Small field dosimetry

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Acknowledgements

IAEA/AAPM small and composite field working group

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Overview

Problems and proposed solutions of small field dosimetry

Recent efforts:

- IPEM Report 103
- AAPM TG-101, TG-148, TG-135
- DIN, NCS, French working groups
- IAEA formalism, CoP for small fields being developed

Dosimetry formalism

Availability of data
Need

Increased interest in small fields for SRS and IMRT

Accidents have happened due to the use of inappropriate detectors for small fields

Output factors for fields < 1 cm show considerable spreads and outliers

Cavity theory not really a problem but perturbation factors
Example: Large differences in Output Factors among users/machines

Statistics of 45 Output Factors for 6 mm and 18 mm square fields Novalis, SSD = 100 cm, depth = 5 cm, various detectors)

factor of 2 in dose determination!

From Wolfgang Ullrich, BrainLab
REPORT

concerning the radiotherapy incident at the university hospital centre (CHU) in Toulouse – Rangueil Hospital

Although the origin of the event is clearly identified (use of a measuring device which was inappropriate for calibrating microbeams), the underlying causes remain to be determined; this, however, was not the main goal of the inspection. The letter following the inspection therefore asks the CHU to analyse the organisational and human factors, especially human resources, work load, skills and training.
When is a field

Loss of lateral charged particles

Partial occlusion of the primary source

Detector size too large

Why is loss of CPE problem?

Small detectors - Bragg-Gray cavity

\[
\frac{D_w}{D_{med}} = s_{w,med}
\]

Intermediate detectors - Burlin

\[
\frac{D_w}{D_{med}} = [d \cdot s_{w,med} + (1 - d) \cdot (\mu_{en}/\rho)_{w,med}]
\]
Why is loss of CPE problem?

Small detectors - Bragg-Gray cavity

\[
\frac{D_w}{D_{med}} = s_{w,med} \cdot p_{fl}
\]

Intermediate detectors - Burlin

\[
\frac{D_w}{D_{med}} = [d \cdot s_{w,med} + (1 - d) \cdot (\mu_{en}/\rho)_{w,med}] \cdot p_{fl}
\]
Ion chambers perturbations

Solution

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

$$r_{LCPE} \text{ (in cm)} = 5.973 \cdot TPR_{20,10} - 2.688$$

(Li et al. 1995 Med Phys 22, 1167-1170)
Problem: small field size / apparent field widening

From Das et al. 2008 Med Phys 35:206-15
Problem: beam quality

Problem: beam quality

Problem: beam quality

Problem: dose determination with ion chambers

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

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

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

correction factor
Ion chambers for small field dosimetry - Water to air stopping power ratios


Andreo & Brahme, PMB 8:839 (1986)
Field output factors – correction factors / components


Figure 1. Schematic illustration of the cavities simulated in this work, and the perturbation factors required to obtain the dose to a point in water.
Other proposals to factorize SF correction factors


Diodes for small field dosimetry

Sauer and Wilbert
2007 Med Phys
34:1983-8
Correction factors for unshielded diodes

Francescon et al 2011, Med Phys 38:6513

Benmakhlouf et al 2014, Med Phys 41:041711

Fig. 7. Correction factor \( k_{Q_{\text{clin}},Q_{\text{msr}}} \times 10^{10} \) for five detector diode types, for 6 MV beams of Siemens (dotted line) linacs.

Fig. 7. Monte Carlo calculated output correction factors, \( k_{Q_{\text{clin}},Q_{\text{msr}}} \), 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 compared with the measured values.
IAEA draft TECDOC small field dosimetry

Code of Practice / working document
Physics relevant to reference and relative dosimetry
Formalism
Instrumentation
Practical implementation
  Machine-specific reference dosimetry
  Relative dosimetry
Data
Ch. 2 - Physics of small fields

e.g. Small field conditions

LCPE  
source occlusion  
detector size

Seuntjens  
MC  
Aspradakis et al 2010  
IPEM Report 103  
Meltsner et al. 2009  
Med Phys 36:339-50
Ch3. - Formalism (Alfonso et al) / $D_w$ in machine specific reference (msr) fields

Chamber calibrated specifically for the msr field

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

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

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

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

$$D_{w,Q_{msr}}^f = M_{Q_{msr}}^f \cdot N_{D,w,Q_0}^{f_{ref}} \cdot k_{Q_0}^{f_{ref}} \cdot k_{Q_{msr},Q}^{f_{msr},f_{ref}}$$
Note on the use of plastic phantoms

\[
D_{w,Q_{msr}}^{f_{msr}}(z_{ref}) = M_{plastic,Q_{msr}}^{f_{msr}}(z_{eq,plastic}) \cdot N_{D,w,Q_0}^{f_{ref}} \cdot k_{Q_{msr},Q_0}^{f_{msr},f_{ref}} \cdot k_{plastic,w}^{plastic,w}
\]

\[
k_{Q}^{plastic,w} = \frac{D_{w,Q}(z_{ref})}{D_{plastic,Q}(z_{eq,plastic})} \cdot \frac{(s_{plastic,air})_{Q}}{(s_{w,air})_{Q}} \cdot \frac{p_{Q,plastic}}{p_{Q,w}}
\]

