Small photon field dosimetry

Introduction to hospital exercise

M. Severgnini

Dr. Mara Severgnini
Department of Medical Physics of Trieste Hospital
mara.severgnini@asuits.sanita.fvg.it

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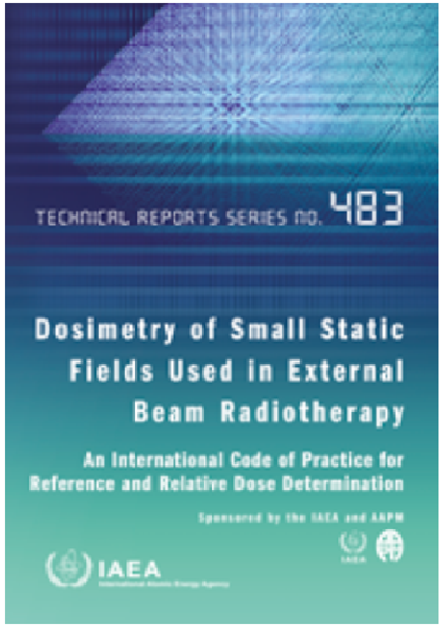
What is small field?

3 physical conditions determine if an external photon beam can be designated small (IAEA-AAPM CoP) :

1. There is a **loss of lateral charged particle equilibrium**

2. There is **partial occlusion** of the primary photon source by the collimating devices

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



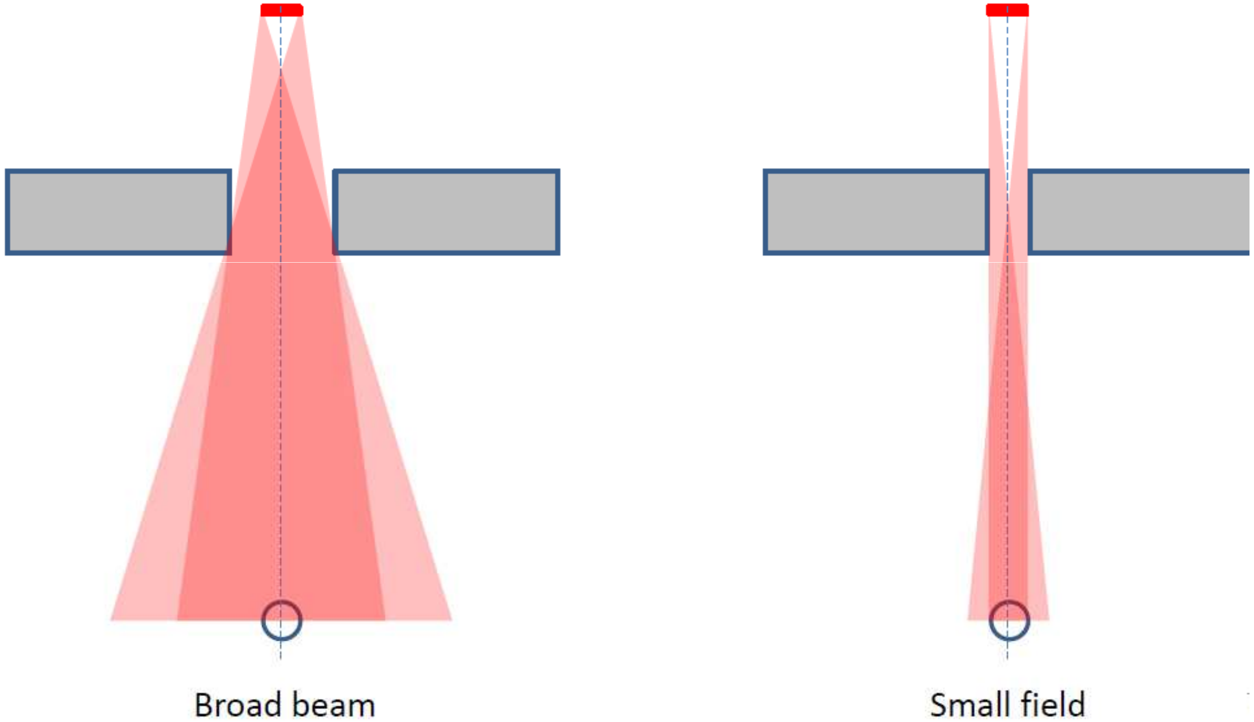
1. Loss of lateral charged particle equilibrium

Beam radius to achieve complete lateral electron equilibrium in water: measure of the range of laterally scattered electrons

Beam	TPR_{10}^{20}	$\%dd(10)_x$	$r_{LEE}(g/cm^2)$
^{60}Co		57.8	0.6
6 MV	0.670	66.2	1.3
10 MV	0.732	73.5	1.7
15 MV	0.765	77.9	1.9
24 MV	0.805	83.0	2.1

2. Partial source occlusion

Overlap of penumbra over the detector



2. Partial source occlusion

Small Field Dosimetry

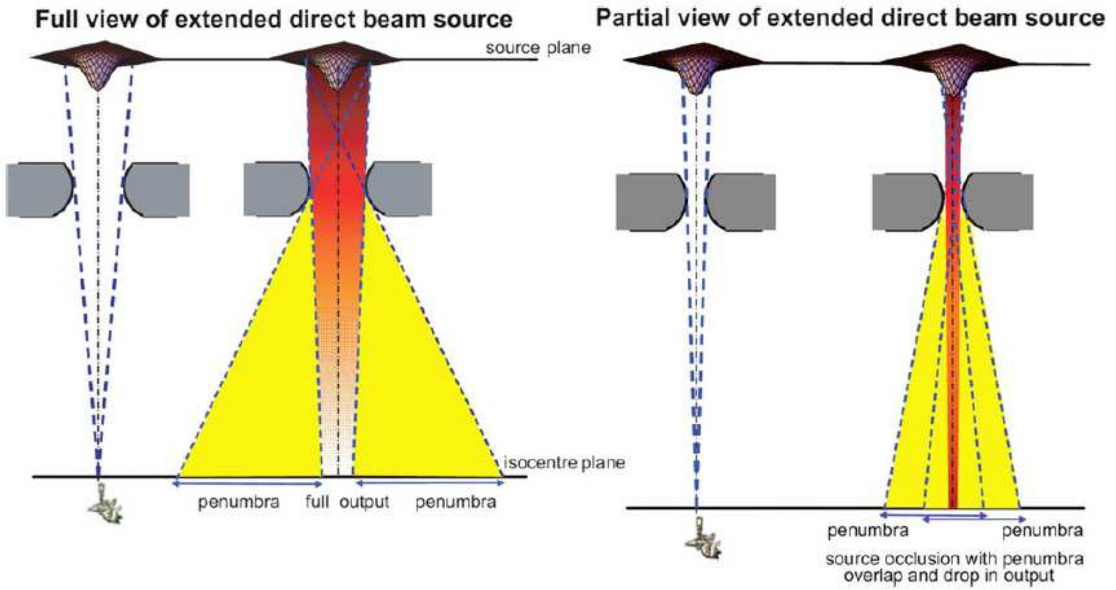
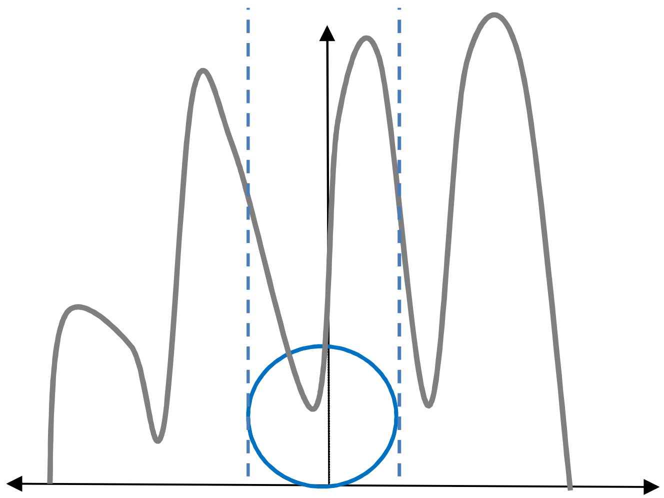


Figure 2.2. Schematic illustration of source occlusion. *Left*: the full, extended source can be "viewed" by an observer on the central axis. *Right*: only partial view of the source is possible by an observer on the central axis. (Adapted from IPEM Report 103 (Aspradakis *et al.* (2010).)

