Universitätsklinikum Würzburg

Small Field Dosimetry

Relative dosimetry: detector choice and corrections

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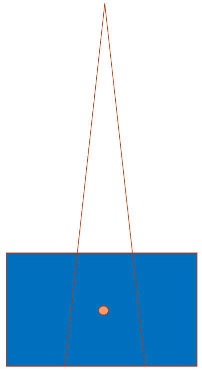
Relative dosimetry

Measurement tasks:

- Rel. profiles (OARs)
- Rel. depth dose
- Tissue phantom ratios (TPR)
- Total scatter factor (output measured in phantom, S_{cp})
- Head scatter factor (output measured in air S_c)
- Phantom scatter factor S_p



Desired detector properties

- High spatial resolution
- High signal, low noise
- Low energy dependence
- Low directional dependence
- Low perturbation
- dose (rate) linearity
- High stability, robust
- easy to use in a clinic

Some detectors

- Ionization chamber PTW 31010, 0.125cc
- Ionization chamber PTW 31006, PinPoint, 0.015cc
- Shielded Si-diode Sc.-Wellhöfer PFD Photon, 0.0003cc
- Mini Si-diode Sc.-Wellhöfer SFD stereotactic, 0.000017cc
- Si-MOSFET Thomson & Nielsen TN-502 RD
- Diamond detector PTW 60003, ca. 0.002cc
- microLion Chamber 0.0017cc

Detector response

$$D(\mathbf{r}) = \prod k(\mathbf{r}) \cdot NM(\mathbf{r})$$

M: measured value
N: calibration factor
k: correction factor

Reference dosimetry:

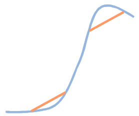
- Product of correction factors should be known (use dosimetry protocol)

Relative dosimetry:

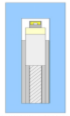
- Product of correction factors *k* should be constant or the relation k_{meas}/k_{ref} should be known

Influence factors on detector response

- Volume averaging

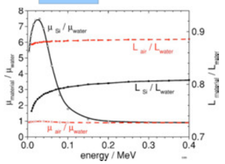


- Perturbation of the radiation field
  displacement of water



(image from Cranmer-Sarginson et al., PMB 57 (2012))

- Energy dependence of stopping power (dE/dx) and energy absorption coefficient μ_{en} -ratios

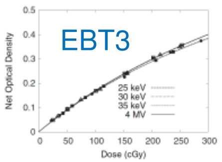


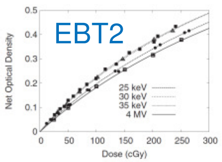
- Temperature, pressure, dose rate, dose, age …

Detectors, pros and cons

- Polymer gel
  - *3D, high spatial resolution, difficult readout, calibration, preparation*
- Radiochromic film
  - *2D, difficult calibration, stability of scanning*
- Micro ionization chamber
  - *Volume effect, signal/noise, background, energy dependence*
- TLD, alanine, MOSFET, all non direct reading 1D detectors
  - *Position uncertainty*
- Diamond
  - *Dose rate dependence, volume effect, robustness*
- Si-diodes
  - *High spatial resolution, energy & field size dependent response*

Gafchromic Film





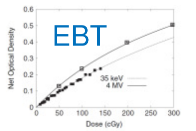


FIG. 1. Net optical density versus dose for EBT film. The film was calibrated at 35 keV (filled squares) and 4 MV (hollow squares). Both sets of data were fitted with the function shown in Eq. (2).

FIG. 3. Net optical density versus dose for EBT3 film. The film was calibrated at 25 keV (circles), 30 keV (triangles), 35 keV (filled squares), and 4 MV (hollow squares). Each set of data were fitted with the function shown in Eq. (2).

FIG. 2. Net optical density versus dose for EBT2 film. The film was calibrated at 25 keV (circles), 30 keV (triangles), 35 keV (filled squares), and 4 MV (hollow squares). Each set of data were fitted with the function shown in Eq. (2).

