Electron therapy
Class 2: Review questions
Raphex Question: T63, 2002

- In what situation is electron backscatter likely to be a problem?

A. Using 1cm of tissue equivalent bolus on the skin.
B. Using a lead intra-oral shield to protect the tongue when treating a cheek.
C. When electrons are incident at an angle greater than 30°.
D. When electrons of different energies are matched on the skin.
Raphex Question: T63, 2000

- The %DD at 5 cm for a 6MeV electron beam is approximately:

  A. 100%
  B. 90%
  C. 80%
  D. 50%
  E. <5%
Raphex Question: T55, 1999

• The internal mammary nodes (IMN) can be included in wide tangents or treated with a direct beam. In the latter case, a combination of photons and electrons can be used. The reason for adding photons, instead of using electrons alone, is:

A. To reduce dose to underlying lung.
B. To keep cord dose below tolerance.
C. To reduce the skin dose.
D. All of the above.
Raphex Question: T62, 2002

A lateral neck tumor is treated with a single direct electron field. The max depth of the treatment volume is 1.5cm, and the minimum cord depth is 5.0cm. Two techniques are considered:

- 6MeV electrons
- 9MeV electrons with 0.5cm bolus

Which of the following is TRUE?

A. The cord dose will be at least 50% of prescribed dose in either case.
B. The surface dose will be higher with the 6MeV Beam.
C. The dose falloff beyond the tumor will be steeper with 6MeV
D. The tumor would be underdosed with 9MeV
Raphex Question: T64, 2000

Which of the following properties of electron beams are true?

1. The range in tissue in cm is about is about ½ the beam energy in MeV.
2. The distance between the 90% and 20% isodose levels on the axis increases with increasing energy.
3. The width of the 90% isodose decreases with depth.
4. As energy increases, skin dose decreases.

A. 1,2,3
B. 1,3
C. 4 only
D. All of the above
Raphex Question: T46, 2001

Compared with 6MeV electrons, 16MeV electrons have:

1. A greater surface dose.
2. A lower bremsstrahlung tail.
3. A broader plateau region.
4. A sharper fall-off between 80% and 20% isodose levels.

A. 1,3  
B. 2,4  
C. 1,2,3  
D. 4 only  
E. 1,2,3,4
A 12 MeV electron beam has a range of____cm, and a 90% DD at approximately_____cm.

A. 6,4
B. 12,4
C. 12,6
D. 4,3
E. 9,6
When a custom electron insert has dimensions smaller than the range of the electrons, all of the following are likely to occur except:

A. The output (cGy/MU) will be reduced
B. Surface dose will decrease.
C. PDD will decrease beyond $d_{max}$.
D. $D_{max}$ will shift toward a shallower depth.
Electron therapy
Class 2: Fundamentals
continued
Field flatness and symmetry

- Plane perpendicular to beam axis
- Uniformity index (ICRU): $A_{dose}/A_{geom} > 90\%$
- Specifies dose $< 103\%$ of CAX value
- Depth: e.g. 95% beyond $d_{max}$ (AAPM TG#25)
- Area: 2cm inside geometrid edge of fields larger than 10x10cm
- $\pm 5\%$ (optimally be within $\pm 3\%$) TG#25
- Symmetry: compares dose profile on one side of central axis to the other. Max 2% variation (AAPM)
- Flatness and symmetry change: $< 1\%$ of baseline
The MU calculation is given by:

\[ MU = \frac{D}{\%D \cdot O} \]

- **D** Prescribed dose
- **\%D** Prescribed %
- **O** Dose output at R\(_{100}\)

Output depends on energy, applicator, field size, SSD and skin collimation.

