Small field radiation therapy: physics and recent recommendations from IAEA and ICRU
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Educational Objectives
• To review the physics of small fields
• To review detectors suitable for small fields
• To provide an overview of the IAEA small field dosimetry recommendations
• To provide an overview of the content of the ICRU report on Prescribing, Reporting and Recording of Small Field Radiation Therapy

Table of contents
• Physics of small field radiation therapy
• Dosimetric challenges in small fields
  – Detector suitability for small field dosimetry
  – Correction factors for nonstandard reference fields
  – Correction factors for small fields
  – Beam quality specification in nonstandard reference fields
  – Uncertainties
• Overview of the IAEA Code of Practice
• Overview of the ICRU recommendations on “Reporting and Recording of Small Field Radiation Therapy”
• Conclusions

Specialized radiation equipment
Specialized radiation equipment

- Characteristics that lead to dosimetric issues of two kinds:
  - Reference dose calibration
    - Reference fields are not 10 x 10 cm², 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
- We will first review the basics of small field physics, then come back to these two items

What constitutes small-field conditions?

- Beam-related small-field conditions
  - the existence of lateral charged particle disequilibrium
  - change in photon fluence spectrum ⇒ beam quality
  - partial geometrical shielding of the primary photon source as seen from the point of measurement
- Detector-related small-field condition
  - detector size compared to field size

Lateral charged particle loss

A small field can be defined as a field with size smaller than the “lateral range” of charged particles

Detector size relative to field size

- 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 \(r_{LCPF}\) away from the edge of the field
  \[ f_{msr} < 6 \times 6 \text{ cm}^2 \]

\[ r_{LCPF}[\text{cm}] = 8.369 \cdot \text{TPR}_{95}(10) - 4.382 \]
\[ r_{LCPF}[\text{cm}] = 0.07797 \cdot \text{%dd}(10) - 4.112 \]
Source occlusion

- Definition of field size is not unique!!

Overlapping of beam penumbras

Consequences of partial occlusion of the source

- Field size definition
  - Apparent widening
  - Overlapping penumbra
    - The nominal field size setting does not correspond to FWHM of the dose profile
- Drastic reduction in dose on the central axis (“output”)
  - These considerations have a severe impact on the data required in the treatment planning system (TPS)

Detector issues in small field dosimetry

- Energy dependence of the response
- Perturbation effects
  - Central electrode, wall effects
  - The cavity is different from water, fluence perturbation
  - Volume averaging
- These effects depend on the beam spot size

Spectral changes

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

6 MV photon spectrum in a small water volume as a function of field size
Stopping power ratio water to air $s_{w,\text{air}}$

Very small effects!


Ionization chamber perturbation effects

Very large effects!


Magnitude of correction factors on and off-axis

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

Correction factors for ionization chambers

Very large effects!


Issues with diode detectors

- Even though diode has small active volume, thus small $P_{\text{vol}}$ effect, it may give errors due to energy dependences for low energy photons.
- This applies output measurements for very small fields and depth dose measurement for very large fields.


Diodes for small field dosimetry

Sauer and Welcker 2007
Med Phys 34:1983-8
Nonstandard reference fields (msr)

- 3 issues
  - Field size is not 10 x 10 cm²
    - recommendation for equivalent field size
  - FFF versus WFF beams
    - Beam quality correction factors
    - Non-uniformity of the profile
  - Chamber types suitable for reference dosimetry

Equivalent square fields - msr

\[
s = \frac{1}{\pi} \int \left( \lambda e^{-\lambda r} - \mu \lambda e^{-\lambda r} + \mu \lambda^2 r e^{-\lambda r} \right) F(r) dr d\theta
\]
Application to FFF beams

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

$$k_{QFF, QWF}$$

$$D_{QFF, 0} = M_{QFF} \cdot N_{QFF} \cdot k_{QFF, 0} \cdot k_{QFF, QWF} \cdot k_{QFF, 0}$$