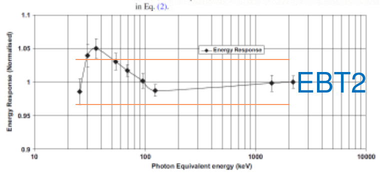


Fig. 1. Change in Optical density to Dose response curve for varying x-ray energies from 50 kVp to 10 MV for EBT2 Gafchromic film.

- Brown et al: Dose-response curve of EBT EBT2 and EBT3 radiochromic films, MP2012, 7412
- Butson et al: Energy response of the new EBT2 radiochromic film …., Rad. Meas. 45(2010)836-839

Ionization chamber – energy dependence

- High volume effect

or

- Low current

but

- Low energy dependence:
  $\delta_{FS=\infty \to 0.5cm} s_{w,a}$ < 1% @ 6MV z=10cm

Photon stopping power data 853

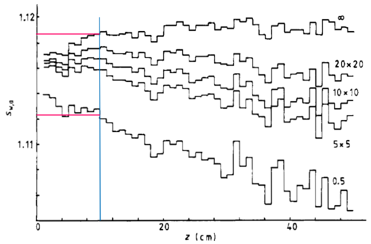


Figure 9. Field size dependence of the depth variation of the water/air stopping power ratio for an experimental 6 MV photon spectrum (Jessen 1973).

Figure from Andreo & Brahme 1986 Phys. Med. Biol. 31 839

Ionization chamber - Volume effect

- Mean relative dose on the sensitive area of the detector perpendicular to the beam axis
- PinPoint, FS=2cm $\rightarrow \varepsilon \approx 0.5\%$
- (assumption: constant sensitivity
- $\rightarrow$ volume effect is overestimated)

$$\varepsilon(A,l,r) = \frac{100\int_{-l/2}^{l/2}\int_{-r}^{r}|\mathrm{OAR}(A,x,y)-1|\mathrm{d}x\mathrm{d}y}{\int_{-l/2}^{l/2}\int_{-r}^{r}\mathrm{d}r\mathrm{d}y}$$

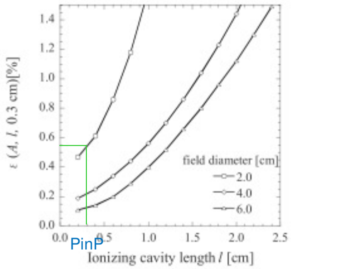


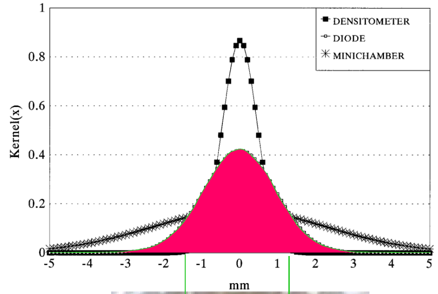
Fig. 2. The error of dosimeter reading $\varepsilon(A,l,0.3$ cm) (%) as a function of cavity length l of ionization chamber and field A. The cavity radius r is calculated in 0.3 cm, and these values are for a SCD of 80 cm at a depth of 10 cm in water.

OAR: off-axis ratio

Kawachi et al. Medical Physics, Vol. 35, No. 10, 2008, 4591f

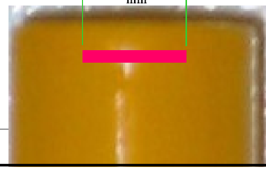
Volume effect (2)

- Deconvolution with the detector response function K
- D_m: measured dose
- D: "true" dose
- F: Fourier transform



