IAEA/AAPM Code of Practice for the Dosimetry of Static Small Photon Fields

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- Some brand names of commercial products are mentioned in this presentation. This does not represent any endorsement of one product or manufacturer over another

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Medical Physics
RESEARCH TRAINING NETWORK

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Learning Objectives

- Review the problems of small field dosimetry and the solutions that have been identified
- Learn about the IAEA-AAPM recommendations and data for small field dosimetry

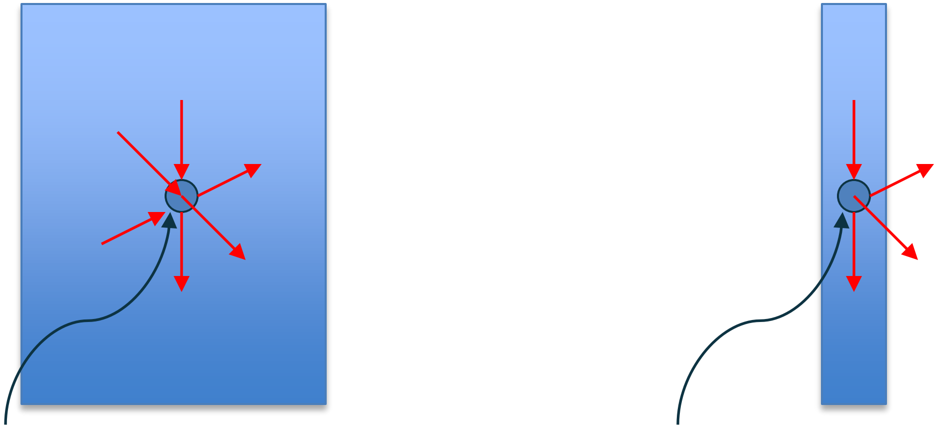
Overview

- The problems in small-field dosimetry
- The IAEA dosimetry formalism
- Conclusions

What constitutes small-field conditions?

- Beam-related small-field conditions
  - the existence of lateral charged particle disequilibrium
  - partial geometrical shielding of the primary photon source as seen from the point of measurement
- Detector-related small-field condition
  - detector size compared to field size

Lateral charged particle loss



broad photon field

narrow photon field

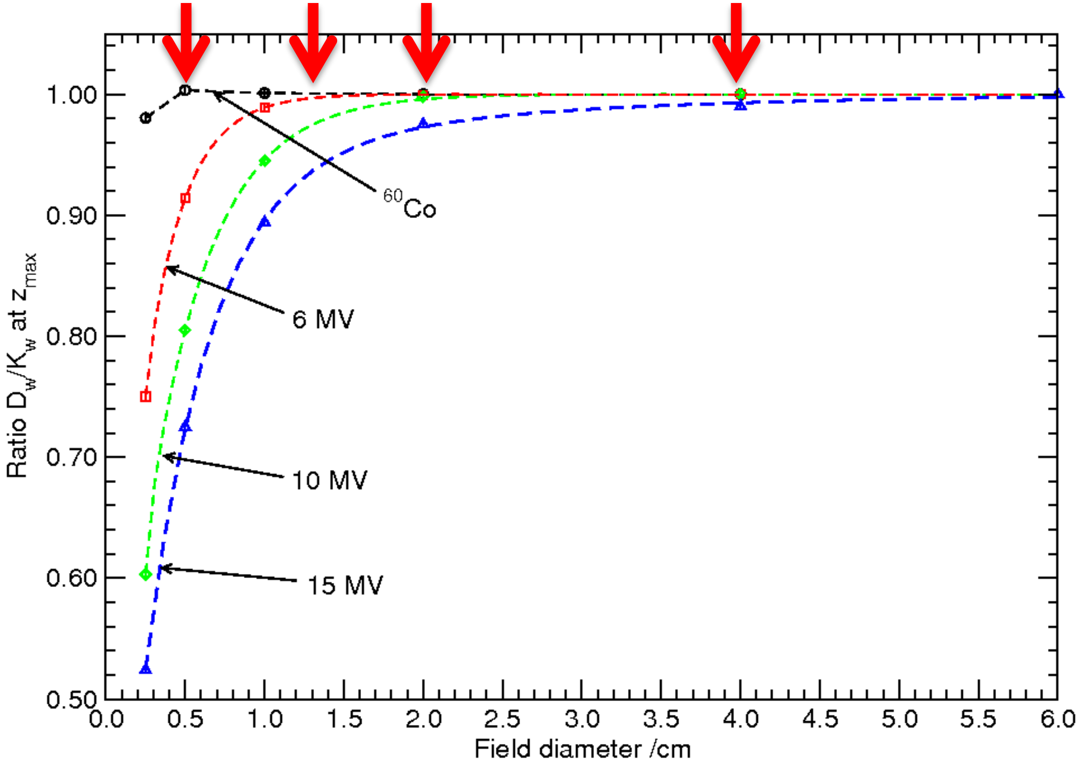
volume

volume

A small field can be defined as a field with size smaller than the "lateral range" of charged particles

$\dfrac{D}{K_{\mathrm{coll}}}$ is a measure of the degree of charged particle equilibrium or transient equilibrium

Lateral charged particle loss



Concept of r_{LCPE}

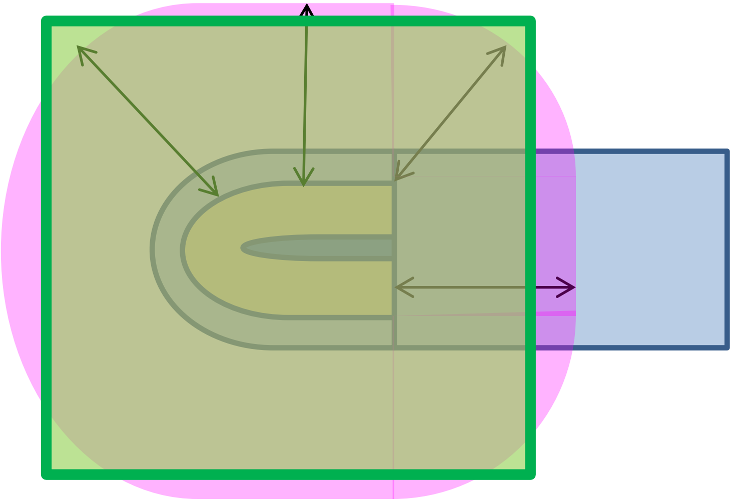
MC calculations, Seuntjens (2013)

Detector size relative to field size

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

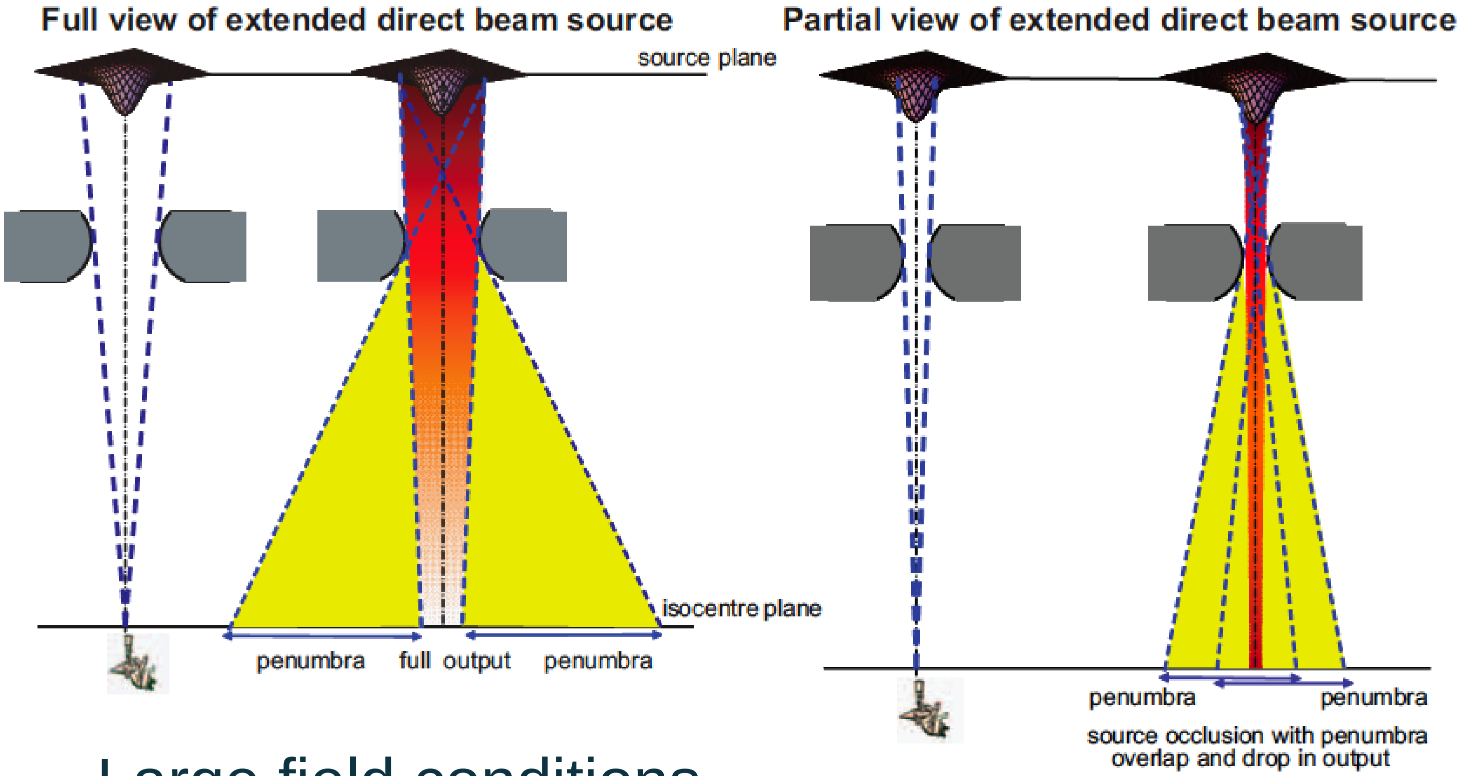
r_{LCPE} (in cm) = 5.973•TPR$_{20,10}$ – 2.688

(Li et al. 1995 *Med Phys* 22, 1167-1170)



Slide courtesy: H. Palmans

Source occlusion

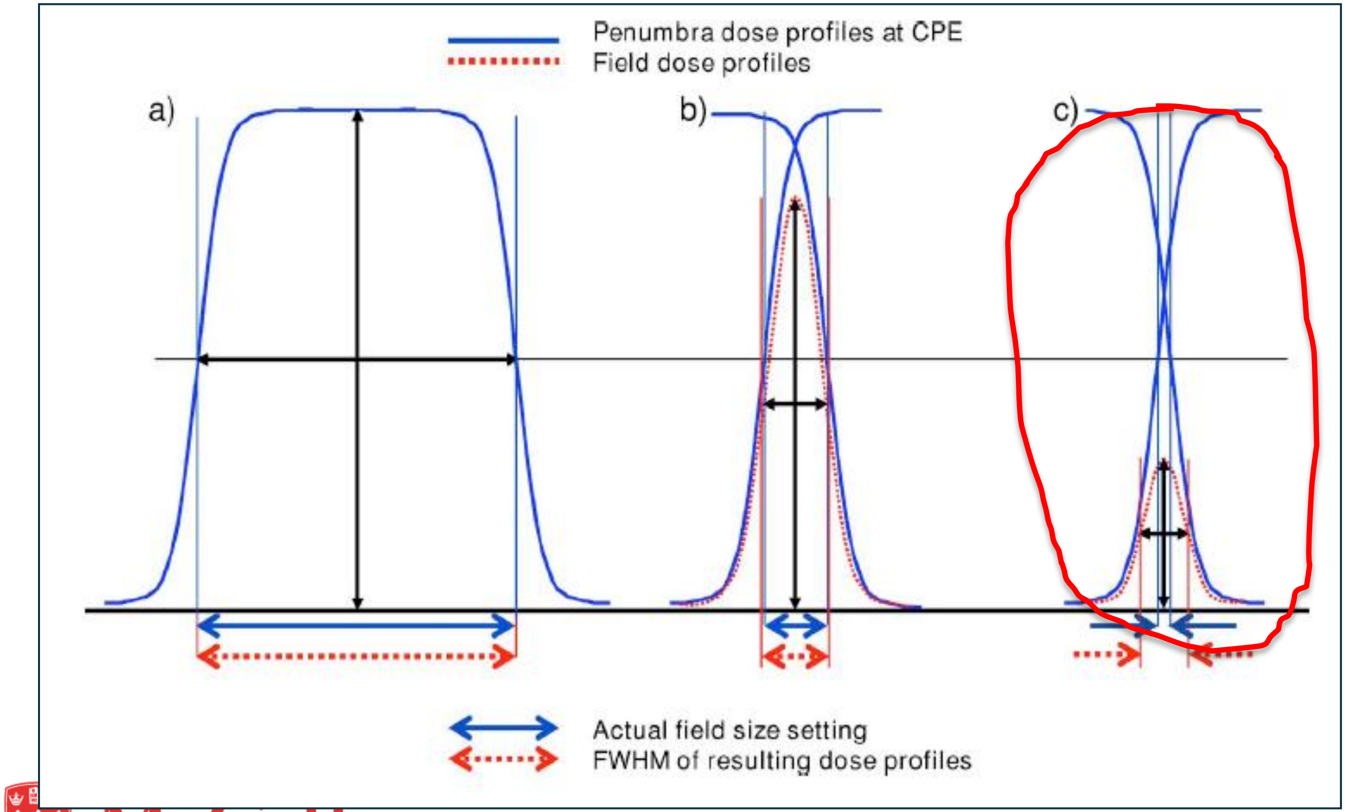


Large field conditions

Small field conditions

(Figure courtesy M.M. Aspradakis et al, IPEM Report 103)