First consider different cones and field sizes:

\[ O(E, CS, FS) = OF(E, CS, FS) \cdot O_{cal}(E) \]

Note: All at R\(_{100}\), which is dependent of field size and energy

\[ MU = \frac{D}{\%D \cdot OF(E, CS, FS) \cdot O_{cal}(E)} \]

(more on MU calcs later)
Skin blocking

- Useful for:
  - Small fields
  - Critical structures close to field
  - Need to restore beam penumbra (e.g. extended SSD, arc therapy)
Effect of skin collimation on dosimetry

• **PDD:**
  - mostly scatter in patient
  - Use field size determined by skin collimation

• **Output factor:**
  - Mostly scatter in air
  - Use field size determined by secondary collimator (e.g. cerrobind cutout)
Field equivalence

• For rectangular fields:

\[ D_{X,Y} = [D_{X,X} \cdot D_{Y,Y}]^{1/2} \]

• (Note: neglects collimator scatter)

• Equivalent circular fields (field width=2a):

\[ R_{\text{equiv}} \approx 1.116a \]
\[ OF_{LxW} = \sqrt{OF_{LxL} \times OF_{WxW}} \]
Calculating PDD for non-square fields

- Depth dose can be determined from data from square fields:
  \[ D_{(0,0,Z)}^{WX,WY} = \left( D_{(0,0,Z)}^{WX,WX} D_{(0,0,Z)}^{WY,WY} \right)^{1/2}. \]

- Need to renormalize for 100% at \( d_{\text{max}} \) for new PDD

- Can use same formula for output calculations
A possible scenario:

- Skin collimation 2x5
- Cutout in cone: 4x6
- Energy: 6MeV
- What determines output factor?
- What determines PDD?
An electron beam with a custom insert has a measured OF of 0.954cGy/MU at \(d_{\text{max}}\). If 200cGy are prescribed to the 90\% isodose, the MU setting is ____.

A. 117  
B. 210  
C. 212  
D. 222  
E. 233
Bonus question

- The patient is to be treated to 200cGy, prescribed to the 80% isodose level.
- The calibrated output for the 15 cone is 1cGy/MU at $d_{\text{max}}$.
- The field size is 4x12cm$^2$ (15cone).
- The output factor for a 4x4 field in the 15 cone is 0.954.
- The output factor for a 12x12 field in the 15 cone is 0.997.
- The MU setting is ____.

A. 176
B. 184
C. 218
D. 250
E. 256
Another bonus question

• We decide to add 1cm bolus to a 6MeV electron field. Which of the following is not true (if we do not change the MUs)?
  a) The position of dmax moves upstream by 1cm
  b) The dose at 2cm depth in the tissue goes down
  c) The skin dose increases to almost $d_{max}$
  d) The maximum dose increases by 2%
  e) The maximum dose decreases by 2%
Raphex Question: T58, 1999

• Output for an electron cones depends on:

1. Cone size.
2. Size of cut-out.
4. SSD
   A. 1,2,3
   B. 1,3
   C. 2,4
   D. 4 only
   E. All of the above.

• Correct Answer: E. Output for electron beam depends on ALL of these factors.
Electron therapy
Class 2: Algorithms

Laurence Court

Acknowledgements

- Many images, data and many slides are from Richard Popple, Ph.D., Department of Radiation Oncology, The University of Alabama at Birmingham, Birmingham, Alabama
- Paul Yokoyama (Varian) was also very helpful
Pencil beam algorithm

\[ d_p(r,z) = d_p(0,z) e^{-r^2/a_r^2(z)} \]

\[ D(x,y,z) = \int \int d_p(x - x', y - y', z) \, dx' \, dy' \]
Schematic of Hogstrom algorithm

\[ \sigma^2_X(z) = \frac{1}{2} \int \left( \frac{\theta^2}{\rho l(z')} \right) \rho(z') (z - z')^2 dz' \]
Heterogeneity correction in original Hogstrom pencil-beam algorithm

Slab approach to heterogeneity correction

![Diagram of pencil beam with heterogeneity correction](image-url)
Redefinition pencil-beam algorithm

Figure 5. Schematic representation in XZ plane of pencil beams at Z being transported to Z + ΔZ, where new pencil beams are defined (from Shiu 1991a).
Experimental evaluation

- Dose measured using watertank and diode

20-MeV Horizontal Bone Slab

Varian Clinac 2100, 15x15-cm² open applicator, 100 cm SSD

Depth (cm)

Off-Axis Position (cm)