Beam quality: nonstandard reference fields

$$\%TPR_{20,10}(10) = \frac{\%TPR_{20,10}(S) + c (10 - S)}{1 + c (10 - S)}$$

$$c = (16.15 \pm 0.12) \times 10^{-3} \text{ for } 4 \text{ cm} \leq S \leq 12 \text{ cm}$$

Volume averaging in FFF beams

IAEA-AAPM protocol

- Chapter 1 – Introduction
- Chapter 2 - Physics of small field dosimetry
- Chapter 3 – Concepts and Formalism
- Chapter 4 – Detectors and Equipment
- Chapter 5 - Code of practice for reference dosimetry of machine-
specific reference fields
- Chapter 6 - Code of practice for relative dosimetry of small fields
- Appendix A - Determination of beam quality correction factors for
reference dosimetry and their uncertainty estimates
- Appendix B - Determination of field output correction factors and
their uncertainty estimates
16-07-31

Ch 3 Formalism
Machine specific reference (msr) fields

- Chamber calibrated specifically for the msr field
  \[ \frac{D_{\text{msr}}}{D_{\text{msr}}^{\text{ref}}} = M_{\text{msr}}^{\text{ref}} \cdot N_{\text{msr}} \]

- Chamber calibrated for the conventional reference field and generic correction factors are available
  \[ \frac{D_{\text{ref}}}{D_{\text{msr}}} = M_{\text{msr}}^{\text{ref}} \cdot N_{\text{msr}} \cdot k_{\text{msr}}^{\text{ref}} \cdot k_{\text{msr}}^{\text{cor}} \]

- Chamber calibrated for the conventional reference field and generic correction factors not available
  \[ \frac{D_{\text{msr}}}{D_{\text{msr}}^{\text{ref}}} = M_{\text{msr}}^{\text{ref}} \cdot N_{\text{msr}} \cdot k_{\text{msr}}^{\text{ref}} \cdot k_{\text{msr}}^{\text{cor}} \]

Ch 3 Formalism for FFF beams

- Identical formalism
  \[ \frac{D_{\text{msr}}^{\text{ref}}}{D_{\text{msr}}^{\text{ref}}} = M_{\text{msr}}^{\text{ref}} \cdot N_{\text{msr}} \cdot k_{\text{msr}}^{\text{ref}} \cdot k_{\text{msr}}^{\text{cor}} \]

\[ D_{\text{msr}}^{\text{FFF}} = M_{\text{msr}}^{\text{FFF}} \cdot N_{\text{msr}}^{\text{FFF}} \cdot \frac{k_{\text{msr}}^{\text{FFF}}}{k_{\text{msr}}^{\text{cor}}} \]

\[ \text{BQI}_{\text{FFF}} \equiv \text{BQI}_{\text{WFF}} \]

Ch 3. Formalism plastic phantoms

\[ \left( \frac{D_{\text{msr}}^{\text{ref}}}{D_{\text{plastic}}^{\text{ref}}} \right)_{\text{plastic}} = \left( \frac{D_{\text{msr}}^{\text{ref}}}{D_{\text{plastic}}^{\text{ref}}} \right)_{\text{plastic}} \cdot \frac{k_{\text{plastic}}}{k_{\text{plastic}}^{\text{ref}}} \]

Exception: GammaKnife, plastic conversion integrated within correction factor.

\[ \left( \frac{D_{\text{msr}}^{\text{ref}}}{D_{\text{plastic}}^{\text{ref}}} \right)_{\text{plastic}} = \left( \frac{D_{\text{msr}}^{\text{ref}}}{D_{\text{plastic}}^{\text{ref}}} \right)_{\text{plastic}} \cdot \frac{k_{\text{plastic}}}{k_{\text{plastic}}^{\text{ref}}} \]

Ch 4 – Instrumentation

- Equipment for machine-specific reference dosimetry

- Required equipment, detectors, phantoms for relative dosimetry

IAEA-AAPM protocol – Reference fields
Ch 4 – Equipment for machine-specific reference dosimetry

• (a) One or more ionization chambers, including the permanently attached cable and connector. The ionization chambers chosen should be specifically designed for the intended purpose such as modality and radiation quality.
• (b) One or more phantoms with waterproof sleeves if needed.
• (c) A measuring assembly (electrometer), often separately calibrated in terms of charge or current per scale division.
• (d) The dosimeter system also includes one or more stability check devices, specifically designed for the chosen ionization chamber.
• (e) Calibrated thermometer and barometer.