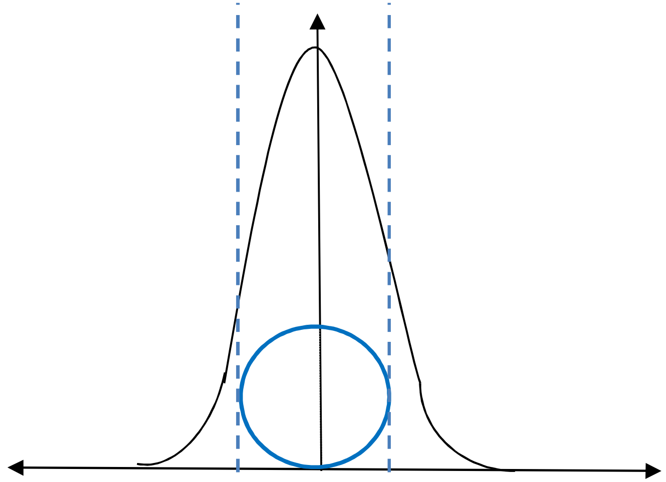
There will always be a size of a field (created by the collimators) below which part of the direct focal spot viewed from the measurement point is occluded by the collimators. This results in the direct photon penumbrae overlapping, with the consequence that the output is reduced when the field size further decreases.

3. Size of detector vs field size

- **Several perturbation effects** occur when modulation or dose gradients exist over the chamber volume
- The most obvious one is **volume averaging**



Detector volume



Detector volume

Why do small fields require correction factors?

There a 4 main effects related to the characteristics of the detector:

1. The **density** of the sensitive volume of the detector
2. The **atomic properties** of the sensitive volume
3. The presence of **extracameral components**
4. **Volume averaging**

4) Volume averaging

This effect can be described mathematically using the profile shape and detector geometry

$$D_V = \frac{1}{V} \iiint\limits_V D(\vec{r}) dV. \qquad \min_V \{D(\vec{r})\} \leq D_V \leq \max_V \{D(\vec{r})\}.$$

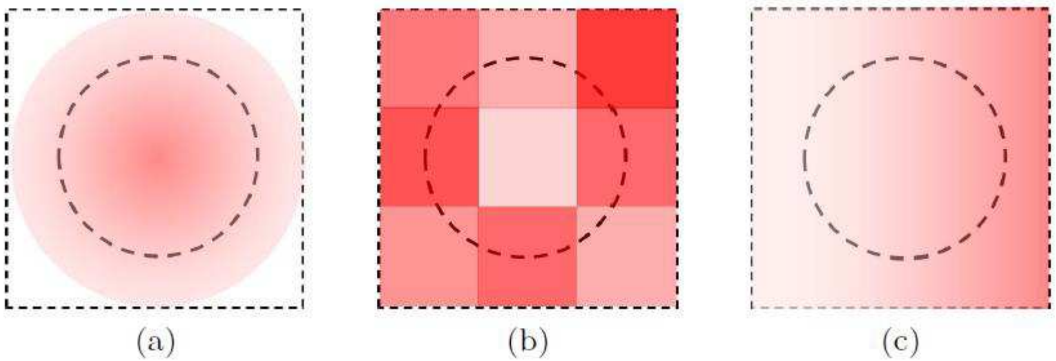
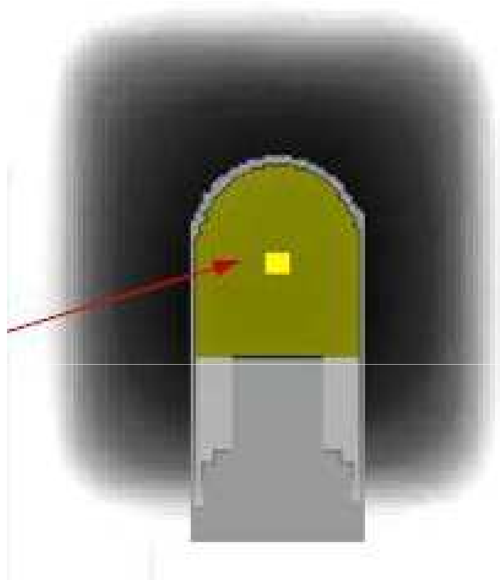


Fig. 4. Beam's-eye view illustrations of the lateral volume averaging effects in a pancake-like detector (sketched in a dashed line): (a) the maximum absorbed dose being at the point of measurement (the centroid of the pancake), (b) a modulated beam where absorbed dose of interest is smaller than the average absorbed dose over the detector cavity, and (c) a wedged beam with linear lateral fluence gradient.

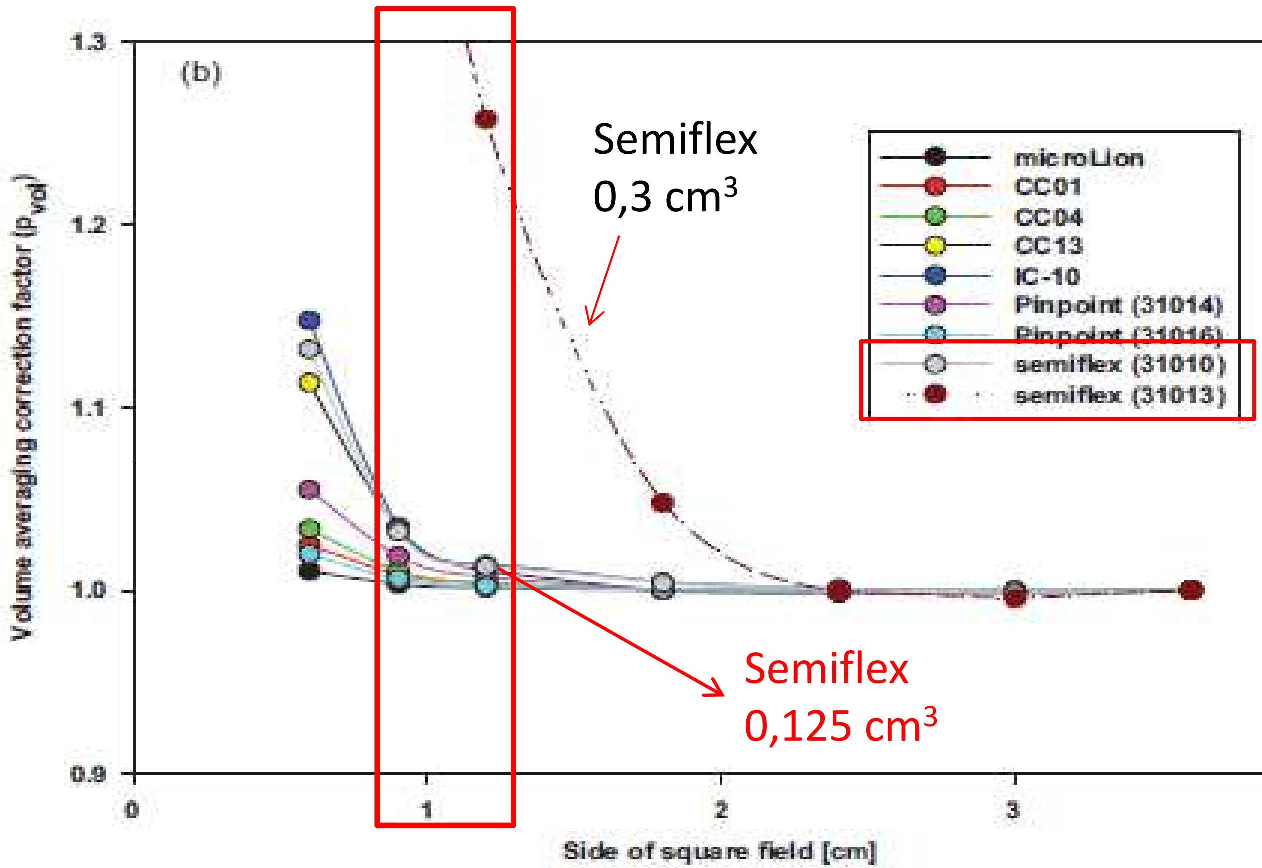
Bouchard et al.: Detector response in small beams. I. Theoretical concepts, Medical Physics, Vol. 42, No. 10, October 2015

