ICTP School of Medical Physics for Radiation Therapy:
Dosimetry and Treatment Planning for Basic and Advanced Applications

Dosimetry of small MV photon beams: TRS-483 Code of Practice

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1. Background

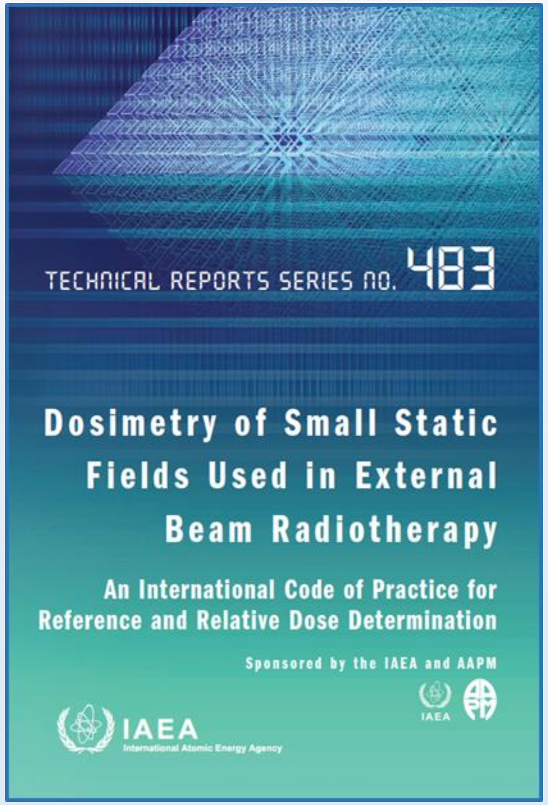
2. Basic physics of small fields

3. TRS-483 CoP: concepts and formalism

4. Detector specific output correction factors

Background

- Rapid development of **modern technologies** has facilitated the use of advanced radiotherapy techniques such as IMRT, SRS, SBRT, VMAT.
- Modern RT techniques use **single or multiple/composite small (narrow) fields** (< 4 cm)
- Dosimetry protocols designed for broad beams (TRS-398, TG 51, …) are not suitable for small beam dosimetry and do **not provide guidance** for dosimetry in small fields
- Misunderstanding of this limitations and absence of suitable dosimetry protocol for small fields resulted in the occurrence of **dosimetric errors and several clinical accidents**



IAEA TRS – 483 Code of Practice for small field dosimetry (2017)

… however, issues pointed out in the TRS-483

- *"… there is a large amount of experimental and Monte Carlo calculated data available for specific output correction factors, $k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}}$, particularly for certain solid state detectors and ionization chambers on the central axis of* ***6 MV beams****."*
- *"Unfortunately, the published data are* ***rather scattered for certain field sizes****, especially for the smallest fields, and* ***lack homogeneity*** *with regard to the SSD or SDD used, the depth of measurement or calculation, the* ***definition of field size*** *at the surface or at a reference depth, etc."*
- *"To further complicate the determination of average values for the different detectors and their subsequent statistical analysis, most of the published data* ***lack a proper estimation of the uncertainty*** *in the various steps involved in the determination of the correction factors given by different authors."*

H. Palmans, P. Andreo, M. S. Huq, J. Seuntjens and K. Christaki. Dosimetry of small static fields used in external beam radiotherapy: An IAEA-AAPM international Code of Practice for reference and relative dose determination. IAEA Technical Report Series No. 483. International Atomic Energy Agency, Vienna, 2017.

Small field conditions

At least one of the **three** physical conditions should be fulfilled for an external photon beam to be designated a small as defined in new dosimetry protocol for small static beams IAEA/AAPM TRS-483 CoP

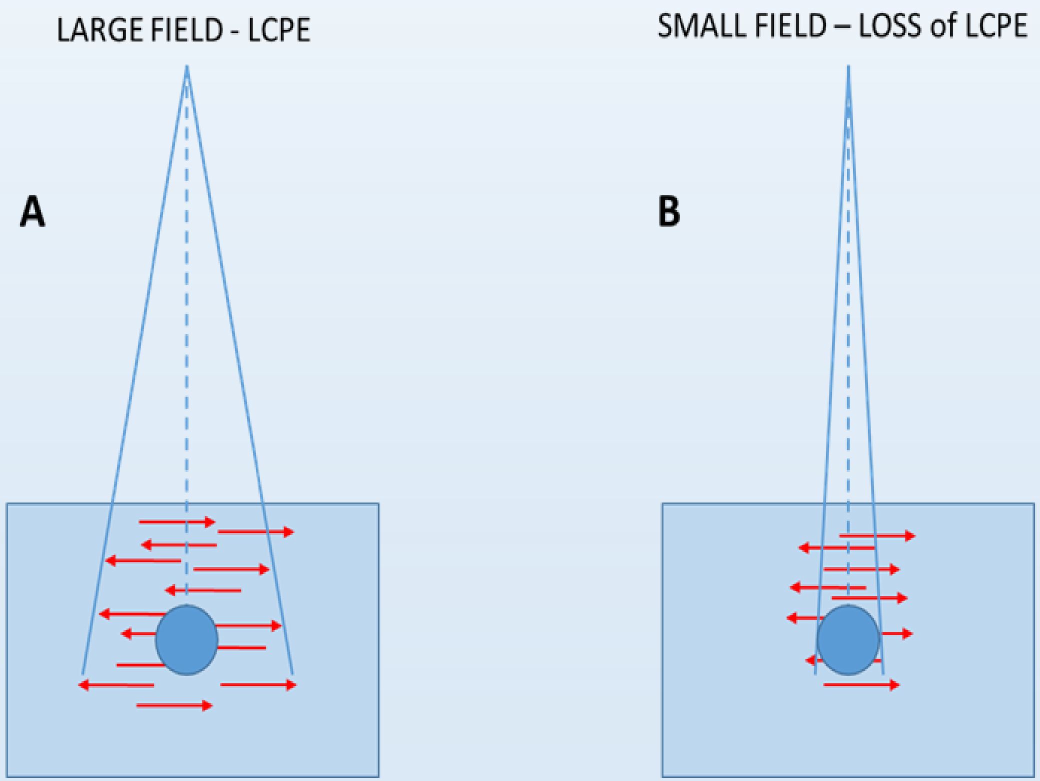
Beam related small field conditions

1. There is a **loss of lateral charged particle equilibrium (LCPE)** on the beam axis
2. There is **partial occlusion (geometrical shielding) of the primary photon source** by the collimating devices (MLC, jaws) as seen from the point of measurement - on the beam axis

Detector related small field condition

3. The **size of the detector** is similar or large compared to the beam dimensions

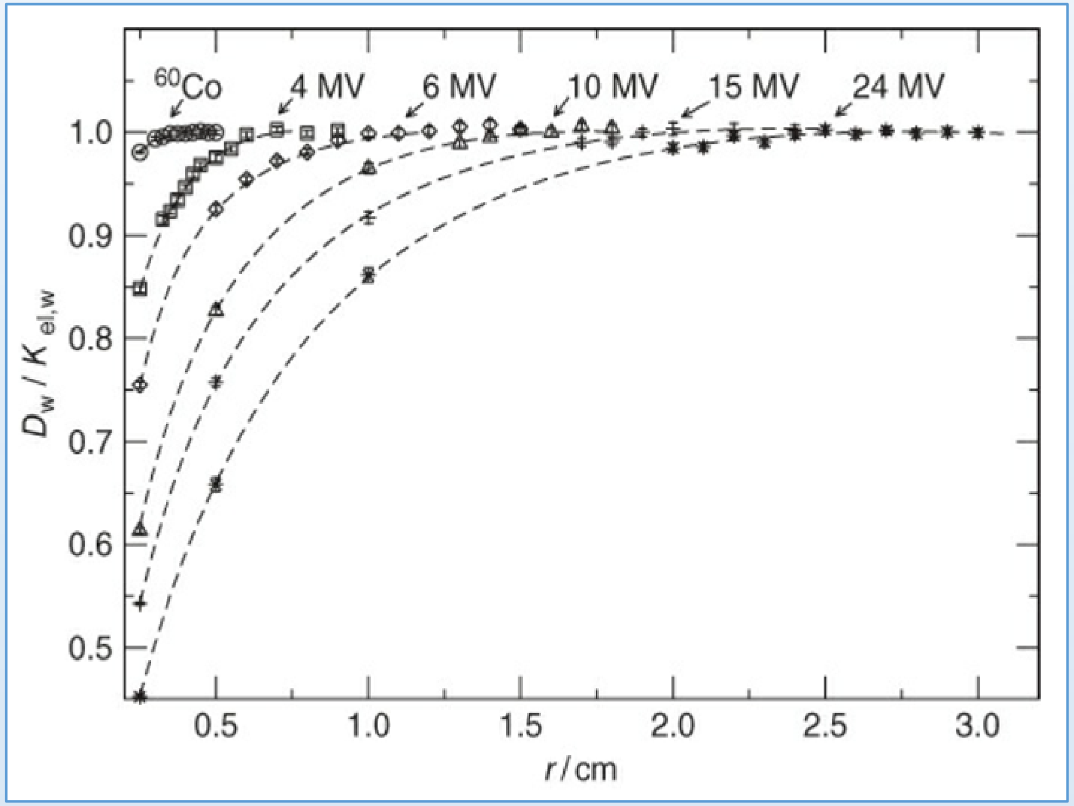
1.1. Loss of LCPE on the beam axis



- LCPE - the number of charged particles exiting the sensitive volume (cavity) of the detector - ***"out-scattering"*** - is equal to the number of charged particles entering the sensitive volume (cavity) of the detector – ***"in-scattering"***

