Detectors for small field and relative dosimetry

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Disclosures

- My work is supported in part by the Canadian Institutes of Health Research, the Natural Sciences and Engineering Research Council, Canada through operating grants and training grants.
- I am working with Sun Nuclear Corporation and Lifeline Software Inc on technology commercialization projects
- I am working with RefleXion Medical on a nonstandard field dosimetry project
- I am a founding advisor of Gray Oncology Solutions, Inc

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

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Content

- Reference fields and small fields
  - Nonstandard reference field calibration
  - Some post-TRS483 comments
- Small field dosimetry
  - Characteristics of suitable detectors
  - Unanswered questions

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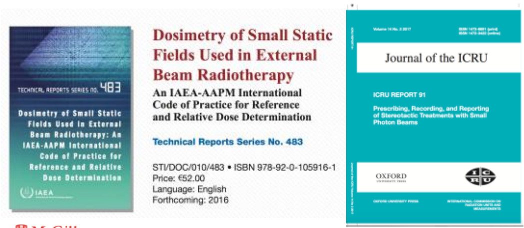
Two important reports came out in 2017



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Dosimetry of nonstandard and small fields

- Characteristics that lead to dosimetric issues of two kinds:
  - Reference dose calibration
    - Reference fields are not 10 x 10 cm^2, 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
- Problem put on the backburner: calibration of composite fields


Dosimetry of small static fields used in external photon beam radiotherapy: Summary of TRS-483, the IAEA–AAPM International Code of Practice for reference and relative dose determination

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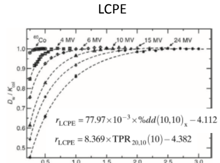
Physics of small fields

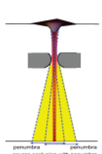
Small field conditions

LCPE

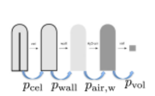


Repercussions in when we call a field a reference field

Source occlusion



Detector correction factors



Repercussions on how we determine dose in a small field

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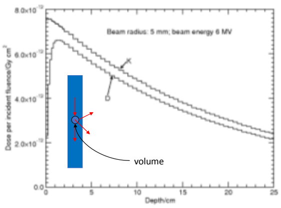
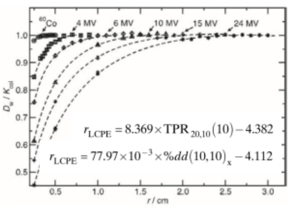
Lateral charged particle loss





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

Note: r_{LCPE} estimates using this method are inaccurate for FFF beams

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Reference calibration fields

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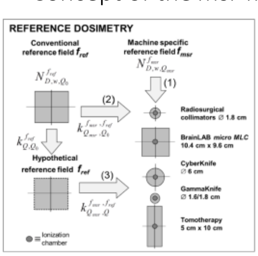
Concept of the *msr* field



$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} \cdot N_{D,w,Q_{msr}}^{f_{msr}}$$ Route 1

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

f_{ref}=10 x 10 cm²

Q_0= ^{60}Co

Route 2

$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} \cdot N_{D,w,Q_0}^{f_{ref}} \cdot k_{Q,Q_0}^{f_{ref}} \cdot k_{Q_{msr},Q}^{f_{msr},f_{ref}}$$ Route 3

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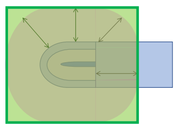
Detector size relative to field size

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

$f_{msr} < 6 \times 6$ cm²

$$r_{LCPE}[cm] = 8.369 \times TPR_{20,10}(10) - 4.382$$
$$r_{LCPE}[cm] = 0.07797 \times \%dd(10)_x - 4.112$$



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

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

- $\%dd_X(10) = 67.2$ → $r_{LCPE} = 11.2$ mm.
- An IBA CC08 ion chamber has a cavity length $l = 4$ mm, a cavity radius $r = 3$ mm and a wall thickness $t_{wall} = 0.07$ g/cm²; with ρ(C-552) = 1.76 g/cm³, t_{wall} = 0.40 mm.
  - → $d_l = l + t_{wall} = 4.4$ mm
  - → $d_r = 2(r + t_{wall}) = 6.8$ mm
- $d_r > d_l$, → $d = d_r = 6.8$ mm
- FWHM should be at least 2 × 11.2 mm + 6.8 mm = 29.3 mm at a depth of 10 cm in water.