Correction for volume averaging

The volume averaging correction factor can be defined as the ratio of the detector response in its central part to the detector response over its whole volume

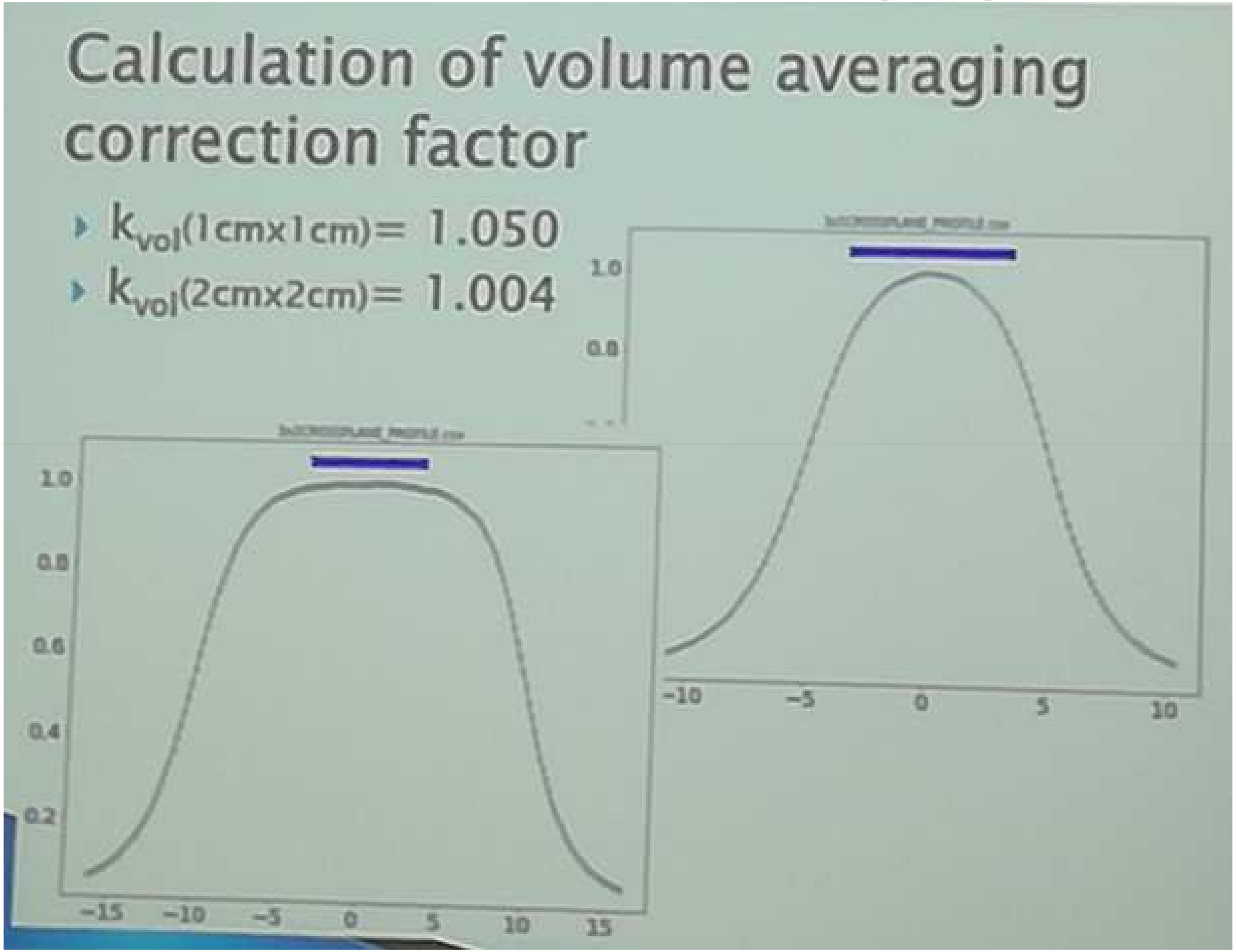


Correction for volume averaging



Azangwe et al., Detector specific correction factors for small radiotherapy fields, Med. Phys. 41 (2014) 072103-1

Correction for volume averaging- semiflex



Detector characteristic to consider in small field dosimetry

- **Spatial resolution** – output measurements & scans
- **Dimensions**
- Sensitivity – **signal/noise**
- **Density**
- Angular dependence
- **Energy dependence**
- Water-equivalence
- Dose linearity or known dose dependence