$$D_m(x) = \int_{-\infty}^{+\infty} D(u)K(u-x)du$$

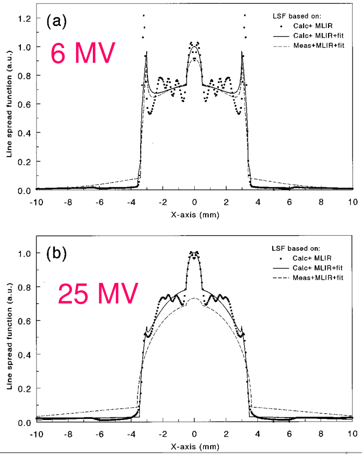
$$F[D_m(x)] = F[D(u)]F[K(u-x)]$$



Garcia-Vicente et al Med. Phys. 25, 1998, 202-7

Measured and calculated LSF for a IC

- FIG. 7. Calculated ~solid lines! and measured ~dashed lines! line spread functions ~LSFs! of an IC15 ionization chamber based on 0.2 and 0.4 mm slit beams, respectively, in a 6 MV (a) and 25 MV (b) x-ray beam. The points represent the calculated LSF after the application of Eq. 3 using a maximum likelihood iterative reconstruction (MLIR) algorithm; the lines represent the LSFs after a fit according to Eq. 4. The calculated and fitted LSFs have been normalized to a central value of 1.0; the other LSFs were normalized to the same area under the curves.
- **van't Veld et al.: Detector line spread functions, Medical Physics, Vol. 28, No. 5, May 2001**

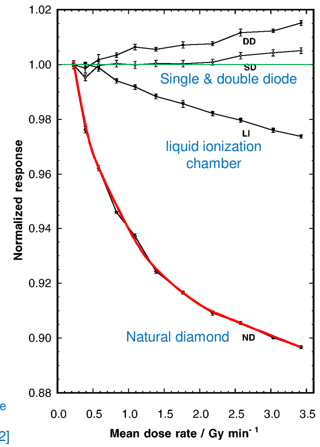


Dose rate dependence

- Determine by $1/r^2$-law

A diamond detector

- may have a huge dose rate dependence
- is not really small (> 3mm)
- has a huge production spread
- has low energy dependence



Detector response for different dose rates in a 6 MV bremsstrahlung beam expressed as ratios of detector response and dose rate, determined by a Farmer ionization chamber, and normalized at the lowest dose rate. The error bars represent the statistical uncertainty (1SD).
[Westermark et al. Phys. Med. Biol. 45 (2000) 685–702]

Silicon - Energy dependence, Perturbation, no B-G Cavity

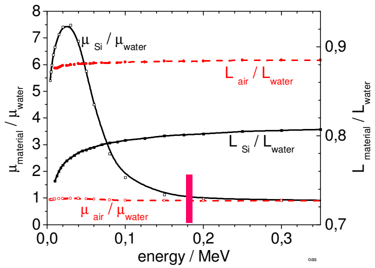
Silicon detector

- ✓ Small: width < 1mm
  hardly any volume effect
- ✓ Sensitive →

- Dimension not small against electron range
  General cavity theory applies
- strong increase of response below hν = 200 keV
  over response in regions with high scatter fraction
- High density
  displacement of water
  perturbation of the local field

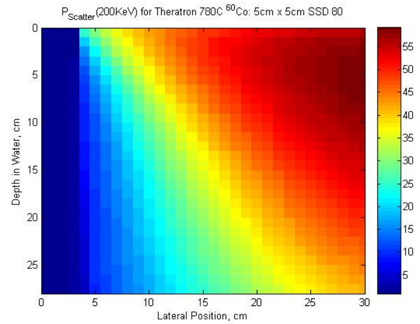
$$D_w = k'_p\left[\alpha\frac{\mu_{en,w}}{\mu_{en,\det}} + (1-\alpha)\frac{L_w}{L_{\det}}\right]D'_{\det} = k'_p k'_E D'_{\det}$$

	Z	Z³	ρ/[g/cm³]	(W/e)/eV
SI	14	2744	2,33	3,8
air	7,64	446	0,0013	34
water	7,42	409	1	
carbon	6	216	3,1 -3,5	



% dose from photons below 200 keV for ^{60}Co

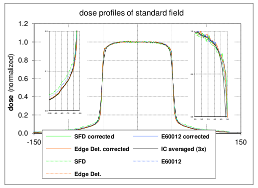
- Field size = 5cm x 5cm

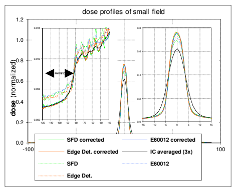


Ndimofor Chofor et al 2007 *Phys. Med. Biol.* **52** N137 doi: **10.1088/0031-9155/52/7/N03**