→ The "equivalent square field size" should exceed 3 cm for the field to be an *msr*!

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Equivalent square fields *msr*

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

Make the scattering component equivalent!

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

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

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

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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Getting the beam quality in nonstandard reference fields

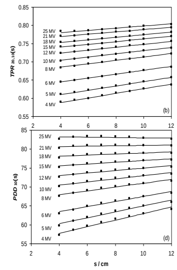
for $\mathrm{TPR}_{20,10}(10) = \mathrm{TPR}_{20,10}$

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

for $\%dd(10,10) = \%dd(10,10)_X = \%dd(10)_X$

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

Note!: FFF beams → use the Pb filter and equations in TG-51 to get $\%dd(10,10)_X$



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$f_{\mathrm{msr}} \geq 6 \times 6\ \mathrm{cm}^2$

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 (cm³)	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	0.65	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 [d]	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.

$f_{\mathrm{msr}} < 6 \times 6\ \mathrm{cm}^2$

Table 4.3: CHARACTERISTICS OF IONIZATION CHAMBERS SUITABLE FOR REFERENCE DOSIMETRY OF *msr* FIELDS $f_{msr} < 6\,\mathrm{cm} \times 6\,\mathrm{cm}$.

Ionization chamber type [a]	Cavity volume (cm³)	Cavity length (mm)	Cavity radius (mm)	Wall material	Wall thickness (g cm⁻²)	Central electrode material [b]	Waterproof
Capintec PR-05P mini [a]	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 [a]	0.016	2.0	2.0	C-552	0.176	C-552	Y
Exradin A14SL micro Shonka slimline [a]	0.016	2.1	2.1	C-552	0.194	C-552	Y
Exradin A14P micro planar [a]	0.002	1.0	2.0	C-552	0.176	C-552	Y
Exradin A16 micro [a]	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 [a]	0.01	3.6	1.0	C-552	0.088	Steel	Y
IBA CC04 [a]	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 [a]	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 [f]	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

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

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

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

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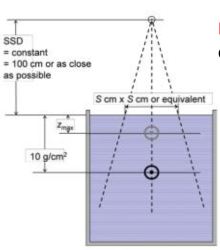
Practical implementation *msr* dosimetry – beam quality index



Note!: FFF beams → use the Pb filter and equations in TG-51 to get $\%dd(10,10)_X$

$$\%dd(10,10) = \%dd^{\mathrm{SSD}}(10,10) \times \frac{\mathrm{TMR}(10,11)}{\mathrm{TMR}\left(10, \frac{\mathrm{SSD}+10}{\mathrm{SSD}}10\right)} \times \frac{\mathrm{NPSF}(11)}{\mathrm{NPSF}\left(\frac{\mathrm{SSD}+10}{\mathrm{SSD}}10\right)} \times \left(\frac{100+z_{\max}}{110}\,\frac{\mathrm{SSD}+10}{\mathrm{SSD}+z_{\max}}\right)^2$$

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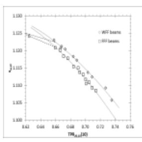
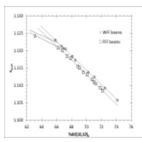
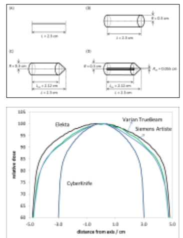
What is included in $k_{\mathrm{Q,Q_0}}^{f_{\mathrm{ref}}}$?

- FFF beams → $s_{w,air}$
- Volume averaging in generic FFF fields (P_{rp} is included!)







$$(k_{vol})_{Q^{FFF}}^{f_{ref}} = \frac{\iint_A w(x,y)dxdy}{\iint_A \mathrm{OAR}(x,y)w(x,y)dxdy}$$

$$(k_{vol})_{Q}^{f_{ref}} = 1 + (0.000059 \cdot \%\mathrm{dd}(10,10)_X - 0.00338) \cdot \left(\frac{100}{SDD}\right)^2 \cdot L^2$$

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

$k_{\mathrm{Q,Q_0}}^{f_{\mathrm{ref}}}$ $(k_{Q_{\mathrm{msr}},Q}^{f_{\mathrm{msr}},f_{\mathrm{ref}}} \approx 1)$