(Seuntjens et al 2005, Med. Phys. 32: 2945)
Note on the application to FFF beams

Note on the application to FFF beams

$Q$ refers to a hypothetical field at the same machine, i.e. is FFF

\[
D_{w,Q_{\text{FFF}}}^{f_{\text{msr}}} = M_{Q_{\text{FFF}}^{f_{\text{msr}}}} \cdot N_{D,w,Q_{0}^{WFF}} \cdot k_{Q_{\text{FFF}},Q_{WFF}} \cdot k_{f_{\text{msr}},f_{\text{ref}}}^{Q_{\text{msr}},Q_{\text{FFF}}}
\]
Note on the application to FFF beams

\[
\begin{align*}
&k_{Q_WFF, Q_0} \\
&k_{Q_{FFF}, Q_{WFF}} \\
&k_{f_{msr}, f_{ref}}_{Q_{msr}, Q_{0}} \\
&k_{f_{msr}, f_{ref}}_{Q_{msr}, Q_{FFF}} \approx 1
\end{align*}
\]
Volume averaging in FFF beams

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

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

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

(Palmans 2012 Med Phys 39:5513)
Ch 3. – Formalism / equations for beam quality in non-standard reference fields

for $PDD_{10x}(10) = \%dd(10)_x$

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

(Palmans 2012 Med Phys 39:5513-9)

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

(TG-51)
Note on the application to FFF beams

\[ s = \frac{1}{2\pi} \int \left( \lambda e^{-\lambda r} - \mu \lambda e^{-\lambda r} + \mu \lambda^2 r e^{-\lambda r} \right) F(r) dr d\theta \]
Ch3. - Formalism / determination of field output factors

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

\[ \Omega_{Q_{\text{clin}}, Q_{\text{ref}}}^{f_{\text{clin}}, f_{\text{ref}}} = \frac{M_{Q_{\text{clin}}, Q_{\text{ref}}}^{f_{\text{clin}}}}{M_{Q_{\text{ref}}}^{f_{\text{ref}}}} \cdot K_{Q_{\text{clin}}, Q_{\text{ref}}}^{f_{\text{clin}}, f_{\text{ref}}} \]

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

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

where

\[ K_{Q_{\text{clin}}, Q_{\text{ref}}}^{f_{\text{clin}}, f_{\text{ref}}} = k_{Q_{\text{clin}}, Q_{\text{det}}}^{f_{\text{clin}}, f_{\text{int}}} (\text{det}) \cdot k_{Q_{\text{int}}, Q_{\text{ref}}}^{f_{\text{int}}, f_{\text{ref}}} (\text{IC}) \]
Ch 4 - Instrumentation

Required equipment, detectors, phantoms for msr dosimetry

Required equipment, detectors, phantoms for relative dosimetry
Ch 5 - Practical implementation msr dosimetry

Reference conditions for beam quality and msr dosimetry
Overall correction factors for ionization chambers
Correction for influence quantities
Measurement in plastic phantoms and cross-calibration
### Ch 5 - Practical implementation msr dosimetry / availability

<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>Dosimeter constant $k_{Q_{msr},Q_{ref}}$</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 $\times$ 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 $\times$ 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 $\times$ 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 $\times$ 10 cm</td>
<td>NE2611, NE2571</td>
<td>Exradin A1SL</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</td>
<td>MD-55</td>
<td>0.997 (19)</td>
</tr>
</tbody>
</table>
Ch 6 - Practical implementation relative dosimetry

Required equipment, detectors, phantoms

Measurements of profiles and field output factors

Correction factors for determination of output factors
Ch 6 - Practical implementation relative dosimetry / correction factors for OF

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

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

\[
\Omega f_{\text{clin}} \cdot f_{\text{msr}} = \frac{D f_{\text{clin}}}{D f_{\text{msr}}} \cdot \frac{M f_{\text{clin}}}{M f_{\text{msr}}} \cdot \left[ \frac{D f_{\text{clin}}}{D f_{\text{msr}}} \cdot \frac{M f_{\text{clin}}}{M f_{\text{msr}}} \right] = \frac{M f_{\text{clin}}}{M f_{\text{msr}}} \cdot k f_{\text{clin}} \cdot f_{\text{msr}}
\]

\[
k f_{\text{clin}} \cdot f_{\text{msr}} = \frac{D f_{\text{clin}}}{D f_{\text{msr}}} \cdot \frac{M f_{\text{msr}}}{M f_{\text{clin}}}
\]

\[
\frac{k f_{\text{clin}} \cdot f_{\text{msr}}}{k f_{\text{clin}} \cdot f_{\text{msr}}^\text{(1)}} = \frac{M f_{\text{msr}}}{M f_{\text{clin}}} \cdot \frac{M f_{\text{msr}}}{M f_{\text{msr}}} \cdot \frac{M f_{\text{msr}}}{M f_{\text{msr}}} = \frac{M f_{\text{fs}}}{M f_{\text{rel}}} \cdot \frac{M f_{\text{fs}}}{M f_{\text{rel}}} \cdot \frac{M f_{\text{fs}}}{M f_{\text{rel}}}
\]
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
Conclusions

Solutions to most SF dosimetry problems have been described and translated in formalised procedures.

An IAEA CoP will be published.
One thought to end with

082102-12  Underwood et al.: Small field dosimetry: Integral versus point dose measurement