- Loss of LCPE - out-scatter from the beam **is not compensated** by the in-scatter

1.2. LCPE and equivalency of D_w and $K_{col,w}$



- Water collision kerma $K_{col,w}$ is equal to the absorbed dose to water D_w as long as CPE exists
- The minimum half width (radius) of the beam at which $\boldsymbol{K_{col,w} = D_w}$ still holds is defined as the *lateral charged particle equilibrium range* $\boldsymbol{r_{LCPE}[cm]}$

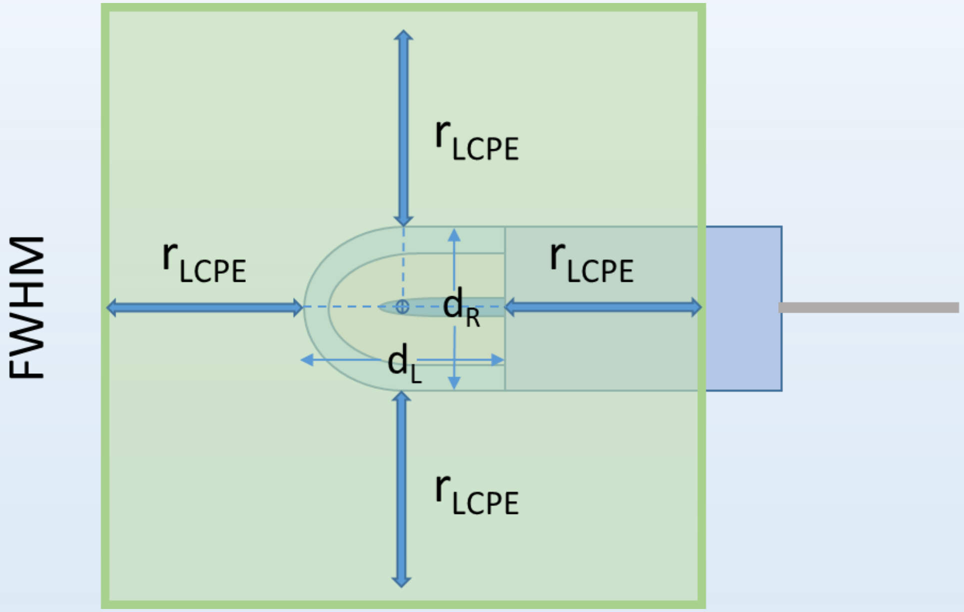
1.3. Lateral charged particle equilibrium range

The first condition defining small fields is a size parameter $\boldsymbol{r_{LCPE}}$, which is a measure of the range of laterally scattered electrons

$$\boxed{r_{LCPE}[cm] = 8.369 \cdot TPR_{20,10} - 4.382}$$

LCPE exists when radiation field extends at least a distance r_{LCPE} beyond the outer boundaries of the ionization chamber