Measured
PBRA

Criteria not met
20-MeV Horizontal Air Slab

Varian Clinac 2100, 15x15-cm² open applicator, 100 cm SSD

Measured
PBRA

Criteria not met
Parotid Gland - Transverse View

Varian 2100, 16 MeV, 15x15-cm² applicator, 100 cm SSD
Parotid Gland - Transverse View

Varian 2100, 16 MeV, 15x15-cm² applicator, 100 cm SSD

Monte Carlo
PBRA

10%
90%

AIR
LUNG
TISSUE
BONE

The University of Texas M. D. Anderson Cancer Center
Department of Radiation Physics
IMC - Transverse Plane

Varian 2100, 16 MeV, 15x15-cm² applicator, 105 cm SSD
IMC - Transverse Plane

Varian 2100, 16 MeV, 15x15-cm² applicator, 105 cm SSD

The University of Texas M. D. Anderson Cancer Center
Department of Radiation Physics
Electron Monte Carlo dose calculations

- Accurate electron dose calculations (distributions) are very difficult
- Monte Carlo has potential to be most accurate method
- MC is very calculation intensive:
  - 2% SD at peak dose for 10x10cm field, 0.5cm resolution requires 1,000,000 histories.
- Macro Monte Carlo (MMC) significantly reduces calculation time
Primary Particle Transport – PDFs

‘Kugel’(!)

Precalculate PDFs for various Kugel sizes, materials
Primary Particle Transport

- Electron direction and step size from previous sphere
- Step size reduction near boundary
- Inhomogeneity
- Stop at interface
- Boundary crossing between materials
Eclipse implementation of MMC

1. Initial phase space model
2. Local simulation
3. Geometric pre-processing
4. Global simulation
(1) Initial Phase Space Model

- Four-source model
- Compute probability distributions of position, energy, direction of electrons and photons for each source, specified at PSP
(2) Local Simulation

• Over 200,000 electrons transported through uniform spheres:
  – 0.05cm, 0.1cm, 0.15cm, 0.2cm, 0.3cm
  – Air, lung, water, bone
  – 0.2MeV – 25MeV (25 electron energies)

• Gives PDF representing direction and energy of exiting particles, and also secondary particules
(3) Geometric pre-processing

Pre-processing:
• CT# to density and material conversion (user-defined resolution)
• Identify heterogeneities, and assign ‘krugel index’
• Calculate mean ‘krugel density’
(4) Global simulation

• Position, direction, energy of particles exiting sphere (‘kugel’!) determined by random sampling of PDF for appropriate sphere (size, material, energy)
• Dose deposited along straight line inside kugel

\[ \Delta E = E_i - E_f - E_\delta, \]

• Secondary particles forced to interact in sphere
• Always transported with 20deg angle relative to incident electron
## Calculation parameters – user interaction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation grid size</td>
<td>1 mm, 1.5 mm, 2 mm, 2.5 mm, 5 mm</td>
<td>Spacing of calculation points in the CT image plane. Calculation spacing in the longitudinal direction is the CT slice spacing.</td>
</tr>
<tr>
<td>Accuracy</td>
<td>1%, 2%, 3%, 5%, 8%</td>
<td>Mean statistical error in dose within the high dose volume.</td>
</tr>
<tr>
<td>Accuracy limit</td>
<td>1%, 2%, 3%, 5%, 8%</td>
<td>Monitor units are calculated only if the achieved accuracy is ≤ Accuracy Limit. Can only be set in calculation defaults.</td>
</tr>
<tr>
<td>Maximum number of particle histories</td>
<td>≥ 0</td>
<td>Specifies the maximum number of particles to be transported in a calculation. Calculation stops once set number of particles have been transported even if desired Accuracy is not reached. Option off if set to 0.</td>
</tr>
<tr>
<td>Random generator seed number</td>
<td>1 to 2100000000</td>
<td>Sets start point of the random number generator.</td>
</tr>
<tr>
<td>Smoothing method</td>
<td>No smoothing</td>
<td>Dose distribution is not smoothed.</td>
</tr>
<tr>
<td>Smoothing method</td>
<td>No smoothing</td>
<td>Dose distribution is not smoothed.</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>2-D Median</td>
<td></td>
<td>Applies a median filter to the dose distribution on each CT slice. The dose at each calculation point is replaced by the median dose in a neighborhood defined by the Smoothing Level.</td>
</tr>
<tr>
<td>3-D Gaussian</td>
<td></td>
<td>Convolves the dose distribution with a 3 dimensional gaussian, the standard deviation of which is defined by the Smoothing Level.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Smoothing level</th>
<th>1-Low</th>
<th>2-D Median: neighborhood = 5mm x 5mm.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3-D Gaussian: standard deviation = 0.5 x Calculation Grid Size.</td>
</tr>
<tr>
<td>2-Medium</td>
<td></td>
<td>2-D Median: neighborhood = 10mm x 10mm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3-D Gaussian: standard deviation = Calculation Grid Size.</td>
</tr>
<tr>
<td>3-Strong</td>
<td></td>
<td>2-D Median: neighborhood = 15mm x 15mm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3-D Gaussian: standard deviation = 1.5 x Calculation Grid Size.</td>
</tr>
</tbody>
</table>
Evaluation data set (dose distributions, impact of heterogeneities)


