Physics of small megavoltage photon beam dosimetry

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When a field is small?

• **Fundamental condition**
  1. Loss of Lateral Charged-Particle Equilibrium (LCPE)

• **Machine-related issues**
  2. Partial source occlusion

• **Detector-related issues**
  3. Mismatch of detector vs field size and perturbation effects much larger than in broad beams
1. Loss of Lateral Charged-Particle Equilibrium

A small radiation field has dimension(s) smaller than the “lateral range” of charged particles

broad photon field

narrow photon field

$D/K_{col}$ is a measure of the degree of CPE or TCPE
Lateral Charged-Particle Equilibrium Range

$r_{\text{LCPE}}$: minimum beam radius for $D=K_{\text{col}}$

$r_{\text{LCPE}} \text{ (cm)} = a \times Q - b$

where

- $Q$ is $\text{TPR}_{20,10}$ or $\%\text{dd}(10)_x$
- $a$ and $b$ are fit coeffs to MC data
Intrinsic condition

For a given beam quality, the distance from the detector outer boundary to the field edge is less than $r_{LCPE}$.

$\Rightarrow$ to achieve CPE, $FWHM_{field}$ must be $\geq 2 \times r_{LCPE} + d$
2. Partial source occlusion

Broad photon beam

Narrow photon beam

penumbra overlap

IPEM Report 103 (2010)
Apparent widening of the field and decreased output

Ahnesjö and Saxner Radioth Oncol 81 (2006) S124
Consequences of partial source occlusion

• Overlap of the penumbra
  - Related to machine spot (source) size

• Reduction of relative central-axis dose
  - Decreased machine output

• Apparent field widening
  - Mismatch between FWHM (true field size) and collimator setting (nominal field size)
  - Severe impact on data required for the TPS!
Related issues:
(i) hardening of energy spectrum

Decreasing field size:
- Reduces head and phantom scatter
- Filtering low energies => increase mean energy

6 MV photon spectra for different field sizes at 10 cm depth (in a small water volume)

Related issues:

(ii) $s_{w, \text{air}}$ dependence on energy spectrum

- Water/air stopping-power ratios for ion-chamber reference dosimetry are practically independent of field size (and depth)

- Known since years, confirmed by other authors
  (e.g. Sánchez-Doblado et al 2003; Eklund & Ahnesjö, 2008)

6 MV photons

Andreó & Brahme
3. Detector related issues

- Ion chambers have been the “backbone” of RT dosimetry
  1) Not suitable in high-dose gradients or non-uniform beams
  2) Constraints regarding size versus sensitivity
  3) Require small fluence perturbation corrections
  4) Require a region of uniform fluence around the chamber

Item (4) poses an additional chamber-size constraint, never of concern in broad beams, but of great importance in small beams
Chamber-size related problems: Volume-averaging effect
Chamber reading provides a signal averaged over its volume

Field size < chamber Ø

Exradin A16 diameters
inner
outer

Fluence over detector not uniform

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Chamber-size related problems:
Ionization chamber perturbation factors in broad beams

\[ D_{w,Q}(z_{\text{ref}}) = D_{\text{air},Q}(z_{\text{ref}}) \left[ S_{w,\text{air}} \prod_i p_{\text{ch},Q} \right] \]

Overall perturbation correction factor, \( p_{\text{ch},Q} \)

\[ \text{Photon beam quality, } TPR_{20,10} \]

- A-150 \( r=2.3 \text{ mm} \)
- A-150 \( r=2.0 \text{ mm} \)
- C-552 \( r=4.8 \text{ mm} \)

Most ionization chambers

~6MV

Andreo et al. FIORD (2017)
Chamber-type related issues

Perturbation factors in small fields

MC calcs for 6 MV, 0.8 cm x 0.8 cm field size, 10 cm depth

PTW PinPoint 31006 (steel electrode)

\[ P_{\text{wall}}, P_{\text{dis}}, P_{\text{cel}}, P_{\text{tot}}, P_{\text{vol}} \]

Data from Crop et al Phys Med Biol 54(2009)2951

These are very large correction factors!
3. Detector related issues (cont.)

