Small field radiation therapy: physics and recent recommendations from IAEA and ICRU

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Educational Objectives

- To review the physics of small fields
- To review detectors suitable for small fields
- To provide an overview of the IAEA small field dosimetry recommendations
- To provide an overview of the content of the ICRU report on Prescribing, Reporting and Recording of Small Field Radiation Therapy

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- Physics of small field radiation therapy
- Dosimetric challenges in small fields
  - Detector suitability for small field dosimetry
  - Correction factors for nonstandard reference fields
  - Correction factors for small fields
  - Beam quality specification in nonstandard reference fields
  - Uncertainties
- Overview of the IAEA Code of Practice
- Overview of the ICRU recommendations on “Reporting and Recording of Small Field Radiation Therapy”
- Conclusions

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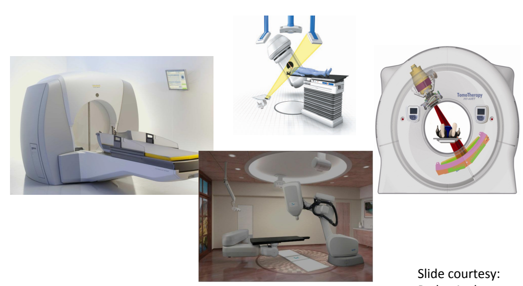
Specialized radiation equipment



Slide courtesy: Pedro Andreo

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Specialized radiation equipment

- Characteristics that lead to dosimetric issues of two kinds:
  - Reference dose calibration
    - Reference fields are not 10 x 10 cm², SSD/SAD is not 100 cm, etc; they are called "machine-specific reference fields" (*msr*)
    - Flattening filter-free beams, beam quality specification
  - Output factors
    - Small fields
    - Detector correction factors
- We will first review the basics of small field physics, then come back to these two items

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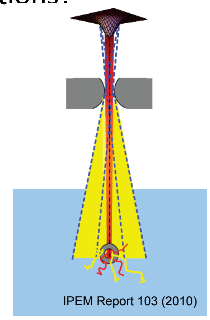
What constitutes small-field conditions?

- Beam-related small-field conditions
  - the existence of lateral charged particle disequilibrium
  - change in photon fluence spectrum -> beam quality
  - 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



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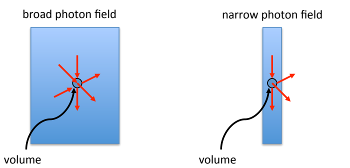
Lateral charged particle loss



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

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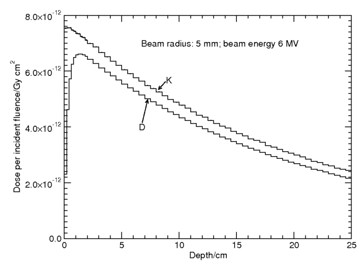
Lateral charged particle loss



In small fields there is **no depth** at which D ≈ K_{col}

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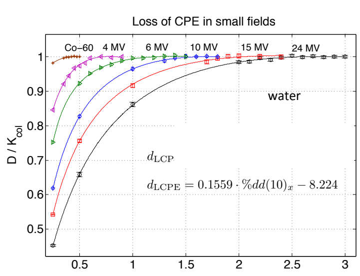
Lateral charged particle loss



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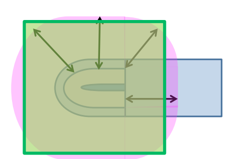
Detector size relative to field size

- 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

  fmsr < 6 x 6 cm²

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

$$r_{LCPE}[cm] = 0.07797 \cdot \%dd(10)_x - 4.112$$



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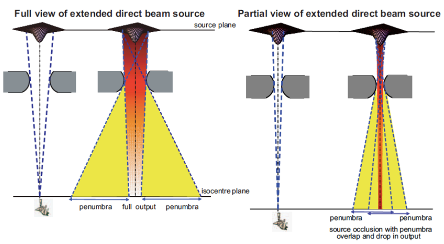
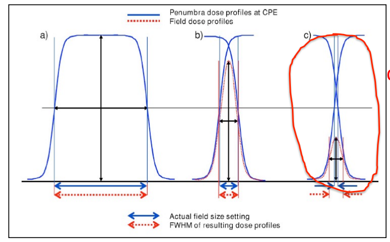
Source occlusion



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

Source occlusion

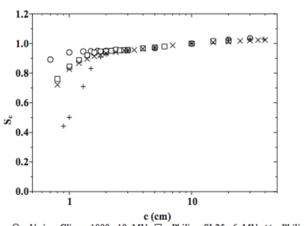


definition of field size is not unique!!

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

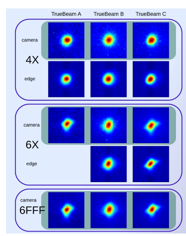
Overlapping of beam penumbras

Source occlusion – S_c and x-ray source sizes for different Linacs.



○—Varian Clinac 1800, 10 MV, □—Philips SL25, 6 MV, ×—Philips SL75-5, 6 MV, +—Varian Clinac 6/100, 6 MV. [Adapted from Zhu *et al.* (Ref. 100)].

Zhu et al, Med Phys 36:5261 (2009)



Measured spot sizes for the Varian TrueBeam for different beams. Data and Figure from Sawkey et al (Sawkey, et al., 2012). The dimension of one film square is 8 mm x 8 mm.

Consequences of partial occlusion of the source

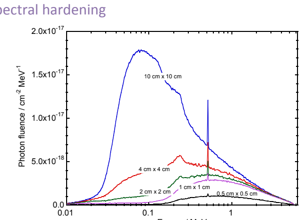
- Field size definition
  - Apparent widening
  - Overlapping penumbra
    - The nominal field size setting does not correspond to FWHM of the dose profile
- Drastic reduction in dose on the central axis ("output")
  - These considerations have a severe impact on the data required in the treatment planning system (TPS)

Detector issues in small field dosimetry

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

Spectral changes

- The photon fluence spectrum is modified as a function of field size
  - Spectral hardening

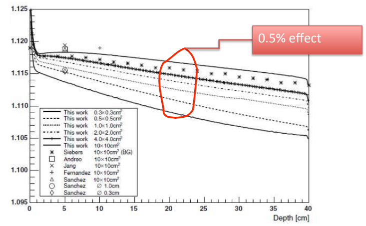


6 MV photon spectrum in a small water volume as a function of field size

Benmakhlouf Sempau Andreo *Med. Phys.* **41** (2014)

Stopping power ratio water to air $s_{\mathrm{w,air}}$

Very small effects!