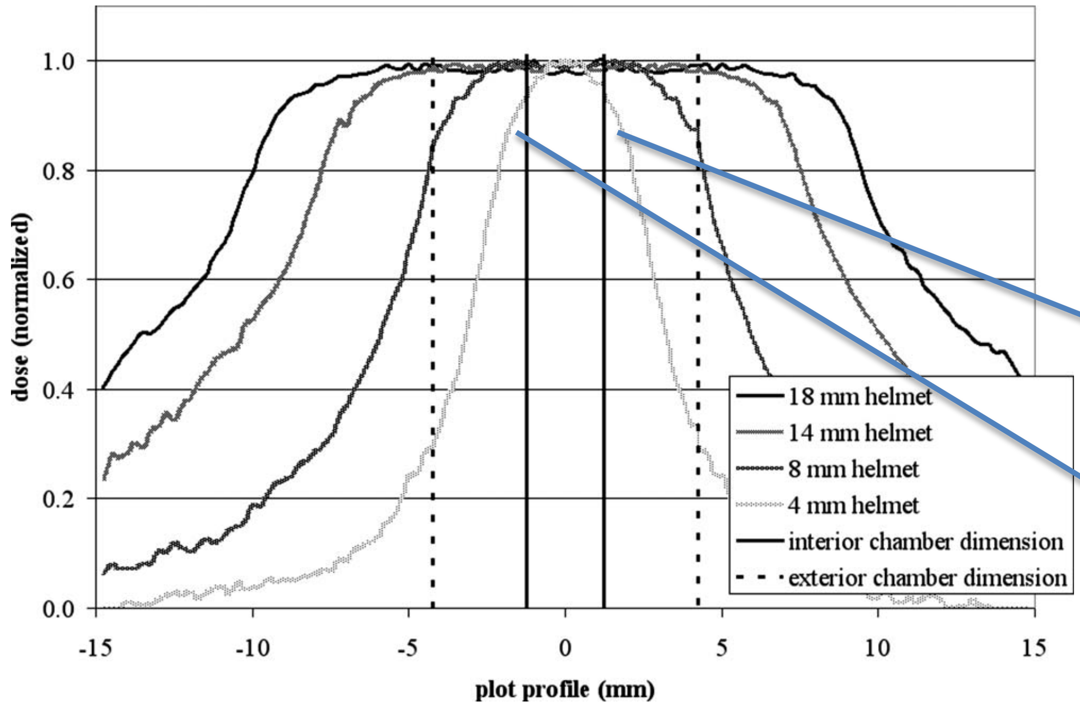
Overlapping of beam penumbras



definition of field size is not unique

Das et al. 2008 Med Phys **35**: 206-15

Detector-related small field condition

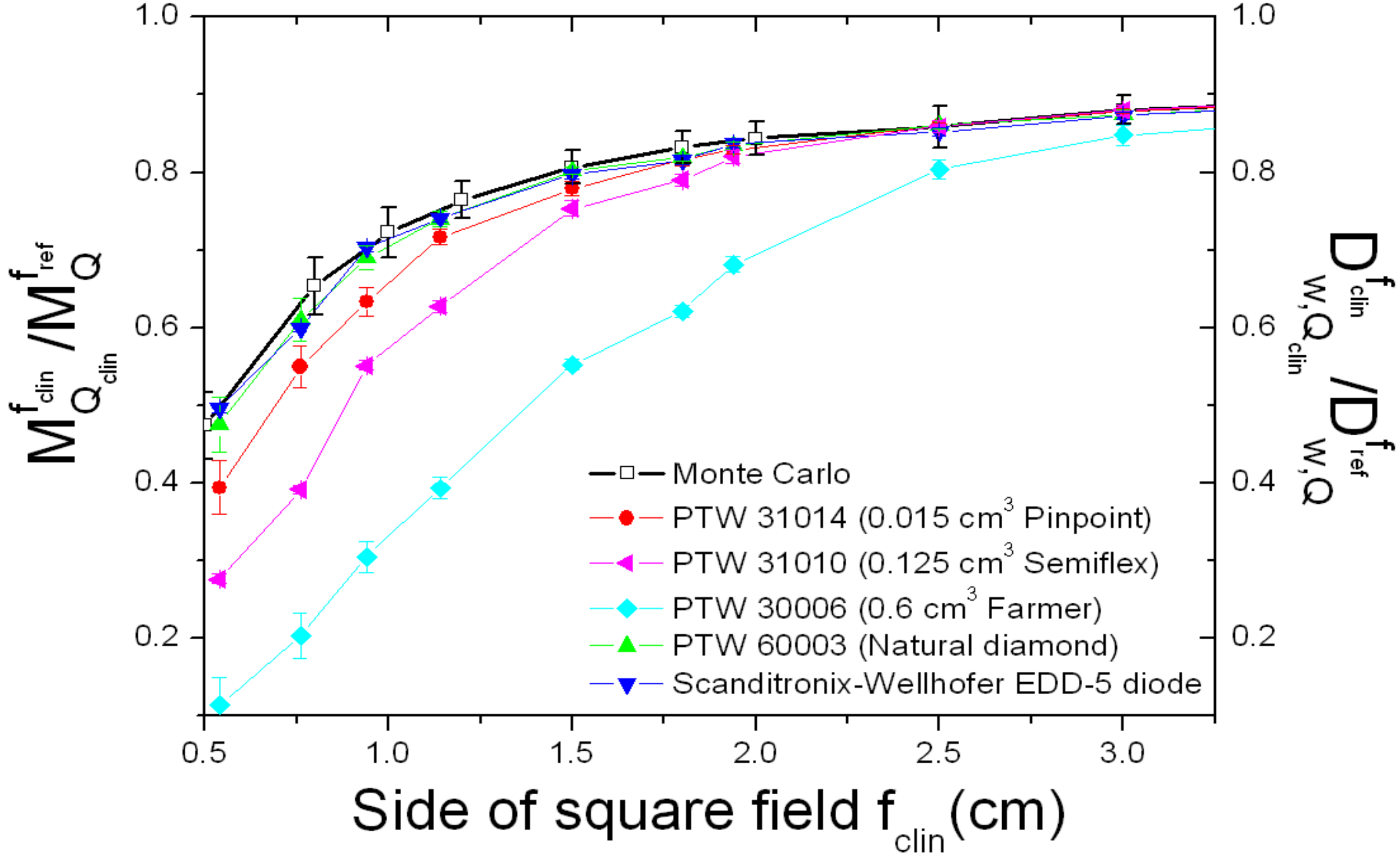


Meltsner et al., Med Phys 36:339 (2009)

Exradin A16 outer diameter

Exradin A16 inner diameter

Based on criterion 1, one could claim that the GammaKnife 18 or 14 mm diameter fields are not small (quasi point source + electron equilibrium length about 6 mm).



From Sanchez-Doblado et al. 2007 Phys Med 23:58-66

Detector issues in small field dosimetry

- Energy dependence of the response
- Perturbation effects
  - Central electrode
  - Wall effects
  - Fact that cavity is different from water, fluence perturbation
  - Volume averaging
- These effects depend somewhat on the beam spot size

Detector issues in small field dosimetry

$$D_{\mathrm{w,Q}} = M_{\mathrm{Q}} N_{\mathrm{D,w}} k_{\mathrm{Q}}$$

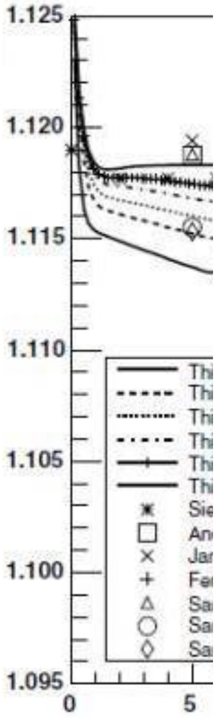
$$k_{\mathrm{Q}} = \left[\left(\frac{\overline{L}}{\rho} \right)^{\mathrm{w}}_{\mathrm{air}} P_{\mathrm{wall}} P_{\mathrm{repl}} P_{\mathrm{cel}} \right]^{\mathrm{Q}}_{^{60}\mathrm{Co}}$$

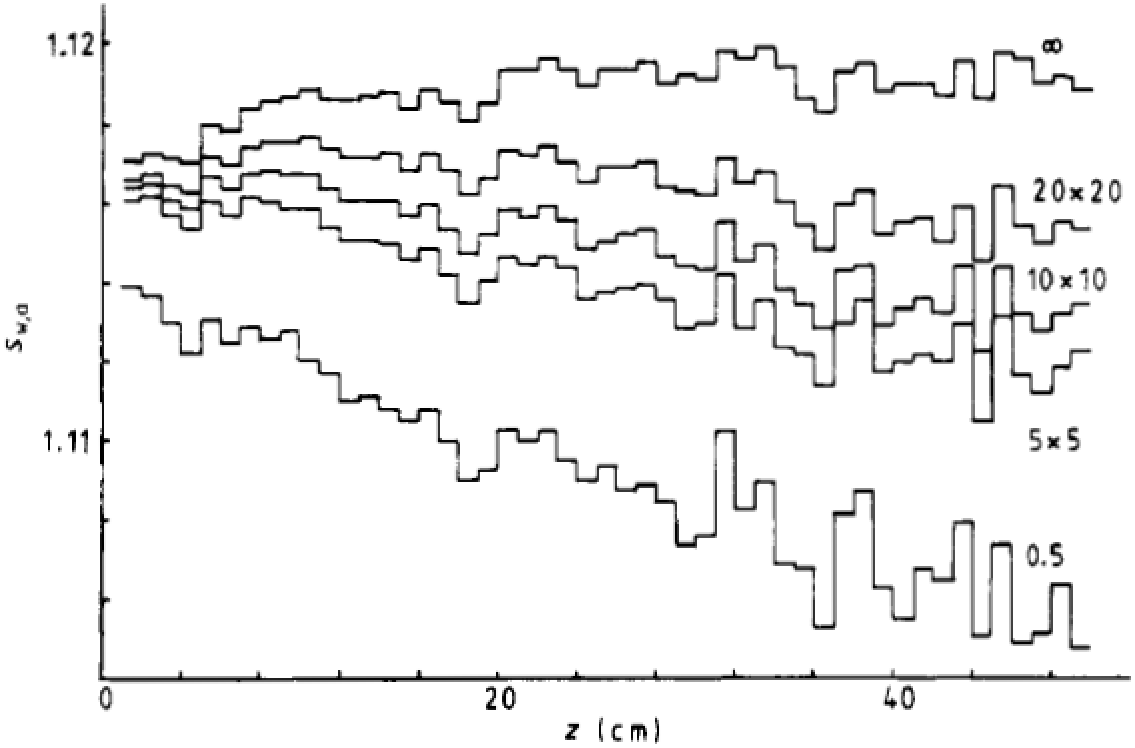
Dosimetry protocol values (e.g., TG-51) of these factors are applicable usually **only in TCPE and only** for the conditions:

10 x 10 cm^2; z_{ref} = 10 cm; *SSD* or *SAD* 100 cm

Stopping power ratio water to air $\left(\frac{\overline{L}}{\rho}\right)_{\mathrm{w,air}}$

Very small effects!





Eklund and Ahnesjö, Phys Med Biol 53:4231 (2008)

Andreo&Brahme PMB 8:839 (1986)

Role of different perturbation factors

PP31006 and PP31016 chambers

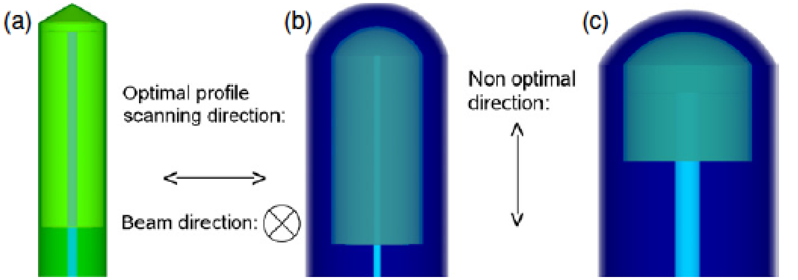
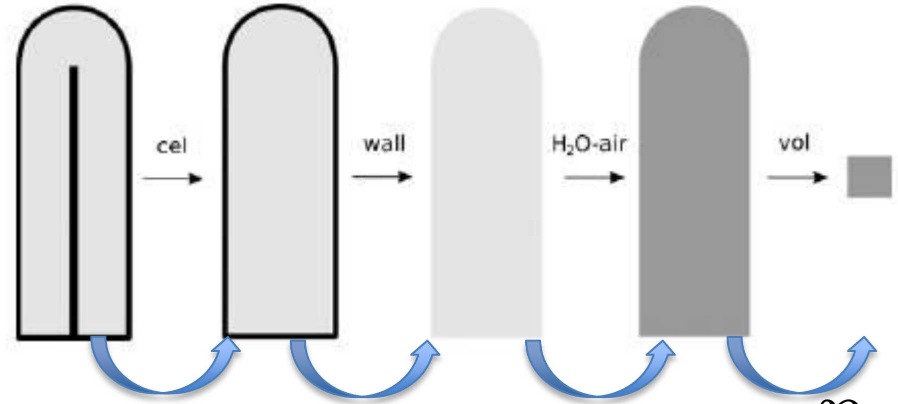


Figure 2. Geometrical models of (a) NE2571, (b) PinPoint 31006 and (c) PinPoint 31016 chambers (images are not on the same scale).

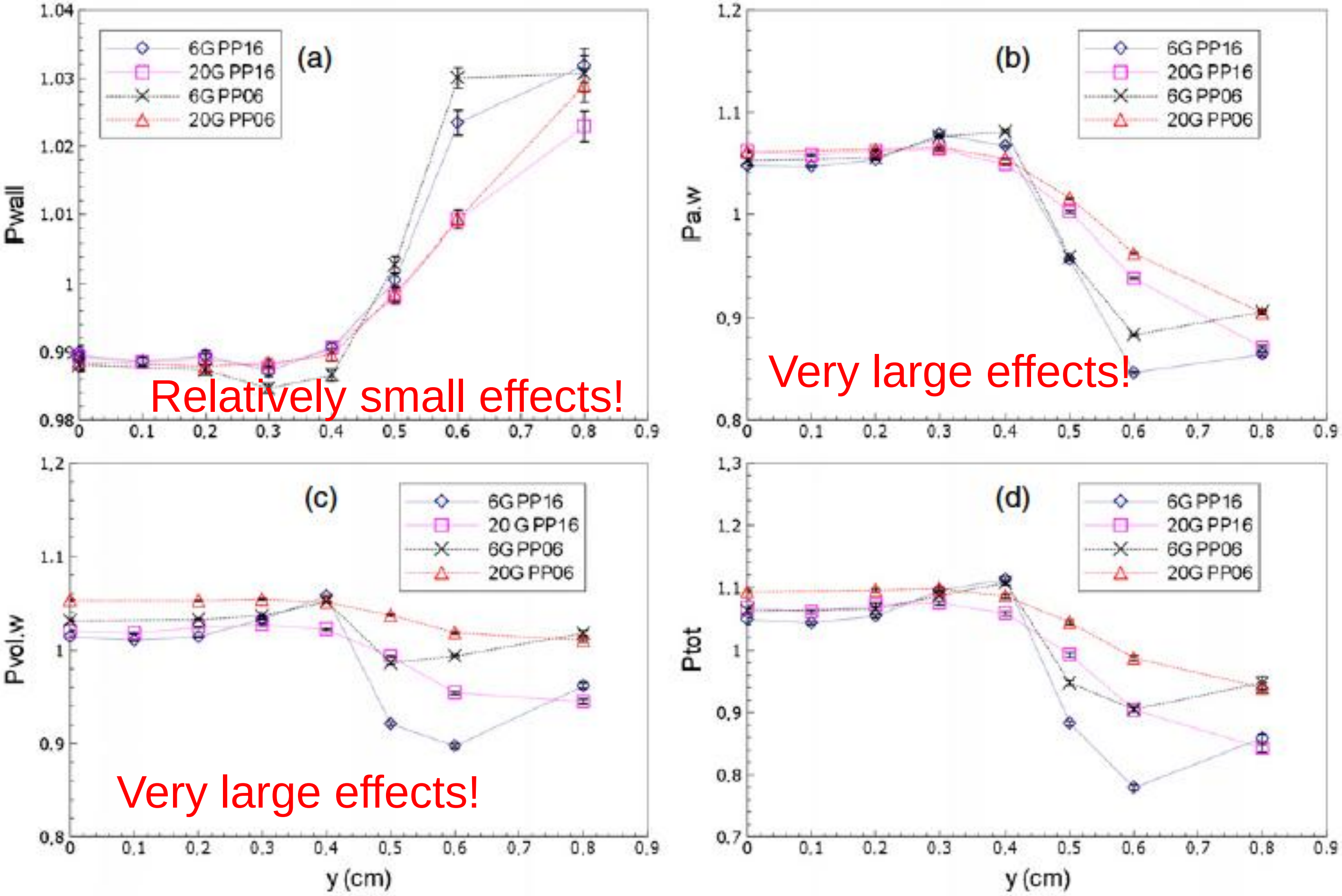


p_{cel} p_{wall} $p_{\mathrm{air,w}}$ p_{vol}

Crop et al., Phys Med Biol 54:2951 (2009)

