr}$) using the percentage difference,

$$\Delta(\%) = \frac{\Omega_{TPS}^{fclin,fmsr} - \Omega_{Qclin,Qmsr}^{fclin,fmsr}}{\Omega_{Qclin,Qmsr}^{fclin,fmsr}} \times 100 \quad (7)$$

3. Results and discussion

3.1. Uncertainty budget

Table 2 summarizes the estimated uncertainties for the measured field output factors. Overall, ionization chambers showed larger uncertainty values than solid-state detectors. The associated uncertainty to the output correction factors was the main contribution to ionization chambers' uncertainty. For the smallest field, the positional uncertainty was the main contribution to solid-state detectors' total uncertainty. For all detectors and field sizes, the contribution of the electrometer reading was $< 0.5\%$. Positional and collimator uncertainties diminished for field sizes ≥ 2.0 cm length side.

3.2. Experimental field output factors

3.2.1. Jaw shaped beams for Acuros® XB

Table 3 shows the measured field output factors for 6 MV WFF and FFF beams for jaw-shaped fields. The field output factors were interpolated to the nominal field sizes projected at the phantom's surface.

Table 2

Field factor uncertainty for each radiation detector as a function of field size. It is reported the relative uncertainty (%) at 1σ .

Field Size (cm)	IBA-SFD	microDiamond	IBA-CC01	PP3D	Total (σ_Ω)
0.5	1.7	1.9	–	–	1.8
1.0	0.7	0.7	1.9	3.0	1.8
1.5	0.5	0.5	0.8	1.1	0.8
≥ 2.0	≤ 0.4	≤ 0.3	≤ 0.5	≤ 0.4	≤ 0.4

Table 3

Measured field output factors for 6 MV FFF and FFF beams shaped with the jaw collimators. The standard deviation is reported at 1σ . Data were compared with values reported by Mamesa et al. [10] for 6 MV flattened beams. The differences ($\Delta(\%)$) were calculated using Eq. (8) and they were only calculated for 6 MV WFF beams.

Nominal Field Size (cm)	6 MV WFF	Mamesa et al. [10]	$\Delta(\%)$	6 MV FFF
6.0	0.921 ± 0.004	0.923 ± 0.006	0.2	0.928 ± 0.004
4.0	0.865 ± 0.003	0.867 ± 0.008	0.2	0.873 ± 0.003
3.0	0.834 ± 0.003	0.834 ± 0.008	0.0	0.843 ± 0.003
2.0	0.795 ± 0.003	0.795 ± 0.010	0.0	0.806 ± 0.003
1.0	0.694 ± 0.013	0.707 ± 0.012	1.9	0.705 ± 0.013

The measured field size at 10 cm depth was scaled using a factor of 10/11 (100 cm/110 cm). The resulting fitting parameters of Eq. (5) might be consulted in the [Supplement material](#). The data were compared to those field output factors reported by Mamesa et al. [10] for flattened beams. Up to date, to the best of our knowledge, there are not jaw-field output factors reported for 6 MV unflattened beams measured with an SSD of 100 cm at 10 cm depth.

The field output factors were compared by calculating the mutual difference defined as following,

$$\Delta(\%) = \left(\frac{\Omega_1 - \Omega_2}{\Omega_1 + \Omega_2} \right) \times 200 \quad (8)$$

An agreement within 0.5% was found for jaw-field sizes greater than 1.0 cm length side. The jaw-field size of 1.0 cm showed a difference about 2%; it may be caused by S_{clin} differences and interpolation biasing. The field output factors shown in Table 3 were used to configure the output factor table for Acuros® XB. The asymmetric field sizes were used without any correction.

3.2.2. Field output factors for HDMLC® shaped fields

Field size (S_{clin}) and the detector's signal at the central beam axis were measured. The signal ratios were determined for each radiation detector and output correction factors were applied. The field output factors were calculated according to Eq. (2). The field output factors for all the detectors were averaged as a function of S_{clin} ; afterward, Eq. (5) was used to interpolate the data as a function of the nominal field size. The resulting field factors were compared with those field output factors reported in the literature for the TrueBeam STx® under the same measurement conditions. The literature data was also interpolated only for data with available S_{clin} values as a function of the nominal field size. Data interpolation facilitates a direct comparison [17].