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

Table 5.5: $k_{Q,Q_0}^{f_{ref}}$ 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	$TPR_{20,10}(10)$ =	0.63	0.66	0.69	0.72	0.75
	$\%dd(10,10)_X$ =	63.6	65.2	67.5	70.4	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		0.998	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

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

FFF beams, Tomo (5x10 cm²), CyberKnife (6 cm), Q_0 = Co-60

Table 5.6: $k_{Q_{msr},Q_0}^{f_{msr},f_{ref}}$ 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	$TPR_{20,10}(10)$ =	0.63	0.66	0.69	0.72	0.75	Cyber	Tomo
	$\%dd(10,10)_X$ =	64.0	65.7	68.3	71.7	76.0	Knife	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	0.988	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	0.988	0.985	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	0.993	0.993	0.987	0.978	1.002	0.995
IBA FC-65G (Wellhöfer IC 70) Farmer		0.997	0.998	0.994	0.990	0.983	1.004	0.997

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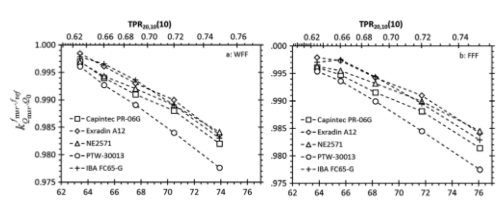

Data consistent with TG51-Addendum data

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In summary

Get $N_{D,w,Q0}$(Co)

For the beam of interest:

- Get equivalent square *S*
- Measure the %*dd*(10,S) (if FFF: use lead filter!)
- use conversion formula for SSD, Pb, *S* to get $\%dd_X(10,10)$
- Look up $k^{f_{\rm ref}}_{Q,Q_0}$ or $k^{f_{\rm msr},f_{\rm ref}}_{Q_{\rm msr},Q_0}$

$$D^{f_{\rm msr}}_{{\rm w},Q_{\rm msr}} = M^{f_{\rm msr}}_{Q_{\rm msr}} N^{f_{\rm ref}}_{D,{\rm w},Q_0} k^{f_{\rm ref}}_{Q,Q_0} k^{f_{\rm msr},f_{\rm ref}}_{Q_{\rm msr},Q}$$

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

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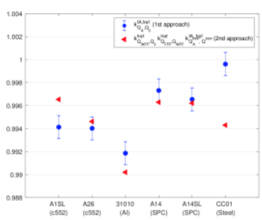
What to do when largest field size is not *msr*?



a) 10 × 2 cm² field size

Mirzakhanian et al 2019 (*submitted*)

RefleXion

- Reference dosimetry field size (10 x 2 cm^2)
- SDD = 85 cm
- $2r_{\rm LCPE}+d$ > FWHM
- Two approaches
  - Direct MC calculation
  - $k^{f_{\rm msr},f_{\rm ref}}_{Q_{\rm msr},Q_0}$

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Small fields and detectors

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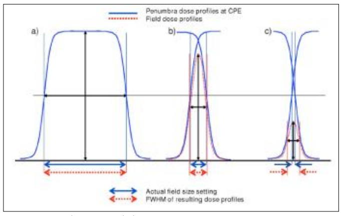
Source occlusion



FWHM > geometric field size

Small field dosimetry-related parameters must be specified as a function of FWHM

Das et al. 2008 Med Phys **35**: 206-15
Overlapping of beam penumbras

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Field size specification S_{clin}

$$S_{\mathrm{clin}} = \sqrt{A \cdot B}$$
$$0.7 < A/B < 1.4$$
$$S_{\mathrm{clin}} = r \cdot \sqrt{\pi}$$

951 Casar *et al.*: Relative dosimetry of small static fields 951

TABLE II. Nominal field sizes and corresponding equivalent square small field sizes S_{clin} on the Elekta Versa HD and Varian TrueBeam linacs measured with EBT3 films and applying Eq. (3).