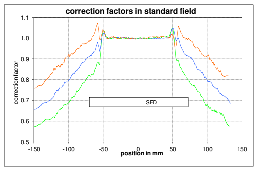
Over response outside the useful beam

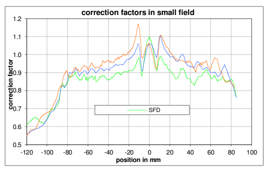
Profile measurements: Energy-response of diodes





$$k(x) = \frac{D_{IC}\otimes S_{SD}(x)}{D_{SD}\otimes S_{IC}(x)}$$

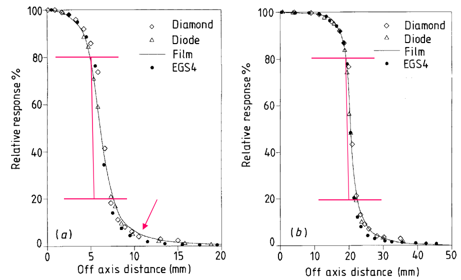




- standard field 10.4x9.6 cm^2, narrow field 0.8x10.4 cm^2, Q = 10 MV, water phantom, meas. depth = 10 cm

Profile measurements

- To detect the penumbra correctly use a small diode
- Check the detector response outside the geometrical field
- Correct for over/under-response or use an appropriate detector. [e.g. shielded diode or radiochromic film]

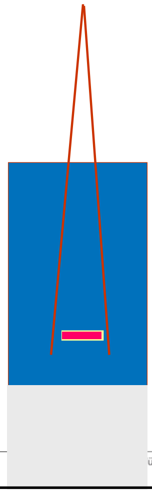


Off axis profiles at the isocentre (FAD D 100 cm), 6 cm deep, measured with diamond, shielded diode, and radiographic film and calculated using MC (EGS4), for (*a*) 7 mm and (*b*) 23 mm SRS collimators.

Heydarian et al PMB 41 (1996) 93–110

Depth dose and TPR measurements

- Use a small diode for small fields and BU, an IC otherwise
- Estimate the changing volume effect with depth
- Carefully align CAX with scan direction
- Measure TPR directly
- Examine data
  - *Fit to a function*
  - *Corroborate by different means*
- energy dependence, i.e. depth dependence of response is low for small fields



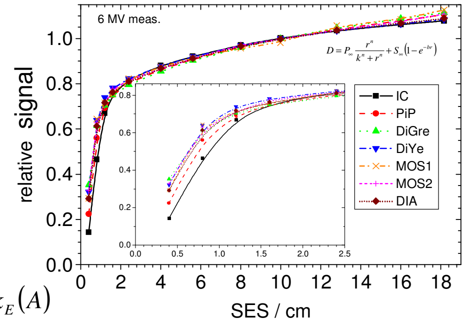
Change of correction factors with depth

depth dependence	PTW60012				
	Cranmer-Sargison			Ralston 12	
	Field size /cm				
depth /cm	0.5	1	5	0.5	1
1.5	0.941	0.98	1	0.96	0.99
5	0.94	0.983	1	0.96	0.98
10	0.948	0.989	1	0.95	0.98
mean	0.943	0.984	1.000	0.957	0.983
Std. dev.	0.004	0.005	0.000	0.006	0.006

Depth dependence is negligible also for unshielded diodes
At which field size will it start to be relevant?

Output measurement S_{cp}: Field size dependence of k_{NR}

$$S_{cp} = \frac{D_w(A, z_{ref})}{D_w(A_{ref}, z_{ref})} \approx$$



$$k_{NR}(A) = k_V(A) k_p(A) k_E(A)$$

- perturbation correction factor k_p
- energy correction factor k_E
- *volume averaging correction factor* k_V

Output terminology: conventional vs. AAPM/IAEA

- Calibration conditions → reference conditions → measurement conditions
- Output factor = total scatter factor = collimator scatter x phantom scatter

$$D_w(A) = k(A) D_{det} = k(A) N M_{det}(A)$$

$$D_w(A, z_{ref}) = S_{cp}(A) D_w(A_{ref}, z_{ref})$$

$$k(A) N M_{det}(A) = S_{cp}(A) k(A_{ref}) N M_{det}(A_{ref})$$

$$S_{cp}(A) = \frac{k(A)}{k(A_{ref})} \frac{M_{det}(A)}{M_{det}(A_{ref})}$$

$$S_{cp}(A) = k_{NR}(A) \frac{M_{det}(A)}{M_{det}(A_{ref})}$$

$$k_{NR}(A) = \frac{1}{RF}$$

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

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

Behavior of $k_{NonReference}$ with field size?