Detector characteristic to consider in small field dosimetry

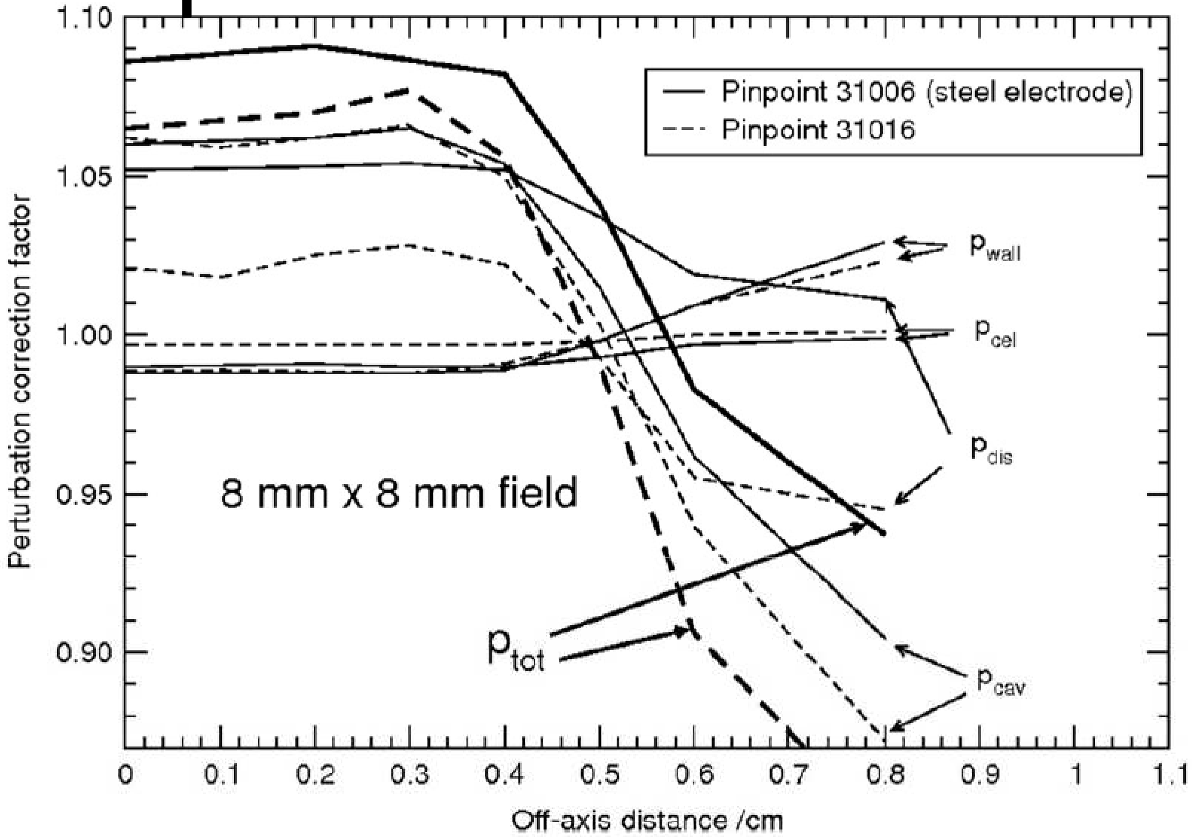
The **ideal detector** for measurement dosimetry would be a point detector that is energy indipendent and requires only a single calibration that is valid for all possible energies and irradiation scenarios

Ionization Chamber Detector Response in Small Fields

The component-independent perturbation effect of placing a cavity in a narrow beam can potentially be very large and vastly different from its value in broad field conditions.

Physically this is an expression of the fact that**, in narrow fields, large fluence perturbation effects as well as large gradient effects play a dominant role.**

Pinpoint pertubation in small Field



For hospital exercices Pinpoint 31014, 0.015 cm^3

Figure 2.8. Perturbation correction factors for PTW Pinpoint chamber types (31006 steel electrode, 31016 Al electrode) in a small 8 mm × 8 mm field. The outer diameter of the thimble of the 31006 and the 31016 chamber are 3.4 and 4.3 mm, respectively. The off-axis dimension is specified to the detector axis. The detector is scanning with its axis perpendicular to the axis of motion (optimal resolution). Individual components of perturbation correction factors, p_{wall}, p_{cel}, p_{dis}, p_{cav}, and p_{tot} are wall correction factor, central electrode correction factor, displacement correction factor, fluence perturbation correction factor and total perturbation correction factor, respectively. (Data from Crop *et al.* (2008).)

TABLE 3. SPECIFICATIONS FOR REFERENCE CLASS IONIZATION CHAMBERS FOR REFERENCE DOSIMETRY OF msr FIELDS, f_{msr} [107]

Parameter	Specification
Chamber settling	Monitoring chamber response with accumulated dose: equilibrium is reached in less than 5 minutes; the initial and equilibrium readings agree within 0.5%.
Leakage	Smaller than 0.1% of the chamber reading.
Polarity effect	Smaller than 0.4% of the chamber reading. The polarity energy dependence is less than 0.3% between ^{60}Co and 10 MV photons.
Recombination correction	1. The correction is linear with dose per pulse. 2. Initial recombination (the dose rate or dose per pulse independent part of the total charge recombination) is below 0.2% at polarizing voltages around 300 V. 3. For pulsed beams, a plot of $1/M_Q$ (charge reading) vs $1/V$ (polarizing voltage) is linear at least for practical values of V. 4. For continuous beams, a plot of $1/M_Q$ vs $1/V^2$ is linear, describing the effect of general recombination. The presence of initial recombination disturbs the linearity but this is normally a small effect, which may be neglected. 5. The difference in the initial recombination correction obtained with opposite polarities is less than 0.1%.
Chamber stability	Change in calibration coefficient over a typical recalibration period of 2 years below 0.3%. Same figure for long term (>5 y) stability.
Chamber material	Wall material not exhibiting temperature and humidity effects.

Note: Chamber types that potentially do not meet these criteria but have been proven to be suitable for reference dosimetry of the Gamma Knife are marked in Table 5.

Technical Repots series no. 483.
Dosimetry of Small Static Fields Used in External Beam radioterapy, IAEA

Solid state detectors Detector Response in Small Fields

Solid State detectors can be made small while remaining sufficiently sensitive. Their disavantages are energy dependence and dose-rate dependance.

Unshielded diode can be used to measure in field smaller than 3 cm x 3 cm througnh cross calibration against an air-filled ionization chamber at 3 cm x 3 cm and provide the appropriate correction factors are applied.

Table 2.2. Detector classes and types and their performance for small field dosimetry

Detector class	Detector type	Mechanism of detection and detection medium	Advantages	Disadvantages in small fields
1. Calorimeters				
	Water	Temperature rise in water	Dose at a point in water	Magnitude of signal and reproducibility, heat loss
	Graphite	Temperature rise in graphite	Reproducibility, electrical calibration	Dose conversion to water
2. Solid state detectors				
	TLD, OSLD	Ionization in LiF or aluminum oxide	Small size	High density, non-trivial protocol for processing
	Diode	Ionization in silicon	Small size, ease of use	Energy dependence, perturbations caused by the substrate
	MOSFET	Ionization in silicon	Small size	Energy dependence, perturbations caused by the substrate
	Diamond	Ionization in diamond	Small size, tissue equivalent	Dose rate dependence
3. Liquid detectors				
	Liquid ionization chamber	Ionization in liquid	Small collection volume, small perturbation correction factors, energy independent	Recombination effects (dose rate dependent), temperature dependence
4. Scintillating detectors				
	Scintillating fibers	Luminescence	Small detector, water equivalent, small perturbations	Cerenkov correction, LET dependence
5. Chemical detectors				
	Fricke dosimeter	Change in optical density due to change in Fe^{3+} concentration	Energy independent, high reproducibility	Low sensitivity, volume averaging, involved process, volume averaging
	Gel dosimeter	Change in light transmission or proton composition due to chemical reactions	3D dosimeter	Non-trivial protocol for processing, involved instrumentation, reproducibility for point type measurements
	Radiochromic film (EBT™, EBT2™, EBT3™)	Change in optical density due to chemical reactions	Nearly energy independent, density of detection material close to unity, high resolution, 2D dosimeter	Measurement protocol is involved; non-linear response, reproducibility for low doses is limited
	Alanine	Radicals resulting from chemical reactions	Nearly energy independent, density of detection material close to unity	Volume averaging, sensitivity

Journal of icru, ref N°4

Detector Response in Small Fields

3 criteria:

1) Sensitivity region of detector is Water equivalent
2) Density of the sensitive region and surrounding materials is the same as that of water
3) The size of the sentitive region can be made small compared to the field size.