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

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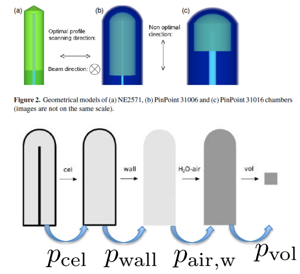
Ionization chamber perturbation effects

PP31006 and PP31016 chambers



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

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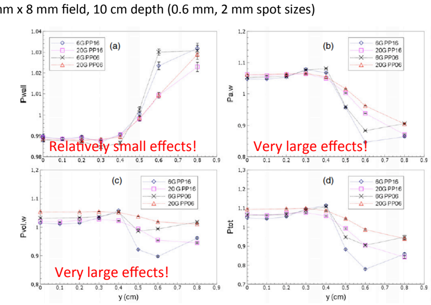
Magnitude of correction factors on and off-axis

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



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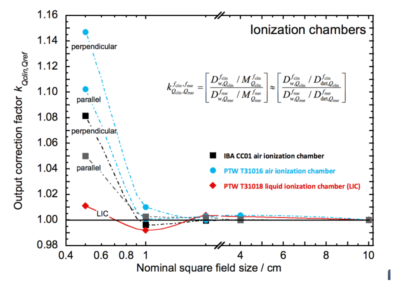
Crop et al., Phys Med Biol 54:2951 (2009)

Correction factors for ionization chambers



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Benmahklouf and Andreo (2013)

Issues with diode detectors

- Even though diode has small active volume, thus small P_{vol} effect, it may give errors due to energy dependences for low energy photons.
- This applies output measurements for very small fields and depth dose measurement for very large fields.

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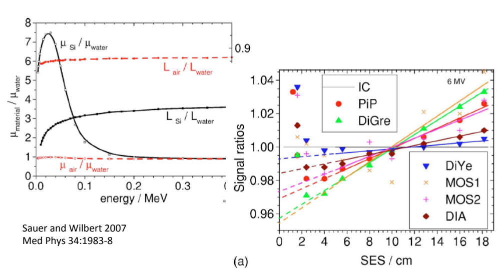
Diodes for small field dosimetry



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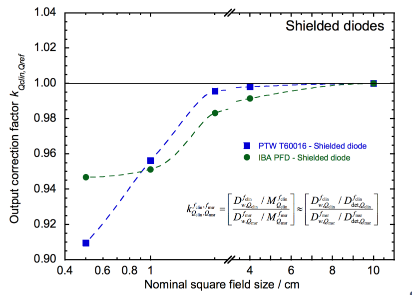
Shielded and unshielded diodes



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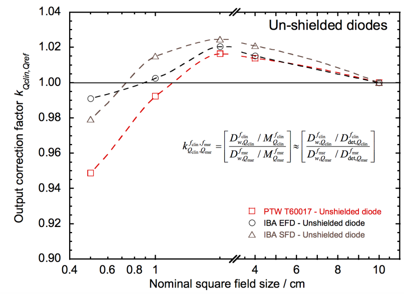
Benmahklouf and Andreo (2013)

Shielded and unshielded diodes



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Benmahklouf and Andreo (2013)

Nonstandard reference fields (*msr*)

- 3 issues
  - Field size is not 10 x 10 cm^2
    - recommendation for equivalent field size
  - FFF versus WFF beams
    - Beam quality correction factors
    - Non-uniformity of the profile
  - Chamber types suitable for reference dosimetry

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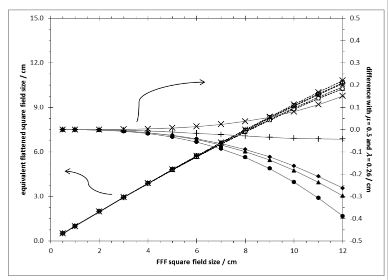
Equivalent square fields - *msr*

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

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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Equivalent square fields - *msr*

WFF

Table 5.7: **EQUIVALENT SQUARE *msr* FIELD SIZE (IN CM) OF RECTANGULAR FIELDS WITH DIMENSIONS X AND Y AND OF CIRCULAR FIELDS WITH DIAMETER Ø FOR FLATTENED BEAMS.**

Y (cm) X (cm)	12	11	10	9	8	7	6	5	4	3
12	12.0	11.5	10.9	10.3	9.6	8.9	8.1	7.2	6.2	5.1
11		11.0	10.5	9.9	9.3	8.6	7.8	7.0	6.0	5.0
10			10.0	9.5	8.9	8.3	7.5	6.8	5.9	4.8
9				9.0	8.5	7.9	7.2	6.5	5.7	4.7
8					8.0	7.5	6.9	6.2	5.4	4.5
7						7.0	6.5	5.9	5.1	4.3
6							6.0	5.5	4.8	4.1
5								5.0	4.5	3.8
4									4.0	3.4
3										3.0
Ø (cm)	12	11	10	9	8	7	6	5	4	3
	10.7	9.8	8.9	8.0	7.1	6.2	5.4	4.5	3.6	2.7

6 MV FFF

Table 5.8: **EQUIVALENT SQUARE *msr* FIELD SIZE (IN CM) OF RECTANGULAR FIELDS WITH DIMENSIONS X AND Y AND OF CIRCULAR FIELDS WITH DIAMETER Ø FOR 6 MV FLATTENING-FILTER-FREE BEAMS.**

Y (cm) X (cm)	12	11	10	9	8	7	6	5	4	3
12	11.2	10.8	10.3	9.8	9.2	8.5	7.8	7.0	6.0	5.0
11		10.4	9.9	9.4	8.9	8.3	7.6	6.8	5.9	4.9
10			9.5	9.1	8.6	8.0	7.3	6.6	5.7	4.8
9				8.7	8.2	7.6	7.0	6.3	5.5	4.6
8					7.8	7.3	6.7	6.1	5.3	4.5
7						6.8	6.3	5.8	5.1	4.3
6							5.9	5.4	4.8	4.0
5								4.9	4.4	3.8
4									4.0	3.4
3										3.0
Ø (cm)	12	11	10	9	8	7	6	5	4	3
	10.2	9.4	8.6	7.8	7.0	6.1	5.3	4.4	3.5	2.7

