Detectors for small field dosimetry

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Overview

Ideal detector

Water calorimeter

Ionization chamber

Alanine

Diodes, diamond, film, TLD,...
Which detector to

Read literature:

IPEM report 103

Manufacturers manuals, e.g. P...
### Table 3.8 Solid-state detectors available from PTW GmbH, Scanditronix Wellhöfer/IBA Dosimetry and Sun Nuclear Corpora

<table>
<thead>
<tr>
<th>Type of detector</th>
<th>PTW Diamond 60003</th>
<th>PTW Diode P 60006</th>
<th>PTW Diode E 60012</th>
<th>Scanditronix/IBA PFD SC</th>
<th>Scanditronix/IBA EFD SC</th>
<th>Scanditronix/IBA SFD Stereotactic diode</th>
<th>Sun Nuclear diode</th>
<th>Edge Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitive volume</td>
<td>(1...6) mm³</td>
<td>0.0025 mm³</td>
<td>0.0025 mm³</td>
<td>0.19 mm³</td>
<td>0.19 mm³</td>
<td>0.017 mm³</td>
<td>0.0019 mm³</td>
<td></td>
</tr>
<tr>
<td>Sensitive area</td>
<td>(3...15) mm²</td>
<td>1.12 mm²</td>
<td>1.12 mm²</td>
<td>2.0 mm²</td>
<td>2.0 mm²</td>
<td>0.6 mm²</td>
<td>0.8 mm²</td>
<td>0.8 mm²</td>
</tr>
<tr>
<td>Thickness of sensitive area</td>
<td>(0.1...0.4) mm</td>
<td>depth 2.5 mm</td>
<td>depth 2.5 mm</td>
<td>0.06 mm</td>
<td>0.06 mm</td>
<td>0.06 mm</td>
<td>0.05 mm</td>
<td></td>
</tr>
<tr>
<td>Outer dimensions of detector</td>
<td>7.3 mm</td>
<td>7.0 mm length 47 mm</td>
<td>7.0 mm length 45.5 mm</td>
<td>7.0 mm length 75 mm</td>
<td>7.0 mm length 75 mm</td>
<td>5.0 mm length 75 mm</td>
<td>3.8 mm length 38 mm</td>
<td></td>
</tr>
<tr>
<td>Cover thickness, material</td>
<td>Polystyrene</td>
<td>Entrance window: 2.2 mm</td>
<td>Entrance window: 0.7 mm</td>
<td>Epoxy resin (with tungsten at the back)</td>
<td>Epoxy resin</td>
<td>Epoxy resin</td>
<td>0.13 mm, Brass</td>
<td></td>
</tr>
<tr>
<td>Density of cover material</td>
<td>-1.05 g/cm³</td>
<td>Total window area density 221 mg/cm²</td>
<td>Total window area density 68 mg/cm²</td>
<td>2.0 g/cm² at back</td>
<td>1.2 g/cm²</td>
<td>1.2 g/cm²</td>
<td>Beass</td>
<td></td>
</tr>
<tr>
<td>Depth of effective point of measurement</td>
<td>1.0 mm from tip with detector axis  / CAX</td>
<td>2.0 mm from tip with detector axis  / CAX</td>
<td>0.6 mm from tip with detector axis  / CAX</td>
<td>0.5 mm 0.15 mm</td>
<td>0.45 mm 0.1 mm</td>
<td>0.5 mm 0.15 mm</td>
<td>0.5 mm</td>
<td></td>
</tr>
<tr>
<td>Bias voltage [V]</td>
<td>+100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Which detector to use?

Read literature:

IPEM report 103

Manufacturers manuals, e.g. PTW
Which detector to use?

Detector EDGE™

The Ultimate Small Field Dosimeter
An ultra small dosimetry detector for small field beam scanning.