$$\boxed{FWHM \geq 2r_{LCPE} + d}$$

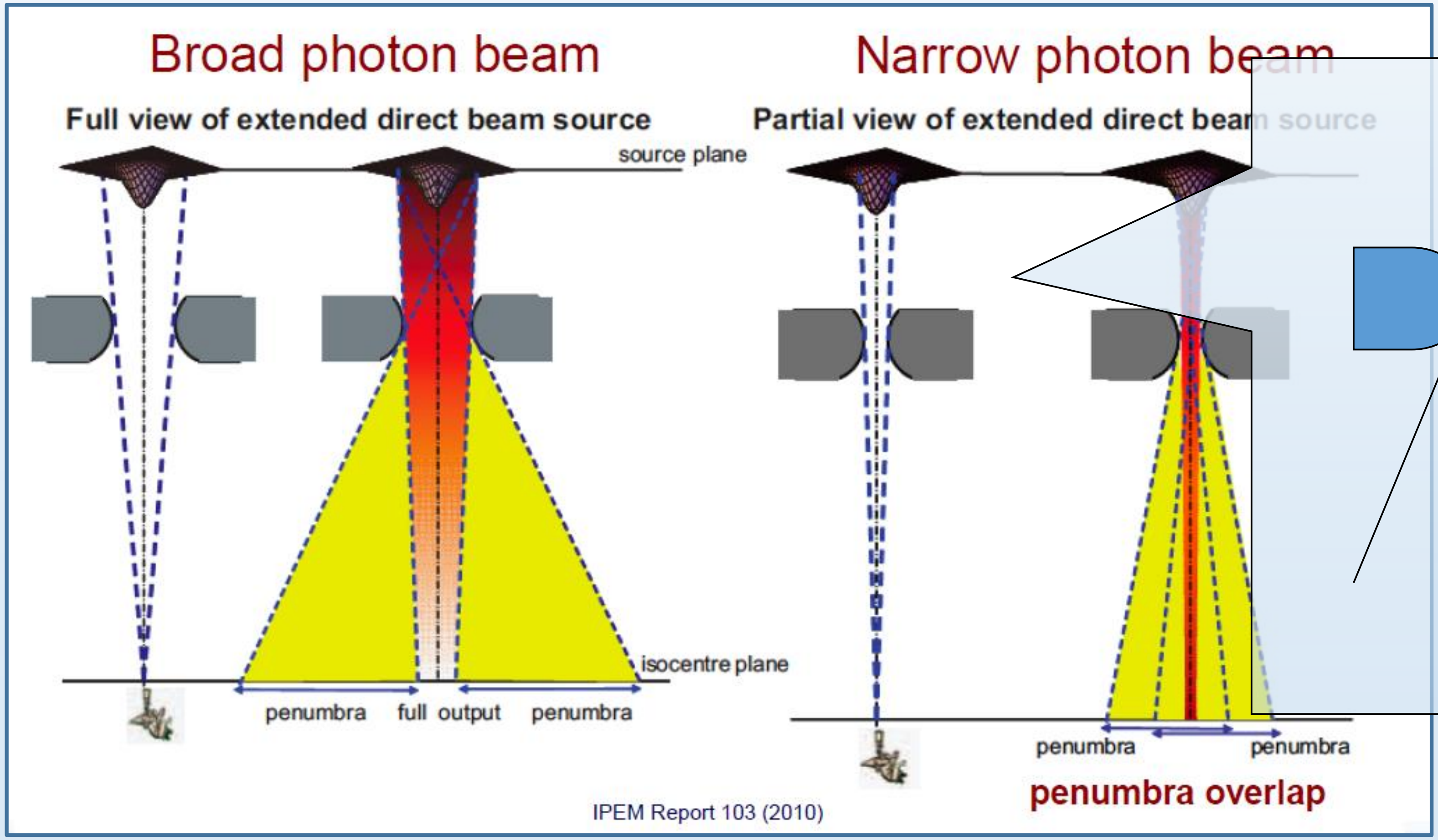


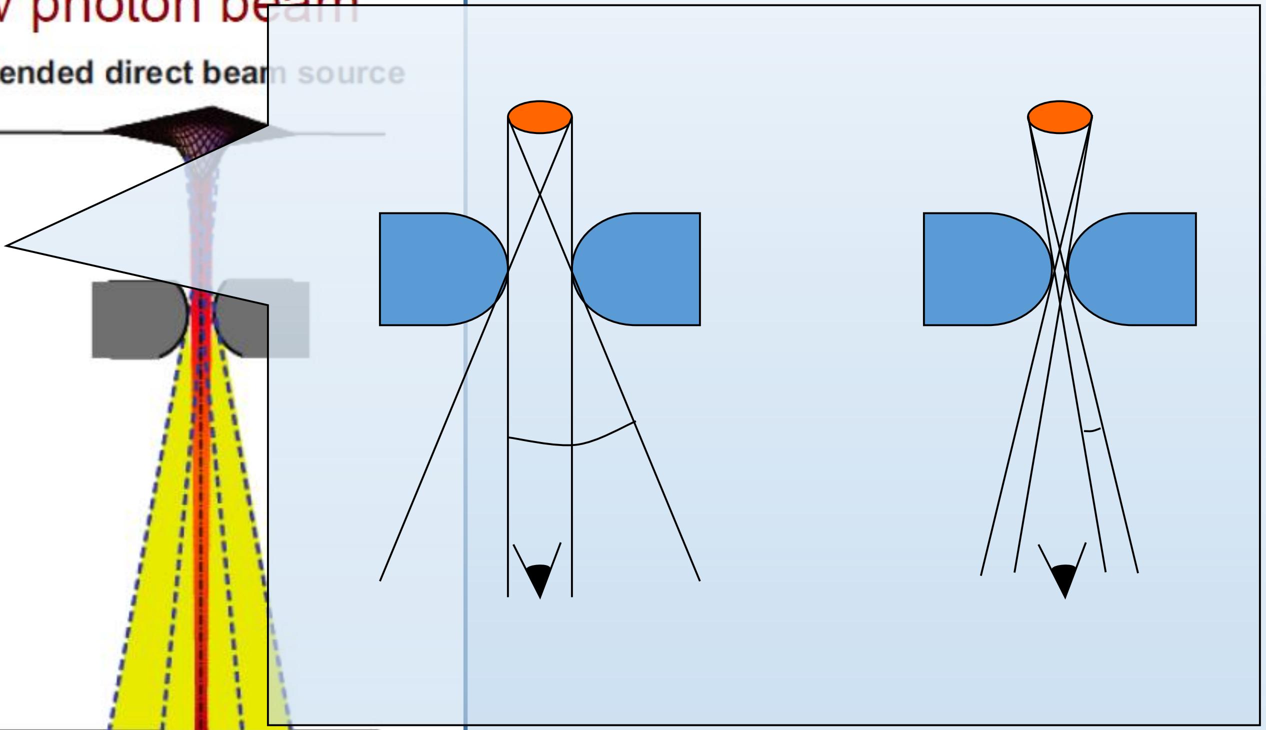
6 MV photons: $r_{LCPE} \approx 1.2$ cm

X.A. Li, M. Soubra, J. Szanto and L.H. Gerig. Lateral electron equilibrium and electron contamination in measurements of head-scatter factors using miniphantoms and brass caps. Medical Physics, 1995, 22, 1167-70.

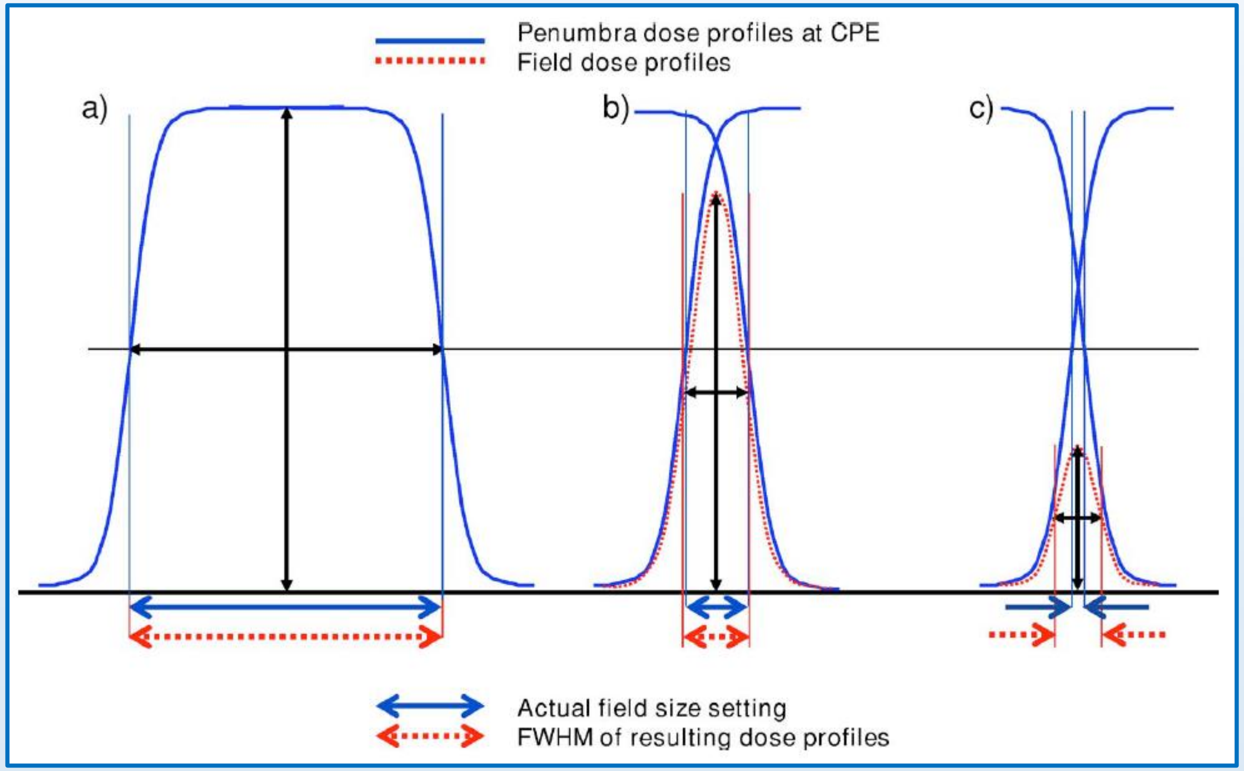
P. Papaconstadopoulos. On the detector response and the reconstruction pf the source intensity distribution in small photon fields. PhD Thesis, 2016, McGill University, Montreal, Canada.

2.1 Partial source occlusion





2.2. Partial source occlusion



a) Large field sizes: LCPE exists, source fully viewed;
   FWHM = nominal field size

b) Field sizes of the same order as the charge particle diffusion distance;
   FWHM ≥ nominal field size
   output lowered

c) Small fields: LCPE does not exist, radiation source partially hidden by the collimators;
   FWHM > nominal field size
   output further lowered

Figure from I. J. Das, G. X. Ding, and A. Ahnesjö. Small fields: Non-equilibrium radiation dosimetry. *Med. Phys.*, 35:206-215, 2008.

3.1 Volume averaging

- Any detector will average the dose across its sensitive volume if not infinitesimally small.
- This averaging can yield to a different signal compared to the signal which would be measured by an infinitesimally small detector.