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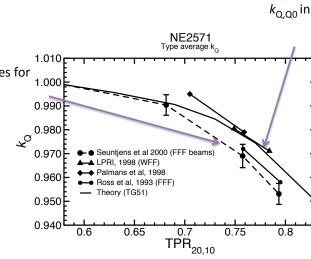
FFF beams

Experimental values for $k_{Q,Q0}$ in WFF beams

Experimental values for $k_{Q,Q0}$ in FFF beams



Seuntjens et al 2000

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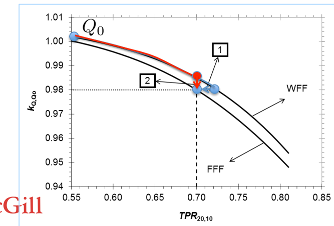
Application to FFF beams

- *Q* refers to a hypothetical field at the same machine, i.e. is FFF $k_{Q^{\mathrm{FFF}},Q_0^{\mathrm{WFF}}}$

$$D^{f_{\mathrm{msr}}}_{w,Q^{\mathrm{FFF}}_{\mathrm{msr}}} = M^{f_{\mathrm{msr}}}_{Q^{\mathrm{FFF}}_{\mathrm{msr}}} \cdot N_{D,w,Q_0^{\mathrm{WFF}}} \cdot k_{Q^{\mathrm{WFF}},Q_0^{\mathrm{WFF}}} \cdot k_{Q^{\mathrm{FFF}},Q^{\mathrm{WFF}}} \cdot k^{f_{\mathrm{msr}},f_{\mathrm{ref}}}_{Q^{\mathrm{FFF}}_{\mathrm{msr}},Q^{\mathrm{FFF}}}$$



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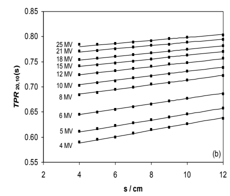
Beam quality: nonstandard reference fields

$$\%\mathrm{TPR}_{20,10}(10) = \frac{\%\mathrm{TPR}_{20,10}(S) + c\ (10 - S)}{1 + c\ (10 - S)}$$

$$c = (16.15 \pm 0.12) \times 10^{-3} \text{ for } 4 \text{ cm} \ \leq\ S \ \leq\ 12 \text{ cm}$$



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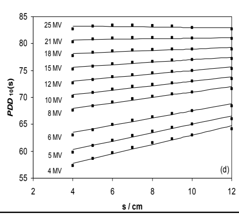
Beam quality: nonstandard reference fields

$$\%dd(10,10) = \frac{\%dd(10,S) + 80\ c\ (10 - S)}{1 + c\ (10 - S)}$$

$$c = (53.4 \pm 1.1) \times 10^{-3} \text{ for } 4 \text{ cm} \ \leq\ S \ \leq\ 12 \text{ cm}$$



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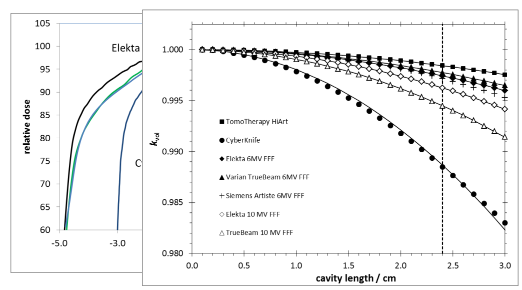
Volume averaging in FFF beams



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IAEA-AAPM protocol

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IAEA-AAPM protocol, outline

- Chapter 1 – Introduction
- Chapter 2 - Physics of small field dosimetry
- Chapter 3 – Concepts and Formalism
- Chapter 4 – Detectors and Equipment
- Chapter 5 - Code of practice for reference dosimetry of machine-specific reference fields
- Chapter 6 - Code of practice for relative dosimetry of small fields
- Appendix A - Determination of beam quality correction factors for reference dosimetry and their uncertainty estimates
- Appendix B - Determination of field output correction factors and their uncertainty estimates

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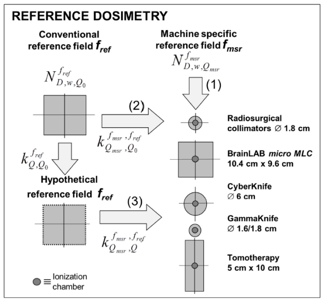
IAEA-AAPM protocol – Reference fields



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Ch 3 Formalism
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

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

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Ch 3 Formalism for FFF beams

- Identical formalism

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

$$D_{w,Q_{\mathrm{msr}}^{\mathrm{FFF}}}^{f_{\mathrm{msr}}} = M_{Q_{\mathrm{msr}}^{\mathrm{FFF}}}^{f_{\mathrm{msr}}} \; N_{D,w,Q_0^{\mathrm{WFF}}}^{f_{\mathrm{ref}}} \; \overbrace{k_{Q^{\mathrm{WFF}},Q_0^{\mathrm{WFF}}}^{f_{\mathrm{ref}}} \; k_{Q^{\mathrm{FFF}},Q^{\mathrm{WFF}}}^{f_{\mathrm{ref}}}} \times k_{Q_{\mathrm{msr}}^{\mathrm{FFF}},Q^{\mathrm{FFF}}}^{f_{\mathrm{msr}},f_{\mathrm{ref}}}$$

$$\mathrm{BQI}_{\mathrm{FFF}} \equiv \mathrm{BQI}_{\mathrm{WFF}}$$

Stopping power ratios and volume averaging corrections

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Ch 3. Formalism plastic phantoms

$$D_{\mathrm{w},Q_{\mathrm{msr}}}^{f_{\mathrm{msr}}}(z_{\mathrm{ref}}) = M_{\mathrm{plastic},Q_{\mathrm{msr}}}^{f_{\mathrm{msr}}}(z_{\mathrm{eq,plastic}}) \; N_{D,\mathrm{w},Q_0}^{f_{\mathrm{ref}}} \; k_{Q_{\mathrm{msr}},Q_0}^{f_{\mathrm{msr}},f_{\mathrm{ref}}} \; k_{Q_{\mathrm{msr}}}^{\mathrm{w,plastic}}$$

$$k_{Q_{\mathrm{msr}}}^{\mathrm{w,plastic}} = \frac{M_{\mathrm{w},Q_{\mathrm{msr}}}^{f_{\mathrm{msr}}}(z_{\mathrm{ref}})}{M_{\mathrm{plastic},Q_{\mathrm{msr}}}^{f_{\mathrm{msr}}}(z_{\mathrm{eq,plastic}})}$$