The EDGE Detector delivers flatter profiles, sharper resolution, and the real beam picture for treatment planning. Compared to ion chambers, EDGE Detector gives approximately 100 times more signal even though it is over 6000 times smaller in volume. Additionally, the EDGE Detector offers the same accuracy for PDD curves, with better accuracy in critical flatness and penumbra measurements.
# Ideal detector

<table>
<thead>
<tr>
<th>Detector properties</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>Short-term detector response should be better than 0.1% for a total combined dose of many hundreds of kGy from multiple exposures.</td>
</tr>
<tr>
<td>Dose linearity</td>
<td>Linearity better than 0.1% should be possible over a dose range of at least three orders of magnitude (e.g. 0.01–10 Gy)</td>
</tr>
<tr>
<td>Dose rate linearity</td>
<td>Linear accelerators are typically operated at dose rates of 100 Gy/s (instantaneous) and 0.01 Gy/s (averaged) and therefore detectors should be linear to better than 0.1% over this range.</td>
</tr>
<tr>
<td>Dose per pulse linearity</td>
<td>A detector’s response with changing dose per pulse should remain stable to better than 0.1% after correction for ion recombination.</td>
</tr>
<tr>
<td>Energy response</td>
<td>Essentially water equivalent</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>The choice of suitable detector in terms of spatial resolution is usually based on a trade-off between adequately high signal-to-noise ratio and dosimeter size.</td>
</tr>
<tr>
<td>Size of detector</td>
<td>The detector size should be such that the volume averaging correction is not larger than 5%.</td>
</tr>
<tr>
<td>Orientation</td>
<td>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 ±60° from the axis normal to the detector axis.</td>
</tr>
</tbody>
</table>
Calorimetry

Radiation energy turns into heat

heat is tiny, but measurable – our primary standards for absorbed dose are calorimeters
Water calorimeter - thermistor probes (LSDG)
Water calorimeter – chemical heat defect

\[ D_w = c_w \Delta T \frac{1}{1-h} \]

Simulation:
- 25 µM O₂
- 100 µM H₂

Experiment:
- Data points
Water calorimetry – why does it not work for small fields

Heath flow:
Problem: dose determination with ion chambers

\[ D_w = D_{air} \cdot S_{w,air} \cdot p \]

\[ D_{air} = \frac{M}{m_{air}} \cdot \frac{W}{e} = \frac{M}{\rho \cdot V_{air}} \cdot \frac{W}{e} \]

\[ OF = \frac{D_{field}}{D_{ref}} = \frac{M_{field} \cdot (s_{w,air})_{field} \cdot p_{field}}{M_{ref} \cdot (s_{w,air})_{ref} \cdot p_{ref}} \]
Which one is right?

0.40 0.50 0.60 0.70 0.80 0.90 1.00
0 20 40 60 80 100

square field width / mm

M / M ref

PTW 31002 (0.125cc)
PTW 31016 (PinPoint)
PTW 31003 (0.3cc)

Krauss, Vienna, Feb. 2009,
Ion chambers for small field dosimetry
- Water to air stopping power ratios

Andreo & Brahme, PMB 8:839 (1986)
Calibration in a $^{60}\text{Co}$ beam

$$P_0 \square D_{w,^{60}\text{Co}}$$

$$N_{D,w} = \frac{D_{w,^{60}\text{Co}}}{M_{\text{corr},^{60}\text{Co}}}$$
Dosimetry in a high-energy x-ray beam

\[ D_{w,Q}(P_0) = M_{\text{corr},Q} \cdot N_{D,w} \cdot k_Q \]

Only BQ!
Dosimetry in a high-energy x-ray beam

\[ D_{w,Q}(P_0) = M_{corr,Q} \cdot N_{D,w} \cdot k_Q \]

Only BQ!
Dosimetry in a high-energy x-ray beam

\[ D_{w,Q}(P_0) = M_{corr,Q} \cdot N_{D,w} \cdot k_Q \]

Only BQ!
Dosimetry in a high-energy x-ray beam

\[ D_{w,Q}(P_0) = M_{corr,Q} \cdot N_{D,w} \cdot k_Q \]

Only BQ!
Dosimetry in a high-energy x-ray beam

\[ D_{w,Q}(P_0) = M_{corr,Q} \cdot N_{D,w} \cdot k_Q \]

Only BQ!
Plane-parallel chamber

OF

square field width / mm
Plane-parallel chamber
Plane-parallel chamber

\[ \text{OF} \]

\[ \text{square field width / mm} \]
Ion chambers: recombination

LeRoy et al., PMB 56:5637-51 (2011)
Ion chambers: polarity

Which one is right?