<u>None of the detectors currently available are perfect for small field dosimetry.</u>

Detector that attempt to sullfill the 3 criteria:

- scintillation detectors,
- liquid ionization chamber,
- <u>single crystal diamond</u>

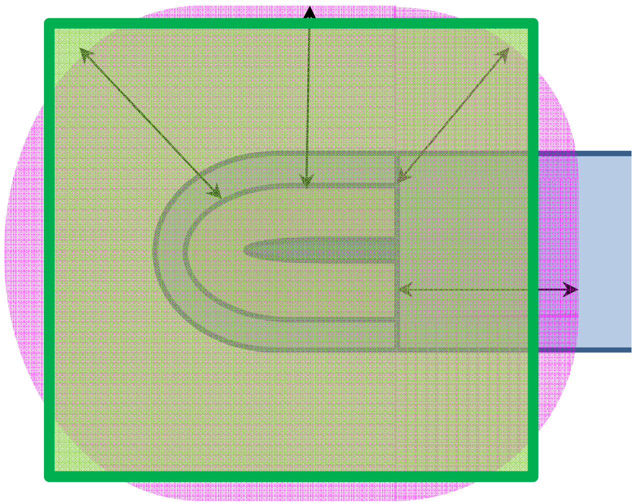
Detector related small field condition

Small field conditions exist when one of the edges of the sensitive volume of a detector is less then a lateral charged particle equilibrium range (r_{LCPE}) away from the edge of the field