Exception: GammaKnife, plastic conversion integrated within correction factor.

$$z_{\mathrm{eq,plastic}} = \frac{\rho_{\mathrm{w}}}{\rho_{\mathrm{plastic}}} \; \frac{\left(\frac{Z}{A}\right)_{\mathrm{w}}}{\left(\frac{Z}{A}\right)_{\mathrm{plastic}}} \; z_{\mathrm{ref}}$$

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Ch 3. 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

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

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Ch 4 – Instrumentation

- Equipment for machine-specific reference dosimetry
- Required equipment, detectors, phantoms for relative dosimetry

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Ch 4 – Equipment for machine-specific reference dosimetry

- (a) One or more ionization chambers, including the permanently attached cable and connector. The ionization chambers chosen should be specifically designed for the intended purpose such as modality and radiation quality.
- (b) One or more phantoms with waterproof sleeves if needed.
- (c) A measuring assembly (electrometer), often separately calibrated in terms of charge or current per scale division.
- (d) The dosimeter system also includes one or more stability check devices, specifically designed for the chosen ionization chamber.
- (e) Calibrated thermometer and barometer.

Ch 4 - Ionization chambers

- f_{msr} >= 6 x 6 cm^2 equivalent
  - *WFF*
    - robust air-filled chambers, often waterproof and simple to use for reference in-phantom measurements: V_{eff} 0.3 cm^3 and 1 cm^3 (i.e., Farmer type 0.6 cm^3)
  - *FFF*
    - a length shorter than that of typical Farmer-type chamber given the non-uniformity of the lateral beam profile: V_{eff} 0.1 cm^3 and 0.3 cm^3

Ch 4 - Ionization chambers

Parameter	Specification
Chamber setting	Monitor chamber response with accumulated dose, equilibrium should in < 5 min; initial and equilibrium reading <0.5%.
Leakage & Polarity effect	Smaller than 0.1% of the chamber reading. Smaller than 0.4% of the chamber reading. The polarity energy dependence should be less than 0.3% between ^{60}Co and 10 MV.
Re-combination	1. The correction must be linear with dose per pulse. 2. Initial recombination (dose rate or dose-per-pulse independent part of the total charge recombination) <0.2% at 300 V. 3. For pulsed beams, a plot of $1/M_Q$ (charge reading) vs 1/V hould be linear at least for practical values of V . 4. For continuous beams, a plot of $1/M_Q$ vs $1/V^2$ should be linear 5. The difference in the initial recombination correction obtained with opposite polarities should be less than 0.1%.
Chamber stability	Change in calibration coefficient over a typical recalibration period of 2 y below 0.3%. Same figure for long term (> 5 y) stability.
Chamber material	Wall material not exhibiting temperature and humidity effects.

Ch 4 – Ionization chambers

Table 4.2: **CHARACTERISTICS OF CYLINDRICAL IONIZATION CHAMBERS FOR REFERENCE DOSIMETRY OF *msr* FIELDS $f_{msr} \geq 6\,\mathrm{cm} \times 6\,\mathrm{cm}$.**

Ionization chamber type [a]	Cavity volume (cm^3)	Cavity length (mm)	Cavity radius (mm)	Wall material	Wall thickness (g cm^{-2})	Central electrode material [b]	Waterproof
Capintec PR-06C/G Farmer	0.65	22.0	3.2	C-552 [c]	0.050	C-552	N
Exradin A2 Spokas	0.53	11.4	4.8	C-552	0.176	C-552	Y
Exradin A12 Farmer	0.65	24.2	3.1	C-552	0.088	C-552	Y
Exradin A12S	0.25	11.6	3.1	C-552	0.088	C-552	Y
Exradin A19	0.63	25.0	3.1	C-552	0.088	C-552	Y
FZH TK 01	0.4	12.0	3.5	Delrin	0.071		Y
Nuclear Assoc 30-751 Farmer	0.69	23.0	3.1	Delrin	0.056	Aluminium	Y
Nuclear Assoc 30-752 Farmer	0.69	23.0	3.1	Graphite	0.072	Aluminium	Y
NE 2505/3, 3A Farmer	0.6	24.0	3.2	Graphite	0.065	Aluminium	N
NE 2571 Farmer	0.6	24.0	3.2	Graphite	0.065	Aluminium	N
NE 2611	0.33	9.2	3.7	graphite	0.090	Aluminium (hollow)	N
PTW 23331 rigid	1.0	22.0	4.0	PMMA [d]	0.060	Aluminium	N
PTW 23332 rigid	0.3	18.0	2.5	PMMA [d]	0.054	Aluminium	N
PTW 23333 (3 mm cap)	0.6	21.9	3.1	PMMA [e]	0.059	Aluminium	N
PTW 30001 Farmer	0.6	23.0	3.1	PMMA [d]	0.045	Aluminium	N
PTW 30010 Farmer	0.6	23.0	3.1	PMMA [d]	0.057	Aluminium	N
PTW 30002/30011 Farmer	0.6	23.0	3.1	Graphite	0.079	Graphite	N
PTW 30004/30012 Farmer	0.6	23.0	3.1	Graphite	0.079	Aluminium	N
PTW 30006/30013 Farmer	0.6	23.0	3.1	PMMA [d]	0.057	Aluminium	Y
PTW 31003/31013 Semiflex	0.3	16.3	2.8	PMMA [d]	0.078	Aluminium	Y
SNC 100730 Farmer	0.6	24.4	3.5	PMMA	0.060	Aluminium	N
SNC 100740 Farmer	0.6	24.4	3.5	Graphite	0.085	Aluminium	N
Victoreen Radocon III 555	0.3	23.0	2.4	polystyrene	0.117		N
Victoreen 30-348	0.3	18.0	2.5	PMMA	0.060		N
Victoreen 30-351	0.6	23.0	3.1	PMMA	0.060		N
Victoreen 30-349	1.0	22.0	4.0	PMMA	0.060		N
Victoreen 30-361	0.4	22.3	2.4	PMMA	0.144		N
IBA FC-65P Farmer	0.65	23.1	3.1	Delrin [e]	0.057	Aluminium	Y
IBA FC-65G Farmer	0.65	23.1	3.1	Graphite	0.073	Aluminium	Y
IBA FC-23C Farmer	0.23	8.8	3.1	C-552	0.070	C-552	Y
IBA CC13	0.25	10.0	3.0	C-552	0.070	C-552	Y