Krauss, Vienna, Feb. 2009,
Which one is right?

Krauss, Vienna, Feb. 2009,
Which one is right?

Krauss, Vienna, Feb. 2009,
Diodes for small field dosimetry

Sauer and Wilbert
2007 Med Phys
34:1983-8
Diamond detectors

Lechner 2013 Radiother Oncol 109:356

Vorlage / template. ZA000_10700_1310013, Vers4.0

PPRIG workshop, Teddington UK, 12-13 Mar 2014

30
Diodes and diamonds...
Organic scintillators

Cfr. Louis Archambault
Liquid ionization chambers
Radiochromic film

Figure 1. Output factors measured with the FOD (corrected for volume averaging) and EBT2 film for 4–10 mm cones and 5 and 10 mm MLC fields. The detectors were positioned isocentrically at depths 1.5, 5 and 10 cm, the FOD in water and the film in Virtual Water. The Type A uncertainties (1 SD) for the FOD were 1.1%, 0.8%, 0.4%, 0.2% and 0.2% for the 4 mm cone, 5 mm MLC field, 7.5 mm cone, 10 mm cone and the 10 mm MLC field, respectively. The Type A uncertainty for the film was 2.5% for all field sizes.

Ralston 2012 Phys Med Biol 57:2587
Alanine

Amino acid / readout by ESR

Pellets 2.5 mm thick and Ø 5 mm or 2.5 mm

Water-equivalent density 1.2 g cm\(^{-3}\)


Figure 1. Mass energy absorption coefficient (\(\mu_{en}/\rho\)) ratio and mass collision stopping power ratio (\(S/\rho\)) between alanine and water (dotted line) and the same coefficient ratio between alanine dosimeter material and water (solid line). The \(\mu_{en}/\rho\)-coefficients are obtained with the programme XMuDat (Nowotny 1998), while the \(S/\rho\)-coefficients are obtained with the NIST online database ESTAR of Berger et al (1999).
## Table I. Summary of properties of detectors used in this study – solid state detectors

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Dimensions of sensitive volume [mm]</th>
<th>Material</th>
<th>Z(_{\text{eff}})</th>
<th>Material density [g/cm(^3)]</th>
<th>Electron density [e^-/g] relative to water</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLD chips</td>
<td>3.2×3.2×0.89</td>
<td>TLD-100 LiF:Mg,Ti</td>
<td>7.51</td>
<td>2.64</td>
<td>0.833</td>
</tr>
<tr>
<td>TLD (\mu)-cubes</td>
<td>1×1×1</td>
<td>TLD-100 LiF:Mg,Ti</td>
<td>7.51</td>
<td>2.64</td>
<td>0.833</td>
</tr>
<tr>
<td>RPLD (GD-302M), Japan</td>
<td>Length 6, diameter 1.5</td>
<td>Silver activated phosphate glass</td>
<td>10.86</td>
<td>2.61</td>
<td>0.885</td>
</tr>
<tr>
<td>Alanine, NPL</td>
<td>Thickness 2.3, diameter 5</td>
<td>Alanine/Paraffin</td>
<td>5.96</td>
<td>1.23</td>
<td>0.976</td>
</tr>
<tr>
<td>Alanine, DTU</td>
<td>Thickness 2.8, diameter 4.8</td>
<td>Alanine/Paraffin</td>
<td>5.96</td>
<td>1.23</td>
<td>0.976</td>
</tr>
<tr>
<td>IBA SFD diode</td>
<td>Thickness 0.06, diameter 0.6</td>
<td>Silicone</td>
<td>14</td>
<td>2.33</td>
<td>0.901</td>
</tr>
<tr>
<td>IBA PFD diode</td>
<td>Thickness 0.06, diameter 2</td>
<td>Silicone</td>
<td>14</td>
<td>2.33</td>
<td>0.901</td>
</tr>
<tr>
<td>IBA EFD diode</td>
<td>Thickness 0.06, diameter 2</td>
<td>Silicone</td>
<td>14</td>
<td>2.33</td>
<td>0.901</td>
</tr>
<tr>
<td>PTW 60003 diamond</td>
<td>Thickness 0.1-0.4</td>
<td>Diamond</td>
<td>6</td>
<td>approximately 3.5(^*)</td>
<td>0.901</td>
</tr>
<tr>
<td>(\text{Al}_2\text{O}_3):C, DTU</td>
<td>0.5×0.5×2</td>
<td>(\text{Al}_2\text{O}_3):C</td>
<td>10.60</td>
<td>3.97</td>
<td>0.883</td>
</tr>
<tr>
<td>Saint Gobain BCF-60 scintillator 1</td>
<td>Length 1, diameter 1</td>
<td>Polystyrene</td>
<td>5.70</td>
<td>1.06</td>
<td>0.975</td>
</tr>
<tr>
<td>Saint Gobain BCF-60 scintillator 2</td>
<td>Length 2, diameter 0.5</td>
<td>Polystyrene</td>
<td>5.70</td>
<td>1.06</td>
<td>0.975</td>
</tr>
</tbody>
</table>