⇓

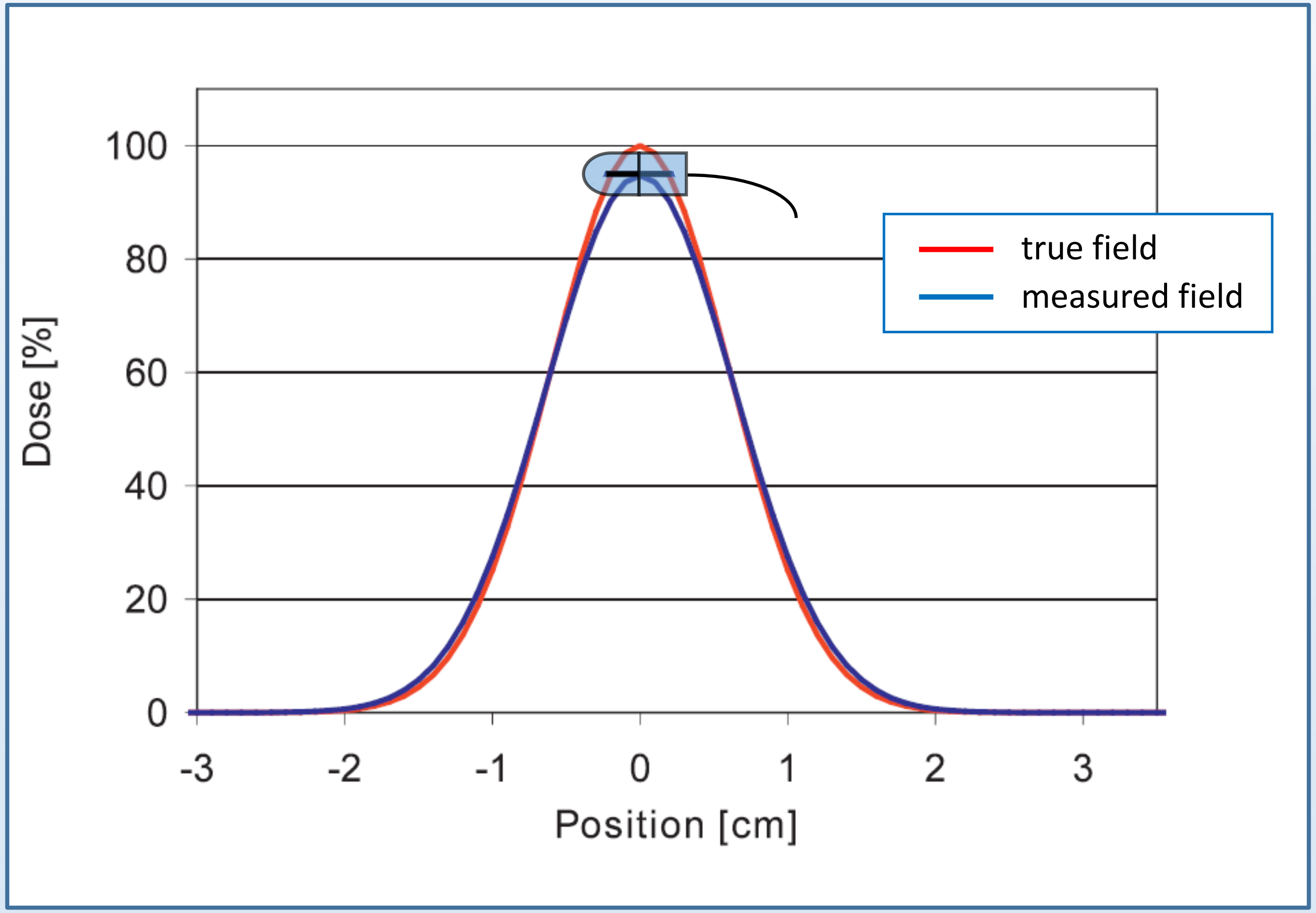
VOLUME AVERAGING EFFECT

⇓

- Dose underestimation when measuring output factors in small fields
- Broadening of the penumbra in beam profile measurements

!

3.2. Volume averaging



- The size of ionization chamber in 1.5 x 1.5 cm^2 photon field of approximately Gaussian shape.
- IC is too big for accurate measurements in that field
- Signal (collected charge) will be averaged across its sensitive volume → **volume averaging** → **lower dose**
- Blue curve is the result after averaging: **the CAX dose is underestimated, and the penumbra is broadened**

1. Background

2. Basic physics of small fields

3. TRS-483 CoP: concepts and formalism

4. Detector specific output correction factors

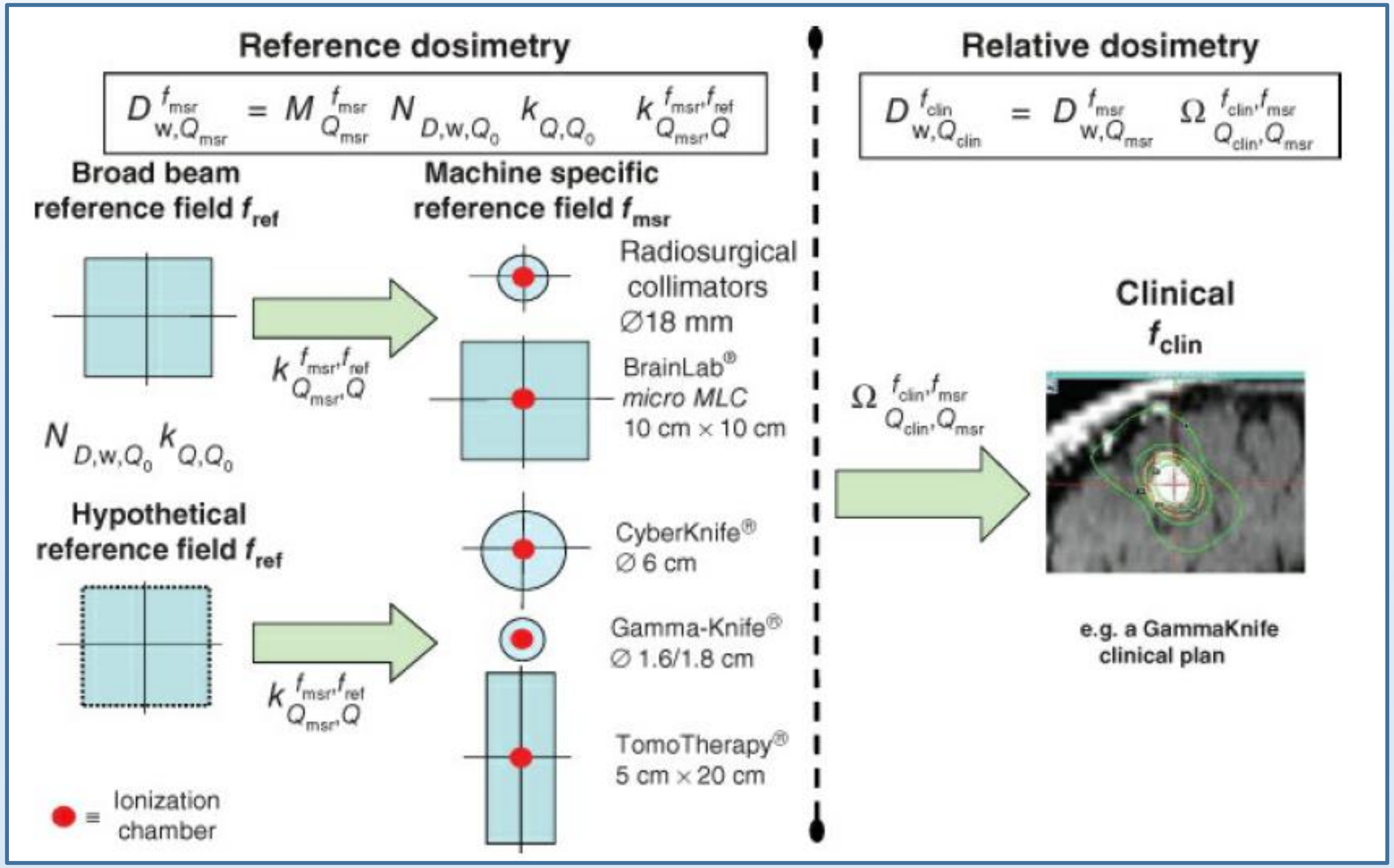
TRS-483 content

- The IAEA TRS-483 CoP (collaboration of IAEA and AAPM) provides **guidelines for reference and relative dosimetry in small static fields used in radiotherapy**.

- In addition to the recommendation on the characteristics of detectors suitable for reference and relative dosimetry, as well as on required measurement conditions, TRS-483 presents **a dosimetry formalism based on the work of Alfonso et al. (slightly modified).**

- In particular, TRS-483 provides the guidance for the determination of **field output factors** and **detector specific output correction factors** in small fields which were two key elements in our work.

TRS-483 formalism: Alfonso et al.



R. Alfonso, P. Andreo, R. Capote, M. S. Huq, W. Kilby, P. Kjall, T. R. Mackie, H. Palmans, K. Rosser, J. Seuntjens, W. Ullrich, and S. Vatnitsky. A new formalism for reference dosimetry of small and nonstandard fields. *Med. Phys.,*35:5179-5186, **2008.**

Concepts of small fields

- The field size is the **pair of dimensions** (in the case of rectangular fields) or the **diameter** (in the case of a circular field) that define(s) the area of the field at the measurement distance.

- Each dimension is defined by the **FWHM** of the lateral beam profile measured at a depth sufficient to eliminate the contribution of contamination electrons - depth of 10 cm in water with the detector's reference point at the isocentre is advised.

- It is advised to record the collimator settings as a **nominal** identification for practical purposes.

WHY?

- the treatment planning system (TPS) and the record and verify (R&V) system use the nominal field setting rather than the FWHM relative to which the profile data, patient treatment plan and radiation delivery are referenced. This guidance is analogous to that of stating the nominal accelerating potential (MV) to refer in practice to a beam with a certain quality index *Q*.