Table 4 shows the differences between field output factors measured in this work and those reported in the literature for flattened and unflattened beams as a function of the nominal field size. The data from Dufreneix et al. [16] were not interpolated because the S_{clin} values were not reported; possibly explaining the difference found for the $1 \text{ cm} \times 1 \text{ cm}$ field. For field sizes ≥ 1.0 cm, the differences were less than 1.5% for both beam qualities. The data was not compared for the $0.5 \text{ cm} \times 0.5 \text{ cm}$ field because it was not possible to interpolate the field output factors down to this field size. Huq et al. [9] reported $S_{clin} > 0.6$ cm for both beam qualities, while the S_{clin} measured in this work were 0.54 and 0.52 cm for unflattened and flattened beams, respectively. Nevertheless, the data from Huq et al. and this work fully agree within the reported uncertainties for field sizes greater than 0.5 cm length side. The field output factors shown in Table 4 were used to evaluate the TPS field output factors as a function of the focal spot size.

Table 4

Comparison of the average field output factors from this work and those reported by Dufreneix et al. [16] and Huq et al. [9] for flattened and unflattened beams. The data from this work and from Huq et al. were interpolated to the nominal field sizes for comparison. The data from Dufreneix et al. were not interpolated because S_{clin} values are not reported. The differences (Δ) were reported in percentage (%) using Eq. (8).

Nominal Field Size (cm)	6 MV WFF			Δ (%)	
	This Work	Dufreneix et al. [16]	Huq et al. [9]		
6.0	0.923	–	0.924	–	0.1
4.0	0.865	–	0.868	–	0.3
3.0	0.832	0.837	0.836	0.6	0.5
2.5	0.814	–	0.818	–	0.5
2.0	0.792	0.798	0.797	0.8	0.6
1.5	0.758	–	0.763	–	0.7
1.0	0.691	0.700	0.697	1.3	0.9
0.5	0.541	0.537	0.591	–	–
Nominal Field Size (cm)	6 MV FFF			Δ (%)	
	This Work	Dufreneix et al. [16]	Huq et al. [9]		
6.0	0.929	–	0.928	–	0.1
4.0	0.875	–	0.876	–	0.1
3.0	0.844	0.847	0.843	0.4	0.1
2.5	0.827	–	0.824	–	0.4
2.0	0.806	0.808	0.804	0.2	0.2
1.5	0.774	–	0.773	–	0.1
1.0	0.711	0.714	0.715	0.4	0.6
0.5	0.561	0.567	0.604	–	–

3.3. Evaluation of TPS calculated field output factors

The calculated field output factors were compared against measurements for flattened and unflattened beams. The difference between calculated and measured field output factors was calculated using Eq. 7. Unless otherwise is stated, the backup jaws were set 0.5 cm larger than the MLC-fields. Dose calculations' voxel size was set 1 mm length side (the highest resolution allowed by the TPS) for all field sizes and both beam qualities.

3.3.1. TPS field output factors as a function of the focal spot size

Table 5 shows the percentage of differences between calculated and measured field output factors for MLC-fields. An excellent agreement within ~0.5% can be observed between calculated and measured field

Table 5

Comparison between calculated and measured field output factors for flattened and unflattened beams as a function of the focal spot size (in mm). The photon beams were shaped with the HDMLC. The values are the percentage difference relative to the measured field output factors.

