Small Field Dosimetry and IAEA/AAPM Protocol

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Madison WI

Conflict of Interest Statement:
Consultant to Accuray
Outline

• Relevant to IMRT, SRS, and SBRT
• Main Dosimetry Issues
  • Charged Particle Equilibrium
  • Temporal Non-Constancy
  • Partial Volume Effects
  • Perturbation Effects for Small Chambers
• Calibration of Non-Standard Fields
  • IMRT as a Large Collection of Small Non-Standard Fields
  • IAEA Calibration Initiative for Non-Standard Fields
Model-Based Calculation Methods Are Need for IMRT Treatment Planning

- $\text{IMRT} = \sum \text{small fields}$
- Dose = function(penumbra+leakage+head scatter)
- Need accurate treatment head model to get this right

From Michael Sharpe, U. of Toronto
IMRT Is All About Using Small Fields

Intensity Profile
possibly unconstrained
intensity levels

Intensity Grouping
limit delivery to a few
discrete intensity levels

Reconstituted from Beam Segments includes MLC constraints

From Michael Sharpe, U. of Toronto
IMRT Is All About Using Small Fields

- Accuracy of dose model at small field sizes is a consideration
- Convolution-superposition or Monte Carlo desirable

From Michael Sharpe, U. of Toronto
Leaf Penumbra is Important

- It is important to have an accurate model of the curved leaf ends.
- More important for summation of small fields.
Gap Error is Fundamental for Conventional MLCs

Gap error $\rightarrow$ Dose error

From Tom Losasso, Memorial Sloan Kettering
Potential Dosimetry Issues

- Charged particle equilibrium
  - Different spectrum for collection of small fields
  - Non-uniform dose
- Temporal non-constancy
  - A very small effect for ion chambers
  - May not be true for other dosimeters
- Partial volume effect
  - Most important effect especially when measuring output factors for small fields
- Perturbation effects for small chambers
  - Charge multiplication (failure of electronegative gas assumption)
  - Electron emission from electrodes
Non-Uniform Intensity Changes the Energy Spectrum and Intensity

More High Energy Electrons

More Low Energy Electrons
Dose per Incident Energy Fluence
As a Function of Field Diameter
A=Adipose, M=Muscle, B=Bone, L=Lung 4 MV, Parallel Beam

Ahnesjo and Asparadakis, 1999 Phys Med Biol 44:R99-R155
## Change in Stopping Power Ratio

Comparison of Spencer-Attix ($\Delta=10$ keV) restricted mass collisional stopping powers ratios (water/air) at 5 cm depth in water for various 6 MV beams with stereotactic and MLC beams.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Elekta SL-18 10 x 10 cm$^2$</td>
<td>0.690</td>
<td>1.1187</td>
<td>1.1188</td>
<td>1.000</td>
</tr>
<tr>
<td>1.0 cm diameter stereo field</td>
<td></td>
<td></td>
<td>1.1155</td>
<td>0.997</td>
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<tr>
<td>0.3 cm diameter stereo field</td>
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<td></td>
<td>1.1153</td>
<td>0.997</td>
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<td>Siemens Primus 10 x 10 cm$^2$</td>
<td>0.677</td>
<td>1.1213</td>
<td>1.1221</td>
<td>1.001</td>
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<tr>
<td>2 x 2 cm$^2$ irregular on-axis beamlet</td>
<td></td>
<td></td>
<td>1.1203</td>
<td>0.999</td>
</tr>
<tr>
<td>2 x 2 cm$^2$ irregular 8 cm off-axis</td>
<td></td>
<td></td>
<td>1.1250</td>
<td>1.003</td>
</tr>
</tbody>
</table>
Temporal Delivery of IMRT

Delivery of Dose to a Single Voxel

From Tim Holmes, St. Agnes Baltimore
Temporal Delivery of IMRT

Delivery of Dose to a Single Voxel

From Tim Holmes, St. Agnes Baltimore

- Step and Shoot
- Helical Tomo
Partial Volume Effect

Dose to Water For Small Fields

Output Factor vs. Side of Square Field (cm)