[a] Some of the ionization chambers listed are no longer commercially available but are included because they are still in use.
[b] Blanks correspond to no information available.
[c] C-552 is an air-equivalent electrically conducting plastic consisting of a mixture of polyvinylidene fluoride, carbon black, and silica.
[d] Polymethyl methacrylate ($C_5H_8O_2$), also known as acrylic; trade names are *Lucite, Plexiglas or Perspex*. Like most chamber types with non-conductive plastic walls, the chamber wall has an inner conductive layer made of graphite. For this chamber type, the thickness and density of the graphite layer are supplied in the chamber specifications.
[e] Polyoxymethylene (CH_2O). *Delrin* is a trade name.

Ch 4 - Ionization chambers

- f_{msr} < 6 x 6 cm^2 equivalent
  - If:

$$r_{\mathrm{LCPE}}/cm = 8.369 \cdot \mathrm{TPR}_{20,10}(10) - 4.382$$

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

  - the chamber must fulfill:

$$\mathrm{FWHM} \geq 2\, r_{\mathrm{LCPE}} + d$$

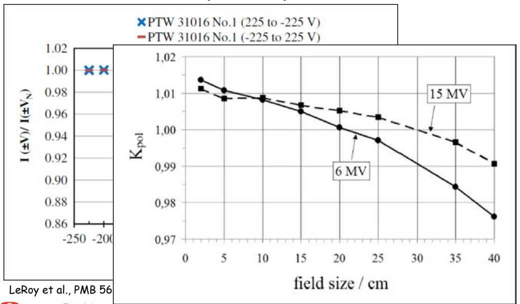
with *d* the largest outer dimension of the ionization chamber (FWHM is the full width half maximum of the field).

Ch4. Ionization chambers, f_{msr} < 6 x 6 cm^2

Table 4.3: **CHARACTERISTICS OF IONIZATION CHAMBERS SUITABLE FOR REFERENCE DOSIMETRY OF *msr* FIELDS f_{msr} < 6 cm × 6 cm.**

Ionization chamber type [a]	Cavity volume (cm^3)	Cavity length (mm)	Cavity radius (mm)	Wall material	Wall thickness (g cm^{-2})	Central electrode material [b]	Waterproof
Capintec PR-05P mini [c]	0.07	5.5	2.0	C-552	0.220	C-552	N
Exradin A1 mini Shonka (2 mm cap)	0.057	5.7	2.0	C-552	0.176	C-552	Y
Exradin A1SL mini Shonka slimline [c]	0.057	5.7	2.1	C-552	0.176	C-552	Y
Exradin A14 micro Shonka [c]	0.016	2.0	2.0	C-552	0.176	C-552	Y
Exradin A14SL micro Shonka slimline [c]	0.016	2.1	2.1	C-552	0.194	C-552	Y
Exradin A14P micro planar [c]	0.002	1.0	2.0	C-552	0.176	C-552	Y
Exradin A16 micro [c]	0.007	1.7	1.2	C-552	0.088	C-552	Y
Exradin A18 thimble	0.125	4.9	2.5	C552	0.176	C-552	Y
IBA CC01 [c]	0.01	3.6	1.0	C-552	0.088	Steel	Y
IBA CC04 [c]	0.04	3.6	2.0	C-552	0.070	C-552	Y
IBA CC08	0.08	4.0	3.0	C-552	0.070	C-552	Y
IBA CC13	0.13	5.8	3.0	C-552	0.070	C-552	Y
IBA CC13-S	0.13	5.8	3.0	PEEK/C-552	0.154	C-552	Y
Nuclear Assoc 30-750	0.03	3.6	2.0	C-552	0.068	C-552	Y
Nuclear Assoc 30-749	0.08	4.0	3.0	C-552	0.068	C-552	Y
Nuclear Assoc 30-744	0.13	5.8	3.0	C-552	0.068	C-552	Y
PTW 31010 semiflex	0.125	6.5	2.8	PMMA [d]	0.078	Aluminium	Y
PTW 31014 PinPoint [c]	0.015	5.0	1.0	PMMA [d]	0.085	Aluminium	Y
PTW 31015 PinPoint	0.030	5.0	1.45	PMMA [d]	0.085	Aluminium	Y
PTW 31016 PinPoint 3D [c]	0.016	2.9	1.45	PMMA [d]	0.085	Aluminium	Y
Victoreen Radocon II 555	0.1	4.3	2.5	Delrin [e]	0.529		N

Ch4. - Ionization chambers, recombination, polarity



LeRoy et al., PMB 56

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

Ch 4 - Phantoms

- Water phantoms
  - recommended
- Plastic phantoms
  - If not otherwise possible, should be water equivalent
  - Density and homogeneity should be verified
  - Note : GammaKnife

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Ch 4 – Detectors for small fields

Table 4.4: **RECOMMENDED CHARACTERISTICS OF DETECTORS FOR RELATIVE DOSIMETRY IN SMALL FIELDS. (ADAPTED FROM [13]).**

Detector properties[a]	Recommendation	Comments
Stability	Short-term detector response should be 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 should be 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^{-1}; detectors should be linear to better than 0.1% over the range of operation of the linac.	The range of dose rates are typical for WFF and FFF beams.
Dose per pulse linearity	A detector's response with changing dose per pulse should remain 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	Detectors for small field MV radiotherapy should have a useful energy range from ^{60}Co to 10 MV for photons.	An ideal detector should be 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.
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.

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Ch 4 – Detectors for small fields

		of interest.
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 should be such that the volume averaging correction is not larger than 5%.	
Orientation	The response of a detector should ideally be independent of the orientation of the detector with respect to the beam and the variation should be less than 0.5% for angles of less than 60° between the beam axis and the detector axis that should normally be aligned with the beam 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 should be 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	Corrections over the full range of working conditions should enable any influence to be reduced to better than 0.3%.	Measurements should ideally be independent of temperature, atmospheric pressure and humidity changes or be corrected accurately for these influence quantities.