Nominal Field Size (cm)	0.0	0.5	1.0	1.5	1.0,0.0	1.0,0.5	1.5,0.0
6 MV WFF							
3.0	0.3	0.3	0.4	0.2	0.3	0.3	0.4
2.5	0.7	0.7	0.6	0.5	0.7	0.6	0.6
2.0	0.1	–0.1	–0.1	–0.1	–0.1	–0.1	–0.1
1.5	–0.1	–0.1	0.3	–0.4	–0.3	–0.3	–0.3
1.0	0.6	0.6	0.4	0.6	0.6	0.6	0.6
0.5	–0.8	–2.1	–7.2	–20.3	–2.6	–3.6	–8.0
RMS	1.3	2.3	7.2	20.4	2.7	3.7	8.0
6 MV FFF							
3.0	0.4	0.4	0.4	0.4	0.4	0.4	0.4
2.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6
2.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
1.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
1.0	–1.4	–1.4	–1.7	–1.8	–1.4	–1.4	–1.7
0.5	0.9	–0.3	–5.2	–19.8	–1.0	–1.8	–6.9
RMS	1.9	1.7	5.5	19.9	1.9	2.5	7.2

output factors down to a field size of 1 cm × 1 cm, for flattened beams. For unflattened beams, the agreement was within ~2%. No dependence of differences was observed as a function of FSS for square MLC-fields ≥1.0 cm length side. For field sizes ≤1.0 cm, the differences were up to ~20% for both beam qualities. The calculated field output factors showed a FSS dependence for the smaller field sizes, mainly caused by source occlusion modeling [18].

Fig. 1 shows off-axis profiles as a function of the focal spot size of a MLC-field of 0.5 length side at 6 MV WFF beam. The profiles' FWHM were measured, and it was found differences between calculated and measured data within ~0.5 mm, which might be explained by the position uncertainty of the physical MLC related to its calibration. The calculated profiles were scaled to match the measured profile's FWHM. It can be observed an FSS dependence of the dose fall-up (gradient) region caused by source occlusion and penumbrae overlapping [7,18]. The best match (minimum RMS values) between the calculated and measured profiles was found for FSS of (1.0 mm, 0.0 mm). Previous measurements with the microDiamond detector showed the same results, indicating that profile measurement must be performed with a high spatial resolution detector (solid stated or film). The use of an ionization chamber is not encouraged for the measurement of small beam profiles because of volume averaging effects. The differences in penumbra shape might be caused by partial volume averaging present in the calculated profiles compared to the measured ones.

The above results suggest that the FSS of (1.0 mm, 0.0 mm) showed the best compromise with experimental field output factors and dose profiles. The calculated field output factors showed an accuracy within 3% for all field sizes and beam qualities. Centers worldwide must perform a similar study to optimize the calculated beam profiles as a function of the focal spot size to verify the results of this work.

In the present study, the algorithm's accuracy was evaluated in a homogeneous media, consistent with the scope and recommendations of TRS-483. However, a limit of this work is the dose accuracy of small fields in inhomogeneous media. In heterogeneous media, the algorithm's accuracy in calculating the dose in small fields might be within 10–5%, which is the case of stereotactic body radiation therapy of lung [19]. Thus, it is important to verify and evaluate the dose calculation accuracy in such conditions by further developing methodologies in the context of the TRS-483.

3.3.2. Jaw field size larger than MLC shaped field

Field output factors were calculated for the following square MLC-fields: 3.0, 2.5, 2.0, 1.5, 1.0 and 0.5 cm length side. The jaw collimators were set with the following openings: 2.0, 3.0 and 4.0 cm. The field factors only were calculated for MLC-field sizes less than jaw collimator openings. For these calculations, the FSS was set to (1.0 mm, 0.0 mm) in beam configuration. The experimental field output factors were re-measured using these jaw openings. The DLG and LT values were kept unchanged from their measured values. Table 6 shows a comparison between the calculated and the measured field output factors using large jaw openings. An agreement can be observed for flattened beams and field sizes greater than the 1.0 cm length side within 2% for all the jaw openings. The smallest field showed an agreement within 3%. It can also be seen that the agreement between the data improves as the jaw-field opening increases.