*the density varies depending on the purity of the diamond used
Field output factors – correction factors / components

Other proposals to factorize SF correction factors


Correction factors for unshielded diodes

Francescon et al 2011, Med Phys 38:6513

Benmakhlof et al 2014, Med Phys 41:041711

Fig. 7. Correction factor $k_{Q_{\text{clin}},Q_{\text{msr}}}^{f_{\text{clin}},f_{\text{msr}}}$ for five different field sizes, for 6 MV beams of Siemens (dotted line) linacs.

Fig. 7. Monte Carlo calculated output correction factors, $k_{Q_{\text{clin}},Q_{\text{msr}}}^{f_{\text{clin}},f_{\text{msr}}}$, of three silicon diode detectors for Varian Clinac iX 6 MV beams, as a function of the nominal square field size at the phantom surface. The output correction factors are shown for unshielded silicon diodes and shielded silicon diodes.
# Ch 5 - Practical implementation

Practical implementation of msr dosimetry / availability, \( k_{Q_{msr}, Q_{ref}}^{f_{msr}, f_{ref}} \) data

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

e.g. CyberKnife / iris collimator $E_0 = 7.0$ MeV, FWHM spot 2.1 mm

<table>
<thead>
<tr>
<th>Field size / mm</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
<th>12.5</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTW 60008</td>
<td>0.947</td>
<td>0.964</td>
<td>0.976</td>
<td>0.987</td>
<td>0.991</td>
<td>0.998</td>
<td>1.005</td>
</tr>
<tr>
<td>PTW 60012</td>
<td>0.964</td>
<td>0.975</td>
<td>0.979</td>
<td>0.992</td>
<td>0.996</td>
<td>0.999</td>
<td>1.002</td>
</tr>
<tr>
<td>PTW 60017</td>
<td>0.960</td>
<td>0.971</td>
<td>0.981</td>
<td>0.991</td>
<td>0.996</td>
<td>0.999</td>
<td>1.002</td>
</tr>
<tr>
<td>PTW 60018</td>
<td>0.954</td>
<td>0.966</td>
<td>0.978</td>
<td>0.988</td>
<td>0.994</td>
<td>0.998</td>
<td>1.002</td>
</tr>
<tr>
<td>SN Edge</td>
<td>0.947</td>
<td>0.959</td>
<td>0.973</td>
<td>0.980</td>
<td>0.986</td>
<td>0.993</td>
<td>1.000</td>
</tr>
<tr>
<td>Exradin A16</td>
<td>1.095</td>
<td>1.039</td>
<td>1.009</td>
<td>1.006</td>
<td>1.003</td>
<td>1.004</td>
<td>1.005</td>
</tr>
<tr>
<td>PTW 31014</td>
<td>1.102</td>
<td>1.044</td>
<td>1.010</td>
<td>1.006</td>
<td>1.003</td>
<td>1.001</td>
<td>0.999</td>
</tr>
<tr>
<td>PTW microLion</td>
<td>1.027</td>
<td>1.001</td>
<td>0.997</td>
<td>0.993</td>
<td>0.996</td>
<td>0.998</td>
<td>0.999</td>
</tr>
</tbody>
</table>