From Roberto Capote, IAEA
High Uncertainty in Output Factors

Example: Statistics of 45 Output Factors for 6 mm and 18 mm square fields (Novalis, SSD = 1000 mm, depth = 50 mm, various detectors)

From Wolfgang Ullrich, BrainLab
Dose in 76 patients exceeded prescription by 50%
Beam measurement error by physicist

Detector too large – blurs measured dose profile for small beams

50% underestimate in peak dose
50% overestimate in beam on time needed
Reasons for Drop in Output with Small Field Size

- Backscatter into monitor unit from beam defining jaws
- Reduced scatter (phantom and head)
- Electronic disequilibrium
- Obscuration of the source
Backscatter into Monitor Chamber

The effect is due to backscattered photons entering the monitor and resulting in feedback to the linac to lower its output.

Varian 2100 – 10 MV. Results with other jaw completely open

Problems with Measuring Conventional Output Factors

- Small field openings obscure the source which is difficult to measure and error prone.
- Amount of phantom scatter changes as well as lateral disequilibrium.
- Partial volume effects can mask machine output factor.
Point source assumption starts breaking down for small fields.

<table>
<thead>
<tr>
<th>Coll</th>
<th>FWHM 1.4 mm</th>
<th>FWHM 1.8 mm</th>
<th>FWHM 2.2 mm</th>
<th>FWHM 2.6 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured $s_{c,p}$</td>
<td>Simulated $s_{c,p}$</td>
<td>Simulated $s_{c,p}$</td>
<td>Simulated $s_{c,p}$</td>
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<tr>
<td>A16</td>
<td>0.614</td>
<td>0.669</td>
<td>0.643</td>
<td>0.611</td>
</tr>
<tr>
<td>PinPoint</td>
<td>0.613</td>
<td>0.661</td>
<td>0.636</td>
<td>0.607</td>
</tr>
<tr>
<td>Diode</td>
<td>0.710</td>
<td>0.757</td>
<td>0.732</td>
<td>0.704</td>
</tr>
<tr>
<td>Diamond</td>
<td>0.613</td>
<td>0.677</td>
<td>0.639</td>
<td>0.609</td>
</tr>
<tr>
<td>Coll 7.5 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A16</td>
<td>0.801</td>
<td>0.809</td>
<td>0.808</td>
<td>0.799</td>
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<tr>
<td>PinPoint</td>
<td>0.798</td>
<td>0.805</td>
<td>0.802</td>
<td>0.795</td>
</tr>
<tr>
<td>Diode</td>
<td>0.852</td>
<td>0.757</td>
<td>0.850</td>
<td>0.843</td>
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<tr>
<td>Diamond</td>
<td>0.815</td>
<td>0.833</td>
<td>0.818</td>
<td>0.813</td>
</tr>
<tr>
<td>Coll 10 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A16</td>
<td>0.859</td>
<td>0.874</td>
<td>0.870</td>
<td>0.860</td>
</tr>
<tr>
<td>PinPoint</td>
<td>0.858</td>
<td>0.867</td>
<td>0.865</td>
<td>0.860</td>
</tr>
<tr>
<td>Diode</td>
<td>0.895</td>
<td>0.909</td>
<td>0.896</td>
<td>0.890</td>
</tr>
<tr>
<td>Diamond</td>
<td>0.871</td>
<td>0.889</td>
<td>0.876</td>
<td>0.872</td>
</tr>
</tbody>
</table>
Chamber Selection For Beams without Field Flattening Filters

- Dose flatness insufficient for Farmer-type chamber
- Cavity length should not be greater than 1 cm
- Option: cross calibrate a short chamber with Farmer-type chamber

Normalized Chamber Response

Courtesy Jessica Snow and Larry DeWerd, UW ADCL
PTW N23333

0.6 cc

![Graph showing the normalized chamber response against applied voltage (V) with two lines for negative and positive charge collection.]