TRS-483 definitions for fields

The formalism for reference dosimetry in the TRS-483 is the same to that recommended by Alfonso et al.[8] with some minor modifications. Several important definitions for field sizes were introduced in the new formalism:

- $\boldsymbol{f_{ref}}$ – **conventional reference field 10 cm × 10 cm** used for calibrations at the standard laboratory and for clinical reference dosimetry for radiotherapy machines where such field can be established in reference conditions i.e., SAD = 100 cm and 10 cm depth

- $\boldsymbol{f_{msr}}$ – **machine specific reference field** for radiotherapy treatment units **where conventional reference field 10 cm × 10 cm cannot be established** e.g., GammaKnife, Tomotherapy, and CyberKnife. The ***msr*** field is usually the largest achievable field as close as possible to the size of the conventional reference field

- $\boldsymbol{f_{clin}}$ – **clinical small radiation field** at which we need to determine the absorbed dose to water

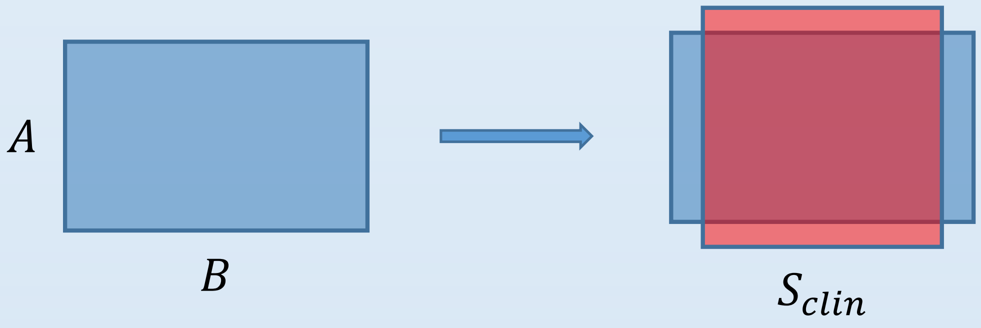
Equivalent square small field size - *rectangular*

For rectangular small fields with uneven in-plane and cross-plane dosimetric field widths defined as the FWHM, the **equivalent square small field size or clinical field size S_{clin}** (or also f_{clin}) s given as

$$\boxed{S_{clin} = \sqrt{A \cdot B}}$$

where A corresponds to the radiation field width (FWHM) in in-line direction y and B (FWHM) for cross-line direction x perpendicular to the former

Condition for the applicability of the equation for S_{clin} : $0.7 < A/B < 1.4$



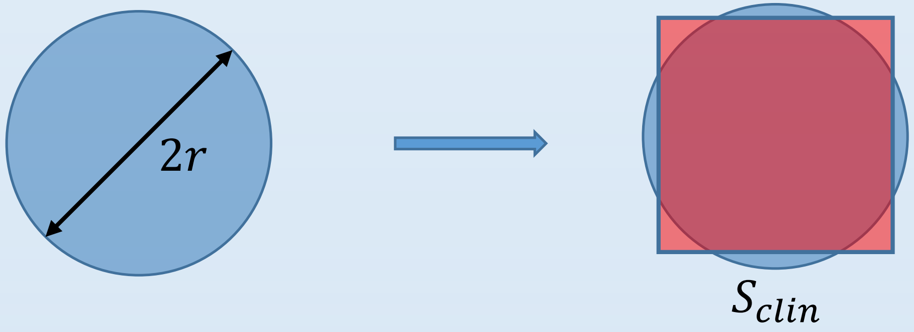
GEOMETRICAL EQUIVALENCY

Equivalent square small field size - *circular*

For **circular** small fields with dosimetric field widths defined as the FWHM, the **equivalent square small field size or clinical field size S_{clin}** is given as

$$\boxed{S_{clin} = r \cdot \sqrt{\pi} \approx 1.77 \cdot r}$$

where r to the radius of the circular field, defined by the points where, on average, the dose level amounts to 50% of the maximum dose at the measurement depth



GEOMETRICAL EQUIVALENCY

Detectors for relative dosimetry

- Assumption: a detector used for dosimetry in large fields will not perform well in small fields.
- Although the air filled ionization chamber is the most commonly used detector in relative dosimetry, there will always be a field size below which volume averaging becomes unacceptably high.
- Below certain field size only ion liquid chambers and solid state detectors are suitable for small field dosimetry. However, even those can exhibit substantial perturbations for the smallest fields.

Detectors for relative dosimetry:

- Air filled ionization chambers
- Liquid ionization chambers
- Silicon diodes
- Diamond detectors
- Plastic and organic scintillators
- Radiographic films
- Radiochromic films
- Thermoluminiscent dosimeters (TLD)
- ALANINE detectors
- ….

No single detector stands out as having characteristics close to the ideal ones!

Characteristics of detectors for relative dosimetry

TABLE 6. CHARACTERISTICS OF DETECTORS FOR RELATIVE DOSIMETRY IN SMALL FIELDS [12]

Detector properties	Guidance	Comments
Stability	Short term detector response is better than 0.1% for a total accumulated absorbed dose of many hundreds of kGy from multiple exposures.	Correction for instabilities over time can be made provided the effect is consistent and recalibration is not frequently required.
Dose linearity	Linearity is better than 0.1% over an absorbed dose range of at least three orders of magnitude (e.g. 0.01–10 Gy).	
Dose rate linearity	Clinical linear accelerators are typically operated at average dose rates of 0.1–0.4 Gy/s; detector is linear to better than 0.1% over the range of operation of the linac.	The range of dose rates is typical for WFF and FFF beams.
Dose per pulse linearity	A detector's response with changing dose per pulse remains stable to better than 0.1% after correction for ion recombination.	Typical dose per pulse operating conditions are 0.2–2.0 mGy per pulse.
Energy dependence of detector response	The useful energy range of the detectors for small field MV radiotherapy is from ^{60}Co to 10 MV.	An ideal detector is constructed to be energy independent with macroscopic interaction coefficients (μ_{en}/ρ for photons and S/ρ for electrons) having a constant ratio to those of water in the energy interval of interest.

TABLE 6. CHARACTERISTICS OF DETECTORS FOR RELATIVE DOSIMETRY IN SMALL FIELDS [12] (cont.)

Detector properties	Guidance	Comments
Spatial resolution	The choice of a suitable detector in terms of spatial resolution is usually based on a trade-off between a high signal to noise ratio and a small dosimeter size.	The requirement for spatial resolution is set by the gradients in the quantity to be measured.
Size of detector	The detector size is such that the volume averaging correction is not larger than 5%.	
Orientation	The response of a detector is ideally independent of the orientation of the detector with respect to the beam and the variation is less than 0.5% for angles of less than 60° between the beam axis and the detector axis.	Detectors do not, in general, have an isotropic response, and either a correction is required to account for the angular response or, more commonly, the beam incidence is fixed (i.e. irradiation from end or side) to minimize the effect.
Background signal	Any form of signal leakage that would contribute to increased background readings is at least three orders of magnitude lower than the detector response per Gy.	The zero dose reading of a detector will affect the low dose limit of the device and the signal to noise ratio.
Environmental factors	Correction over the full range of working conditions enables any influence to be reduced to better than 0.3%.	Measurements are ideally independent of temperature, atmospheric pressure and humidity changes or are corrected accurately for these influence quantities.

From TRS-483

Requirements for detectors

Detector choice for small field dosimetry can be made considering three main rules:

- The detector has a **small active volume** to minimize volume averaging effect. In the ideal case, the detector should sample the fluence at a point.
- The detector is **water equivalent**, i.e., it is constructed of materials which minimize perturbation effects.
- The detector has a **linear response which is energy independent** or with clearly known energy dependence

Detectors for measuring FOF

- There is no ideal detector for measurements of field output factors in small fields.
- The use of two or preferably three different types of suitable detectors is advised.
- A combination of detectors with correction factors above and below unity is advise, so that the product of these factors is close to one.
- TRS-483 recommends:

  - small air filled ionization chamber, radiochromic film and an unshielded diode

  or

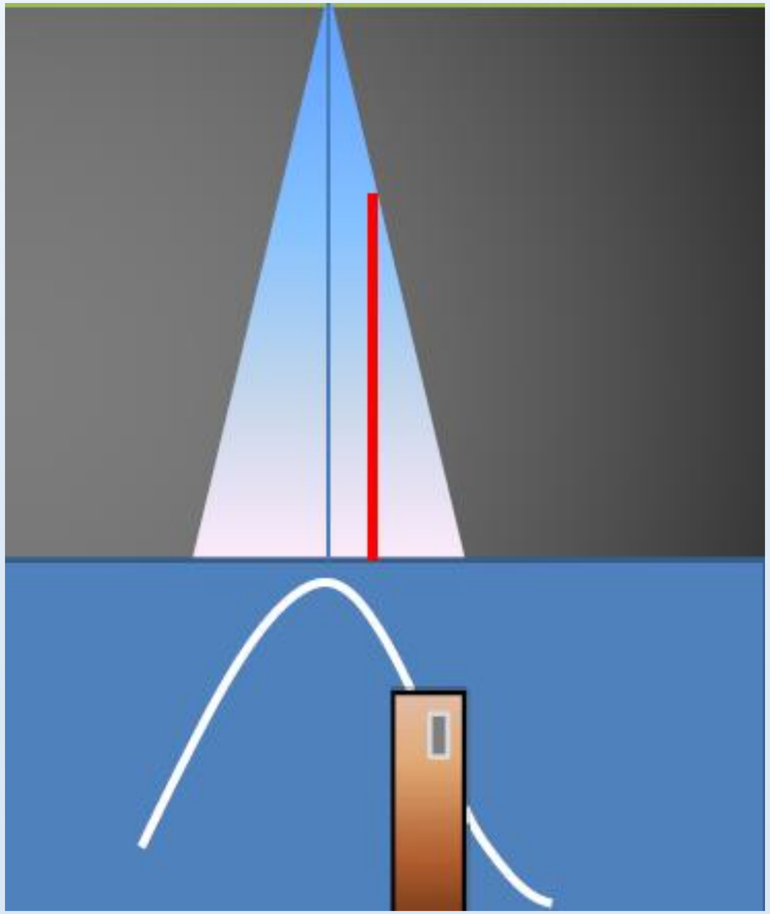
  - diamond detector, liquid ion chamber and an organic scintillator

Detector set-up

- QC on alignment of collimators.
- Accurate set-up of the detector in a 3D full scatter water phantom is required (for waterproof detectors).
- Detector orientation with respect to the beam axis (main axis perpendicular or parallel to the beam axis).
- Placement of the detector's reference point at the reference depth.
- Detector alignment with beam central axis.
- Set-up of SSD or SAD

  - the measurement of FOF and lateral beam profiles is performed at the same SSD or SAD as was used for reference dosimetry

Lateral alignment of detector with central axis of the beam



- For every setup crossline and inline scans (profiles) have to be acquired. ODI and lasers are not accurate enough.
- "True" centre of radiation field is determined on beam axis as a midpoint between two 50% signal values (FWHM).
- Even small misalignment of the detector can result in substantial changes of the absorbed dose to water at the centre of the field, leading to the underestimation of the profile maximum

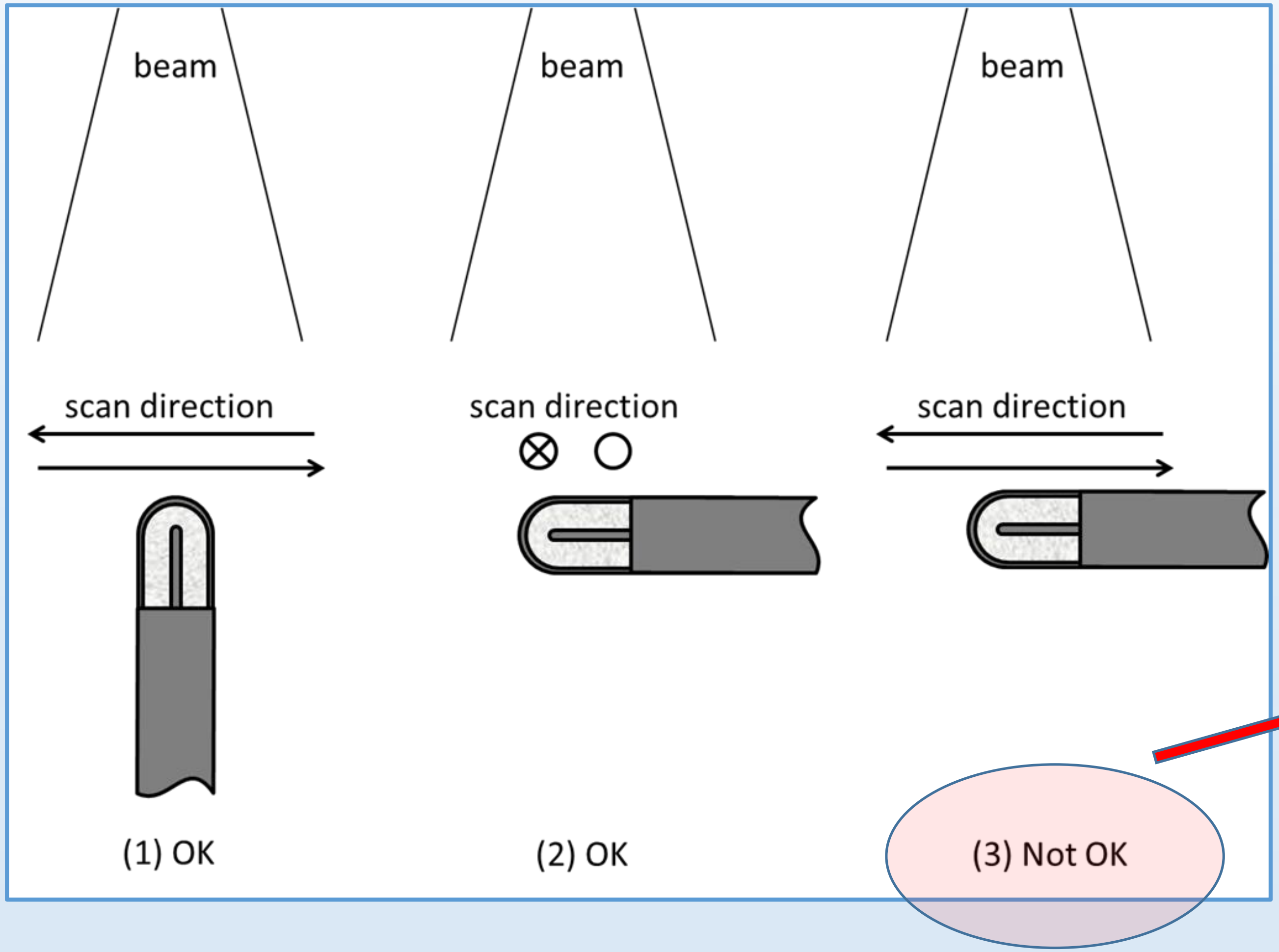
$$M_{eff}(x,y) < M_c \text{ (center: } x=0, y=0)$$