[a] These are based on the assumption that leakage is negligible and appropriate polarity and recombination corrections are applied.

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Ch 4 – Detectors for small fields

Table 4.5: **SILICON DIODE, DIAMOND, LIQUID IONIZATION CHAMBER AND ORGANIC SCINTILLATOR DETECTORS FOR SMALL FIELD DOSIMETRY (CHARACTERISTICS STATED BY MANUFACTURERS). THE REFERENCE POINT QUOTED IS WITH RESPECT TO THE FLAT FACE OF THE DETECTOR AND FOR THE STEM ORIENTATION PARALLEL TO THE BEAM'S CENTRAL AXIS.**

Detector	Sensitive volume (mm^3)	Geometric form of sensitive area[a]	Diameter or side length of sensitive area (mm)	Thickness of sensitive volume (mm)	Reference point (from flat face/tip) (mm)[c]	Shielded
IBA-PFD3G diode	0.19	disc	2	0.06	< 0.9	Yes
IBA-EFD3G diode	0.19	disc	2	0.06	< 0.9	No
IBA-SFD diode	0.017	disc	0.6	0.06	< 0.9	No
PTW 31018 liquid ion chamber [b]	1.7	disc	2.5	0.35	1.0	Yes
PTW-60008 diode [b]	0.03	disc	1.13	0.03	2.0 [c]	Yes
PTW-60012 diode [b]	0.03	disc	1.13	0.03	0.8 [c]	No
PTW-60016 diode	0.03	disc	1.13	0.03	2.4 [c]	Yes
PTW-60017 diode	0.03	disc	1.13	0.03	1.3 [c]	No
PTW-60018 diode	0.3	disc	1.13	0.25	1.3 [c]	No
PTW-60003 natural diamond [b]	1-6	variable	<4	0.1-0.4	1.0 [c]	No
PTW-60019 CVD diamond	0.004	disc	2.2	0.001	1.0 [c]	No
Sun Nuclear Edge Detector	0.0019	square	0.8	0.03	0.3	Yes
Exradin W1 (Standard Imaging)	2.4	cylinder	1.0	3.0	1.5[d]	No

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Ch 4 – Detectors for small fields

Detector type	Mechanism	Comment
Classical vented ionization chambers	Ionization in air	Not suitable
Small size vented air ionization chambers of a volume of 0.01–0.3 cm^3	Ionization in air	Suitable down to 2 x 2 cm^2
Micro ionization chambers of a volume of 0.002–0.01 cm^3	Ionization in air	Reduced sensitivity, leakage, cable currents, etc. Possibly suitable but with correction factors
Liquid ionization chambers	Ionization in iso-octane	Suitable but no longer available
Silicon diodes	Ionization in solid	Shielded vs. unshielded, energy dependence, angular dependence; correction factors
Diamond detectors	Ionization in solid	Dose rate dependence natural diamond, CVD suitable, but have correction factors
Plastic and organic scintillators	Luminescence	Suitable, still issues with Cerenkov
Radiochromic film	Chemical reactions	Suitable, details of the readout protocol are critical

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Other detectors: TLD, OSLD, MOSFET, alanine

Ch 4 – Phantoms for small fields

- Simple water-filled calibration phantoms without a scanning system.
- 3D water phantoms
- Water equivalent plastic cylinders, spheres, hemispheres, cubes and other shapes
- Phantoms with adjustable measurement planes and chamber cavities, which rigidly attach to stereotactic frames or index precisely to imaging and treatment couch-tops.

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Other detectors: TLD, OSLD, MOSFET, alanine

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

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Ch 5 – Reference conditions for beam quality and *msr* dosimetry

Table 5.1: **REFERENCE CONDITIONS FOR THE DETERMINATION OF ABSORBED DOSE TO WATER IN HIGH-ENERGY PHOTON BEAMS.**

Influence quantity	Reference value or reference characteristics
Phantom material	Water
Phantom shape and size	At least 30 cm × 30 cm × 30 cm
Chamber type	Cylindrical
Measurement depth z_{ref}	10 g cm^{-2}
Reference point of chamber	On the central axis at the centre of the cavity volume
Position of reference point of chamber	At the measurement depth z_{ref}
SSD/SDD	100 cm or the closest achievable [a]
Field size	10 cm × 10 cm [b] or size of the msr field [c]

[a] If the reference absorbed dose to water has to be determined for an isocentric set up, the SAD of the accelerator shall be used even if this is not 100 cm.

[b] The field size is defined at the surface of the phantom for a SSD type set-up, whereas for a SAD type set-up it is defined at the plane of the detector, placed at the reference depth in the water phantom at the isocentre of the machine.

[c] The equivalent square *msr* field size, *S*, should be as close as possible to 10 cm but not smaller than 4 cm and not larger than 12 cm. The aspect ratio of rectangular fields (largest dimension/smallest dimension) should be as close as possible to unity.

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

WFF beams,
Q_0 = Co-60
f_{msr} = 10 x 10 cm²

$$k_{Q_{\rm msr},Q_0}^{f_{\rm msr},f_{\rm ref}}$$

Table 5.5: $k_Q^{f_{ref}}$ **DATA FOR THE CONVENTIONAL f_{ref} FIELD (10 cm × 10 cm) FOR REFERENCE IONIZATION CHAMBERS IN LINACS WITH FLATTENING FILTER (WFF), AS A FUNCTION OF THE BEAM QUALITY INDICES TPR$_{20,10}$(10) AND $\%dd(10,10)_x$. (SEE APPENDIX B FOR DETAILS).**