Response versus field size:
influence of photon energy

- Signal of various detectors relative to ionization chamber PTW31010 with 0.125cm³
- Decreasing response of Si-detectors with decreasing field size
- Reason: depletion of low energy photons
- For small fields volume averaging of the 0.125 cm³ large IC is dominant

Sauer, Wilbert MP **34**, 2007, 1983-1988

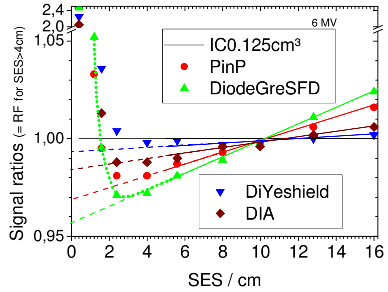
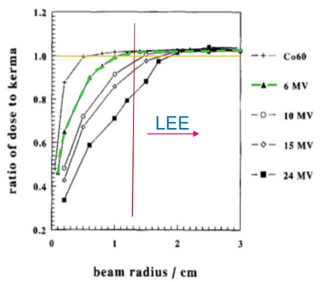
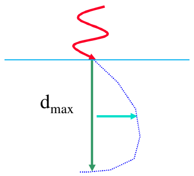


FIG. 3. Detector signals relative to the reference ionization chamber signal $[D_{det}(s)/D_{IC}(s)]$. The factors for SES=8 and 4 mm are not shown. They are in the range of 1.3 and 2.3 respectively. Solid lines: linear regression of $k_E(s)$ for s=SES>5 cm, dashed lines: extrapolation for smaller field sizes. (a) 6 MV; (b) 10 MV.

Lateral electron equilibrium and lateral electron range



Li et al MP **22**, 1995, 1167-1170



Only for field sizes larger than the lateral electron range approximate LEE exists

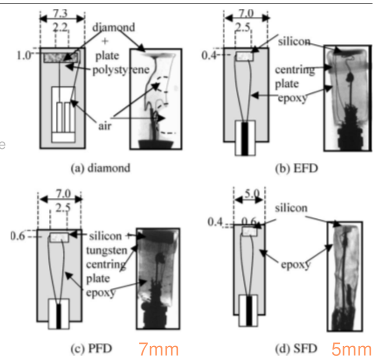
Causes of perturbation

Ionization chamber:

- wall, central electrode, air cavity,
- (low density: blurring or rising of the isodose volume)

Diode:

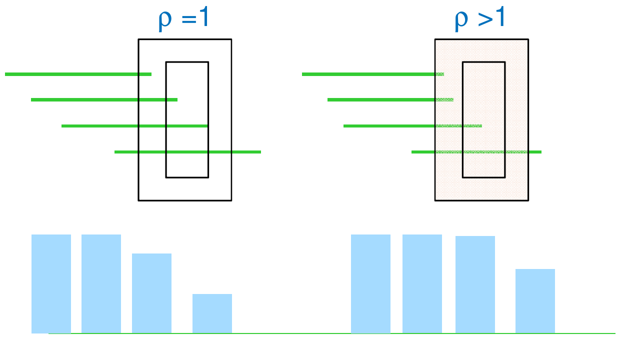
- housing, shielding, contacting silicon chip
- (high density: shrinkage or ebbing of the isodose volume)



C. McKerracher, D.I. Thwaites / Radiotherapy and Oncology 79 (2006) 348–351

➢ Field size dependence of perturbation factors

Response versus field size: Density effect



- See Westermark et al, Phys. Med. Biol. **45** (2000) 685–702 @p693

the influence of detector density (15MV)