$$r_{\mathrm{LCPE}}/cm = 8.360 \cdot \mathrm{TPR}_{20,10}(10) - 4.382$$

$$r_{\mathrm{LCPE}}/cm = 0.07797 \cdot \%dd(10{,}10)_{\mathrm{X}} - 4.112$$

IAEA TRS-483

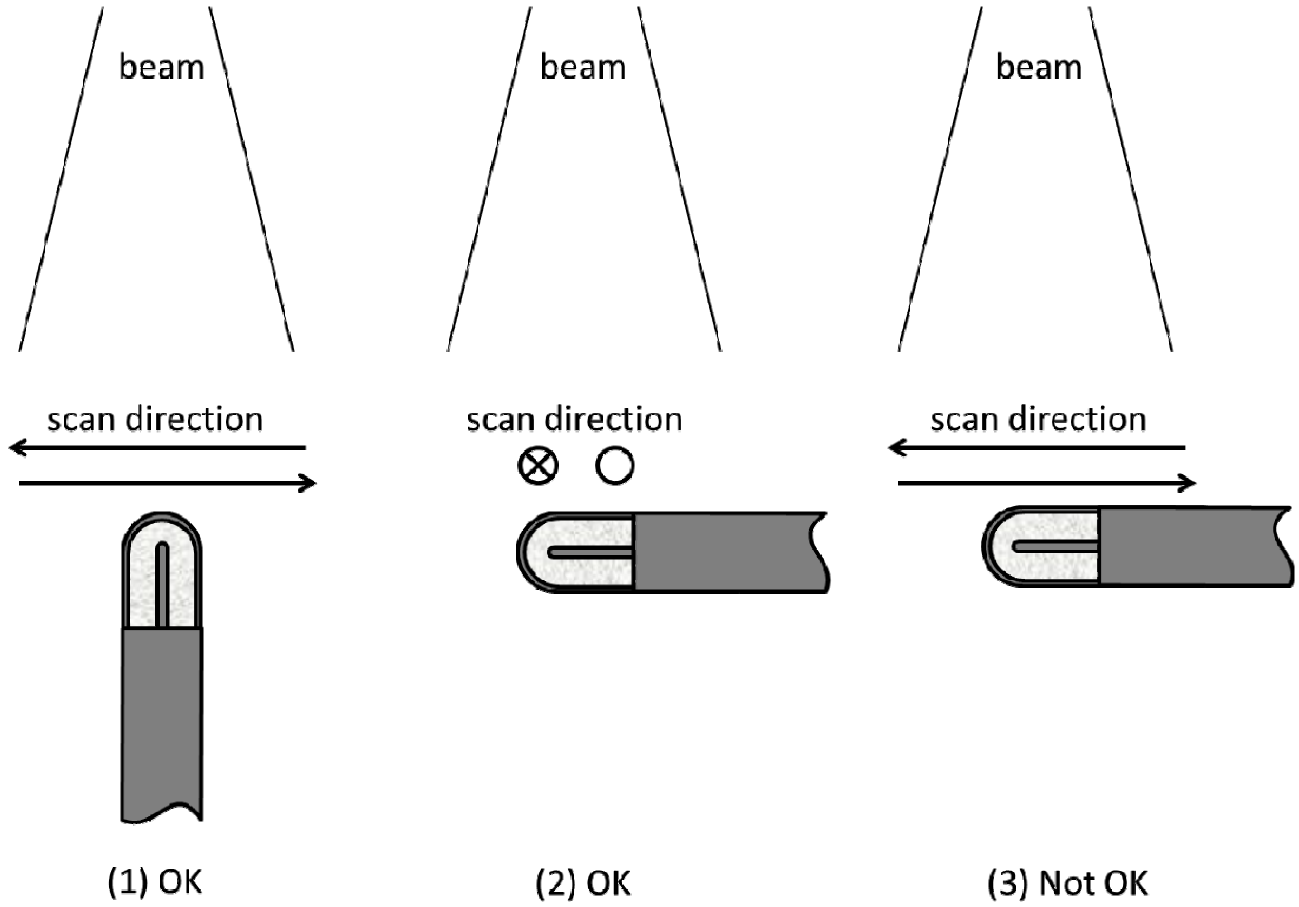


Detector orientation

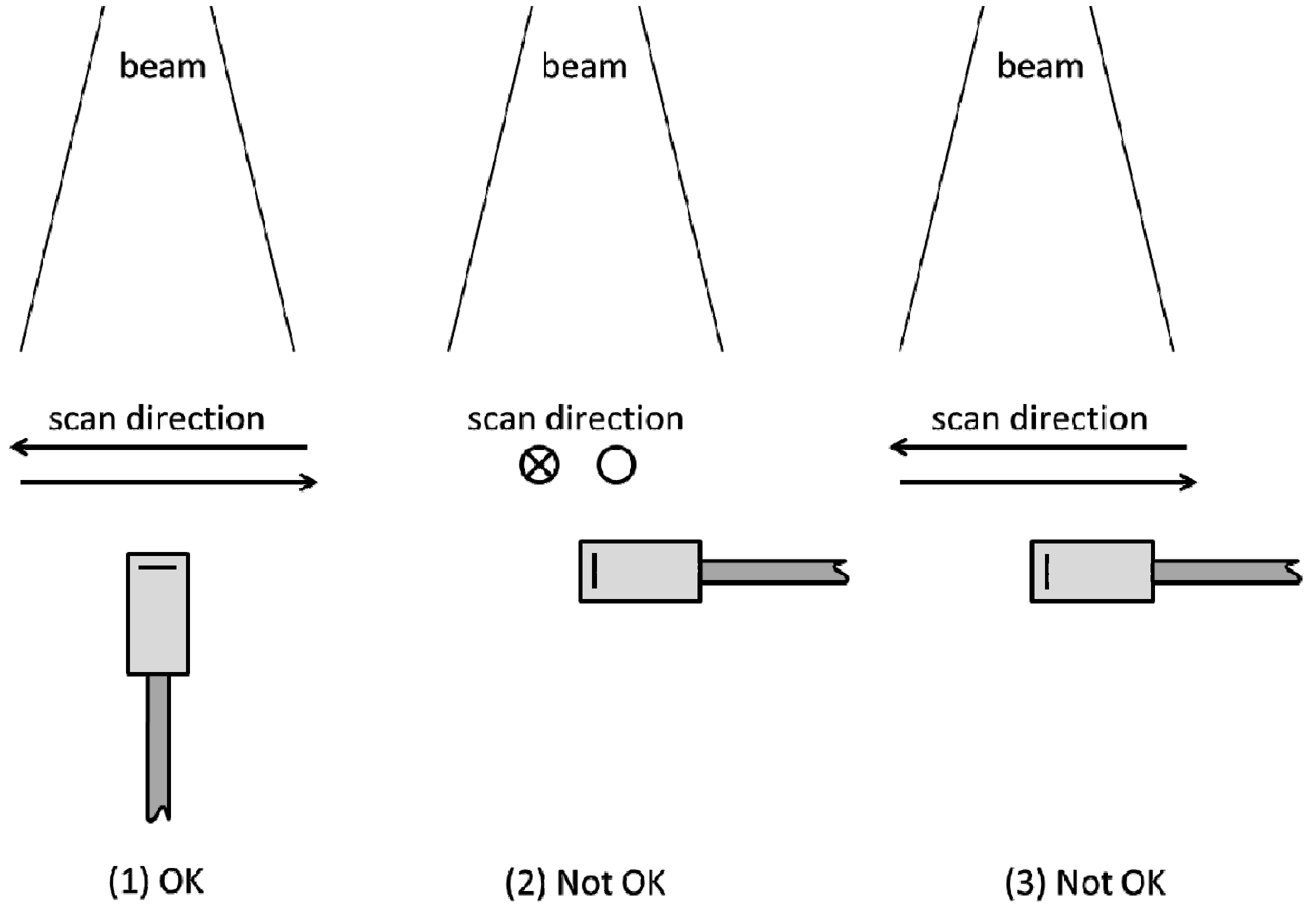
TABLE 22. DETECTOR ORIENTATION, WITH RESPECT TO THE BEAM CENTRAL AXIS, FOR RELATIVE DOSIMETRY IN SMALL PHOTON FIELDS

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 profiles



Detector orientation for lateral profiles



Lateral alignment with the central axis – real-time detectors

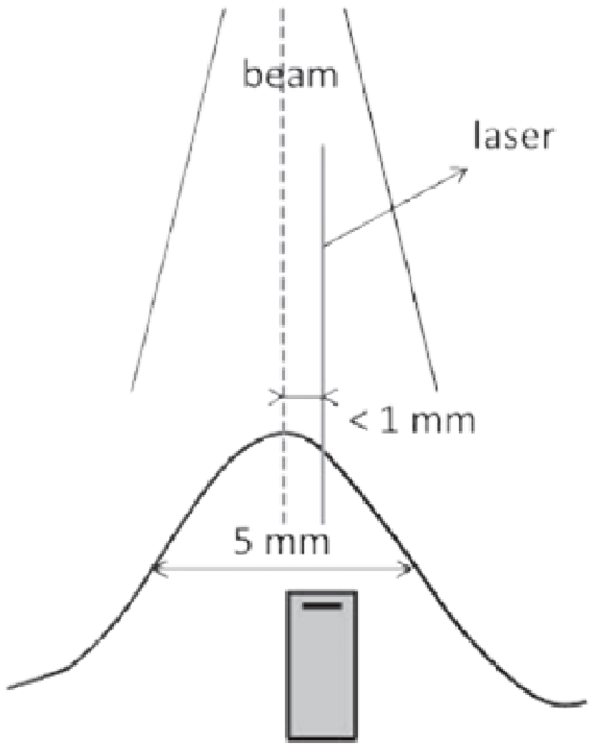


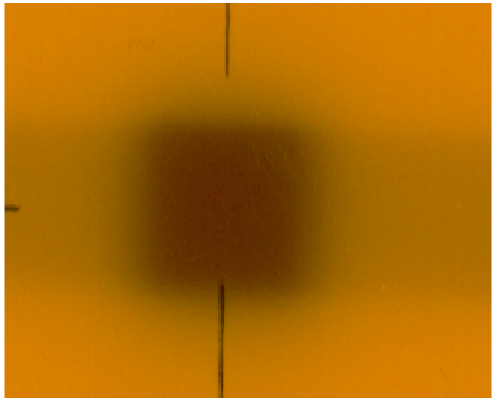
FIG. 16. Demonstration of the influence of clinical set-up accuracy: the beam laser (solid

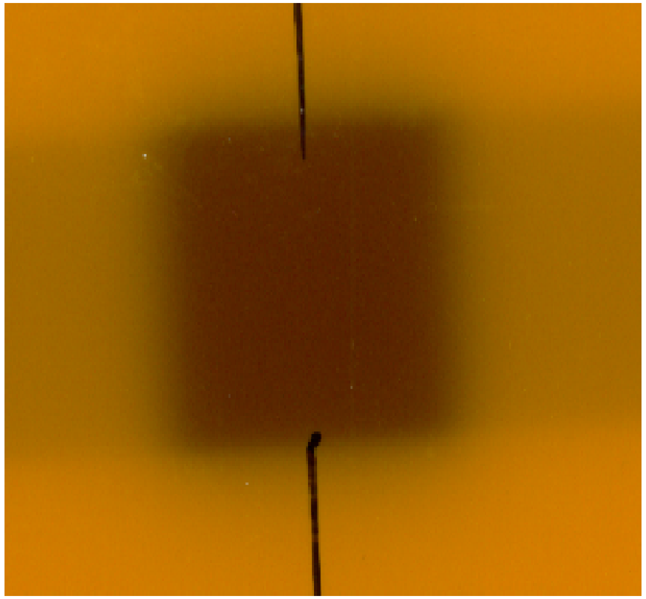
Field size , Collimator field size

Collimators are often not calibrated for small field sizes
(1 mm loss on each of 4 jaws for 1 cm x 1 cm is 40% of beam area)