Detector orientation – beam profiles and FOF

TABLE 22. DETECTOR ORIENTATION, WITH RESPECT TO THE BEAM CENTRAL AXIS, FOR RELATIVE DOSIMETRY IN SMALL PHOTON FIELDS

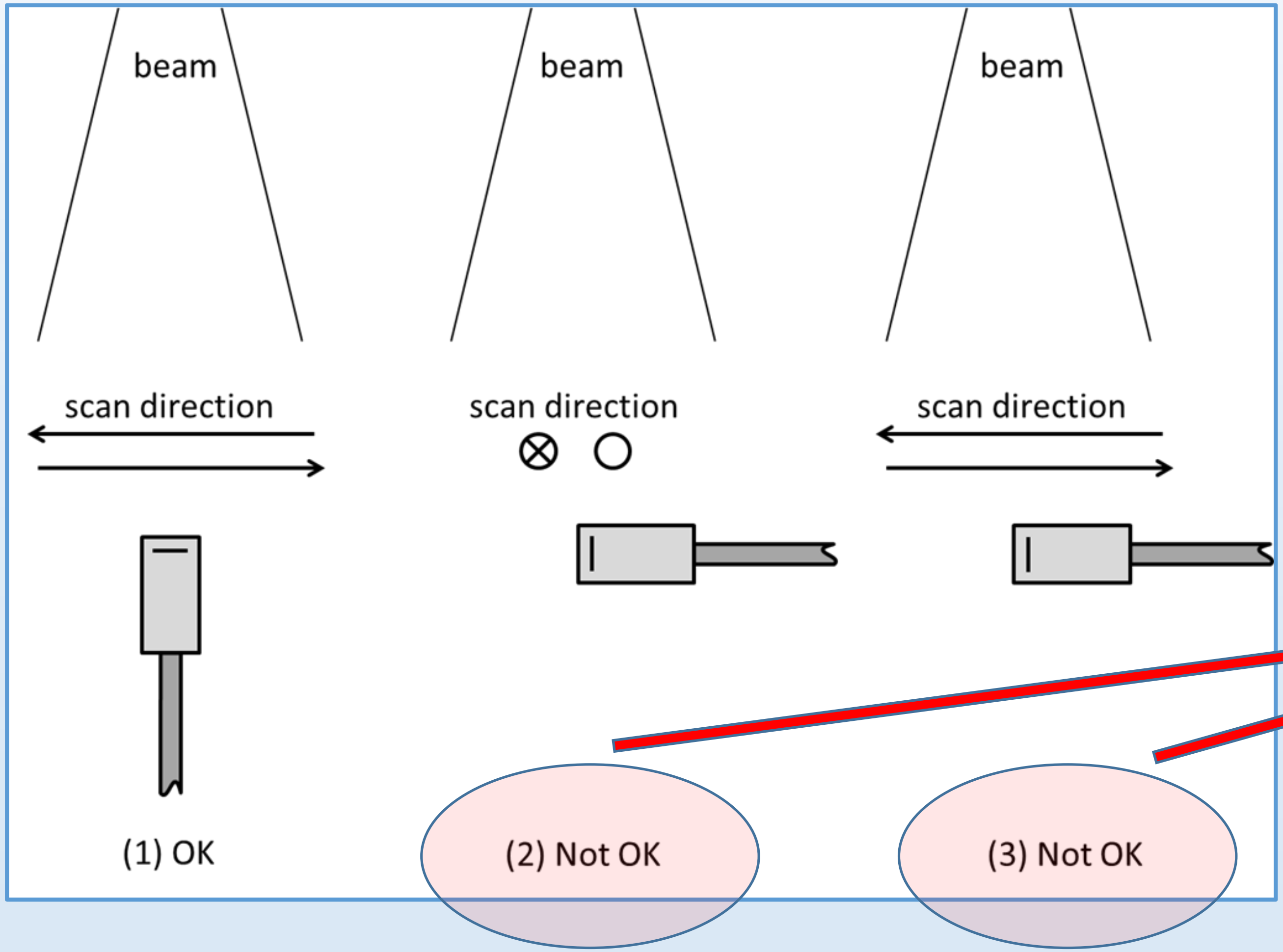
Detector type	Detector's geometrical reference	Lateral beam profiles	Field output factors
Cylindrical micro ion chamber	Axis	Parallel or perpendicular	Perpendicular
Liquid ion chamber	Axis	Perpendicular	Parallel
Silicon shielded diode	Axis	Parallel	Parallel
Silicon unshielded diode	Axis	Parallel	Parallel
Diamond detector	Axis	Parallel	Parallel
Radiochromic film	Film surface	Perpendicular	Perpendicular

Detector orientation for lateral beam profiles



Thimble (cylindrical) ionization chambers

Detector orientation for lateral beam profiles



Solid state detectors (diodes, diamonds)

TRS-483 formalism

Relative dosimetry of large fields (TRS-398 and TG 51): **output factors OF (RDF)**

$$OF = \frac{D_{w,Q_{clin}}^{f_{clin}}}{D_{w,Q_{ref}}^{f_{ref}}} \approx \frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{ref}}^{f_{ref}}}$$

Relative dosimetry of small fields (TRS-483): **Field Output Factors $\Omega_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}}$**

$$\Omega_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}} = \frac{D_{w,Q_{clin}}^{f_{clin}}}{D_{w,Q_{ref}}^{f_{ref}}} \neq \frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{ref}}^{f_{ref}}} \xrightarrow{k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}}} \Omega_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}} = \frac{D_{w,Q_{clin}}^{f_{clin}}}{D_{w,Q_{ref}}^{f_{ref}}} = \frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{ref}}^{f_{ref}}} \cdot k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}}$$

Necessary introduction of ***detector specific field output correction factor*** $k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}}$, which converts detector readings ratio into a true dose ratio.

1. Background

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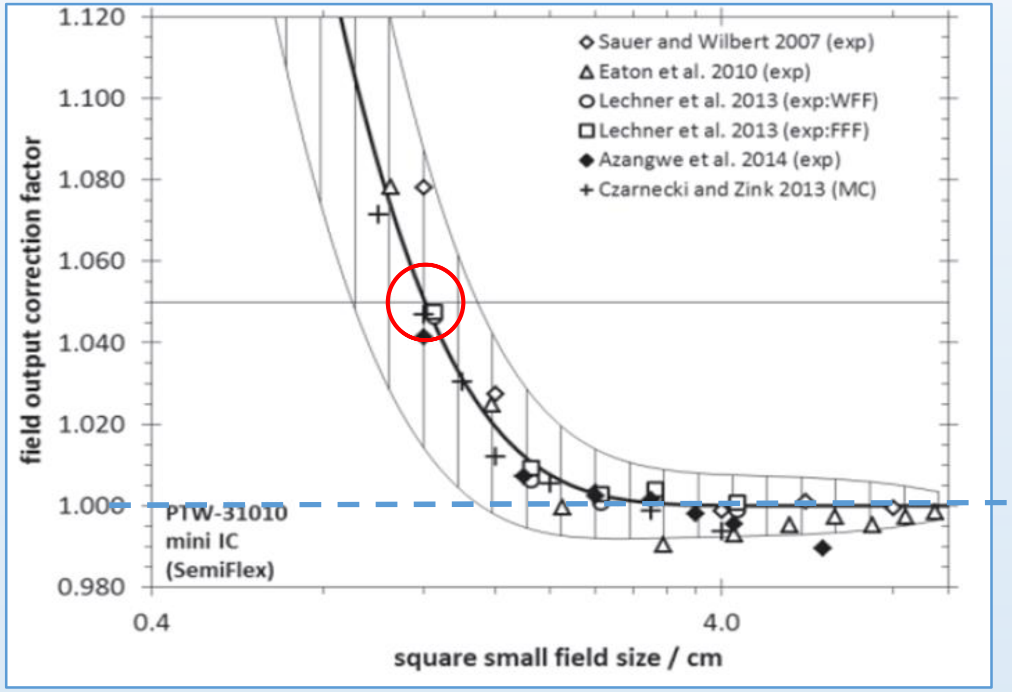
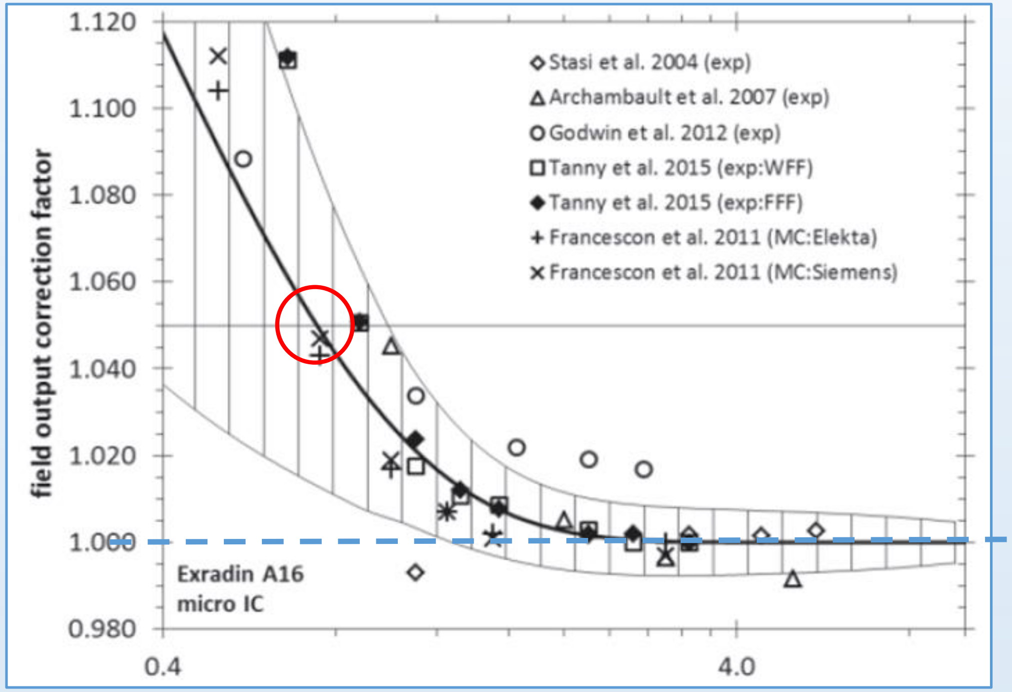
$k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}}$ data for ionization chambers





Under-response for very small fields

$$\boxed{k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}} > 1}$$

ALWAYS!