$k_{NR} \approx$

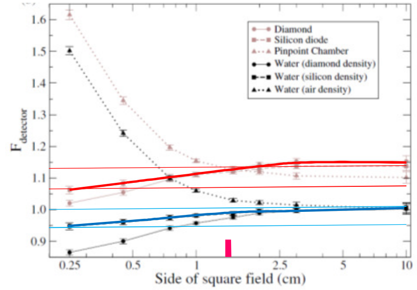


Figure 2. MC calculated dose-to-water to dose-to-detector-in-water ratios, $F_{detector}$, obtained for (a) diamond, diode and Pinpoint detector voxels and (b) the same voxels filled with detector-density water. All points are positioned on-axis at 5 cm depth in a water phantom and displayed with two standard deviation (σ) error bars, reflecting statistical uncertainties of the MC calculations. As with all other figures in this paper the following field sizes have been analysed: 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 10.0 cm.

- Scott et al, Phys. Med. Biol. **57** (2012) 4461–4476

Monte Carlo determination of correction factors

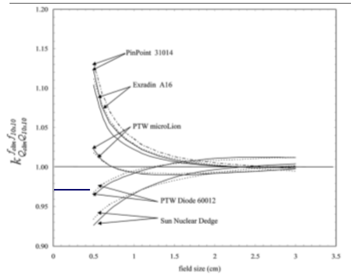


FIG. 7. Correction factor $k^{f_{clin},f_{10\times10}}_{Q_{clin},Q_{10\times10}}$ for five detectors as a function of the field size, for 6 MV beams of Siemens (dotted line) and Elekta (continuous line) linacs.

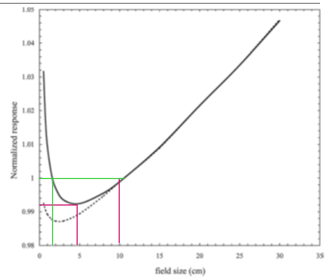
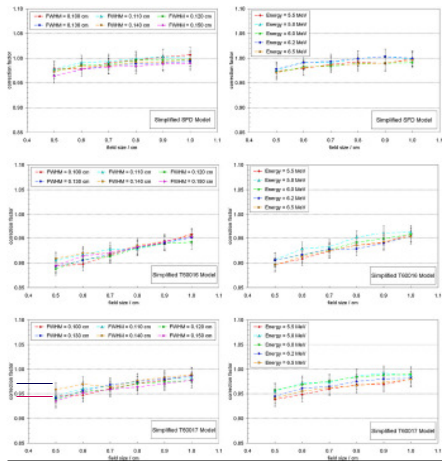


FIG. 8. MC simulation of the normalized response: $\left(D^{f_{clin}}_{det,Q_{clin}}/D^{f_{clin}}_{w,Q_{clin}}\right)/\left(D^{f_{10\times10}}_{det,Q_{10\times10}}/D^{f_{10\times10}}_{w,Q_{10\times10}}\right)$ of PTW 60012 diode using a simplified model (dotted line) and a refined model (continuous line).

- k… contains k_V
- Simplified model not appropriate

Francescon, Cora, and Satariano: Correction factors for several detectors using MC simulation, Medical Physics, Vol. 38, No. 12, December 2011

Monte Carlo determination of correction factors



Cranmer-Sargison et al, Phys. Med. Biol. **57** (2012) 5141–5153
Figure 8. The change in $k_{fclin, fmsr, Qclin, Qmsr}$ as a function of field size shown for various source widths (left) and energies (right) calculated using the simplified SFD (top row), T60016 (shielded, middle row) and T60017 (unshielded bottom row) models.

- k… doesn't contain k_V
- Simplified model sufficient
- Influence of FWHM and energy marginal

Monte Carlo determination of correction factors

Monte Carlo modelling of diode detectors for small field MV photon dosimetry 5151

Table 2. Two data sets are shown for the simplified detector models which, as detailed in the text, are composed of the silicon chip plus nearby high density filtering/shielding only. The top and bottom rows are the average $k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$ values calculated over the FWHM and MeV data shown in figure 8 respectively.