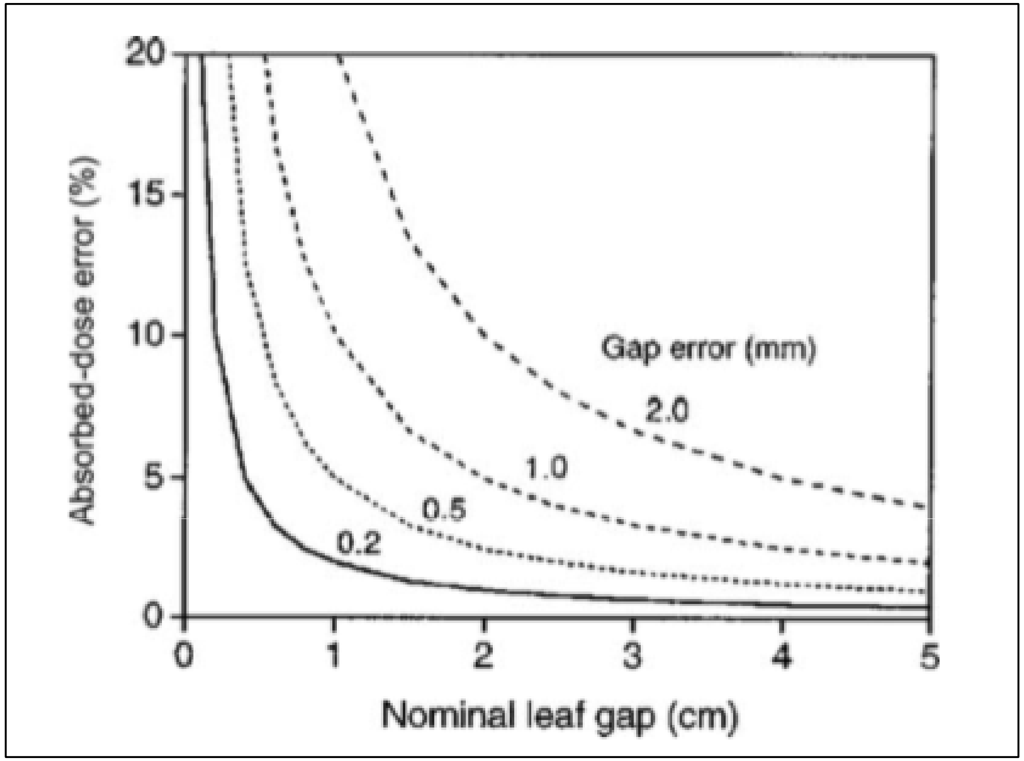
2 cm x 2 cm

1 cm x 1cm





Collimator field size



LEAF POSITION TOLERANCES USED IN CONVENTIONAL 3DCRT ARE NOT SUFFICIENTLY ACCURATE WHEN THE MLCs ARE USED FOR IMRT. ACCURACY FROM 1 mm TO 2 mm IN POSITIONING A LEAF TO PROVIDE BLOCKING, WHILE ADEQUATE FOR 3D-CRT, IS NOT SUFFICIENT WITH THE SMALL FIELDS EMPLOYED IN IMRT

FROM ICRU 83

OUTPUT FACTORS

measurement set-up

- Beam lasers are not always *exactly on central axis*

– Do in plane and crossplane-profile scan
– Set detector to maximum profile in either direction
– Repeat cross profile scan

- Set jaws to reflect clinical plans

OUTPUT FACTORS

Non-uniform fluence across the field, no LCPE

Volume averaging effects

- Any detector will average the dose over its volume.

- the dose in the centre of a small field is underestimated (important for output factors) and reference dosimetry, and the penumbra is washed out (important for profiles)

The volume averaging effect can lead to:

- **Dose underestimation** when measuring output factors in small fields
- **Blurring of the penumbra** in profile measurements
- The safest way to avoid the volume effect, is to choose a detector which is small enough.
- Another possibility is to partially correct the volume effect

OUTPUT FACTORS

Ideal detector for small field dosimetry :

- a uniform spectral response
- a high SNR
- very small.

  "the detector should be smaller than half the size of the region which could be considered 'acceptably' uniform, e.g. if a 3% variation was acceptable across the detector, determine the width of the profile at 97% of CAX and select a detector half that width"

Nyquist sampling theorem

OUTPUT FACTORS

- **Field sizes for output factor should be from FWHM**
- For small fields, **corrections from new CoP** should be used for different detectors to account for all factors (volume averaging, density, etc.)

Monte Carlo calculated output correction factors for diodes and ion chambers for small field

TABLE III. Monte Carlo calculated output correction factors, $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$, for small-field detectors at a reference depth in water of 10 cm (in the beam central axis) for the indicated square fields of a Varian Clinac iX 6 MV clinical accelerator. The values are normalized to a reference field $f_{msr} = 10 \times 10$ cm^2 and have a type-A uncertainty of 0.15% or smaller. The field sizes shown correspond to nominal sizes at the phantom surface. The terms parallel and perpendicular refer to the detector orientation with respect to the beam central axis.

Manufacturer	Model	Type	10×10 cm^2	4×4 cm^2	2×2 cm^2	1×1 cm^2	0.5×0.5 cm^2
PTW	T60016	Diode (photon/shielded)	1.000	0.998	0.996	0.956	0.910
PTW	T60017	Diode (electron/unshielded)	1.000	1.014	1.016	0.992	0.949
PTW	T31016	Ionization chamber Pinpoint 3D) parallel	1.000	1.004	1.003	1.001	1.102
PTW	T31016	Ionization chamber Pinpoint 3D) perpendicular	1.000	1.001	1.000	1.010	1.147
PTW	T31018	Micro liquid ionization chamber (LIC)	1.000	1.003	1.003	0.992	1.011
PTW	T60003	Diamond detector	1.000	1.005	1.008	0.997	1.002
IBA	PFD	Diode (photon/shielded)	1.000	0.991	0.983	0.951	0.947
IBA	EFD	Diode (electron/unshielded)	1.000	1.015	1.021	1.002	0.991
IBA	SFD	Diode (stereotactic/unshielded)	1.000	1.021	1.023	1.016	0.980
IBA	CC01	Ionization chamber (stereotactic/IMRT) parallel	1.000	1.000	1.002	1.003	1.050
IBA	CC01	Ionization chamber (stereotactic/IMRT) perpendicular	1.000	1.000	1.000	0.996	1.081

Benmaklouf et al., Med. Phys. 41 (2014) 041711

OUTPUT FACTORS

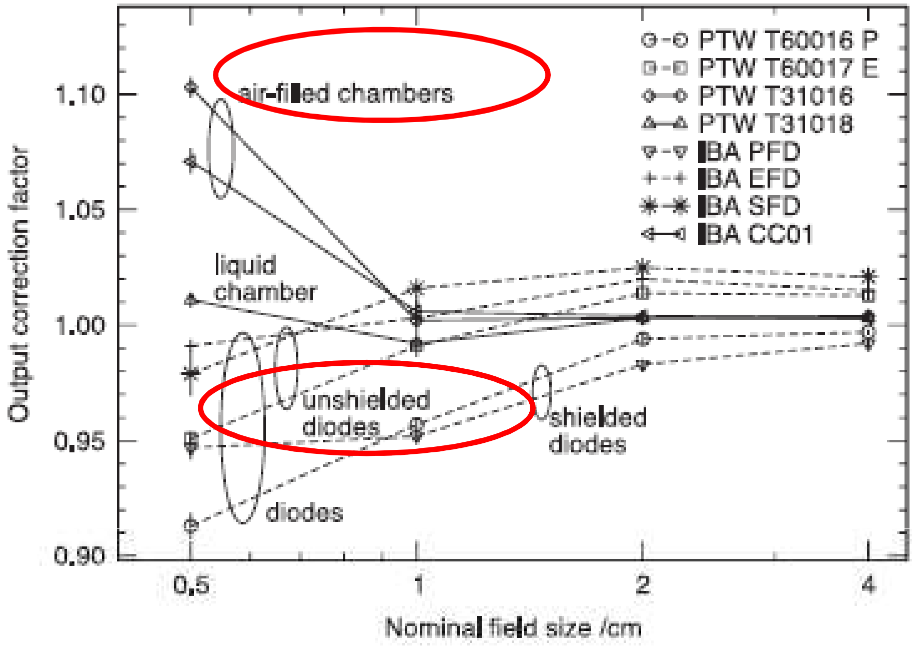


Figure 2.10. Output correction factors, $k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$, for eight detector types in small fields from the Varian IX series for 5 mm, 1, 2, and 4 cm field openings normalized to a 10 × 10 cm^2 field size. Three types of detectors are involved: air-filled ionization chambers (PTW T31016, IBA CC01), liquid ionization chamber (PTW T31018), and diodes (PTW T60016, PTW T60017; IBA PFD, IBA EFD, IBA SFD). The diode data is shown in two classes (*unshielded*: under-response in intermediate field sizes 2–4 cm and over-response in small fields; *shielded*: over-response in fields 4 cm and smaller). The field size is specified as the nominal side of a square field. The data is an average of several studies Monte Carlo and measurements. (Benmakhlouf *et al.*, 2014) and references therein.