Magnitude of correction factors on and off-axis

8 mm x 8 mm field, 10 cm depth (0.6 mm, 2 mm spot sizes)



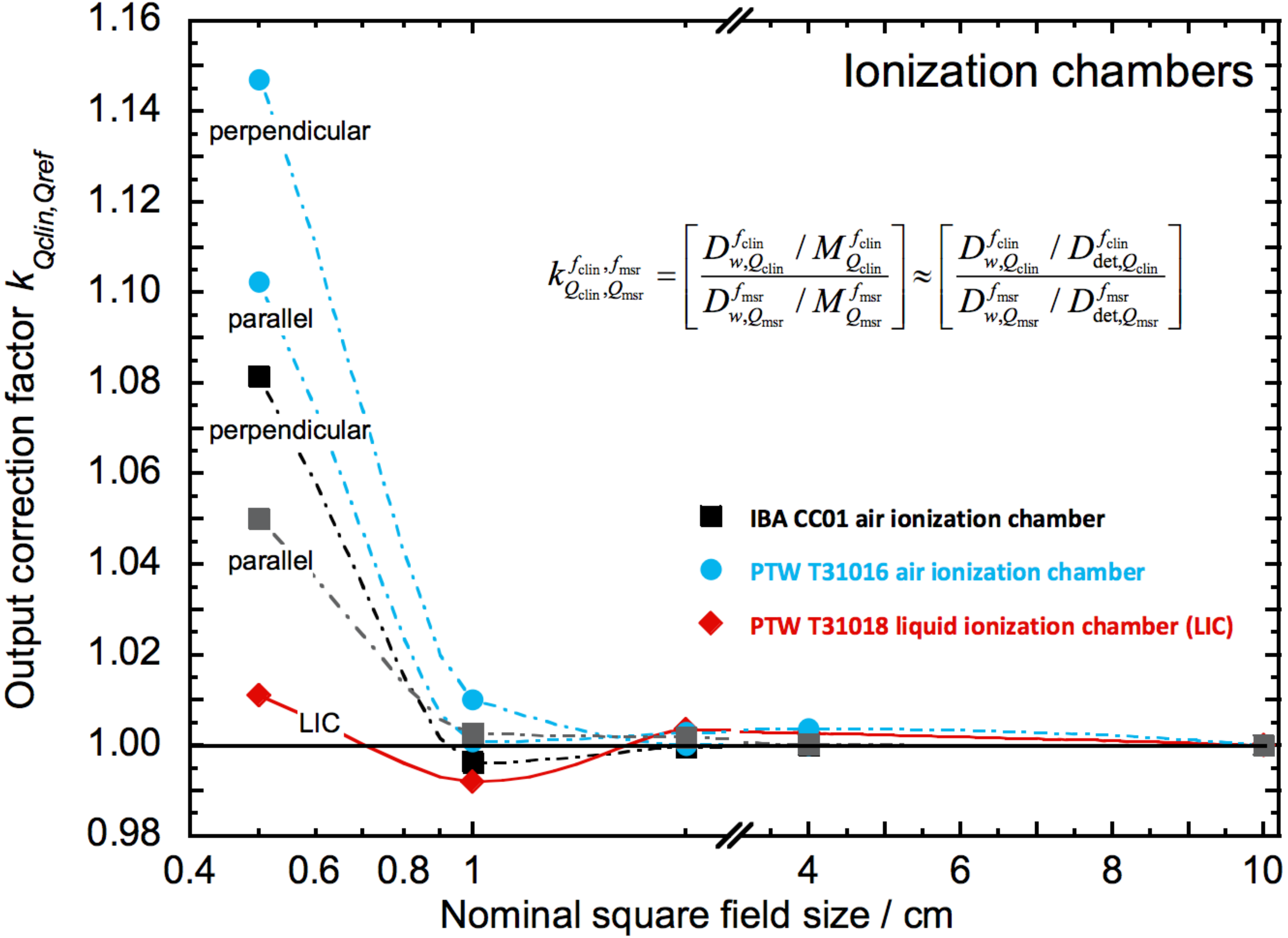
Relatively small effects!

Very large effects!

Very large effects!

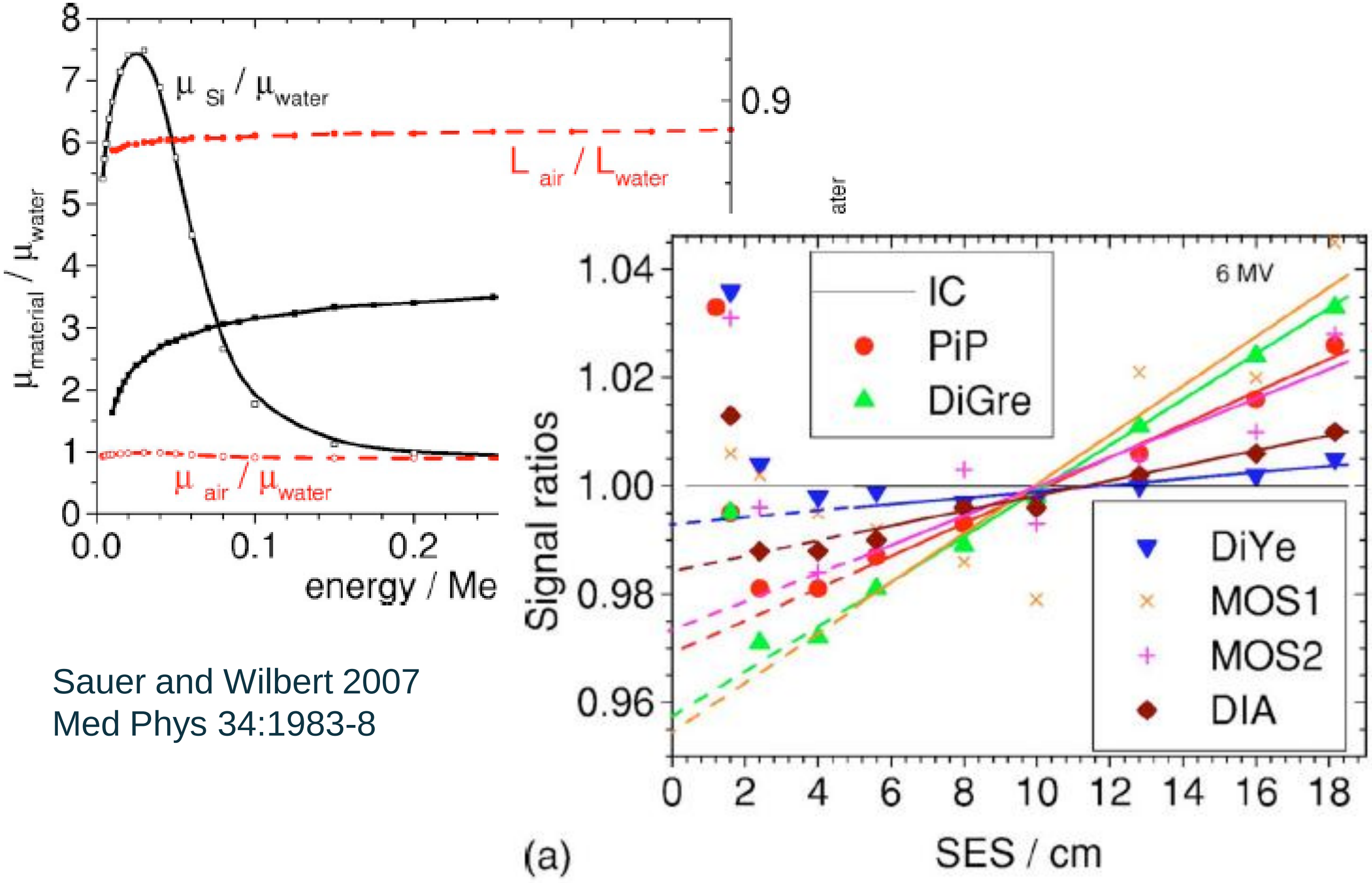
Crop et al., Phys Med Biol 54:2951 (2009)

Benmahklouf and Andreo (2013)

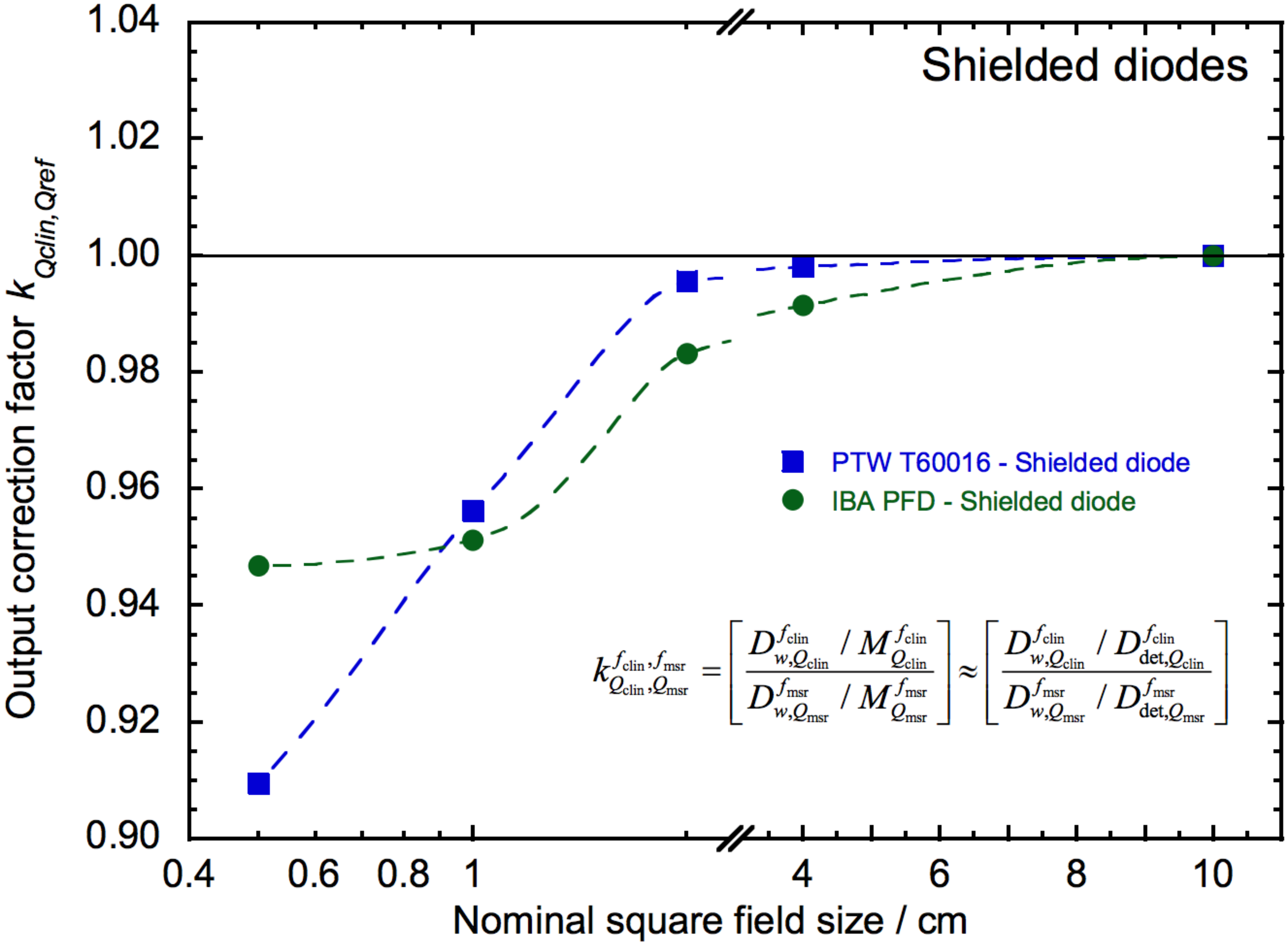


$$k^{f_{\mathrm{clin}},f_{\mathrm{msr}}}_{Q_{\mathrm{clin}},Q_{\mathrm{msr}}} = \left[\frac{D^{f_{\mathrm{clin}}}_{w,Q_{\mathrm{clin}}} / M^{f_{\mathrm{clin}}}_{Q_{\mathrm{clin}}}}{D^{f_{\mathrm{msr}}}_{w,Q_{\mathrm{msr}}} / M^{f_{\mathrm{msr}}}_{Q_{\mathrm{msr}}}}\right] \approx \left[\frac{D^{f_{\mathrm{clin}}}_{w,Q_{\mathrm{clin}}} / D^{f_{\mathrm{clin}}}_{\mathrm{det},Q_{\mathrm{clin}}}}{D^{f_{\mathrm{msr}}}_{w,Q_{\mathrm{msr}}} / D^{f_{\mathrm{msr}}}_{\mathrm{det},Q_{\mathrm{msr}}}}\right]$$