• Volume averaging is critical for ion chamber dosimetry, but
  ▪ Correction can be minimized if a small chamber is used and chamber-to-field edge distance is larger than $r_{LCPE}$, i.e. $\text{FWHM} \geq 2 r_{LCPE} + d$
  ▪ MC-calculated overall perturbation factors include averaging

• Solid-state detectors
  ▪ Small size vs sensitivity overcomes some ion chamber constraints, including most volume averaging issues
  ▪ Very appropriate for relative dosimetry
  ▪ Certain issues arise due to material, detector design, etc
    ➢ sometimes require quite large correction factors
Perturbation factors & Cavity Theory

• MC calcs do not require CPE, but current formulations for converting $D_{\text{det}} \rightarrow D_{\text{med}}$ rely on CPE-based eqs (e.g. $s_{\text{med, det}}$ relies on assuming $\Phi_{\text{med}} \equiv \Phi_{\text{det}}$)

$$D_{\text{med},Q}(P) = \overline{D}_{\text{det},Q} S_{\text{med, det}} \prod p_{\text{det},i}$$

$$S_{\text{med, det}}^{\text{BG}} = \frac{\int_{0}^{E_{\text{max}}}[\Phi_{E}^{\text{prim}}]_{\text{med}}[S_{\text{el}}(E)/\rho]_{\text{med}} \, dE}{\int_{0}^{E_{\text{max}}}[\Phi_{E}^{\text{prim}}]_{\text{med}}[S_{\text{el}}(E)/\rho]_{\text{det}} \, dE}$$

• Bragg-Gray and other theories assume SMALL and INDEPENDENT perturbation correction factors $p_{\text{det},i}$
Perturbation factors & Cavity Theory

• In small MV fields, however, for many real detectors,
  ✓ often, there is no CPE
  ✓ correction factors can be LARGE (up to ~10%)
  ✓ some effects can be strongly CORRELATED

➢ BASIC ASSUMPTIONS USED SO FAR BREAK DOWN!

\[ D_{\text{med},Q}(P) \neq \bar{D}_{\text{det},Q} S_{\text{med,det}} \prod p_{\text{det},i} \]
## Breakdown of Bragg-Gray theory

<table>
<thead>
<tr>
<th>Beam type</th>
<th>Beam-detector configuration</th>
<th>Fluence in det &amp; med</th>
<th>Bragg-Gray applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Broad/large</td>
<td><a href="image">Image</a></td>
<td>$\Phi_{\text{det}} = \Phi_{\text{med}}$</td>
<td>Ideal detector ($\equiv$ B-G), TCPE $D_{\text{med},Q}(P) = D_{\text{det},Q}(P) s_{\text{med,det}}$</td>
</tr>
<tr>
<td>(b) Broad/large</td>
<td><a href="image">Image</a></td>
<td>$\Phi_{\text{det}} \approx \Phi_{\text{med}}$</td>
<td>Real detector ($\approx$ B-G), TCPE $D_{\text{med},Q}(P) = D_{\text{det},Q} s_{\text{med,det}} \prod p_i$ small, approx. independent perturbations $\Rightarrow$ corrected by $p_i$</td>
</tr>
<tr>
<td>(c) Narrow/small</td>
<td><a href="image">Image</a></td>
<td>$\Phi_{\text{det}} \neq \Phi_{\text{med}}$</td>
<td>Real detector ($\neq$ B-G), no TCPE $D_{\text{med},Q}(P) \neq D_{\text{det},Q} s_{\text{med,det}} \prod p_i$ large, non-indept. perturbations $\Rightarrow$ B-G breaks-down</td>
</tr>
</tbody>
</table>

Use MC: $F_{\text{det},Q} = \frac{D_{\text{med},Q}(P)}{D_{\text{det},Q}}$

(c) reduces to (b) if $\Phi_{\text{det}} \approx \Phi_{\text{med}}$, i.e. $F_{\text{det},Q} = s_{\text{med,det}} \prod p_i$.

Andreo et al (2017)
Perturbation effects in small fields

- Caused by changes in FLUENCE ($\Phi_{\text{med}} \neq \Phi_{\text{det}}$) but currently based on MC calcs of DOSE ($D_{\text{med}} / D_{\text{det}}$)
- Common assumption for $\Phi_{\text{med}} \neq \Phi_{\text{det}}$: largely caused by different mass density in med (water) and det (air, Si, C)

Today: $\Phi_{\text{med}} \neq \Phi_{\text{det}}$ is caused by detector design and different mass stopping powers in med and det, i.e.