• Set of measurements developed and published specifically for evaluating electron dose calculation algorithms.
Phantom geometries
# Measurement configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Phantom geometry</th>
<th>SSD (cm)</th>
<th>Energies (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Water</td>
<td>100</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>Water</td>
<td>110</td>
<td>9</td>
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<td>3</td>
<td>Water</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>Water</td>
<td>110</td>
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</tr>
<tr>
<td>5</td>
<td>Horizontal air slab</td>
<td>100</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>Horizontal air slab</td>
<td>100</td>
<td>20</td>
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<tr>
<td>7</td>
<td>Vertical air slab</td>
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<td>8</td>
<td>Horizontal bone slab</td>
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<td>9</td>
</tr>
<tr>
<td>9</td>
<td>Horizontal bone slab</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>Vertical bone slab</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>11</td>
<td>2 cm stepped surface</td>
<td>102</td>
<td>9</td>
</tr>
<tr>
<td>12</td>
<td>2 cm stepped surface</td>
<td>102</td>
<td>20</td>
</tr>
<tr>
<td>13</td>
<td>Nose-shaped surface</td>
<td>102</td>
<td>9</td>
</tr>
<tr>
<td>14</td>
<td>Nose-shaped surface</td>
<td>102</td>
<td>20</td>
</tr>
</tbody>
</table>
Evaluation data set

- The measured data were normalized to the maximum dose on central axis in a water phantom (without inhomogeneity) at 100-cm SSD.
- All data were for a 15 x 15 cm² field and were acquired using a single Varian Clinac 2100C accelerator (Varian Oncology Systems, Milpitas, CA) having a Series III electron foil/applicator set.
- 9MeV, 20MeV
Configuration / commissioning

- Data set of Boyd et al. not sufficient to configure Eclipse MMC engine.
- Depth dose data are present (configurations 1 and 3).
- Not present in data set:
  - CAX fractional depth dose without applicator
  - In-air profile without applicator
  - Absolute output
Evaluation method

• For each configuration/calculation parameter combination, the dose difference and distance-to-agreement were computed.

• The dose difference was determined by interpolating the measured dose at the calculation points using bilinear interpolation.
Results - Accuracy

- Calculations performed for all possible values of accuracy parameter (1%, 2%, 3%, 5%, and 8%).
- 1 mm and 2.5 mm grid spacing for the 9 MeV and 20 MeV configurations, respectively.
- No smoothing.
# Results - Accuracy