Diodes for small field dosimetry

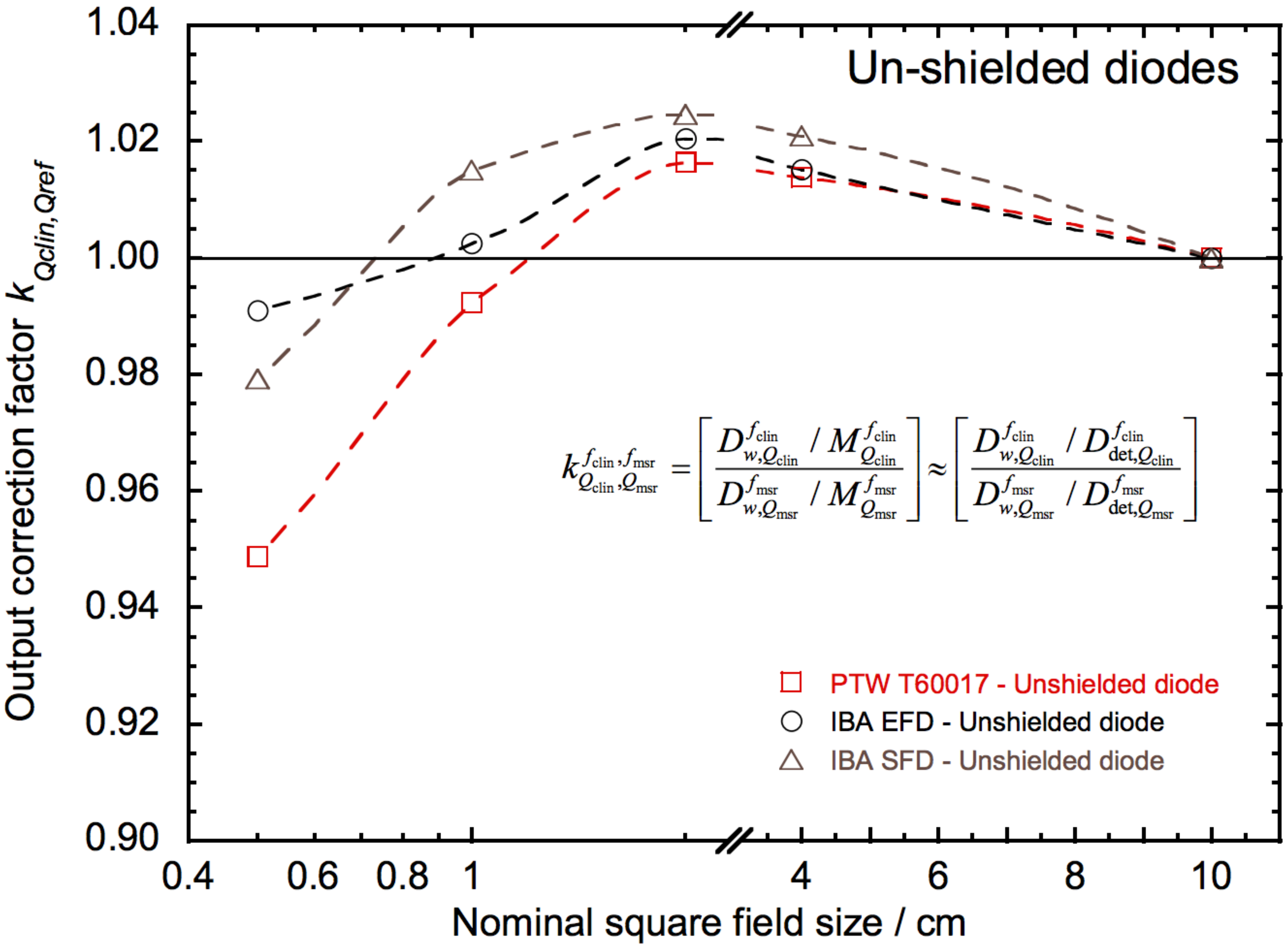


Sauer and Wilbert 2007
Med Phys 34:1983-8



$$k^{f_{\text{clin}},f_{\text{msr}}}_{Q_{\text{clin}},Q_{\text{msr}}} = \left[\frac{D^{f_{\text{clin}}}_{w,Q_{\text{clin}}} / M^{f_{\text{clin}}}_{Q_{\text{clin}}}}{D^{f_{\text{msr}}}_{w,Q_{\text{msr}}} / M^{f_{\text{msr}}}_{Q_{\text{msr}}}} \right] \approx \left[\frac{D^{f_{\text{clin}}}_{w,Q_{\text{clin}}} / D^{f_{\text{clin}}}_{\text{det},Q_{\text{clin}}}}{D^{f_{\text{msr}}}_{w,Q_{\text{msr}}} / D^{f_{\text{msr}}}_{\text{det},Q_{\text{msr}}}} \right]$$

Benmahklouf and Andreo (2013)



$$k_{Q_{\text{clin}},Q_{\text{msr}}}^{f_{\text{clin}},f_{\text{msr}}} = \left[\frac{D_{w,Q_{\text{clin}}}^{f_{\text{clin}}} \;/\; M_{Q_{\text{clin}}}^{f_{\text{clin}}}}{D_{w,Q_{\text{msr}}}^{f_{\text{msr}}} \;/\; M_{Q_{\text{msr}}}^{f_{\text{msr}}}} \right] \approx \left[\frac{D_{w,Q_{\text{clin}}}^{f_{\text{clin}}} \;/\; D_{\text{det},Q_{\text{clin}}}^{f_{\text{clin}}}}{D_{w,Q_{\text{msr}}}^{f_{\text{msr}}} \;/\; D_{\text{det},Q_{\text{msr}}}^{f_{\text{msr}}}} \right]$$

Benmahklouf and Andreo (2013)

Summary of issues leading to dosimetric uncertainties in small fields

- Beam dependent issues
  - Beam focal spot size
  - Lateral disequilibrium
  - How do we measure beam quality in practice?
- Detector effects
  - There is no ideal detector
  - Volume averaging and fluence perturbation effects
  - Corrections depend on beam spot size

What are the **single set of two largest contributors** to correction factors and their uncertainties for commercial air-filled ionization chambers in small photon fields?

1%	1.	The stopping power ratio and the central electrode effect
5%	2.	The stopping power ratio and the chamber wall effect
75%	3.	The fluence perturbation effect and the volume averaging effect
17%	4.	The stopping power ratio and the volume averaging effect
3%	5.	The ionization chamber wall effect and the stem effect

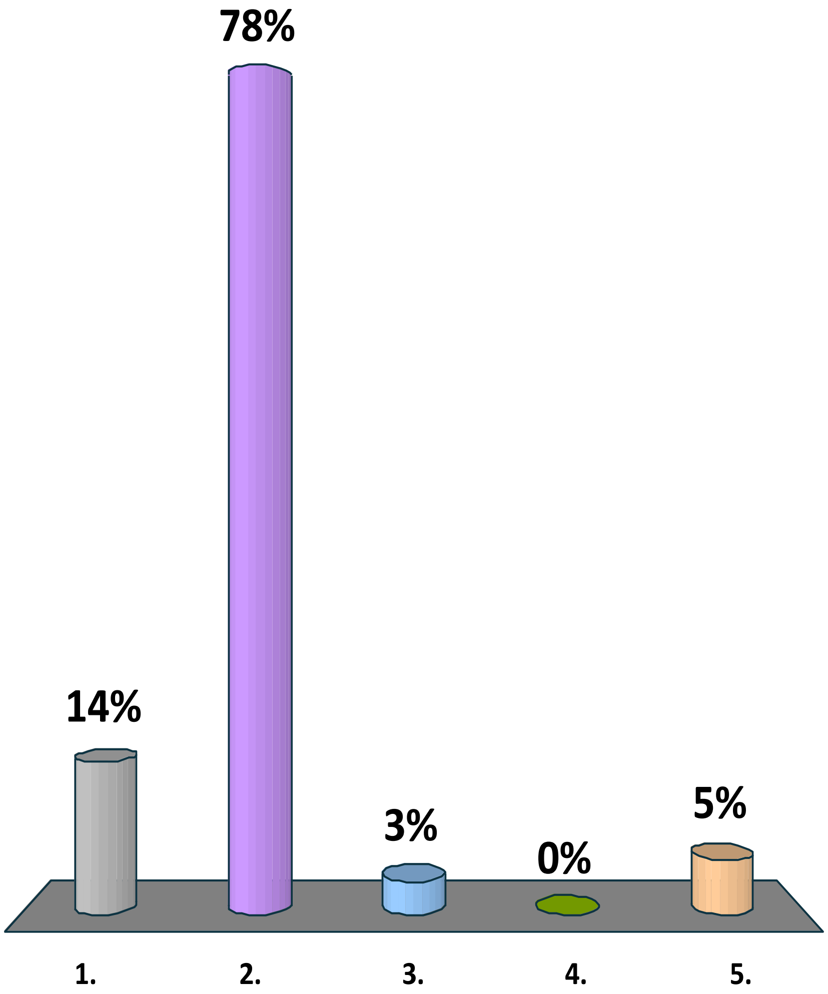
- Correct answer: 3 The fluence perturbation effect and the volume averaging effect

- Discussion: The field size dependence of stopping power ratios is 0.5% or less. For most ionization chambers the field size dependence of wall corrections is limited to a few percent. The volume averaging and fluence perturbation corrections are potentially very large (on the order of 10-30% or more depending on the situation)

- Reference:
  - Crop et al (2009) Phys Med Biol 54 2951-2969
  - Bouchard et al (2009) Med Phys 36 (10), 4654-4663

Which two competing effects lead to field size dependent correction factors of unshielded diode detectors?

1. Intrinsic energy dependence of Si in photon beams and volume averaging
2. Intrinsic energy dependence of Si in photon beams and perturbation effects
3. Polarity effect and recombination
4. Polarity effect and electrometer calibration
5. Recombination effect and diode doping



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- Correct answer: 2 Intrinsic energy dependence of Si in photon beams and electron fluence perturbation effects

- Discussion: Volume averaging is usually small in diodes because of the small size of the sensitive volume. Diodes are not polarized by an external bias, so there is no polarity effect. Recombination effects and diode doping are not relevant in this context.

- References:
  - Francescon et al 2011, Med Phys 38: 6513
  - Benmakhlouf et al 2014, Med Phys 41: 041711

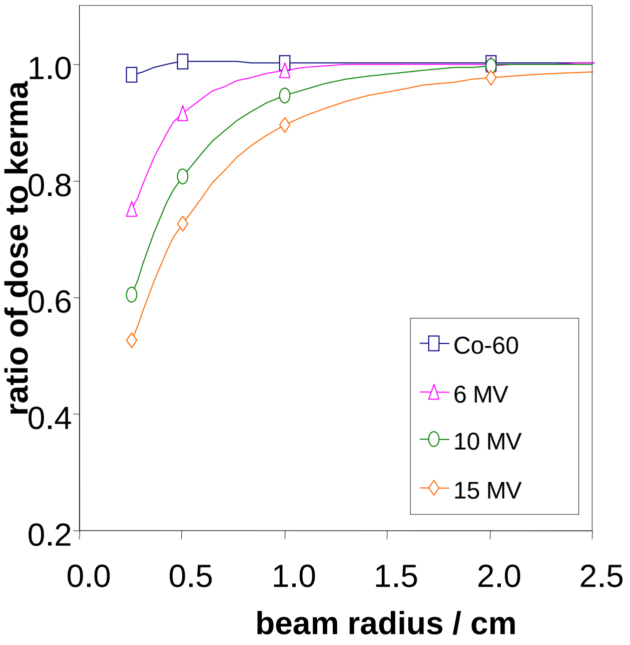
IAEA TECDOC small field dosimetry

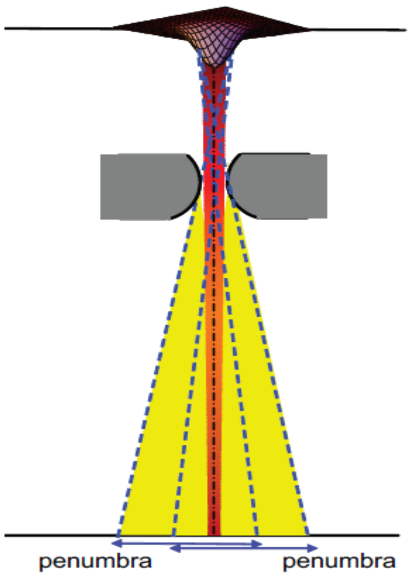
- Code of Practice / working document
- Physics relevant to reference and relative dosimetry
- Formalism
- Instrumentation
- Practical implementation
  - Machine-specific reference dosimetry
  - Relative dosimetry
- Data

Ch. 2 - Physics of small fields

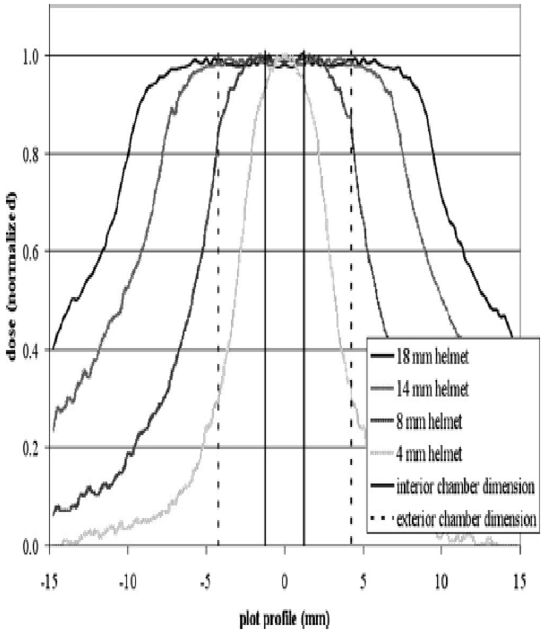
e.g. Small field conditions

LCPE source occlusion detector size





source occlusion with penumbra overlap and drop in output



Seuntjens
MC

Aspradakis et al 2010
IPEM Report 103

Meltsner et al. 2009
Med Phys 36:339-50

Reference Fields Small Fields

REFERENCE DOSIMETRY

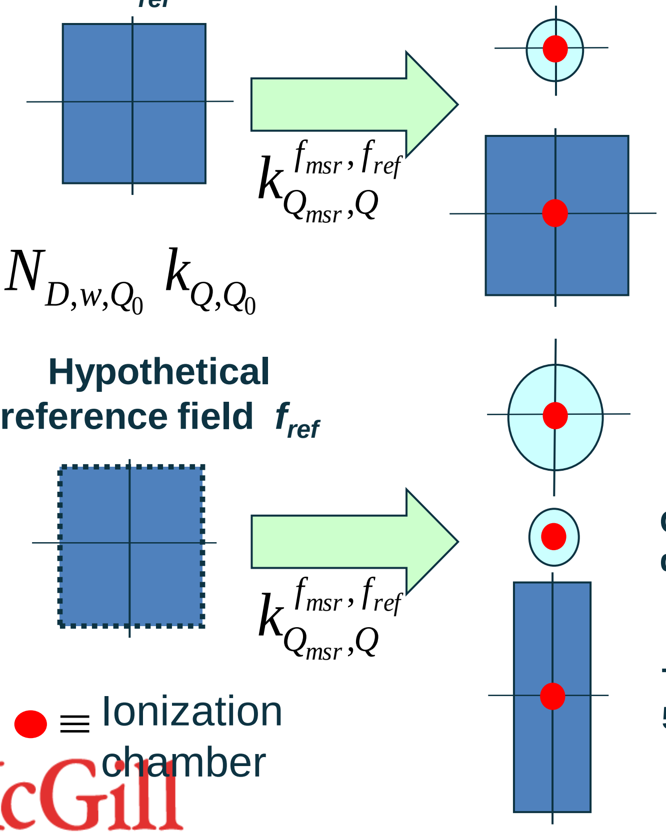
$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} N_{D,w,Q_0} k_{Q,Q_0} k_{Q_{msr},Q}^{f_{msr},f_{ref}}$$