1) Strong dependence on mean excitation energy ($I$-value)
2) Moderate dependence on electron density ($\sim \rho Z/A$)
3) No direct dependence on mass density ($\rho$)

(1) and (2) enter into density-effect correction $\delta$

$$
\frac{1}{\rho} S_{\text{el}} \propto \frac{Z}{A} \frac{1}{\beta^2} \left[ f(\beta) - \ln I - \delta(I^2, \rho \frac{Z}{A}, \beta) \right]
$$

P Andreo - Physics of small field dosimetry

6/23/2017
**Detector (material): Fluenec & Dose**

MC calcs for 6MV, field Ø=1cm, detector r=0.05cm h=0.003cm

![Graph showing electron fluence per incident fluence and density-effect watersilicon approx onset for different materials.](image)

- **Same order as SPR at ~1 MeV**

**Approx "dose spectra"**

- Water
- Diamond
- Graphite
- Silicon
- LiF-phosphorus

**Electron fluence per incident fluence**

- Silicon (2.33,173)
- Phosphorus (2.20,173)
- LiF (2.64,94)
- Water (ρ=0.998 g/cm³, I=78 eV)
- Air (ρ=0.001,86)

**Electron kinetic energy, E / MeV**

- Graphite (1.7, 81)
- Diamond (3.51,81)

**Product Φₐₐₑ, Sₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑ電子郵
Detectors (full simulation): photon fluence

Practically no difference between spectra in water and in det, except…
Detectors (full simulation): electron fluence

small difference in spectra for air and diamond; large for Si
Detector design: electron fluence

Radiation sensitive volume (RSV) & high-Z non-RSV components

Benmakhlouf & Andreo, Med Phys 44(2017)713

Largest contribution to $\Phi_{med} \neq \Phi_{det}$ is due to high-Z components surrounding the RSV (even for an unshielded-diode!)
3. Detector-related issues (cont.)

**Output factor**

- Defined as a ratio of doses in two fields \((f_{\text{clin}}, f_{\text{ref}})\)
- In broad beams, common approach uses ratio of detector readings

\[
OF_{z_{\text{ref}}} (f_{\text{clin}}) = \frac{D(z_{\text{ref}}, f_{\text{clin}})}{D_{\text{ref}} (z_{\text{ref}}, f_{\text{ref}})} \approx \frac{M(z_{\text{ref}}, f_{\text{clin}})}{M_{\text{ref}} (z_{\text{ref}}, f_{\text{ref}})}
\]

- Due to the approximate constancy of stopping power and perturbation ratios with field size
Output factors in small fields

- Constancy arguments **not valid for small fields** due to the detector-related effects discussed (mostly, perturbation factors incl volume averaging)
- Concept “re-defined” to field output factor as a “true” dose ratio

\[
\Omega f_{\text{clin}} \cdot f_{\text{ref}} \frac{D_{f_{\text{clin}}}^{f_{\text{clin}}}}{D_{f_{\text{msr}}}^{f_{\text{msr}}}} = \frac{M f_{\text{clin}}}{M f_{\text{ref}}} k_{f_{\text{clin}}} \cdot f_{\text{ref}}
\]

- \( k_{f_{\text{clin}}} \cdot f_{\text{msr}} \) is a correction factor to the ratio of detector readings, MC calculated or experimental (depends on reference detector)
MC calculations constraints:

- detector-to-detector (same type) differences
- geometry accuracy

Diagrams provided by manufacturers might be incorrect!

See discussions on μDiamond geometry in:

- [http://medicalphysicsweb.org/cws/article/research/63793](http://medicalphysicsweb.org/cws/article/research/63793)
Field output correction factors @ 6MV

Ionization chambers

\[ \Omega \frac{f_{\text{clin}}}{Q_{\text{clin}}} \frac{f_{\text{ref}}}{Q_{\text{ref}}} = \frac{M}{Q_{\text{ref}}} \frac{f_{\text{clin}}}{Q_{\text{clin}}} k \frac{f_{\text{clin}}}{Q_{\text{clin}}} \frac{f_{\text{ref}}}{Q_{\text{ref}}} \]

Solid-state & other detectors

\[ \Omega \frac{f_{\text{clin}}}{Q_{\text{clin}}} \frac{f_{\text{ref}}}{Q_{\text{ref}}} = \frac{M}{Q_{\text{ref}}} \frac{f_{\text{clin}}}{Q_{\text{clin}}} k \frac{f_{\text{clin}}}{Q_{\text{clin}}} \frac{f_{\text{ref}}}{Q_{\text{ref}}} \]

Note the log scale in the abscissa axis below about 2.5 cm field size

Data from IAEA TRS-483 (2017) obtained from statistical average of MC and experimental published values
CyberKnife output factors

Detector-reading ratio

Dose ratio

- Smaller scatter of values
- Change mean value

Conclusions

• Physics of small field dosimetry can be complex
• Perturbation effects may have significant impact on reference dosimetry, to the extent of breaking down Bragg-Gray theory
• Although relative dosimetry is conceptually simple, perturbation effects impact considerably field output factors
• Influence of detector design can be significant (e.g., silicon diodes)
• Comparing different detectors gives information on their adequacy for small field dosimetry
Acknowledgements

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Further details can be found in...

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