Ion chamber	TPR$_{20,10}$(10) = $\%dd(10,10)_x$ =	0.63 63.6	0.66 65.2	0.69 67.5	0.72 70.4	0.75 74.0
Capintec PR-06C/G Farmer		0.998	0.994	0.991	0.988	0.982
Exradin A2 Spokas		0.999	0.997	0.995	0.992	0.988
Exradin A12 Farmer		0.998	0.996	0.993	0.990	0.984
Exradin A12S		0.996	0.994	0.991	0.987	0.981
Exradin A19		0.996	0.993	0.990	0.986	0.980
Nuclear Assoc 30-751 Farmer		0.997	0.993	0.990	0.985	0.979
Nuclear Assoc 30-752 Farmer		0.995	0.995	0.992	0.989	0.983
NE 2505/3, 3A Farmer		0.997	0.994	0.992	0.989	0.984
NE 2571 Farmer		0.997	0.994	0.992	0.989	0.984
NE 2611		0.996	0.993	0.991	0.988	0.984
PTW 23331 rigid		0.996	0.992	0.989	0.985	0.980
PTW 23332 rigid		0.996	0.993	0.989	0.984	0.978
PTW 23333 (3 mm cap)		0.997	0.993	0.989	0.985	0.979
PTW 30001 Farmer		0.997	0.993	0.989	0.985	0.979
PTW 30010 Farmer		0.996	0.993	0.989	0.985	0.979
PTW 30002/30011 Farmer		0.995	0.993	0.991	0.987	0.982
PTW 30004/30012 Farmer		0.997	0.995	0.993	0.989	0.984
PTW 30006/30013 Farmer		0.996	0.993	0.989	0.984	0.978
PTW 31003/31013 Semiflex		0.996	0.994	0.991	0.987	0.981
SNC 100730 Farmer		0.996	0.994	0.991	0.986	0.979
SNC 100740 Farmer		0.997	0.997	0.994	0.990	0.984
Victoreen Radocon III 555		0.994	0.988	0.985	0.979	0.973
Victoreen 30-348		0.995	0.991	0.988	0.982	0.976
Victoreen 30-351		0.995	0.991	0.988	0.983	0.977
Victoreen 30-349		0.995	0.991	0.988	0.983	0.978
Victoreen 30-361		0.996	0.991	0.988	0.983	0.977
IBA FC-65P (Wellhöfer IC 69) Farmer		0.996	0.994	0.992	0.986	0.979
IBA FC-65G (Wellhöfer IC 70) Farmer		0.997	0.997	0.994	0.989	0.983

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$$k_{Q_{\rm msr},Q_0}^{f_{\rm msr},f_{\rm ref}}$$

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

FFF beams
Tomo (5x10)
CyberKnife (6 cm)
Q_0 = Co-60

Table 5.6: $k_{Q_{msr}}^{f_{msr},f_{ref}}$ **DATA FOR THE CONVENTIONAL f_{ref} FIELD (10 cm × 10 cm) FOR REFERENCE IONIZATION CHAMBERS IN FLATTENING FILTER FREE (FFF) LINACS, AS A FUNCTION OF THE BEAM QUALITY INDICES TPR$_{20,10}$(10) AND $\%dd(10,10)_x$, AND FOR THE CYBERKNIFE AND TOMOTHERAPY MACHINES. (NOTE THAT THE CORRESPONDENCE BETWEEN TPR$_{20,10}$(10) AND $\%dd(10,10)_x$ IS DIFFERENT FROM THAT FOR WFF BEAMS.)**

Ion chamber	TPR$_{20,10}$(10) = $\%dd(10,10)_x$ =	0.63 64.0	0.66 65.7	0.69 68.3	0.72 71.7	0.75 76.0	Cyber Knife	Tomo Therapy
Capintec PR-06C/G Farmer		0.997	0.995	0.992	0.988	0.981	1.000	0.996
Exradin A2 Spokas		0.997	0.995	0.993	0.989	0.983	0.997	0.996
Exradin A12 Farmer		0.998	0.997	0.994	0.991	0.984	1.004	0.998
Exradin A12S		0.994	0.992	0.989	0.984	0.977	0.993	0.993
Exradin A19		0.995	0.994	0.991	0.987	0.981	1.002	0.995
Nuclear Assoc 30-751 Farmer		0.996	0.994	0.991	0.986	0.979	1.000	0.995
Nuclear Assoc 30-752 Farmer		0.994	0.996	0.993	0.990	0.983	1.002	0.996
NE 2505/3, 3A Farmer		0.996	0.996	0.993	0.990	0.985	1.003	0.996
NE 2571 Farmer		0.996	0.996	0.993	0.990	0.985	1.003	0.996
NE 2611		0.994	0.992	0.989	0.985	0.979	0.993	0.993
PTW 23331 rigid		0.995	0.993	0.990	0.985	0.980	0.998	0.994
PTW 23332 rigid		0.995	0.993	0.989	0.983	0.976	0.995	0.994
PTW 23333 (3 mm cap)		0.996	0.993	0.990	0.985	0.978	0.998	0.995
PTW 30001 Farmer		0.996	0.994	0.990	0.986	0.979	0.999	0.995
PTW 30010 Farmer		0.995	0.994	0.990	0.986	0.979	0.999	0.995
PTW 30002/30011 Farmer		0.994	0.994	0.992	0.988	0.982	1.001	0.994
PTW 30004/30012 Farmer		0.997	0.996	0.994	0.990	0.984	1.003	0.996
PTW 30006/30013 Farmer		0.995	0.994	0.990	0.985	0.978	0.999	0.995
PTW 31003/31013 Semiflex		0.994	0.993	0.990	0.985	0.978	0.996	0.994
SNC 100730 Farmer		0.996	0.995	0.992	0.987	0.979	1.003	0.996
SNC 100740 Farmer		0.997	0.998	0.995	0.991	0.985	1.005	0.998
Victoreen Radocon III 555		0.994	0.989	0.985	0.980	0.973	0.995	0.991
Victoreen 30-348		0.994	0.991	0.987	0.981	0.973	0.994	0.992
Victoreen 30-351		0.994	0.992	0.988	0.984	0.977	0.998	0.993
Victoreen 30-349		0.994	0.992	0.988	0.983	0.978	0.997	0.993
Victoreen 30-361		0.995	0.992	0.988	0.983	0.976	0.998	0.993
IBA FC-65P (Wellhöfer IC 69) Farmer		0.996	0.995	0.993	0.987	0.978	1.002	0.995
IBA FC-65G (Wellöfer IC 70) Farmer		0.997	0.998	0.994	0.990	0.983	1.004	0.997

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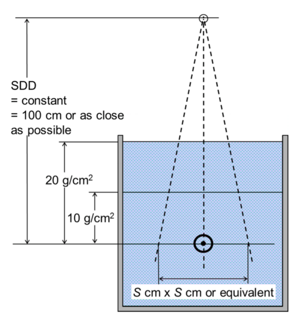
Ch 5 – Practical implementation msr dosimetry – beam quality index