Ch 4 - Ionization chambers

• \( f_{msr} \geq 6 \times 6 \text{ cm}^2 \) equivalent
  • \( \text{WFF} \)
    • robust air-filled chambers, often waterproof and simple to use for reference in-phantom measurements: \( V_{eff} \geq 0.3 \text{ cm}^3 \) and \( 1 \text{ cm}^3 \) (i.e., Farmer type 0.6 cm)
  • \( \text{FFF} \)
    • a length shorter than that of typical Farmer-type chamber given the non-uniformity of the lateral beam profile: \( V_{eff} \leq 0.1 \text{ cm}^3 \) and \( 0.3 \text{ cm}^3 \)

Ch 4 - Ionization chambers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber setting</td>
<td>Monitor chamber response with accumulated dose, equilibrium should in (&lt; 5 \text{ min} ), initial and equilibrium reading (&lt; 0.5% ).</td>
</tr>
<tr>
<td>Leakage &amp; Polarity effect</td>
<td>Smaller than 0.1% of the chamber reading. Smaller than 0.4% of the chamber reading. The polarity energy dependence should be less than 0.3% between ( ^{56}\text{Co} ) and 10 MV.</td>
</tr>
</tbody>
</table>
| Re-combination | 1. The correction must be linear with dose per pulse.
2. Initial recombination (dose rate or dose-per-pulse independent part of the total charge recombination) \(< 0.2\% \) at 300 V.
3. For pulsed beams, a plot of \( 1/M_Q \) (charge reading) vs \( 1/V \) should be linear at least for practical values of \( V \).
4. For continuous beams, a plot of \( 1/M_Q \) vs \( 1/V \) should be linear.
The difference in the initial recombination correction obtained with opposite polarities should be less than 0.1\%.
|
| Chamber stability | Change in calibration coefficient over a typical recalibration period of 2 y below 0.3\%. Same figure for long-term (> 5 y) stability. |
| Chamber material | Wall material not exhibiting temperature and humidity effects. |

Ch 4 - Ionization chambers

\[ f_{msr} < 6 \times 6 \text{ cm}^2 \] equivalent

- \( \text{if:} \)

\[ r_{LCPE/cm} = 8.369 \cdot \text{TPR}_{20,10}(10) - 4.382 \]

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

- the chamber must fulfill:

\[ \text{FWHM} \geq 2 \cdot r_{LCPE} + d \]

with \( d \) the largest outer dimension of the ionization chamber (FWHM is the full width half maximum of the field).
Ch 4 - Ionization chambers, recombination, polarity

LeRoy et al. PMB 56:5637-56 (2011)

Ch 4 - Phantoms

- Water phantoms
  - recommended
- Plastic phantoms
  - If not otherwise possible, should be water equivalent
  - Density and homogeneity should be verified
  - Note: GammaKnife