Francescon et al. 2012 Med Phys 57:3741
Field output factors – Monte Carlo calculated correction factors CyberKnife

Different FWHM primary source

\[ k_{Q_{\text{clin}}, Q_{\text{msr}}} f_{\text{clin}}, f_{\text{msr}} = a \cdot \Omega_{Q_{\text{clin}}, Q_{\text{msr}}} f_{\text{clin}}, f_{\text{msr}} + b \]

\[ k_{Q_{\text{clin}}, Q_{\text{msr}}} f_{\text{clin}}, f_{\text{msr}} = \frac{M_{\text{msr}}}{M_{\text{clin}}} \cdot \Omega_{Q_{\text{clin}}, Q_{\text{msr}}} f_{\text{clin}}, f_{\text{msr}} \]

\[ msr = 60 \text{ mm collimator} \]

Francescon et al 2008 Med Phys 35:504-13
Field output factors:

\[
\Omega_{f_{\text{clin}}, f_{\text{msr}}}^{Q_{\text{clin}}, Q_{\text{msr}}} = \frac{D_{f_{\text{clin}}, Q_{\text{clin}}}}{D_{f_{\text{msr}}, Q_{\text{msr}}}} = \frac{M_{f_{\text{clin}}, Q_{\text{clin}}}}{M_{f_{\text{msr}}, Q_{msr}}} = \frac{M_{f_{\text{clin}}, Q_{\text{clin}}}}{M_{f_{\text{msr}}, Q_{msr}}} \cdot \frac{D_{f_{\text{clin}}, Q_{\text{clin}}}}{D_{f_{\text{msr}}, Q_{msr}}} = \frac{M_{f_{\text{clin}}, Q_{\text{clin}}}}{M_{f_{\text{msr}}, Q_{msr}}} \cdot k_{\Omega_{f_{\text{clin}}, f_{\text{msr}}}^{Q_{\text{clin}}, Q_{\text{msr}}}}
\]

\[
k_{f_{\text{clin}}, f_{\text{msr}}}^{Q_{\text{clin}}, Q_{\text{msr}}} = \frac{D_{f_{\text{clin}}, Q_{\text{clin}}}}{D_{f_{\text{msr}}, Q_{msr}}} \cdot \frac{M_{f_{\text{msr}}, Q_{\text{msr}}}}{M_{f_{\text{clin}}, Q_{\text{clin}}}}
\]

\[
k_{f_{\text{clin}}, f_{\text{msr}}}^{Q_{\text{clin}}, Q_{\text{msr}}} (1) = M_{f_{\text{msr}}, Q_{\text{msr}}} (1) \cdot M_{f_{\text{clin}}, Q_{\text{clin}}} (2) = M_{f_{\text{clin}}, Q_{\text{rel}}, Q_{\text{clin}}} (2)
\]

\[
k_{f_{\text{clin}}, f_{\text{msr}}}^{Q_{\text{clin}}, Q_{\text{msr}}} (2) = M_{f_{\text{clin}}, Q_{\text{rel}}, Q_{\text{clin}}} (1)
\]
Field output factors - CyberKnife:

Pantelis et al. 2010 Med Phys 37:2369
Field output factors – correction factors

PTW-60012

IBA SFD
Field output factors – correction factors

PTW-60008

PTW-31006

PTW-31002