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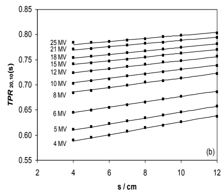
Getting the beam quality index

$$\%\mathrm{TPR}_{20,10}(10) = \frac{\%\mathrm{TPR}_{20,10}(S) + c\,(10 - S)}{1 + c\,(10 - S)}$$

$$c = (16.15 \pm 0.12) \times 10^{-3} \text{ for } 4 \text{ cm} \;\leq\; S \;\leq\; 12 \text{ cm}$$



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Ch 6 – Practical implementation relative dosimetry

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

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Ch 6 – Practical implementation relative dosimetry

- Equipment (detectors & phantoms)
- In-phantom detector setup
  - Detector orientation, positioning, alignment
- Measurement of lateral beam profiles
- Determination of in-phantom field output factors
  - Equivalent field size in small fields:

$$S_{\mathrm{clin}} = \sqrt{A \cdot B} \qquad S_{\mathrm{clin}} = r \cdot \sqrt{\pi}$$

$$0.7 < A/B < 1.4$$

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Field output factors - recall

- 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

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

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

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Ch 6 – Field output correction factors

- IAEA-AAPM code of practice data tables is based on a vetted set of correction factor from the literature
- Uncertainty analysis has been performed and will be discussed in another lecture

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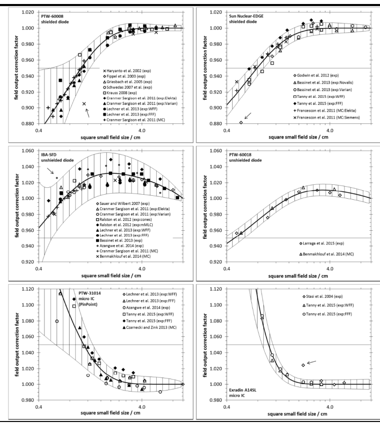
Ch 6 – Field output correction factors

Table 6.7: 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 FFF AND FFF MACHINES, AS A FUNCTION OF THE EFFECTIVE SQUARE FIELD SIZE. THE REFERENCE DEPTH IS 10 cm.

	Equivalent square field size, S_{clin} (cm)												
Detector	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	1.001	1.001	1.002	1.004	1.006	1.013	1.034	1.063	-	-	-	-	-
Exradin A16 micro	1.001	1.001	1.002	1.002	1.003	1.004	1.009	1.017	1.026	1.042	1.070	-	-
IBA/Wellhöfer CC01	1.002	1.003	1.005	1.006	1.006	1.006	1.008	1.010	1.015	1.024	1.044	1.062	-
IBA/Wellhöfer CC04	1.000	1.001	1.001	1.001	1.002	1.003	1.009	1.021	1.039	1.073	-	-	-
IBA/Wellhöfer CC13 (IC15)	1.000	1.001	1.001	1.002	1.003	1.008	1.027	1.062	-	-	-	-	-
PTW 31002 Flexible	0.999	0.998	0.997	1.001	1.007	1.025	1.076	-	-	-	-	-	-
PTW 31010 Semiflex	0.998	0.997	0.995	0.996	0.998	1.005	1.025	1.051	-	-	-	-	-
PTW 31014 PinPoint	1.000	1.000	1.000	1.001	1.003	1.008	1.021	1.037	1.056	-	-	-	-
PTW 31016 PinPoint 3D	1.000	1.000	1.000	1.000	1.001	1.004	1.013	1.025	1.039	1.062	-	-	-
Real-time solid state dosimeters													
IBA-PFD3G shielded diode	0.999	0.999	0.997	0.995	0.992	0.987	0.978	0.970	0.963	0.954	0.944	-	-
IBA-EFD3G unshielded diode	1.003	1.006	1.010	1.011	1.011	1.010	1.007	1.002	0.998	0.991	0.982	0.976	0.969
IBA-SFD unshielded diode (stereotactic)	1.006	1.011	1.017	1.020	1.021	1.021	1.018	1.013	1.006	0.995	0.978	0.966	0.951
PTW-60008 shielded diode	1.000	1.000	0.999	0.998	0.995	0.990	0.977	0.963	0.949	-	-	-	-
PTW-60012 unshielded diode	1.004	1.007	1.011	1.012	1.012	1.010	1.004	0.996	0.989	0.978	0.963	0.954	0.943
PTW-60016 shielded diode	1.000	1.000	0.998	0.995	0.991	0.984	0.970	0.957	0.945	-	-	-	-
PTW-60017 unshielded diode	1.002	1.005	1.007	1.007	1.006	1.004	0.998	0.990	0.982	0.972	0.957	0.947	-
PTW-60018 unshielded diode (stereotactic)	1.003	1.005	1.007	1.007	1.005	1.002	0.994	0.985	0.978	0.968	0.955	0.947	-
PTW-60003 natural diamond	1.001	1.002	1.002	1.003	1.003	1.003	1.003	1.004	1.004	1.004	1.004	1.004	1.004
PTW-60019 CVD diamond	1.000	1.000	0.999	0.999	0.998	0.997	0.993	0.988	0.983	0.977	0.967	0.962	0.955
PTW-31018 liquid ion chamber	0.998	0.997	0.995	0.994	0.994	0.994	0.993	0.993	0.993	0.993	0.992	0.992	0.992
Sun Nuclear Edge Detector	1.000	1.001	1.001	1.000	0.997	0.993	0.983	0.972	0.962	0.949	-	-	-
Standard Imaging W1 plastic scintillator	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Remarks:
1. Uncertainties are k=2
2. Corrections > 5% are not recommended



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ICRU Report

Prescribing Recording and Reporting of stereotactic treatments using small photon fields

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PRESCRIBING, RECORDING, AND REPORTING OF STEREOTACTIC TREATMENTS WITH SMALL PHOTON BEAMS

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Conclusions

- We covered the basics of small field dosimetry
- We introduced practical elements of the IAEA-AAPM protocol for small field dosimetry
- We introduced the content covered in the upcoming ICRU report on Prescribing, Reporting and Recording of Stereotactic Treatments with Small Photon Fields

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