Courtesy Jessica Snow and Larry DeWerd, UW ADCL
Exradin A1SL  0.057 cc

Sign of charge multiplication

- **Normalized chamber response**
- **Applied voltage (V)**
- **Negative charge collection**
- **Positive charge collection**

Courtesy Jessica Snow and Larry DeWerd, UW ADCL
IMRT Is Far from Reference Conditions

From Art Boyer, Stanford
Audit for TRS 398 Reference Dosimetry

From Roberto Capote, IAEA
Sánchez-Doblado F, Hartmann G., Pena J., Capote R. et al
*IJROBP* 68 (2007) 301-310
IAEA/AAPM Meeting for the Dosimetry Code of Practice: Small Fields and Novel Beams

Outside Participants
- Jan Seuntjens
- Hugo Palmans
- Karen Rosser
- Saiful Huq
- Wolfgang Ullrich
- Warren Kilby
- Rock Mackie

IAEA
- Pedro Andreo
- Ken R. Shortt
- Stanislav Vatnitskiy
- Roberto Capote
- Joanna Izewska
- Ahmed Meghzifene
- Rodolfo Alfonso

Examples of Small and Novel Fields

- **GammaKnife** - 1.8 cm diameter collimator (1.6 cm on the Perfexion) is the largest collimator – intrinsically composite field – not 100 cm SSD
- **Linac SRS beams** - extrapolate to small field conditions
- **Accuray** - 6 cm diameter collimator is the largest collimator – no field flattening filter
- **TomoTherapy** - 5 cm is the largest slice width – no field flattening filter
- **IMRT** - made up of numerous small fields
\[ D_{f_{msr}}^{w,Q_{msr}} = M^{f_{msr}} \cdot N_{D,w,Q_0} \cdot k_{Q,Q_0} \cdot k_{f_{msr},f_{ref}} \]

\[ D_{Q_{msr}}^w = M \cdot N^{Co^{-60}}_{D,w} \cdot k_{Q} \cdot k_{Q_{msr}} \]
Overview of Static Field Dosimetry

REFERENCE DOSIMETRY

\[ D_{w}^{Q_{msr}} = M \cdot N_{D,w}^{Co-60} \cdot k_{Q} \cdot k_{Q_{msr}} \]

10 cm x 10 cm Reference Field

Hypothetical 10 cm x 10 cm Reference Field

Linac Stereotactic Field

BrainLab MiniMLC (10 cm x 10 cm)

CyberKnife (6 cm Diameter)

TomoTherapy (5 cm x 10 cm)

\[ D_{w}^{Q_{clin}} = D_{w}^{Q_{msr}} \cdot \Omega_{Q_{clin}}^{Q_{msr}} \]
Static Field Calibration

Uses a machine-specific reference field, \( f_{msr} \)

\[
D_w^{Q_{msr}} = M \cdot N_{D,w}^{Co-60} \cdot k_Q \cdot k_{Q_{msr}}
\]

\[
k_{Q_{msr}} = \frac{(D / M)^{Q_{msr}}_w}{(D / M)^Q_w}
\]

Corrects for the differences between the conditions of field size, geometry, and beam quality of the conventional reference field and the machine-specific reference field.
Calculate Using MC

Using method of Sempau et al 2004 *PMB* 49;4427-44

\[
k_{Q_{msr}} = \frac{\left( \frac{D_w}{\bar{D}_a} \right)^{Q_{msr}}}{\left( \frac{D_w}{\bar{D}_a} \right)^Q}
\]

\(D_w\) is the dose at the reference point in water

\(\bar{D}_a\) is the average dose in the ion chamber

Adapted from Edmond Sterpin
Composite Field Calibration

Uses a plan-class specific reference field, $f_{pcs}r$

$$D_{w}^{Q_{pcs}} = M \cdot N^{Co-60}_{D,w} \cdot k_{Q} \cdot k_{Q_{pcs}}$$

$$k_{Q_{pcs}} = \frac{(D / M)^{Q_{pcs}}_{w}}{(D / M)^{Q}_{w}}$$

Corrects for the differences between the conditions of field size, geometry, and beam quality of the conventional reference field and the plan-class specific reference field.
1. Determine the %dd(10)x[HT Ref] for a tomotherapy unit for a 5 cm x 10 cm field at 85 cm SSD.
2. Using the graph at the right look up the value of %dd(10)x[HT TG-51].
3. Using the graph on the left and the derived value %dd(10)x[HT TG-51] determine the abscissa and this effective \( k_Q \) value is then called \( k_o \cdot k_{orr} \) in the IAEA protocol.