Unflattened beams showed and agreement within 1.5% for all field sizes, even for the smallest field. Contrary to flattened beams, the agreement between the data improves as the jaw opening decreases. Acuros® XB models the MLC as a plane without realizing any radiation transport, explaining the difference in performance for both beam qualities. Unflattened beams are softer, causing them to be blocked more efficiently than flattened ones; suggesting that the MLC modeling performs better for unflattened beams.

The algorithm's accuracy using these jaw openings not only has an impact on static fields but also may impact the dose calculation in modulated fields [10]. Moreover, the dose calculation accuracy of

Fig. 1. Off-axis profiles for 0.5 cm $\times$ 0.5 cm field size as a function of the focal spot size for a 6 MV WFF beam. (a) Cross-plane profiles and (b) in-plane profiles. The measured profiles were acquired with the IBA-SFD detector.

Table 6

The percentage difference between calculated and measured field output factors for flattened/unflattened beams as a function of jaw openings behind the MLC shaped fields.

Nominal Field Size	6 MV WFF			-	6 MV FFF		
	2.0	3.0	4.0		2.0	3.0	4.0
3.0	–	–	–0.1	–	–	–	0.1
2.5	–	0.7	0.2	–	–	0.6	0.2
2.0	–	0.1	0.3	–	–	–0.1	0.2
1.5	–0.3	–0.3	0.1	0.4	0.1	0.5	
1.0	–0.8	0.0	0.5	0.6	1.2	1.5	
0.5	–1.9	–1.1	–0.8	0.6	1.1	1.5	
RMS	2.1	1.3	1.0	0.9	1.7	2.2	

VMAT plans using jaw tracking may be affected because the jaws adjust their size to the MLC apertures to minimize the radiation leakage. Thus, if static and modulated dose delivery to very small targets is planned, then it is required to measure a field output factor table down to a field size of 1.0 cm length side for beam configuration modeling.

Fogliata et al. [6] showed that for a jaw opening of 4.0 cm length side, an agreement of 3% for the smallest field size might be observed. They configured the TPS with an FSS of (1.5 mm, 0.0 mm) consistent with manufacturer recommendations, but DLG and LT values were optimized. They found that the optimum values were 2.0 mm and 1.4% for DLG and LT, respectively. The TPS uses DLG to model the leaf end, increasing the field size by directly adding the value of DLG. For example, an MLC-field of 0.5 cm length side is modeled as a 0.7 cm length side if a DLG of 2.0 mm is used. While this optimization might increase the accuracy in small fields, their effect on the calculated dose distributions was not studied.

The results presented in this work showed that by selecting the FSS that minimize the difference between measured and calculated profiles, the field output factors also show the best agreement. No further optimization of DLG and LT were required.

3.3.3. Minimum field size used to configure Acuros® XB

Two different output factor tables were configured into the TPS using a minimum jaw-field size of 3.0 and 2.0 cm length side. The field output factors were calculated for field sizes of 2.5, 2.0, 1.5, 1.0 and 0.5 cm shaped with the HDMLC®. These field output factors were calculated with jaw openings 5 mm greater than MLC shaped fields. The calculated field output factors were compared with the field output factors shown in Table 4. Table 7 shows the results of this comparison. The difference between calculated and experimental field output factors were less than

Table 7

The percentage difference between calculated and measured field output factors for flattened/unflattened beams as a function of the minimum field size used to configure the beam model.

Nominal Field Size	6 MV WFF		6 MV FFF	
	2.0	3.0	2.0	3.0
3.0	0.3	0.4	0.4	0.4
2.5	0.6	0.7	0.6	0.6
2.0	–0.1	0.8	0.2	0.9
1.5	0.1	0.9	0.3	1.2
1.0	0.7	1.6	1.5	2.4
0.5	–0.7	0.1	2.3	3.0
RMS	1.3	2.1	2.9	4.2

the experimental uncertainties ($\leq 1.8\%$) for the two jaw configuration settings at 6 MV WFF. However, for unflattened beams and the smallest field sizes, the differences were larger than the experimental uncertainties.