Simplified detector models	Square field size of side					
	1.00 cm	0.90 cm	0.80 cm	0.70 cm	0.60 cm	0.50 cm
SFD	0.997 ± 0.006	0.995 ± 0.006	0.992 ± 0.006	0.987 ± 0.004	0.982 ± 0.006	0.972 ± 0.006
	0.996 ± 0.004	0.995 ± 0.008	0.994 ± 0.005	0.988 ± 0.004	0.985 ± 0.006	0.974 ± 0.003
T60016	0.953 ± 0.005	0.941 ± 0.002	0.932 ± 0.002	0.921 ± 0.005	0.910 ± 0.008	0.898 ± 0.008
	0.957 ± 0.009	0.947 ± 0.009	0.939 ± 0.008	0.928 ± 0.004	0.917 ± 0.008	0.902 ± 0.005
T60017	0.983 ± 0.005	0.978 ± 0.005	0.972 ± 0.005	0.962 ± 0.004	0.957 ± 0.008	0.944 ± 0.008
	0.983 ± 0.005	0.980 ± 0.010	0.976 ± 0.009	0.967 ± 0.007	0.961 ± 0.009	0.947 ± 0.008

- stereotactic field diode (SFD) (IBA/Scanditronix),
- T60016 shielded (PTW) and T60017 unshielded (PTW) diodes
- Shielded diode needs a larger correction for very small fields
- above 1cm field size, correction with unshielded diode is very small
- … but medium and large fields demand a shielded diode

Cranmer-Sargison, Phys. Med. Biol. **57** (2012) 5141–5153 & Medical Phys., **38**, No. 12, 2011

Using polymer gel, EBT, alanine, and TLD to determine corrections for diodes

1% difference between shielded/ unshielded diode correction

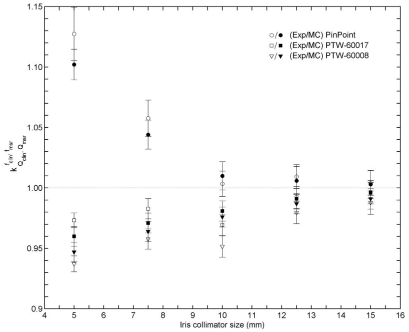


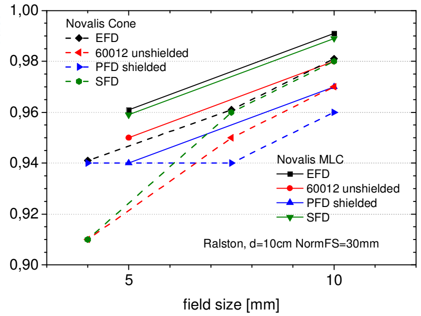
FIG. 6. Measured $k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}$ correction factors for 800 mm SDD plotted as a function of iris collimator size for the PinPoint 31014 microchamber, PTW-60017 unshielded, and PTW-60008 shielded diodes. Corresponding results calculated using MC simulation by Francescon *et al.* (Ref. 37) are plotted for comparison. The uncertainty, at 68% confidence level, of the presented correction factor results are depicted using error bars.

Pantelis et al.: Experimental determination of correction factors for OF measurements Medical Physics, Vol. 39, No. 8, August 2012

Experimental derivation

Table 3. Diode correction factors equal to the ratios of relative FOD readings (corrected for volume averaging) to relative diode readings (not corrected for volume averaging). Both sets of readings were normalized at the 30 mm field size. These correction factors were measured in water using a 6 MV photon beam from a Varian Novalis linear accelerator. These factors may not be valid for irradiation conditions different to those used in this study. The quoted uncertainties in the values of the correction factors are absolute and refer to 1 standard deviation.