Ch 4 – Detectors for small fields

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Sensitivity (mV/µA)</th>
<th>Distance of sensitive area (cm)</th>
<th>Thickness of sensitive area (mm)</th>
<th>Reference point to the surface (mm)</th>
<th>Shielded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classical ionization chambers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small ion (vented ionization chambers)</td>
<td>0.1 mm × 0.1 mm</td>
<td>1 cm</td>
<td>2 mm</td>
<td>0.9 mm</td>
<td>No</td>
</tr>
<tr>
<td>Siliconization chambers of a volume</td>
<td>0.1 mm × 0.1 mm</td>
<td>1 cm</td>
<td>2 mm</td>
<td>0.9 mm</td>
<td>No</td>
</tr>
<tr>
<td>Liquid ionization chambers</td>
<td>0.1 mm × 0.1 mm</td>
<td>1 cm</td>
<td>2 mm</td>
<td>0.9 mm</td>
<td>No</td>
</tr>
<tr>
<td>Superconductor detectors</td>
<td>0.1 mm × 0.1 mm</td>
<td>1 cm</td>
<td>2 mm</td>
<td>0.9 mm</td>
<td>No</td>
</tr>
<tr>
<td>Lead collimator detectors</td>
<td>0.1 mm × 0.1 mm</td>
<td>1 cm</td>
<td>2 mm</td>
<td>0.9 mm</td>
<td>No</td>
</tr>
<tr>
<td>Plastic and organic scintillators</td>
<td>0.1 mm × 0.1 mm</td>
<td>1 cm</td>
<td>2 mm</td>
<td>0.9 mm</td>
<td>No</td>
</tr>
<tr>
<td>Radiochromic film</td>
<td>0.1 mm × 0.1 mm</td>
<td>1 cm</td>
<td>2 mm</td>
<td>0.9 mm</td>
<td>No</td>
</tr>
</tbody>
</table>

Other detectors: TLD, OSLD, MOSFET, alanine

Ch 4 – Detectors for small fields

- Spatial resolution
  - Some field sizes in mm
  - Spatial resolution is defined as the distance from the device to the field size
  - The device size should be less than 1 mm
  - Observation
  - The response of a detector should not be independent of the orientation of the device with respect to the beam and the detector and not more than 1 mm away from the beam axis
  - Background signals
  - The zero reading of a detector will not be close to the absolute minimum of the device and the beam size
  - Environmental factors
  - Correlation over the 10 mm range of working conditions should be within 0.05% and 0.1 mm

IPEM 525
Ch 4 – Phantoms for small fields

- Simple water-filled calibration phantoms without a scanning system.
- 3D water phantoms
- Water equivalent plastic cylinders, spheres, hemispheres, cubes and other shapes
- Phantoms with adjustable measurement planes and chamber cavities, which rigidly attach to stereotactic frames or index precisely to imaging and treatment couch-tops.

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 4 – Reference conditions for beam quality and msr dosimetry

Table 5.1: Reference conditions for the determination of absorbed dose to water in high-energy photon beams.

<table>
<thead>
<tr>
<th>Inhomogeneity</th>
<th>Reference value or reference characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phantom material</td>
<td>Water</td>
</tr>
<tr>
<td>Phantom shape and size</td>
<td>At least 30 cm x 30 cm x 30 cm</td>
</tr>
<tr>
<td>Chamber type</td>
<td>Cylindrical</td>
</tr>
</tbody>
</table>
| Measurement depth | 10 g cm
\(^{-2}\) |
| Reference point of chamber | On the central axis at the centre of the cavity volume |
| Position of reference point of chamber | At the measurement depth of 10 cm or closely achievable |
| Field size | 10 cm x 10 cm or size of the test field

*If the reference absorbed dose to water has to be determined for an inhomogeneous test setup, the SAD of the accelerator shall be 10 cm and the field size should be at least 10 cm. In the case of a 10 cm x 10 cm field, the reference absorbed dose to water shall be defined at the plane of the detector placed at the reference depth in the water phantom at the isocenter of the accelerator.

** Measurement in plastic phantoms and cross-calibration

Ch 5 – Practical implementation msr dosimetry – beam quality index

![Image of beam quality index](image-url)
Getting the beam quality index

\[
\% \text{TPR}_{20,10}(10) = \frac{\% \text{TPR}_{20,10}(S) + c \ (10 - S)}{1 + c \ (10 - S)}
\]

\[c = (16.15 \pm 0.12) \times 10^{-3} \text{ for } 4 \text{ cm} \leq S \leq 12 \text{ cm}\]

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 – Field output correction factors

- IAEA-AAPM code of practice data tables is based on a vetted set of correction factors from the literature
- Uncertainty analysis has been performed and will be discussed in another lecture
Conclusions

- We covered the basics of small field dosimetry
- We introduced practical elements of the IAEA-AAPM protocol for small field dosimetry
- We introduced the content covered in the upcoming ICRU report on Prescribing, Reporting and Recording of Stereotactic Treatments with Small Photon Fields