A second comparison was performed between calculated and measured field output factors. In this case, the measured field output factors were those of the previous Section (3.3.2). This comparison showed the same differences as those reported in Table 6. This result was consistent with the way that TPS models the MLC. As there was no radiation transport in the collimator, the difference between the two cases was the same. Then, the correct set of measured field output factors for comparison were those of the previous section; leading to the same conclusion regarding TPS accuracy.

3.3.4. Field factor value for 1 cm $\times$ 1 cm in beam configuration

The $\Omega_{Q_{clin}, Q_{msr}}^{f_{clin}, f_{msr}}$ (1 cm $\times$ 1 cm) for the jaw-field was 0.694 ± 0.012 and 0.705 ± 0.013 for flattened and unflattened beams, respectively (see Table 3). Table 8 shows the difference between calculated and measured

Table 8

Percentage difference between calculated and measured field output factor for the MLC-field of 0.5 cm $\times$ 0.5 cm, as a function of the jaw-field 1 cm $\times$ 1 cm field output factor used for beam configuration.

$\Omega_{WFF}^{f_{clin}, f_{msr}}$ (1 cm)	Difference (%)	$\Omega_{FFF}^{f_{clin}, f_{msr}}$ (1 cm)	Difference (%)
0.685	–4.3	0.695	–2.3
0.690	–3.0	0.700	–1.6
0.695	–2.4	0.705	–0.9
0.700	–1.5	0.710	+0.2
0.705	–0.9	0.715	+0.5

field output factors for the MLC-field of 0.5 cm length side as a function of the field factor for the jaw-field of 1.0 cm length side. It can be observed that the difference between measured and calculated field output factor might decrease to 1% level. By changing the $\Omega_{Qclin, fmsr}^{clin, fmsr}$ ($1\text{ cm} \times 1\text{ cm}$), it was indirectly changing the CBSF value used for dose calculation for the 0.5 cm field size. This result indicates that the differences reported in Tables 5 and 7 were within the uncertainties of the calculated field output factors for the smallest field. Also, it was found equivalent results for unflattened beams.

Fogliatta et al. [5,6] have previously performed an extensive evaluation of Acuros® XB accuracy for small fields; they found that the agreement between calculated and experimental output factors might be improved ($\leq 3\%$) by optimizing the focal spot size, DLG and leaf transmission (LT) parameters into the beam configuration model. The general findings reported by Fogliatta et al. are still valid and consistent with the results showed in this work. Moreover, the present study's novelty is based on the use of TRS-483, which allowed a better understanding of the accuracy and limits of Acuros® XB. The present work showed that Acuros® XB might achieve acceptable accuracy for field sizes down to 1.0 cm length side for flattened and unflattened beams within the experimental uncertainties for static MLC shaped beams. This accuracy was achieved by only optimizing the focal spot size to match the shape of measured small beam profiles; no further optimization of DLG and LT was required to decrease the difference between calculated and measured field output factors.

The dosimetry of very small fields ($\leq 0.5\text{ cm}$) remains challenging for measurements and calculations. As can be observed from Table 4, the differences increased as the field size decreased. Further research is required about accuracy limits in calculations and measurements for very small field sizes.

4. Conclusions

The accuracy of Acuros® XB for small field dosimetry calculation was evaluated by using the formalism proposed by the code of practice IAEA/AAPM TRS-483. Acuros® XB might have an accuracy better up to 2% for field sizes down to 1.0 cm length size at 6 MV WFF and 6 MV FFF beams. It was shown that this accuracy might be achieved by optimizing the focal spot size to match calculated to measured dose profiles for the field sizes of 1.0 and 0.5 cm length size; no further optimization of dynamic leaf gap and leaf transmission were required. The dosimetry of the $0.5\text{ cm} \times 0.5\text{ cm}$ field size remains challenging. However, the results showed in this work suggest that the differences between calculated and measured field output factors were within the calculated and experimental uncertainties for the smallest field. The results of this work suggest that if static and modulated delivery of very small targets is planned, then a field factor table down to a field size of 1.0 cm is required in the beam configuration model.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.ejmp.2021.06.021>.

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