	Uncertainty (1 SD)	4 mm cone (0.02)	5 mm MLC (0.02)	7.5 mm cone (0.01)	10 mm cone (0.01)	10 mm MLC (0.01)
60012	1.5 cm	0.89	0.95	0.95	0.97	0.99
Stem	5 cm	0.89	0.95	0.96	0.98	0.98
Perpendicular	10 cm	0.87	0.93	0.94	0.97	0.98
60012	1.5 cm	0.93	0.96	0.96	0.99	0.99
Stem	5 cm	0.92	0.96	0.96	0.98	0.98
Parallel	10 cm	0.91	0.95	0.95	0.97	0.98
SFD	1.5 cm	0.92	0.96	0.97	0.98	1.00
Stem	5 cm	0.91	0.97	0.97	0.99	0.99
Perpendicular	10 cm	0.90	0.94	0.96	0.98	0.99
SFD	1.5 cm	0.94	0.97	0.97	0.99	1.00
Stem	5 cm	0.93	0.97	0.98	0.99	0.99
Parallel	10 cm	0.91	0.96	0.96	0.98	0.99
EFD	1.5 cm	0.94	0.97	0.98	0.99	1.00
Stem	5 cm	0.93	0.97	0.98	0.99	0.99
Perpendicular	10 cm	0.92	0.95	0.97	0.98	0.99
EFD	1.5 cm	0.97	0.98	0.98	0.99	0.99
Stem	5 cm	0.96	0.98	0.98	0.99	0.99
Parallel	10 cm	0.94	0.96	0.96	0.98	0.99
PFD	1.5 cm	0.87	0.92	0.94	0.97	0.98
Stem	5 cm	0.85	0.91	0.94	0.97	0.97
Perpendicular	10 cm	0.84	0.89	0.92	0.96	0.97
PFD	1.5 cm	0.96	0.96	0.95	0.97	0.98
Stem	5 cm	0.96	0.95	0.96	0.97	0.97
Parallel	10 cm	0.94	0.94	0.94	0.96	0.97

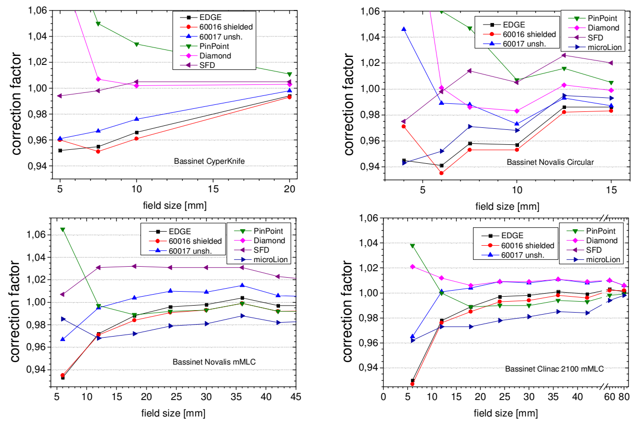


- Largest correction for SFD at 4mm cone size
- Low (<2%) differences between shielded and unshielded detectors

Ralston et al, Small field diode correction factors derived using an air core fibre optic scintillation dosimeter and EBT2 film. Phys. Med. Biol. **57** (2012) 2587–2602

Experimentally derived correction factors

Bassinet et al.: MP, Vol. 40, No. 7, July 2013. Reference: EBT2 & LiF microcubes



Comparison of data from different resources

Compare k @ FS=5mm, d=10cm			reference FS and inclusion of volume effect may vary				
1st Author	PTW60012	PTW60017	PTW60008 shielded	PTW60016 shielded	IBA SFD	Machine	Method
Cranmer-Sargison	0.948	0.947	0.889	0.907	0.966	Varian iX	MC
Francescon 12	0.963	0.956	0.945			CK	MC
Pantelis 12	0.954	0.973	0.937			CK	meas.
Ralston 12	0.921				0.921	Novalis Cone	meas.
Ralston 12	0.930				0.960	Novalis MLC	meas.
Bassinet 13		0.961		0.960	0.994	CK	meas.
						mean	
mean	0.943	0.959	0.924	0.934	0.960	0.95	
Stddev	0.017	0.011	0.030	0.037	0.030	0.03	

- Sample not representative, but
- Shows spread and tendency
- Perturbation and volume effect may mutually almost cancel out

Conclusions

- Output:
- For very small photon fields, detector response is not known with high certainty
  - *Contemporary literature shows over-response, likely due to density effects*
  - but, volume effect, photo-effect and possibly intrinsic effects counteract
- Use a detector needing a low correction
  - *e.g. unshielded diode, radiochromic film*

- Profiles:
- determine dependence of response on energy for each detector
  - *Good detectors are e.g. shielded diodes or radiochromic film*

- Depth dose:
- Any detector works, if small enough

- Corroborate the measurements by
- using different types of detectors