OUTPUT FACTORS

Output correction factors must be reported as a function of FWHM of the small field profile at the point of measurement and FWHM in both in- and cross-plane directions (i.e., FWHMx and FWHMy) are, in general, not identical.

- The IAEA-AAPM (IAEA-AAPM, 2017) code of practice defines the small field equivalent field size s as the geometric mean of FWHMx and FWHMy, i.e., .

$$\breve{s} = \sqrt{\mathrm{FWHM}_x \cdot \mathrm{FWHM}_y}$$

OUTPUT FACTORS

A user in the clinic should compare output factor using two or more distinct detectors, appropriately corrected using correction factors.

Obtaining consistency in the determination of output factors and absorbed dose by using different detectors, after accounting for their corrections , is the best approach to ensuring accurancy in the measurements of small fields.

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OUTPUT FACTORS

Choice of detector

- Dose measurements in a 4 cm × 4 cm field shall be made **with a cylindrical vented ionization chamber** that was calibrated in a 60Co beam.
- Dose measurements at field sizes s ≤ 4 cm × 4 cm shall be made with detectors featuring a high spatial resolution such as **small-size ionization chambers**, **silicon diodes** or diamond detectors. “small field detectors”
- New IAEA CoP

OUTPUT FACTORS

Detector positioning

- For **cylindrical ionization chambers** the effective point of measurement is defined as a point shifted by 0.5*r from the axis of the chamber towards the focus (r is the inner radius of the measuring chamber volume).*

- The location of the effective point of measurement of **solid state detectors** can be taken from the data sheet of the detector.

Radiation quality

kQ varies with Field Size and Depth

A beam quality specifier is, ideally, a unique measurable surrogate for a beam energy fluence spectrum , such that a calibration coeffiecient for a detector can be accurately specified.

For heavily filtered photon beam, as used in conventional radiation therapy beams (WFF) $TPR_{20,10}$ or %dd(10) are well correlated with the water-to-air mass collision stopping-power ratio Sw,air.

MC simulations suggest that the influence of field size on Sw,air is limited to 0.3-0.5% at the refence depth of 5 cm in a 6 MV photon beam from 10 cm x 10 cm reference fields down to 0.3 cm x 0.3 cm.

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kQ varies with Field Size and Depth kQ

Small fields are therefore well-specified by beam quality specifiers meaured in larger fields and no separate measurement of a dedicated “small field beam quality specifier” is needed

When is not possile to use refence field a mashine specific reference field should be used:

$$TPR_{20,10}(10) = \frac{TPR_{20,10}(s) + 0.01615 *(10-s)}{1 + 0.01615 * (10-s)}$$

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Determination of field output factors

Reference conditions

Usually a depth of 5-**10 cm** in order to avoid electron containation from the treatment head

Equivalent field size

Field output factor

Definition

Intermediate field method

Uncertainties of field output factor correction factors

TABLE 37. RELATIVE STANDARD UNCERTAINTIES OF THE FIELD OUTPUT CORRECTION FACTORS IN TABLE 26

Square small field size S/cm	Unshielded diodes and PTW 60019 microDiamond (%)	Shielded diodes (%)	Mini IC (%)	Micro IC (%)	PTW 60003 natural diamond (%)	PTW 31018 liquid ion chamber (%)
0.4	0.9	—	—	—	2.9	2.2
0.5	0.8	—	—	3.2	2.2	1.7
0.6	0.7	1.3	—	2.5	1.7	1.4
0.8	0.6	0.9	3.4	1.6	1.1	1.0
1.0	0.5	0.7	2.5	1.1	0.7	0.9
1.2	0.5	0.6	1.8	0.8	0.6	0.9
1.5	0.5	0.6	1.2	0.6	0.4	0.8
2.0	0.4	0.5	0.7	0.4	0.4	0.8
2.5	0.4	0.4	0.5	0.4	0.4	0.7
3.0	0.4	0.4	0.4	0.4	0.4	0.6
3.5	0.4	0.4	0.4	0.4	0.5	0.6

Conclusions

Correction is field size and depth dependent

No one ideal detector

- Use at least two different acceptable detectors
- Plastic scintillator may be an ideal small field detector
- Unshielded diode good for fields > 1x1 cm^2, for fields < 1x1 cm^2 correction factor from 1-4%
- Stereotactic field diode good for fields- 0.6x0.6 cm2 with correction factor ≈ 2%
- Passive detectors such as TLDs and radiochromic film good for point dose measurements- 0.5x0.5 cm2

hospital exercise

Small field relative dosimetry:

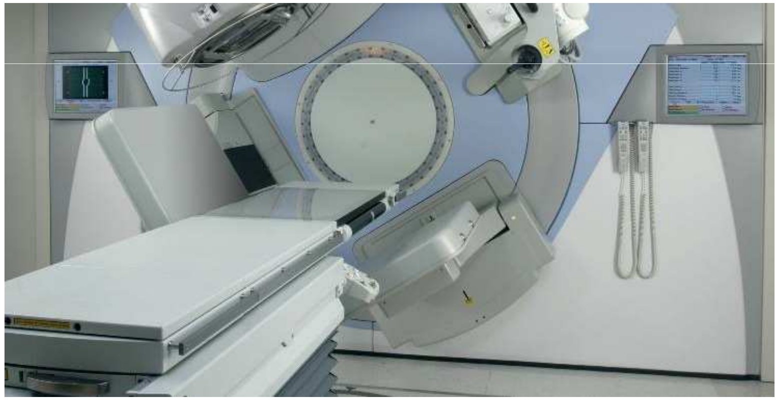
- Equipment
- Small field Profiles (detector alignment, FWHM)
- Small field Output factors (semiflex, pinpoint IC, diode)

hospital exercise

Small field relative dosimetry:

Equipment

Elekta Synergy Agility, **WFF** 6MV



MP3 water phantom (PTW)

hospital exercise

Small field relative dosimetry:

Equipment

Electrometers PTW UNIDOS E

PTW Semiflex type 31010 (0.125 cm^3)

PTW 60017 non-shielded (EFD) diode

PTW pin point 31014

Field output factors for small MV photon fields using semiflex, unshielded diodes and pin point. For field sizes 10 cm x 10 cm, 6 cm x 6 cm, 4 cm x 4 cm, 2 cm x 2cm and 1 cm x 1 cm.

- Set the chamber at 10 cm depth for the SAD=100cm configuration
- **Measure lateral and longitudinal ionization profiles** for the 10 cm × 10 cm field; centre the chamber
- Set default bias voltage. Register P and T. Make a warm-up reading (400 MUs), then record 3 readings, 100 MUs each
- For the square field sizes with 4, 2 and 1 cm side, measure lateral and longitudinal ionization profiles;
- Centre the chamber, then record 3 readings, 100 MUs each for each field size (readings should not differ by more than about 0.5%). Register P and T for each field size.
- Set field size at 10 cm × 10 cm and record 3 readings, 100 MUs each.
- **Determine field output factors**

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