Nominal square field side length (cm)	S_{clin} (cm) — Elekta Versa HD				S_{clin} (cm) — Varian TrueBeam			
	6 MV WFF	6 MV FFF	10 MV WFF	10 MV FFF	6 MV WFF	6 MV FFF	10 MV WFF	10 MV FFF
0.5	0.60	0.59	0.62	0.58	0.56	0.54	0.57	0.55
0.8	0.87	0.85	0.87	0.86	0.81	0.82	0.84	0.81
1.0	1.03	1.03	1.06	1.04	1.01	0.99	1.03	1.02
1.5	1.51	1.52	1.55	1.52	1.50	1.49	1.52	1.51
2.0	2.04	2.03	2.05	2.04	2.00	1.99	2.01	1.99
3.0	3.06	3.04	3.08	3.02	3.03	3.00	3.00	2.98
4.0	4.04	4.03	4.06	4.01	4.03	3.99	4.02	3.98
5.0	5.04	5.01	5.05	4.99	5.02	5.00	5.01	4.96
10.0	10.04	9.94	10.05	9.90	10.03	9.96	10.02	9.87

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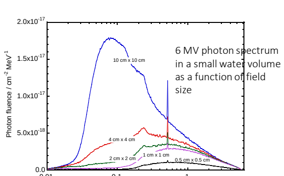
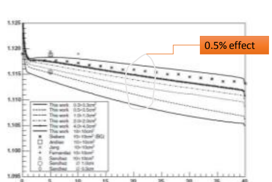
Casar et al Med. Phys. (2019) 46 (2), 944

Spectral changes

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



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



Spectral hardening does not lead to large changes in stopping power ratio!

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

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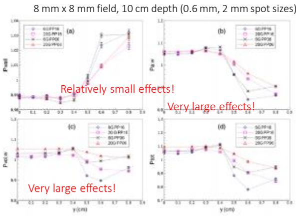
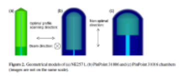
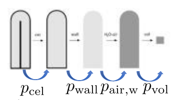
Magnitude of *p* correction factors on- and off-axis

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



PP31006 and PP31016 chambers





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

→ Small field output measurements need to be corrected for these effects!

Concept of field output correction factors

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

$$\Omega^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}} = \frac{M^{f_{clin}}_{Q_{clin}}}{M^{f_{ref}}_{Q_{ref}}} \cdot k^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}}$$

Output factors are DOSE RATIOS not reading ratios!!

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

$$\Omega^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}} = \frac{M^{f_{clin}}_{Q_{clin}}(\mathrm{det})}{M^{f_{int}}_{Q_{int}}(\mathrm{det})} \cdot \frac{M^{f_{int}}_{Q_{int}}(IC)}{M^{f_{ref}}_{Q_{ref}}(IC)} \cdot K^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}}$$

where

$$K^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}} = k^{f_{clin},f_{int}}_{Q_{clin},Q_{det}}(\mathrm{det}) \cdot k^{f_{int},f_{ref}}_{Q_{int},Q_{ref}}(IC)$$

Small field output correction factors

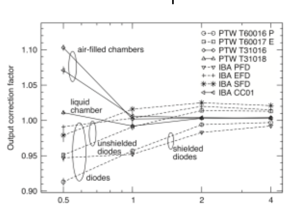


Figure 2.10. Output correction factors, $k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$, for eight detector types in small fields from the Varian iX series for 5 mm, 1, 2, and 4 cm field openings normalized to a 10 × 10 cm² field.

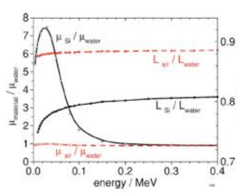
- There are large corrections to reading of virtually any type of detector
- For air-filled chambers: large upwards correction factors in small fields
- For solid state detectors: correction factors depend on the construction, density, Z and size of the sensitive volume

ICRU 91 Report (2017)

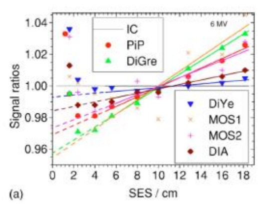
Detector suitability criteria for small fields

- There is no ideal detector
- Suitability in general is tied to
  - the sensitive region of the detector is close to water equivalent in terms of radiation absorption characteristics;
  - the density of the sensitive region is close to the density of water;
  - the size of the sensitive region can be made small compared to the field size while keeping noise levels under control.