RELATIVE DOSIMETRY

$$D_{w,Q_{clin}}^{f_{clin}} = D_{w,Q_{msr}}^{f_{msr}} \Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$$

Broad beam reference field f_{ref}

Machine specific reference field f_{msr}



$k_{Q_{msr},Q}^{f_{msr},f_{ref}}$

N_{D,w,Q_0} k_{Q,Q_0}

Radiosurgical collimators d = 1.8 cm

***micro MLC* 10 cm x 10 cm**

Hypothetical reference field f_{ref}

$k_{Q_{msr},Q}^{f_{msr},f_{ref}}$

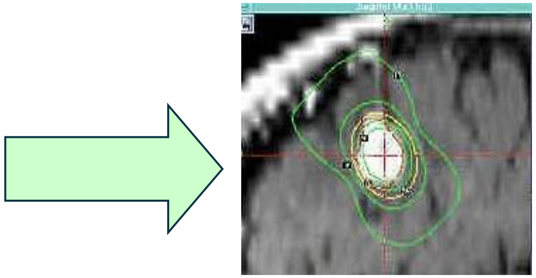
CyberKnife 6 cm

GammaKnife d = 1.6/1.8 cm

Tomotherapy 5 cm x 20 cm

● ≡ Ionization chamber

Clinical field f_{clin}



$$\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = \frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{msr}}^{f_{msr}}} \cdot k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$$

Ch3. – Formalism (Alfonso et al) / D_w in machine specific reference (*msr*) fields

- Chamber calibrated specifically for the msr field

$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} \cdot N_{D,w,Q_{msr}}^{f_{msr}}$$

- Chamber calibrated for the conventional reference field and generic correction factors are available

$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} \cdot N_{D,w,Q_0}^{f_{ref}} \cdot k_{Q_{msr},Q_0}^{f_{msr},f_{ref}}$$

$f_{ref=}$=10 x 10 cm^2

Q_0= ^{60}Co

- Chamber calibrated for the conventional reference field and generic correction factors not available

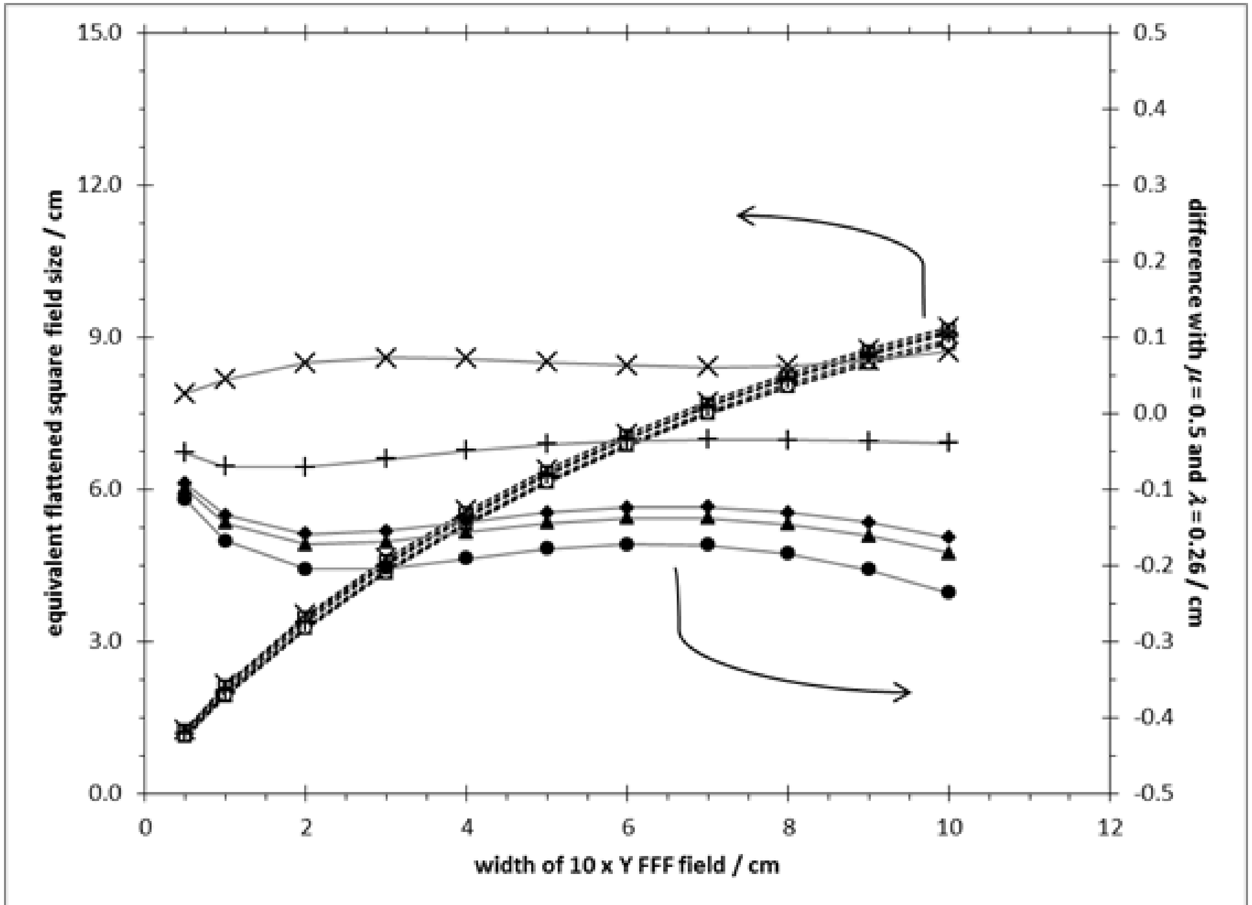
$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} \cdot N_{D,w,Q_0}^{f_{ref}} \cdot k_{Q,Q_0}^{f_{ref}} \cdot k_{Q_{msr},Q}^{f_{msr},f_{ref}}$$

Equivalent square fields - *msr*

$$s = \frac{1}{2\pi}\int\int\left(\lambda e^{-\lambda r} - \mu\lambda e^{-\lambda r} + \mu\lambda^2 r e^{-\lambda r}\right)F(r)\,dr\,d\theta$$

WFF beams:
BJR 25 - equivalent field size is energy independent

FFF beams:
equivalent field size is energy dependent;
Tables are provided for 6 MV and 10 MV



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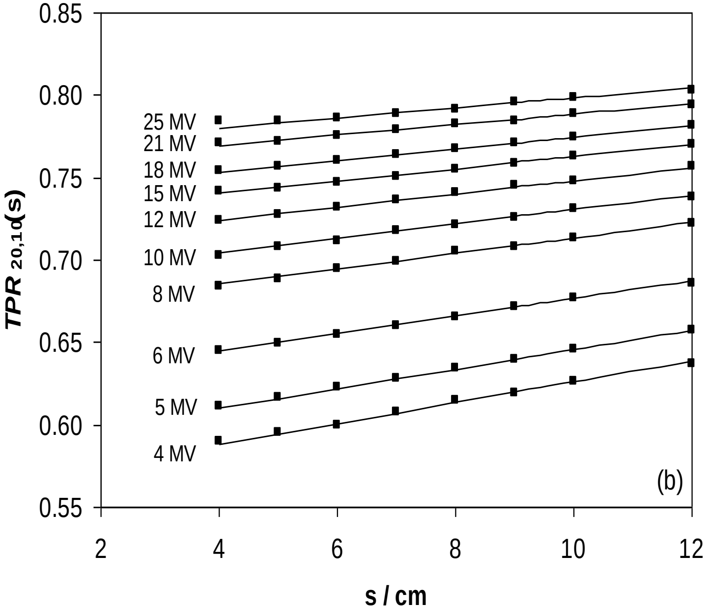
Ch 3. – Formalism / equations for beam quality in non-standard reference fields

for $TPR_{20,10}(10) = TPR_{20,10}$

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

(Palmans 2012 Med Phys 39:5513)

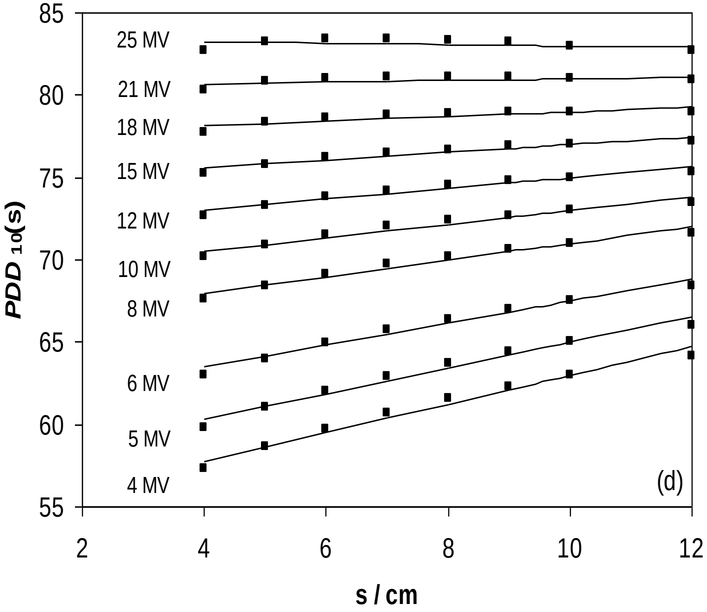


Ch 3. – Formalism / equations for beam quality in non-standard reference fields

for $PDD_{10X}(10) = \%dd(10)_X$

$$PDD_{10}(10) = \frac{PDD_{10}(s) + c_1 \cdot \left(e^{\frac{10-s}{t}} - 1 \right)}{1 + c_2 \cdot \left(e^{\frac{10-s}{t}} - 1 \right)}$$

(Palmans 2012 Med Phys 39:5513-9)



$$PDD_{10x}(10) = \begin{cases} PDD_{10}(10), & PDD_{10}(10) < 75.0 \\ 1.267 \cdot PDD_{10}(10) - 20.0, & PDD_{10}(10) \geq 75.0 \end{cases}$$

(TG-51)

Note about volume averaging in FFF beams

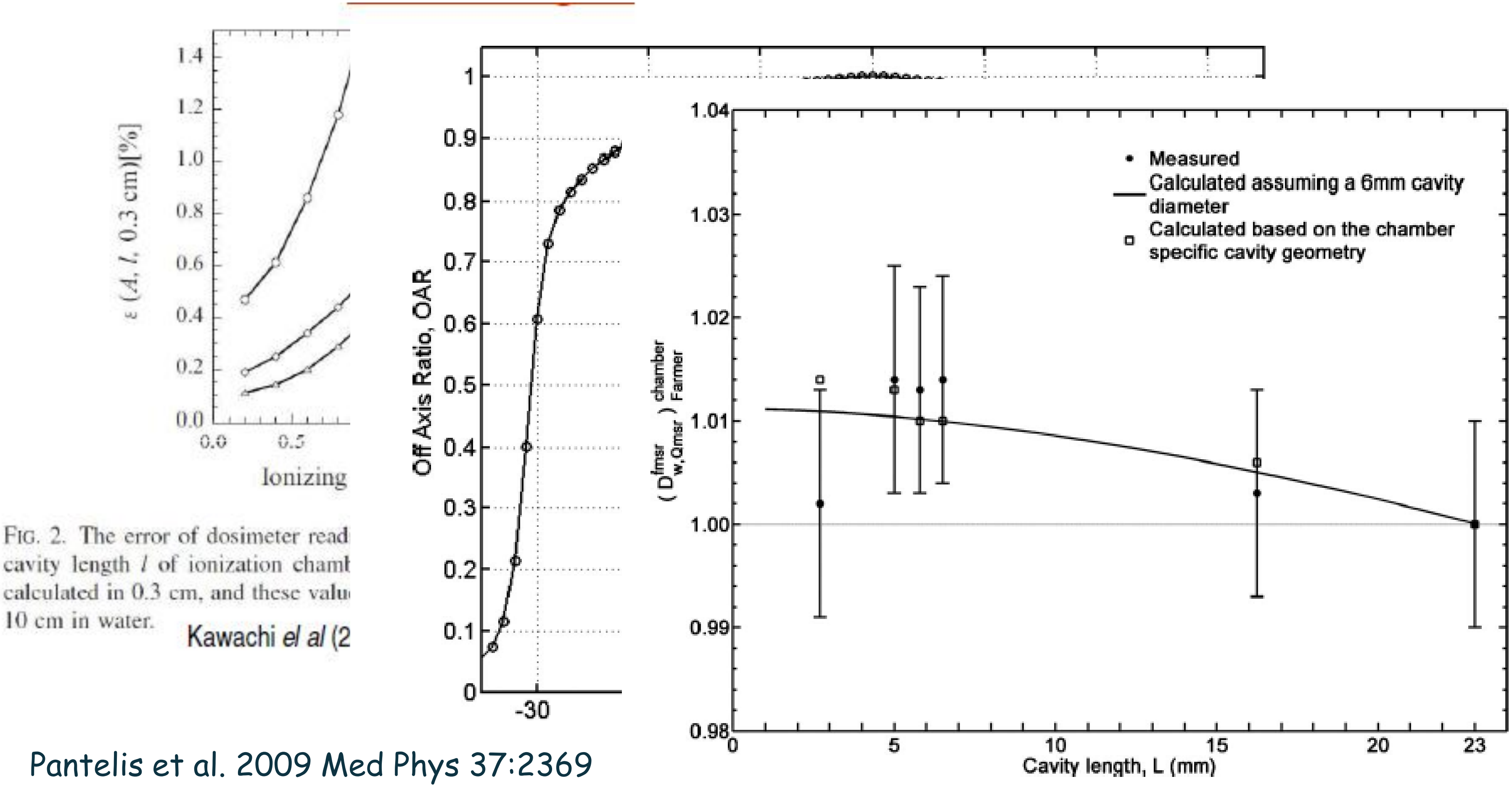
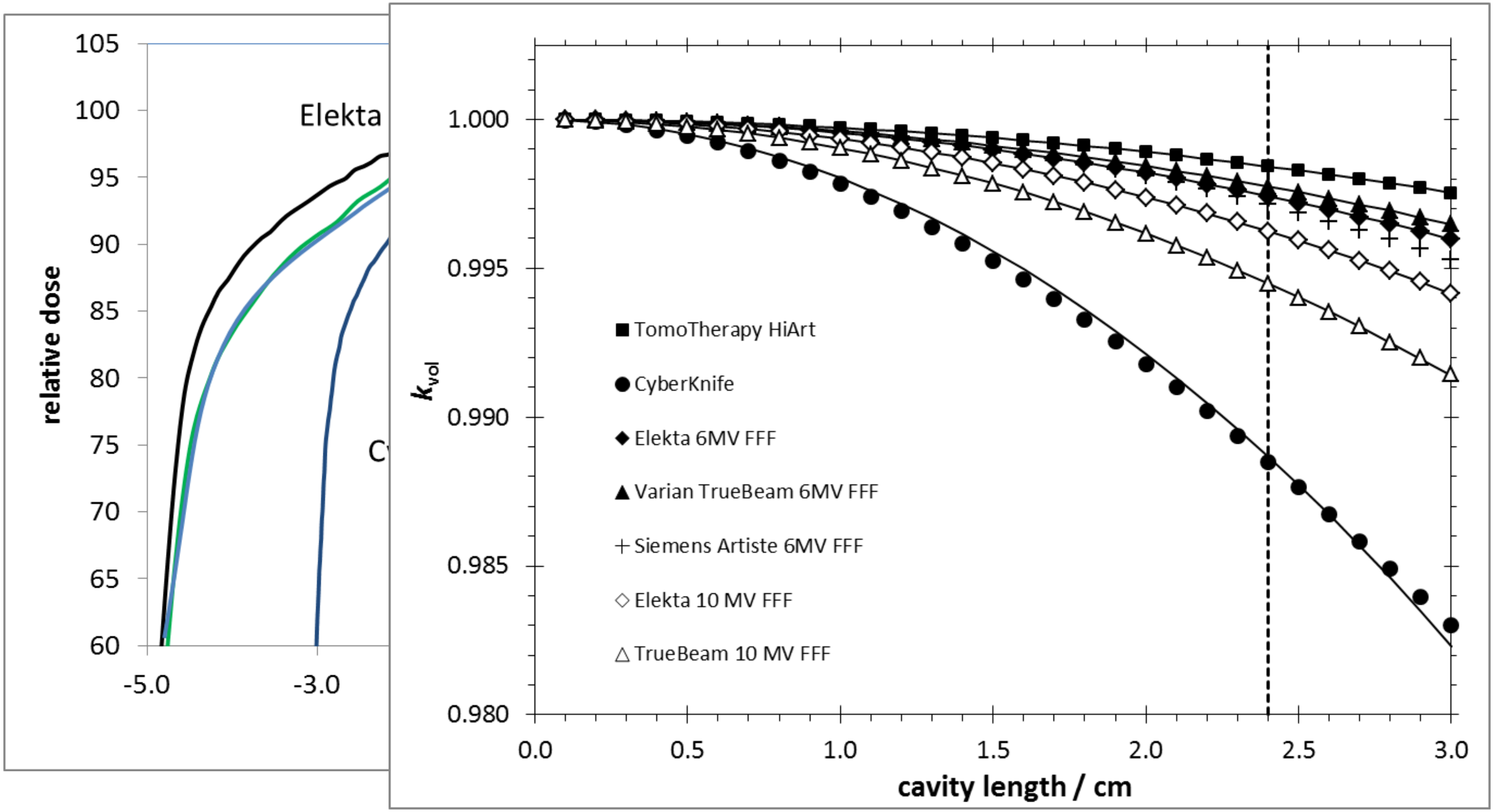