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Accuracy</th>
<th>RMS difference</th>
<th>Fraction failing 3% difference</th>
<th>Fraction failing 3% difference and 3 mm distance-to-agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1%</td>
<td>2.4%</td>
<td>16.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td>2%</td>
<td>3.0%</td>
<td>25.6%</td>
<td>6.6%</td>
</tr>
<tr>
<td></td>
<td>3%</td>
<td>3.7%</td>
<td>37.0%</td>
<td>12.4%</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>5.9%</td>
<td>54.5%</td>
<td>22.8%</td>
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<tr>
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<td>8%</td>
<td>10.5%</td>
<td>72.4%</td>
<td>39.3%</td>
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<td>20</td>
<td>1%</td>
<td>1.9%</td>
<td>9.8%</td>
<td>3.1%</td>
</tr>
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<td>2%</td>
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<td>5.2%</td>
<td>48.8%</td>
<td>33.9%</td>
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<td></td>
<td>8%</td>
<td>8.9%</td>
<td>65.8%</td>
<td>52.6%</td>
</tr>
</tbody>
</table>
Isodose lines are 10%, 30%, 70%, 90%, and 95%. Calculation points violating 3% difference and 3 mm distance-to-agreement are shown in gray.
20 MeV, 100 cm SSD (Configuration 3) 3% Accuracy
20 MeV, nose-shape (Configuration 14)
3% Accuracy
Results – Grid spacing

• Calculations performed for all possible values of grid spacing (1 mm, 1.5 mm, 2 mm, 2.5 mm, and 5 mm).

• 1% accuracy.

• No smoothing.
# Results – Grid spacing

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Grid spacing (mm)</th>
<th>Fraction failing 3% difference</th>
<th>Fraction failing 3 mm Distance-to-agreement</th>
<th>Fraction failing 3% difference and 3 mm distance-to-agreement</th>
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<tbody>
<tr>
<td>9</td>
<td>1.0</td>
<td>16.5%</td>
<td>4.9%</td>
<td>1.5%</td>
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<tr>
<td></td>
<td>1.5</td>
<td>19.1%</td>
<td>6.2%</td>
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<tr>
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<td>2.0</td>
<td>18.3%</td>
<td>5.8%</td>
<td>1.9%</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>23.7%</td>
<td>6.1%</td>
<td>2.9%</td>
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<td></td>
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<td>47.6%</td>
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<tr>
<td>20</td>
<td>1.0</td>
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<td>19.6%</td>
<td>1.6%</td>
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<tr>
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<td>4.6%</td>
<td>20.2%</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>9.3%</td>
<td>21.1%</td>
<td>2.9%</td>
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<td>3.1%</td>
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<tr>
<td></td>
<td>5.0</td>
<td>13.5%</td>
<td>21.8%</td>
<td>3.4%</td>
</tr>
</tbody>
</table>
9 MeV, 2 cm stepped surface (Configuration 11)
1 mm grid spacing
9 MeV, 2 cm stepped surface (Configuration 11)
5 mm grid spacing
Results – smoothing

• Calculations performed for all possible values of 3-D smoothing (Low, Medium, and Strong).
• 1% accuracy.
• Grid spacing
  – 1 mm, 1.5 mm, 2 mm, and 2.5 mm for the 9 MeV configurations.
  – 1.5 mm, 2 mm, 2.5 mm, and 5 mm for the 20 MeV configurations.
## Results – smoothing

<table>
<thead>
<tr>
<th>Energy (mm)</th>
<th>Grid spacing (mm)</th>
<th>None</th>
<th>Low</th>
<th>Medium</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1.0</td>
<td>1.5%</td>
<td>0.7%</td>
<td>0.2%</td>
<td>0.1%</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2.2%</td>
<td>1.5%</td>
<td>0.5%</td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>1.9%</td>
<td>1.2%</td>
<td>0.5%</td>
<td>1.3%</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>3.7%</td>
<td>2.9%</td>
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<td>6.6%</td>
</tr>
<tr>
<td>20</td>
<td>1.5</td>
<td>3.5%</td>
<td>2.0%</td>
<td>0.5%</td>
<td>0.3%</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>2.9%</td>
<td>1.5%</td>
<td>0.3%</td>
<td>0.4%</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>3.1%</td>
<td>1.3%</td>
<td>0.5%</td>
<td>0.6%</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>3.4%</td>
<td>1.1%</td>
<td>3.4%</td>
<td>12.5%</td>
</tr>
</tbody>
</table>
20-MeV beam incident on a flat surface with a horizontal bone heterogeneity (configuration 9) No smoothing
20-MeV beam incident on a flat surface with a horizontal bone heterogeneity (configuration 9) 3D Medium smoothing
Accuracy in presence of lung