Thomas et al (2005)
# Static and Composite Field Calculations for Tomo

<table>
<thead>
<tr>
<th>Static Field Calibration (Section III.A.1)</th>
<th>Composite Field Calibration (Section III.A.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jeraj et al 2005</td>
<td>Duane et al 2006</td>
</tr>
</tbody>
</table>

\[
k_{Q_{msr}} \quad k_{Q_{pcs}}
\]

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Static Field Calibration</th>
<th>Composite Field Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 cm x 10 cm</td>
<td>0.997</td>
<td>Unmodulated Helical Delivery</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 cm Slice Width</td>
</tr>
<tr>
<td>2 cm x 10 cm</td>
<td>0.993</td>
<td>Unmodulated Helical Delivery</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5 cm Slice Width</td>
</tr>
<tr>
<td>2 cm x 2 cm</td>
<td>0.990</td>
<td>Unmodulated Helical Delivery</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 cm Slice Width</td>
</tr>
<tr>
<td>(Standard Uncertainty)</td>
<td>Other References (10 cm x 5 cm)</td>
<td>Sterpin et al. (10 cm x5 cm)</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>Exradin A1SL</td>
<td>0.997 (+- 0.001)</td>
<td>0.996 (+-0.002)</td>
</tr>
<tr>
<td>Exradin A12 Farmer</td>
<td>1.000 (+-0.003)</td>
<td>1.001 (+-0.004)</td>
</tr>
<tr>
<td>PTW-31014 Pinpoint</td>
<td>0.992 (+- 0.003)</td>
<td>0.993 (+-0.002)</td>
</tr>
<tr>
<td>PTW-31010 Semiflex</td>
<td>0.996</td>
<td>0.995 (+-0.002)</td>
</tr>
<tr>
<td>PTW-31006 Farmer</td>
<td>0.995</td>
<td>0.997 (+-0.002)</td>
</tr>
<tr>
<td>PTW-31018 (MicroLion)</td>
<td></td>
<td>0.993 (+-0.002)</td>
</tr>
<tr>
<td>NE2571</td>
<td>0.995</td>
<td>0.997 (+-0.002)</td>
</tr>
</tbody>
</table>

On the output factor measurements of the CyberKnife iris collimator small fields: Experimental determination of the $k^{f_{\text{clin}}} Q^{f_{\text{msr}}} Q_{\text{clin}} Q_{\text{msr}}$ correction factors for microchamber and diode detectors

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I. Seimenis
*Medical Physics Laboratory, Medical School, Democritus University of Thrace, 2nd Building of Preclinical Section, University Campus, 68100 Alexandroupolis, Greece*
Two 6 MV Linacs: Nearly Same $K_{Q\text{eff}} = K_Q \times K_{Q\text{msr}}$

<table>
<thead>
<tr>
<th></th>
<th>TomoTherapy</th>
<th>CyberKnife</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exradin A12 (0.65 cc)</td>
<td>1.000</td>
<td>1.006</td>
</tr>
<tr>
<td>NE2571 (0.67 cc)</td>
<td>0.997</td>
<td>1.003</td>
</tr>
<tr>
<td>Exradin A1SL (0.057 cc)</td>
<td>0.997</td>
<td>0.997</td>
</tr>
</tbody>
</table>

To within about a half percent, TomoTherapy and CyberKnife are like "Co-60 units".
Conclusions

- IMRT, SRS and SBRT uses complex field boundaries and/or one or many small circular fields.
- Partial volume effects can result in severe error in output factor measurements.
- Small chambers exhibit unusual charge collection behavior.
- IMRT deliveries are far from the measurement conditions of calibration.
- IAEA/AAPM is developing a formalism to account for small and novel beams in more realistic beam conditions.