FIG. 2. The error of dosimeter read
cavity length *l* of ionization chamb
calculated in 0.3 cm, and these valu
10 cm in water.

Kawachi *el al* (2

Pantelis et al. 2009 Med Phys 37:2369

Volume averaging in FFF beams



Ch3. – Formalism / determination of field output factors

- Field output factor relative to reference field (ref stands here for a conventional reference or msr field)

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

- Field output factor relative to reference field using intermediate field or ‘daisy chaining’ method

$$\Omega_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}} = \frac{M_{Q_{clin}}^{f_{clin}}(\mathrm{det})}{M_{Q_{\mathrm{int}}}^{f_{\mathrm{int}}}(\mathrm{det})} \cdot \frac{M_{Q_{\mathrm{int}}}^{f_{\mathrm{int}}}(IC)}{M_{Q_{ref}}^{f_{ref}}(IC)} \cdot K_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}}$$

where

$$K_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}} = k_{Q_{clin},Q_{\mathrm{det}}}^{f_{clin},f_{\mathrm{int}}}(\mathrm{det}) \cdot k_{Q_{\mathrm{int}},Q_{ref}}^{f_{\mathrm{int}},f_{ref}}(IC)$$

Ch 4 – Instrumentation

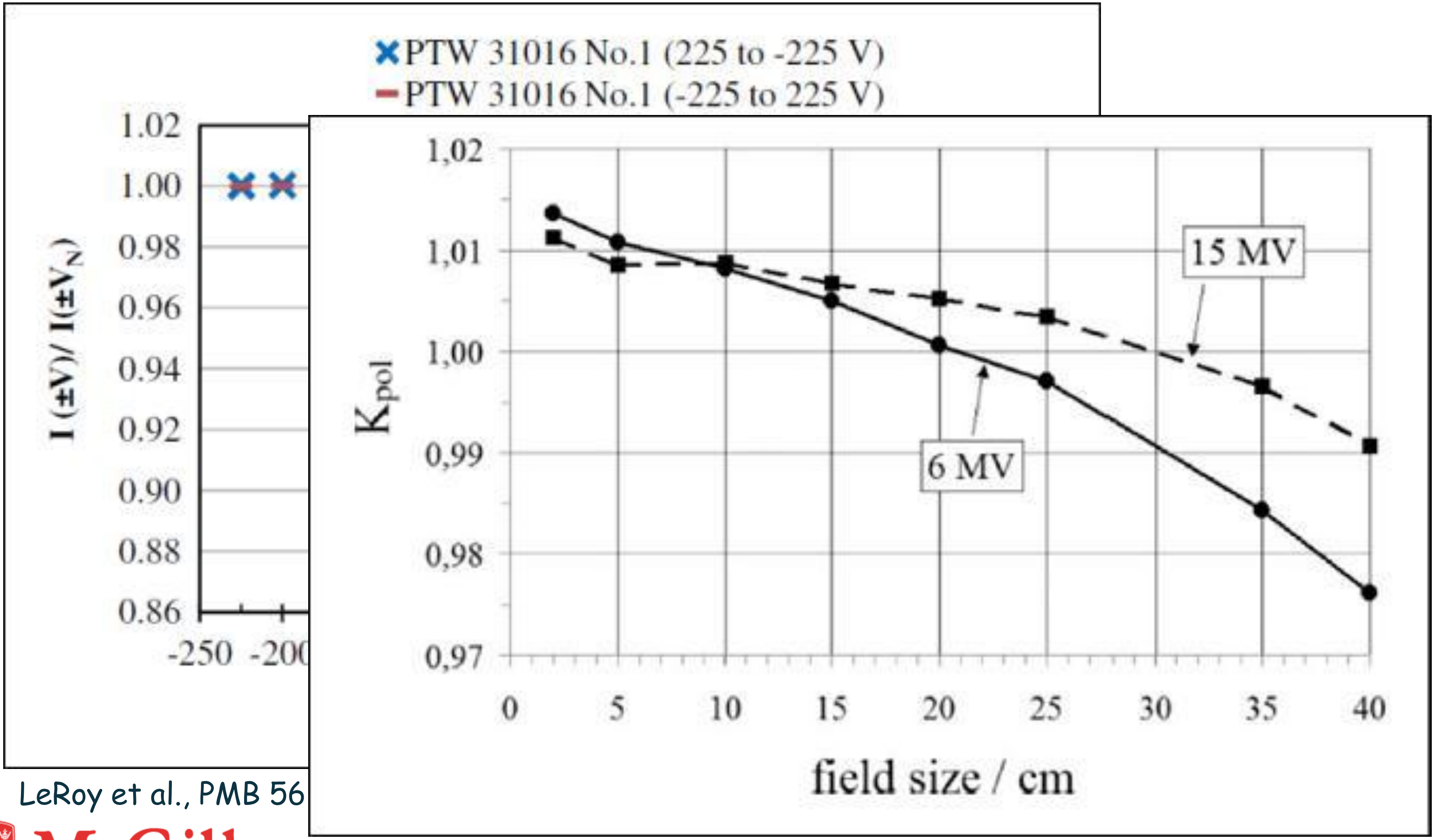
- Required equipment, detectors, phantoms for *msr* dosimetry

- Required equipment, detectors, phantoms for relative dosimetry

Ch 5 – Practical implementation msr dosimetry

- Reference conditions for beam quality and *msr* dosimetry
- Overall correction factors for ionization chambers
- Correction for influence quantities
- Measurement in plastic phantoms and cross-calibration

Ionization chambers, recombination, polarity



LeRoy et al., PMB 56

Agostinelli et al., Med Phys 35:3293-301 (2008)

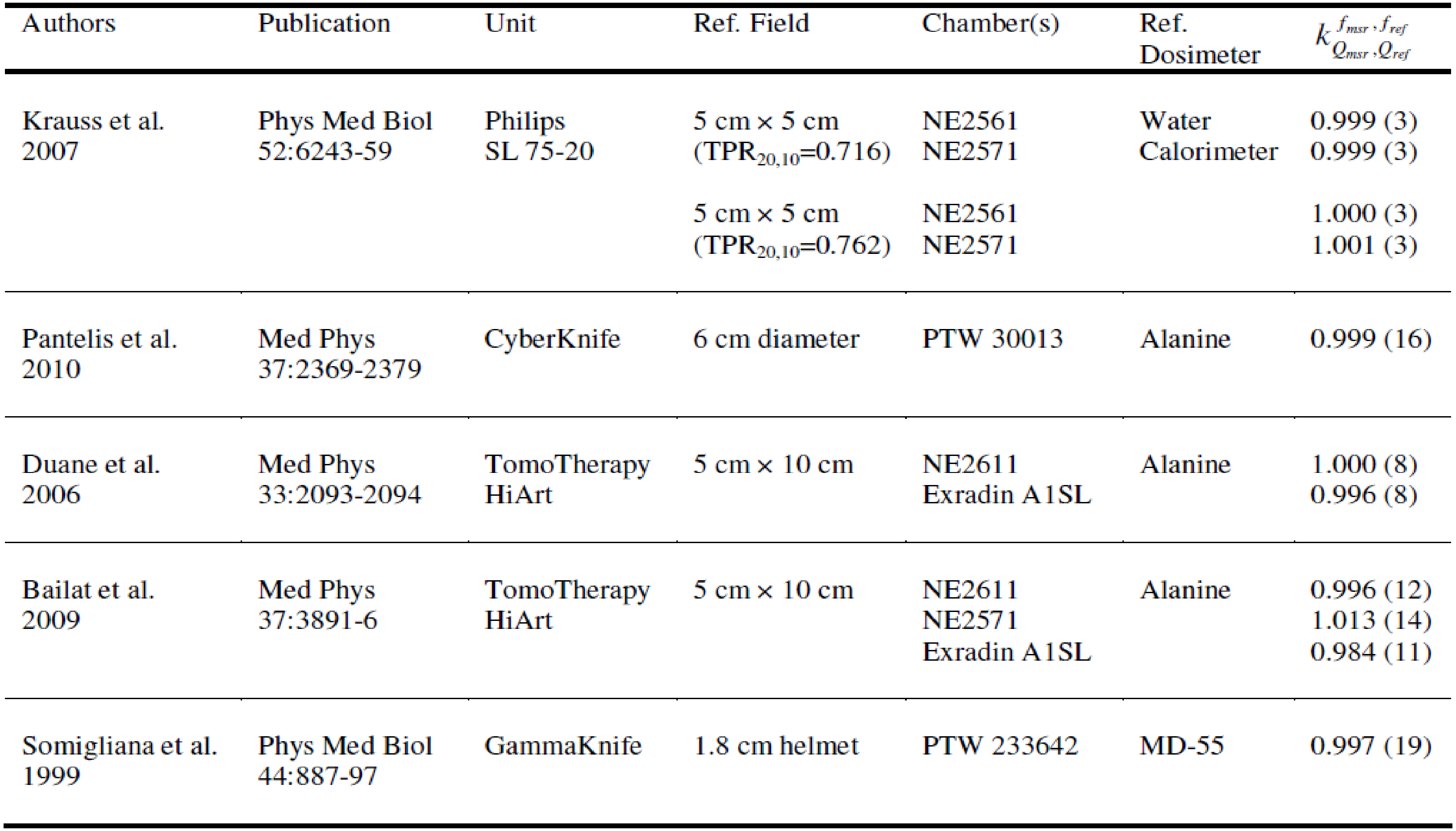
Note on the use of plastic phantoms

$$D^{\mathrm{f}_{\mathrm{msr}}}_{\mathrm{w,Q}}(z_{\mathrm{ref}}) = M^{f_{\mathrm{msr}}}_{\mathrm{pl,Q}_{\mathrm{msr}}}(z_{\mathrm{eq,pl}}) N^{f_{\mathrm{ref}}}_{\mathrm{D,w,Q}_0} k^{f_{\mathrm{ref}}}_{\mathrm{Q}_{\mathrm{msr}},\mathrm{Q}_0} k^{\mathrm{w,pl}}_{Q_{\mathrm{msr}}}$$

$$k_Q^{\mathrm{w,pl}} = \frac{D_{\mathrm{w,Q}}(z_{\mathrm{ref}})}{D_{\mathrm{pl,Q}}(z_{\mathrm{eq,pl}})} \frac{(s_{\mathrm{pl,air}})_Q}{(s_{\mathrm{w,air}})_Q} \frac{p_{\mathrm{Q,pl}}}{p_{\mathrm{Q,w}}}$$