- Experimental data from University of Bern (Switzerland) or Tampere University Hospital (Finland)
- 1cm perspex over lung-equivalent material
- 6MeV Varian beam
Water with Lung Heterogeneity

**Depth Dose along CAX**
- 6 MeV electrons
- 15 cm x 15 cm
- SSD = 100 cm

**Profile at:**
- d = 20 mm
- x = 0 mm
- 6 MeV electrons
- 15 cm x 15 cm
- SSD = 100 cm
Conclusion (dose distributions)

• For judicious choices of parameters, dose calculations agree with expt. to better than 3% dose difference and 3-mm distance-to-agreement.

• Lung dose is less accurate.

• Note: Varian have also shown good results for oblique incidence.

• The Eclipse MMC implementation is limited to
  - 2.5% and 2.5 mm for 9 MeV
  - 3% and 3 mm for 20 MeV
Evaluation of output factors for range of clinical fields

- Data above only for simple field shapes
- Comparison of measured and calculated outputs
- (output includes shape and SSD differences)

<table>
<thead>
<tr>
<th></th>
<th>6 MV</th>
<th>9 MV</th>
<th>12 MV</th>
<th>15 MV</th>
<th>18 MV</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>A06</td>
<td>5</td>
<td>8</td>
<td>4</td>
<td>1 (4)</td>
<td>1 (4)</td>
<td>19 (25)</td>
</tr>
<tr>
<td>A10</td>
<td>13</td>
<td>21</td>
<td>11</td>
<td>8</td>
<td>2 (4)</td>
<td>55 (57)</td>
</tr>
<tr>
<td>A15</td>
<td>19</td>
<td>13</td>
<td>17</td>
<td>10</td>
<td>4</td>
<td>63</td>
</tr>
<tr>
<td>A20</td>
<td>9</td>
<td>20</td>
<td>15</td>
<td>1 (4)</td>
<td>1 (5)</td>
<td>46 (53)</td>
</tr>
<tr>
<td>A25</td>
<td>1 (4)</td>
<td>3 (4)</td>
<td>1 (4)</td>
<td>2 (4)</td>
<td>0 (4)</td>
<td>7 (20)</td>
</tr>
<tr>
<td>All</td>
<td>47 (50)</td>
<td>65 (66)</td>
<td>48 (51)</td>
<td>22 (30)</td>
<td>8 (21)</td>
<td>190 (218)</td>
</tr>
</tbody>
</table>
Eclipse MMC Calculation Parameters

- **Accuracy** (mean statistical error in dose within the high dose volume): 1%.
- **Grid spacing:**

<table>
<thead>
<tr>
<th>Energy</th>
<th>Grid spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 MeV</td>
<td>1 mm</td>
</tr>
<tr>
<td>9 MeV</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>12 MeV</td>
<td>2 mm</td>
</tr>
<tr>
<td>15 MeV</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>18 MeV</td>
<td>2.5 mm</td>
</tr>
</tbody>
</table>

- **No smoothing**
Scatter plot of calculated output factor versus measured output factor

The solid line shows calculation equal to measurement, and the dashed lines show 3% deviation.
Histogram of difference distribution

Mean difference: -0.23%
Std. deviation: 1.09%
Conclusion (output factors)

- The mean difference between the Eclipse MMC calculation and measurement was 0.2%. The standard deviation of the difference distribution was 1.1%.

- Of the 218 measurements,
  - 124 (56.9%) were within 1%.
  - 211 (96.8%) were within 2%.
  - 215 (98.6%) were within 3%.

- The largest difference was 3.4%.
Treatment planning algorithms: Summary

- Pencil beam
- Modified Monte Carlo
- Expect MU to be accurate within ~3%
- Relative isodoses should be accurate for most scenarios, but less reliable for lung
- Algorithms do not include skin collimation, customized bolus or electron arc therapy