6 MV LINAC

LINAC

Under-response for very small fields

$$\boxed{k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}} > 1}$$

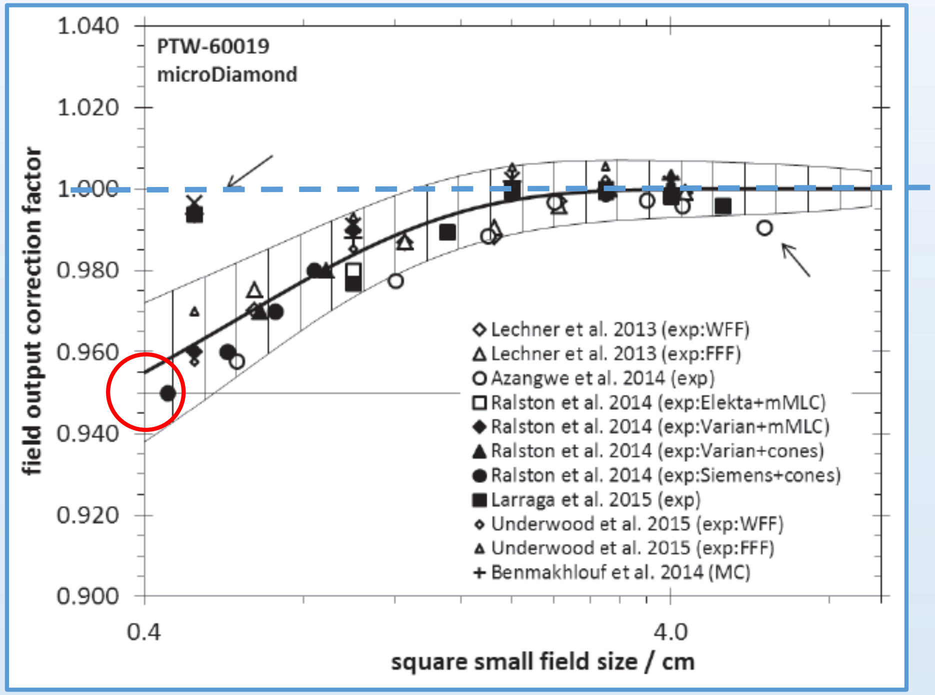
ALWAYS!

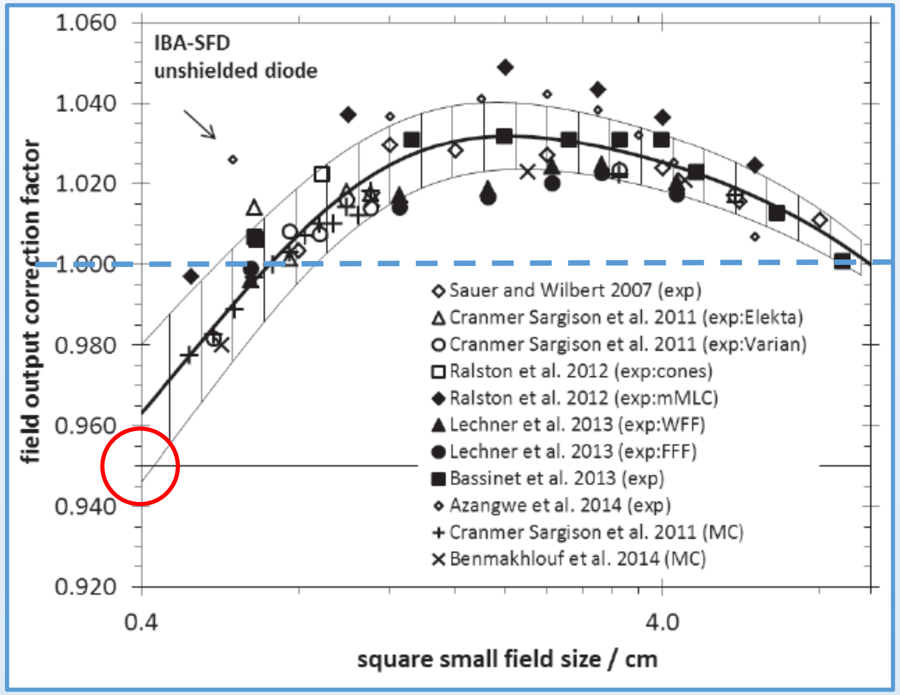
$k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}}$ data for ionization chambers

TABLE 27. FIELD OUTPUT CORRECTION FACTORS $k_{Q_{\text{clin}},Q_{\text{msr}}}^{f_{\text{clin}},f_{\text{msr}}}$ FOR SMALL FIELDS COLLIMATED BY AN MLC OR SRS CONE AT 10 MV WFF AND FFF MACHINES, AS A FUNCTION OF THE EQUIVALENT SQUARE FIELD SIZE

Detector	Equivalent square field size, S_{clin} (cm)												
	8.0	6.0	4.0	3.0	2.5	2.0	1.5	1.2	1.0	0.8	0.6	0.5	0.4
Ionization chambers													
Exradin A14SL micro Shonka slimline	1.000	1.000	1.000	1.000	1.000	1.002	1.010	1.027	—	—	—	—	—
Exradin A16 micro	1.000	1.000	1.000	1.000	1.001	1.003	1.008	1.017	1.027	1.043	—	—	—
IBA/Wellhöfer CC01	1.001	1.003	1.004	1.005	1.005	1.006	1.007	1.009	1.014	1.023	1.043	—	—
IBA/Wellhöfer CC04	1.000	1.000	1.000	1.000	1.000	1.002	1.009	1.022	1.041	—	—	—	—
IBA/Wellhöfer CC13/IC10/IC15	1.000	1.000	1.000	1.001	1.002	1.009	1.030	—	—	—	—	—	—
PTW 31002 Flexible	1.000	1.000	1.001	1.004	1.009	1.023	—	—	—	—	—	—	—
PTW 31010 Semiflex	1.000	1.000	1.000	1.001	1.002	1.008	1.025	—	—	—	—	—	—
PTW 31014 PinPoint	1.000	1.000	1.000	1.002	1.004	1.009	1.023	1.041	—	—	—	—	—
PTW 31016 PinPoint 3D	1.000	1.000	1.000	1.001	1.001	1.004	1.013	1.025	1.039	—	—	—	—

$k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}}$ data for solid state detectors





Over-response for very small fields

$$\boxed{k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}} < 1}$$

ALWAYS!

6 MV BEAM LINAC

Over-response for very small fields

$$\boxed{k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}} < 1}$$

NOT ALWAYS!

$k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}}$ data for solid state detectors

TABLE 26. FIELD OUTPUT CORRECTION FACTORS $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ FOR FIELDS COLLIMATED BY AN MLC OR SRS CONE AT 6 MV WFF AND FFF MACHINES, AS A FUNCTION OF THE EQUIVALENT SQUARE FIELD SIZE (cont.)

Detector	Equivalent square field size, S_{clin} (cm)												
	8.0	6.0	4.0	3.0	2.5	2.0	1.5	1.2	1.0	0.8	0.6	0.5	0.4
Real time solid state dosimeters													
IBA PFD3G shielded diode	1.000	1.000	0.998	0.995	0.992	0.986	0.976	0.968	0.961	0.952	—	—	—
IBA EFD3G unshielded diode	1.005	1.009	1.014	1.016	1.016	1.015	1.012	1.008	1.004	0.998	0.988	0.983	0.976
IBA SFD unshielded diode (stereotactic)	1.008	1.017	1.025	1.029	1.031	1.032	1.030	1.025	1.018	1.007	0.990	0.978	0.963
PTW 60008 shielded diode	1.000	1.000	1.000	0.998	0.995	0.990	0.977	0.962	—	—	—	—	—
PTW 60012 unshielded diode	1.005	1.010	1.015	1.017	1.017	1.016	1.010	1.003	0.996	0.985	0.970	0.960	—
PTW 60016 shielded diode	1.000	1.000	0.999	0.995	0.991	0.984	0.970	0.956	—	—	—	—	—
PTW 60017 unshielded diode	1.004	1.007	1.010	1.011	1.011	1.008	1.002	0.994	0.986	0.976	0.961	0.952	—
PTW 60018 unshielded diode (stereotactic)	1.004	1.007	1.010	1.011	1.009	1.006	0.998	0.990	0.983	0.973	0.960	0.952	—
PTW 60003 natural diamond	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.001	1.003	1.009	1.026	1.045	—
PTW 60019 CVD diamond	1.000	1.000	1.000	1.000	0.999	0.997	0.993	0.989	0.984	0.977	0.968	0.962	0.955

For further reading …

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TG 155 Scientific report AAPM (interesting because of recommendations …)

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THANK YOU
aščitene z avtorskimi pravicami.