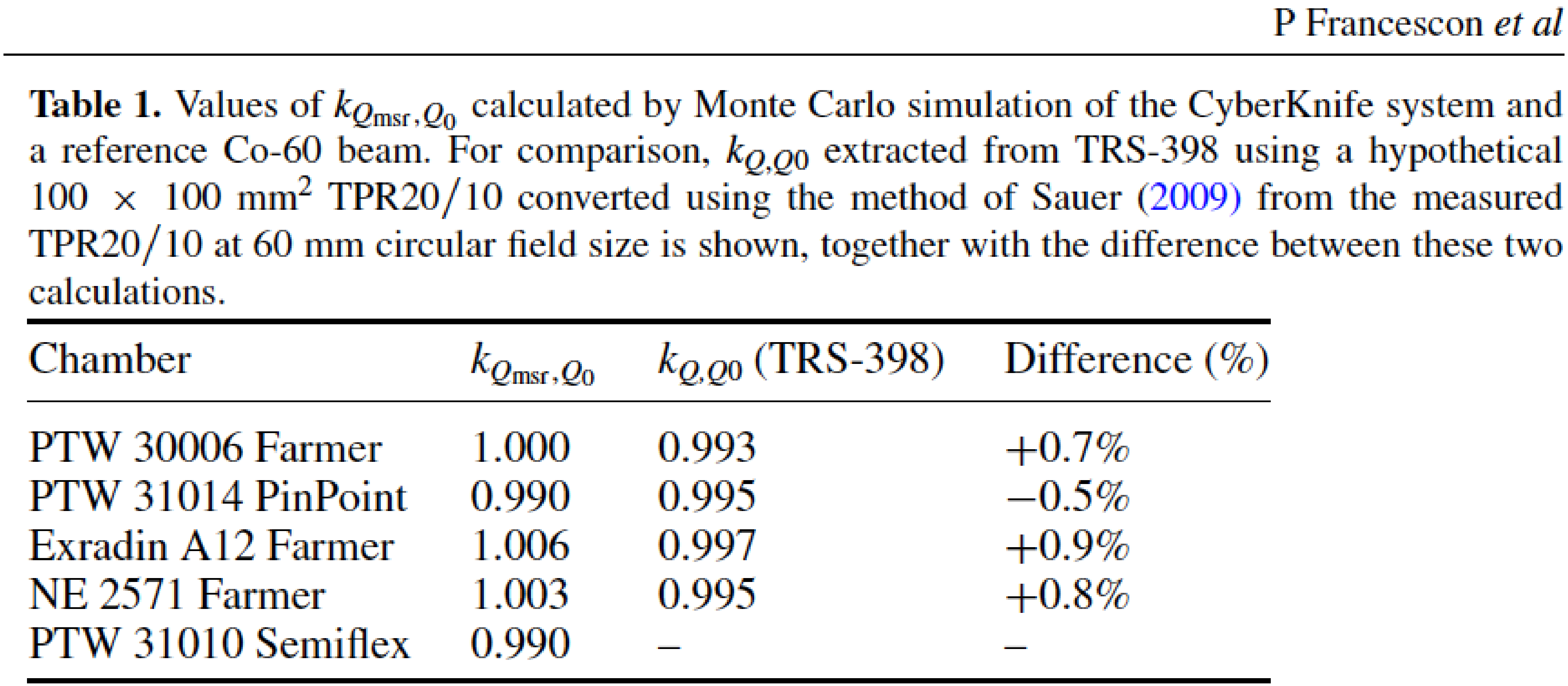
(Seuntjens et al 2005, Med. Phys. 32: 2945)

Ch 5 – Practical implementation msr dosimetry / availability $k_{Q_{msr},Q_{ref}}^{f_{msr},f_{ref}}$ data



Authors	Publication	Unit	Ref. Field	Chamber(s)	Ref. Dosimeter	$k_{Q_{msr},Q_{ref}}^{f_{msr},f_{ref}}$
Krauss et al. 2007	Phys Med Biol 52:6243-59	Philips SL 75-20	5 cm × 5 cm ($TPR_{20,10}$=0.716)	NE2561 NE2571	Water Calorimeter	0.999 (3) 0.999 (3)
			5 cm × 5 cm ($TPR_{20,10}$=0.762)	NE2561 NE2571		1.000 (3) 1.001 (3)
Pantelis et al. 2010	Med Phys 37:2369-2379	CyberKnife	6 cm diameter	PTW 30013	Alanine	0.999 (16)
Duane et al. 2006	Med Phys 33:2093-2094	TomoTherapy HiArt	5 cm × 10 cm	NE2611 Exradin A1SL	Alanine	1.000 (8) 0.996 (8)
Bailat et al. 2009	Med Phys 37:3891-6	TomoTherapy HiArt	5 cm × 10 cm	NE2611 NE2571 Exradin A1SL	Alanine	0.996 (12) 1.013 (14) 0.984 (11)
Somigliana et al. 1999	Phys Med Biol 44:887-97	GammaKnife	1.8 cm helmet	PTW 233642	MD-55	0.997 (19)

Correction factor data $k^{f_{msr},f_{ref}}_{Q_{msr},Q_{ref}}$ (cont'd)



P Francescon *et al*

Table 1. Values of k_{Q_{msr},Q_0} calculated by Monte Carlo simulation of the CyberKnife system and a reference Co-60 beam. For comparison, $k_{Q,Q0}$ extracted from TRS-398 using a hypothetical 100 × 100 mm^2 TPR20/10 converted using the method of Sauer (2009) from the measured TPR20/10 at 60 mm circular field size is shown, together with the difference between these two calculations.

Chamber	k_{Q_{msr},Q_0}	$k_{Q,Q0}$ (TRS-398)	Difference (%)
PTW 30006 Farmer	1.000	0.993	+0.7%
PTW 31014 PinPoint	0.990	0.995	−0.5%
Exradin A12 Farmer	1.006	0.997	+0.9%
NE 2571 Farmer	1.003	0.995	+0.8%
PTW 31010 Semiflex	0.990	–	–

Francescon et al: Phys. Med. Biol. 57 (2012) 3741–3758

Ch 6 – Practical implementation relative dosimetry

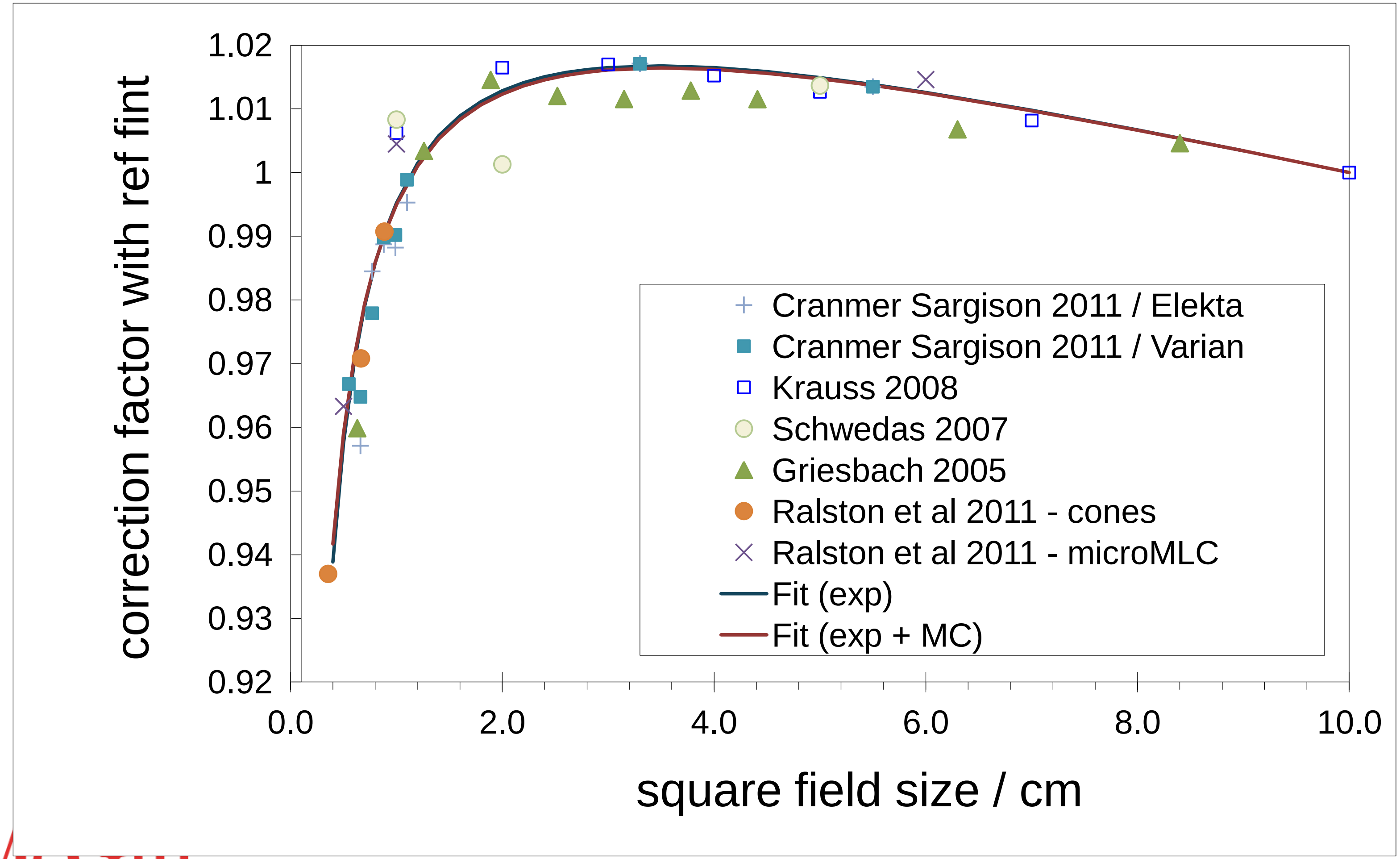
- Required equipment, detectors, phantoms
- Measurements of profiles and field output factors
- Correction factors for determination of output factors

Ch 6 – Practical implementation relative dosimetry / correction factors for OF

- Examples of different sources of correction factors will be further discussed in the next presentation (I. Das)
- IAEA-AAPM code of practice data tables is based on a vetted set of correction factor from the literature
- Uncertainty analysis has been performed

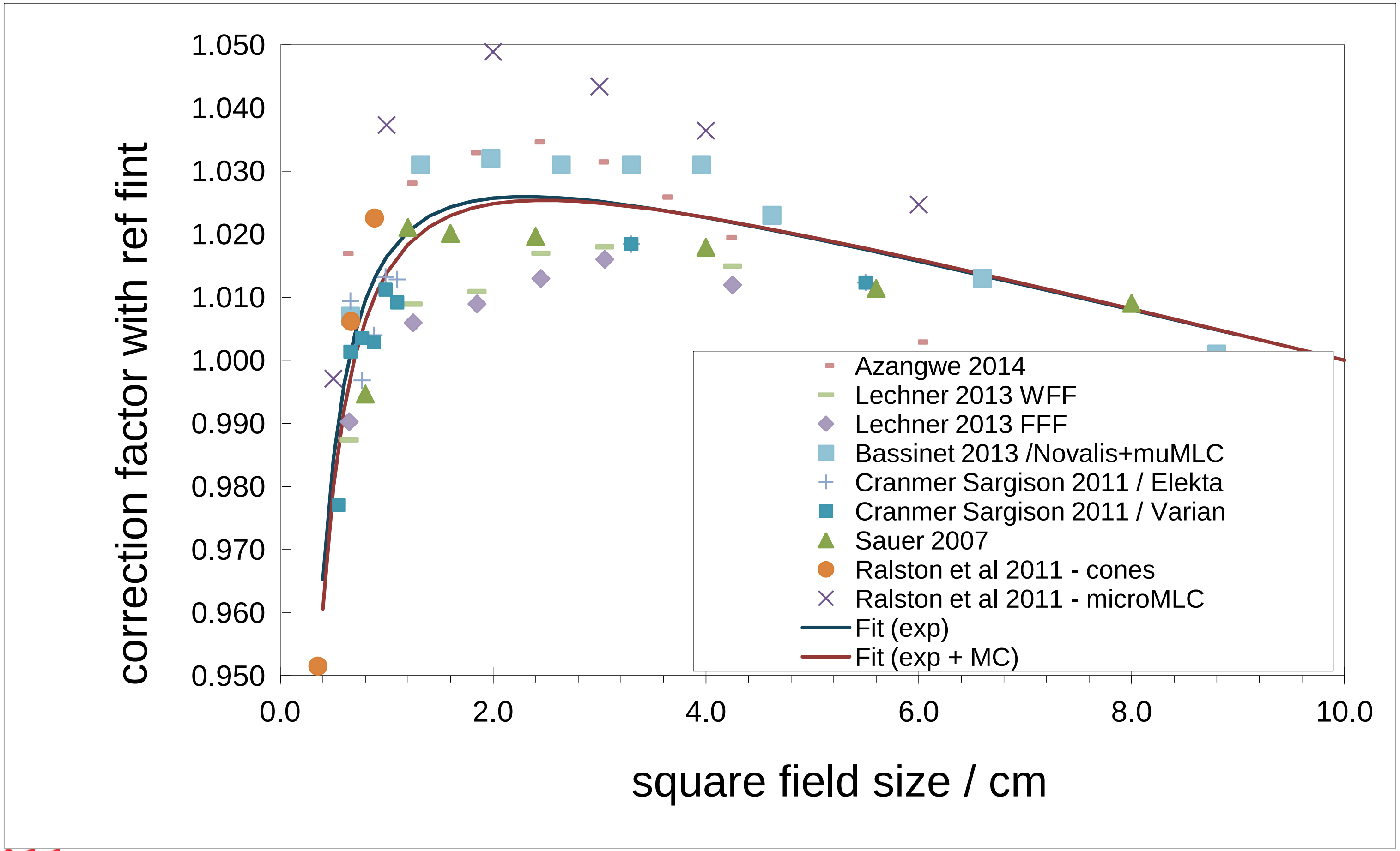
Field output factors – correction factors - example