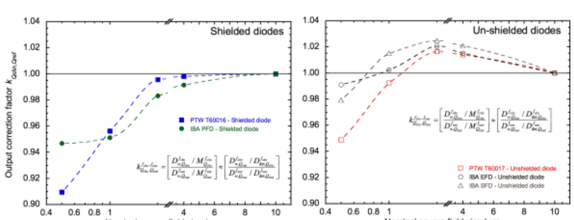
Diodes for small field dosimetry



Sauer and Wilbert 2007
Med Phys 34:1983-8

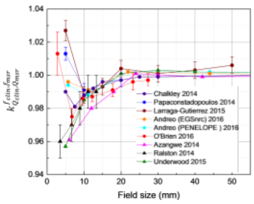


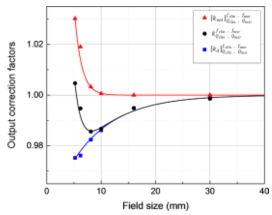
Shielded and unshielded diodes



 Benmahklouf and Andreo (2013)

Microdiamond detector





De Coste et al 2017 Phys. Med. Biol. 62 7036

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Small field correction factor issues

TABLE XII. Statistical significance (P-values) of differences between output correction factors $k_{Q_{clin},Q_{ref}}^{f_{clin},f_{ref}}$ for PTW 60019 mD detector given in TRS-483 and the corresponding values from this study evaluated with a one-tailed Student's t-test. Data for 6 and 10 MV beams from TRS-483 were compared with data from this study for both filtered (WFF) and unfiltered (FFF) 6 and 10 MV beams on the Elekta Versa HD linac.

P-values	Elekta Versa HD			
Field size[a] (cm)	6 MV WFF	6 MV FFF	10 MV WFF	10 MV FFF
PTW 60019 mD				
0.5	0.001	0.003	0.001	0.001
0.8	0.027	0.025	0.001	0.004
1.0	0.014	0.014	0.002	0.010
1.5	0.070	0.059	0.016	0.027
2.0	0.118	0.042	0.023	0.031

[a]Field size is indicated as the nominal square field side length. The relationship between the nominal field size and the corresponding equivalent square field sizes S_{clin} is provided in Table II for all energies and field sizes.

Casar et al Med. Phys. (2019) 46 (2), 944

- The correction factors are likely energy dependent
- Detailed geometry is critical for MC simulations
- SN EDGE detector below 2 cm in 10 MV FFF beam significantly different from IAEA-AAPM 483
- See left panel for similar differences with PTW microdiamond

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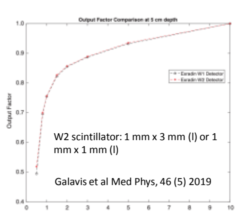
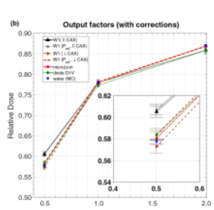
Scintillators W1 and W2





Papaconstadopoulos et al Med Phys 44 (2), 654, 2017

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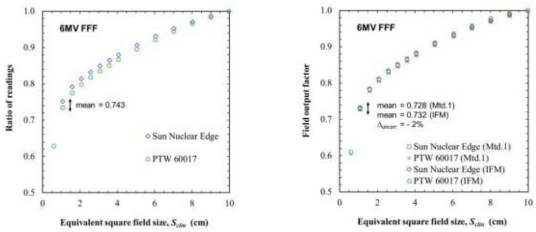
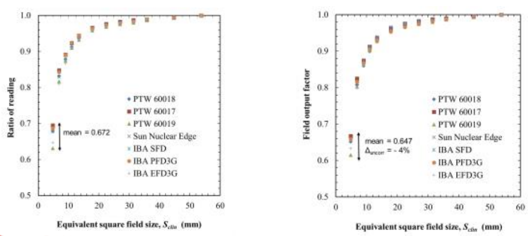
Field output factor (TrueBeam STx)



Huq et al Med Phys (in press) 2018

34

Field output factor (CyberKnife)



Huq et al Med Phys in press 2018

35

Conclusion

- IAEA-AAPM TRS-483 has significantly improved consistency in small field dosimetry
  - The use of more than a single detector to quantify small field output factors is recommended
  - Accelerators are getting increasingly reproducible. It makes therefore sense to compare output factors of a given machine with those of a similar machine
- Post IAEA-AAPM TRS483
  - New machines will come to the market that invalidate nonstandard field conditions
  - The last word about so-called promising detectors has not yet been said
  - Small field dosimetry for field sizes below 1 x 1 cm^2 remains challenging

AAPM, San Antonio 2019