- PTW-60012 – unshielded diode



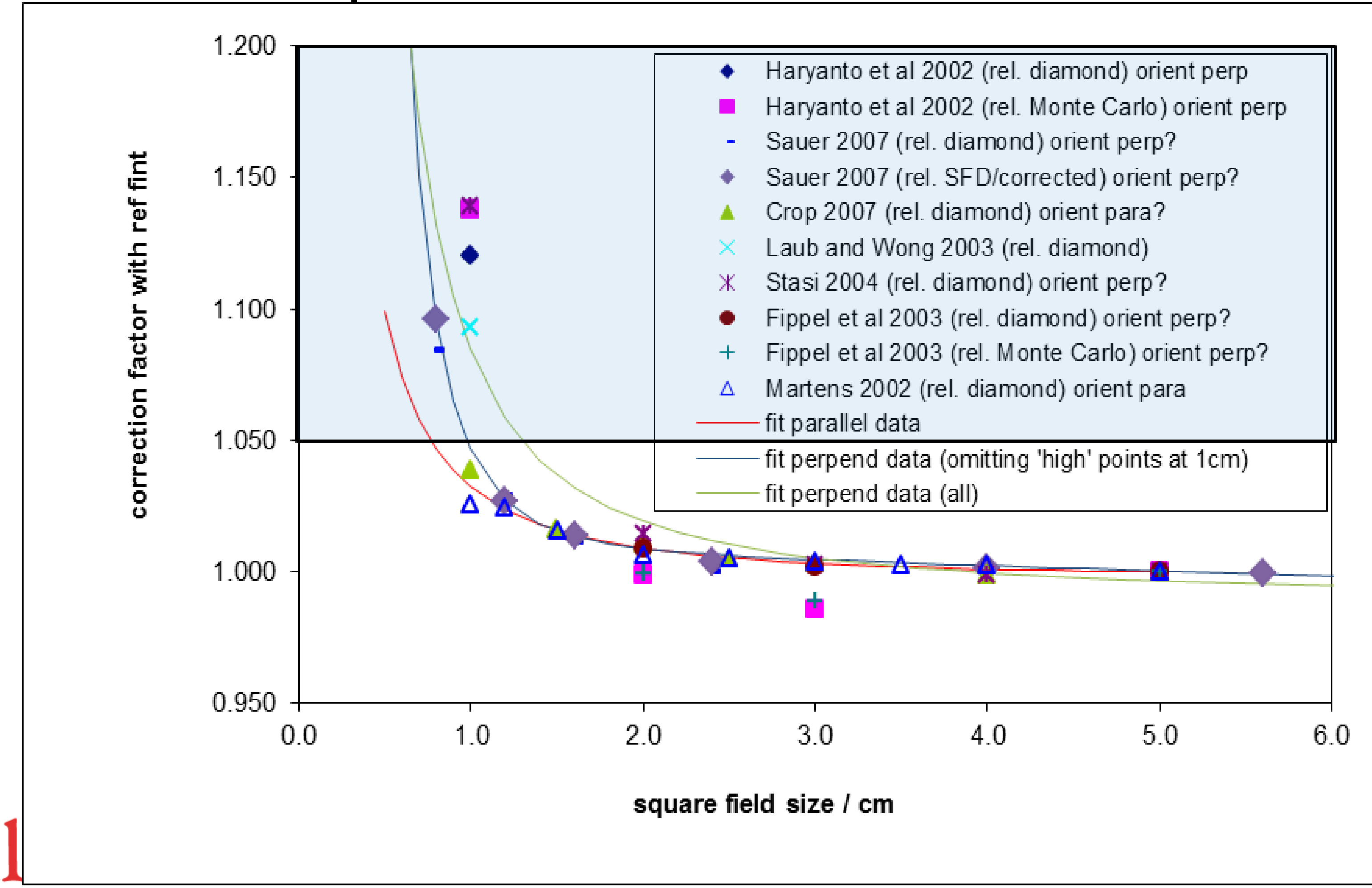
Field output factors – correction factors - diode

- IBA SFD – unshielded diode

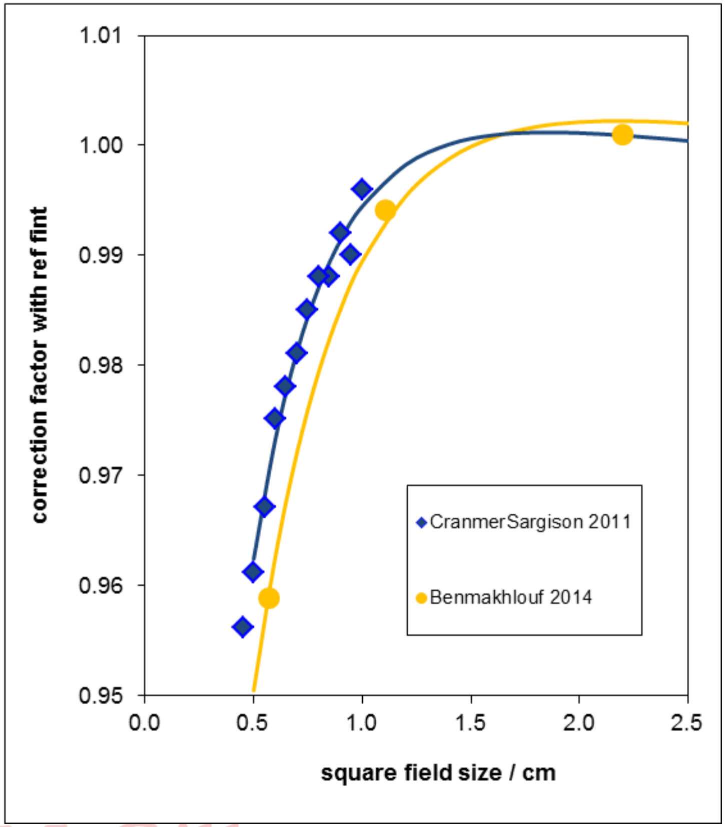


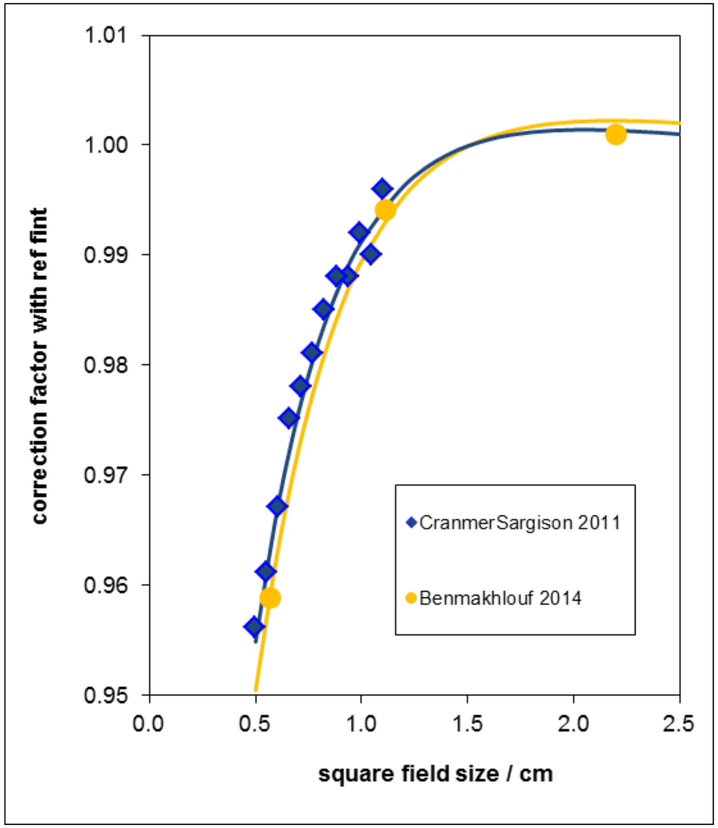
Field output factors – correction factors

- PTW-31006 - Pinpoint



Uncertainty in correction factor introduced due to field size definition





Cranmer Sargison et al Med. Phys. **38**, 6592–6602 (2011)

Benmakhlouf et al Med. Phys. **41**, 041711 (2014)

Output factors – validation methodology

$$\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = \frac{D_{w,Q_{clin}}^{f_{clin}}}{D_{w,Q_{msr}}^{f_{msr}}} = \frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{msr}}^{f_{msr}}} \cdot \left[\frac{D_{w,Q_{clin}}^{f_{clin}} \Big/ M_{Q_{clin}}^{f_{clin}}}{D_{w,Q_{msr}}^{f_{msr}} \Big/ M_{Q_{msr}}^{f_{msr}}} \right] = \frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{msr}}^{f_{msr}}} \cdot k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$$

Where:

$$k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = \frac{D_{w,Q_{clin}}^{f_{clin}}}{D_{w,Q_{msr}}^{f_{msr}}} \cdot \frac{M_{Q_{msr}}^{f_{msr}}}{M_{Q_{clin}}^{f_{clin}}}$$

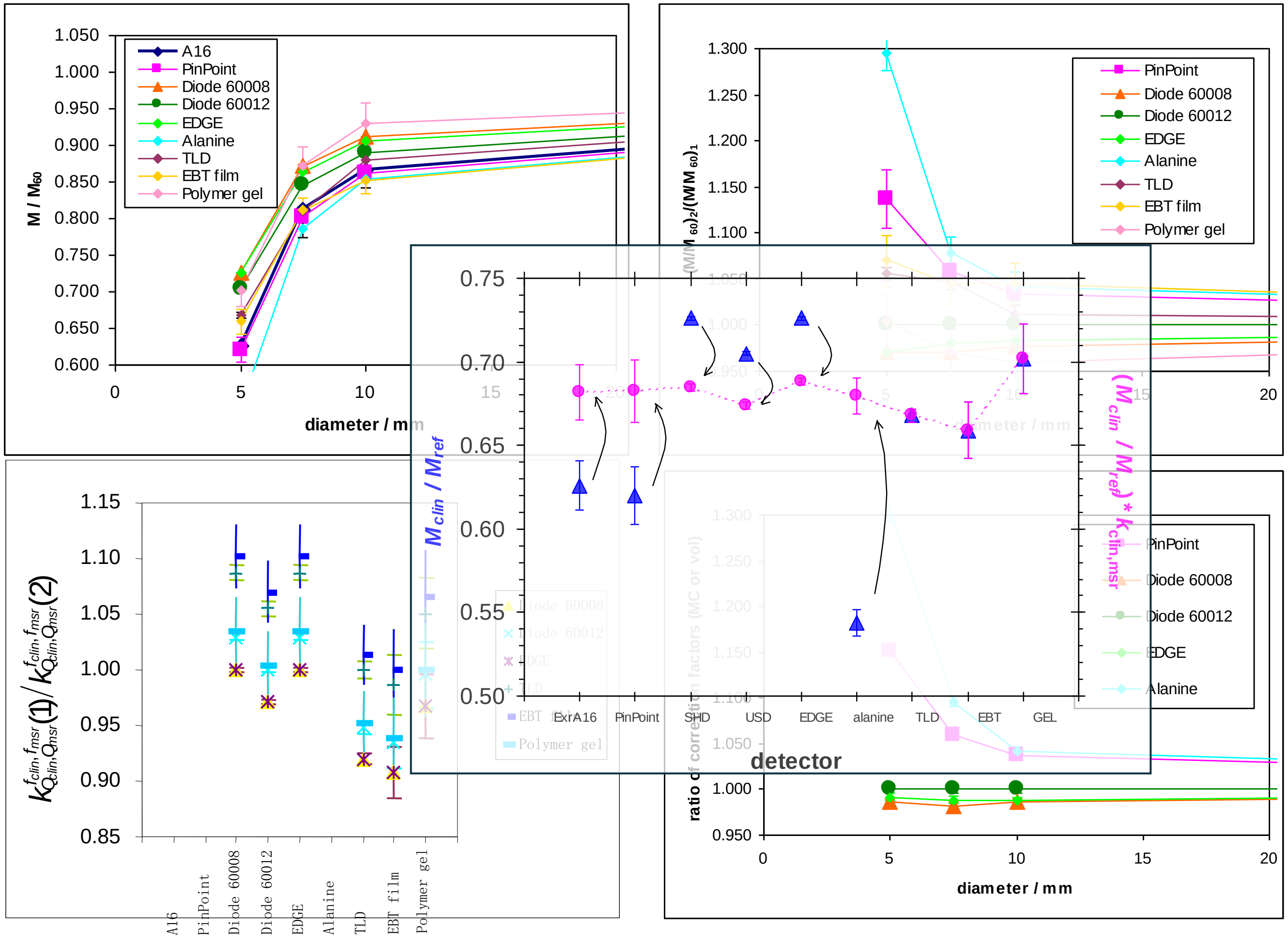
$$\frac{k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}(1)}{k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}(2)} = \frac{M_{Q_{msr}}^{f_{msr}}(1)}{M_{Q_{clin}}^{f_{clin}}(1)} \cdot \frac{M_{Q_{clin}}^{f_{clin}}(2)}{M_{Q_{msr}}^{f_{msr}}(2)} = \frac{M_{rel,Q_{clin}}^{f_{clin}}(2)}{M_{rel,Q_{clin}}^{f_{clin}}(1)}$$

Output factors – example CyberKnife

Pantelis et al.
2010 Med Phys
37: 2369

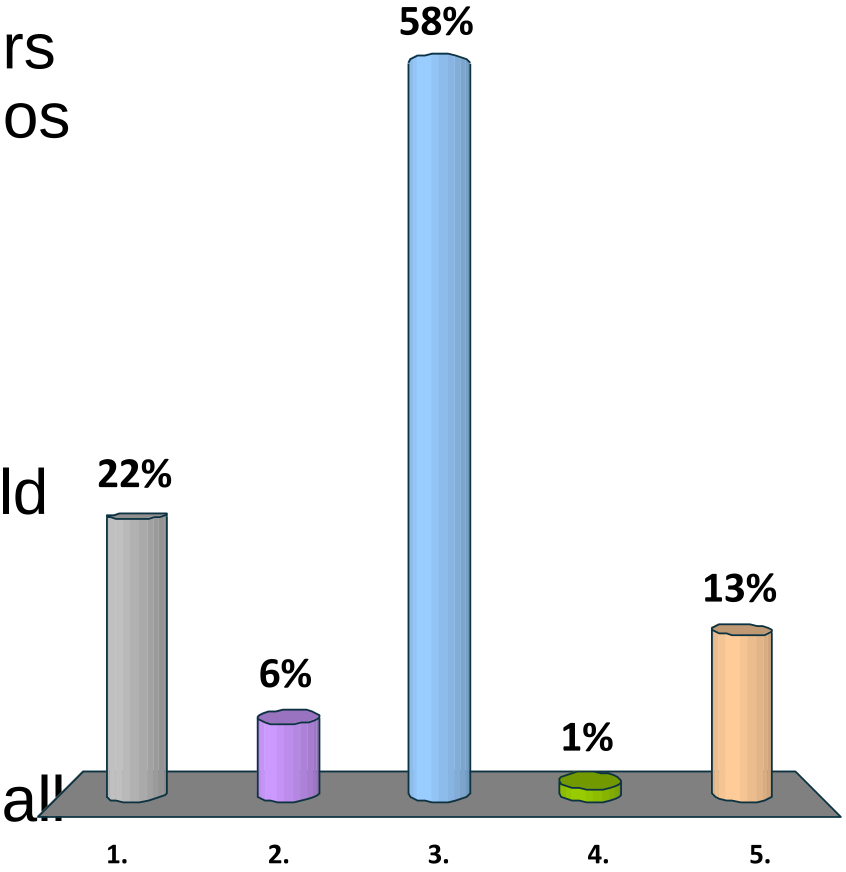
Slide courtesy:
H. Palmans

McGill



For what purpose is the measurement of the beam quality specifier required?

1. To specify the correction factors to be applied to the output ratios measured in small fields
2. To specify small field output factors
3. To specify the beam quality correction factor in the msr field
4. To ensure the beam is of adequate quality
5. To specify the absorbed dose calibration coefficient for a small field



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- Correct answer: 3 To specify the $k_{Qmsr,Qref}$ beam quality correction factor in the msr field

- Discussion: In general, no beam quality measurement is performed in small fields, only in *msr* fields.

- References:
  - Palmans 2012 Med Phys 39: 5513

Conclusions

- Solutions to most small-field dosimetry problems have been described and translated in formalised procedures
- The IAEA CoP will be coming out in the very near future – timeline < 6 months