Electron therapy
Class 2: MU calculations

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Reference: Faiz M. Khan, The Physics of Radiation Therapy

Slide acknowledgements: Karl Prado, Rebecca Howell, Kent Gifford, and Khan’s book

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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%
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 \( \frac{1}{2} \) 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
Raphex Question: T57, 2002

• 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 $d_{\text{max}}$.
D. $D_{\text{max}}$ will shift toward a shallower depth.
MU calculation

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

- **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

\[ R_{100} = R_{100}(E, FS) \]
\[ \text{OF}_{LxW} = \sqrt{\text{OF}_{LxL} \times \text{OF}_{WxW}} \]
Field equivalence

• For rectangular fields:

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

• (Note: neglects collimator scatter)

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

\[ R_{\text{equiv}} \approx 1.116a \]
Example output chart for 9MeV electron (Varian)

<table>
<thead>
<tr>
<th>Field Size (cm²)</th>
<th>10 × 10</th>
<th>15 × 15</th>
<th>20 × 20</th>
<th>25 × 25</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 × 2</td>
<td>0.843</td>
<td>0.846</td>
<td>0.824</td>
<td>0.812</td>
</tr>
<tr>
<td>3 × 3</td>
<td>0.908</td>
<td>0.908</td>
<td>0.891</td>
<td>0.871</td>
</tr>
<tr>
<td>4 × 4</td>
<td>0.963</td>
<td>0.954</td>
<td>0.936</td>
<td>0.911</td>
</tr>
<tr>
<td>5 × 5</td>
<td>0.991</td>
<td>0.982</td>
<td>0.962</td>
<td>0.936</td>
</tr>
<tr>
<td>6 × 6</td>
<td>1.003</td>
<td>0.997</td>
<td>0.976</td>
<td>0.951</td>
</tr>
<tr>
<td>7 × 7</td>
<td>1.005</td>
<td>1.004</td>
<td>0.983</td>
<td>0.960</td>
</tr>
<tr>
<td>8 × 8</td>
<td>1.003</td>
<td>1.006</td>
<td>0.986</td>
<td>0.964</td>
</tr>
<tr>
<td>10 × 10</td>
<td>1.000</td>
<td>1.003</td>
<td>0.985</td>
<td>0.965</td>
</tr>
<tr>
<td>12 × 12</td>
<td>0.997</td>
<td>0.980</td>
<td>0.962</td>
<td></td>
</tr>
<tr>
<td>15 × 15</td>
<td>0.992</td>
<td>0.976</td>
<td>0.955</td>
<td></td>
</tr>
<tr>
<td>20 × 20</td>
<td></td>
<td>0.981</td>
<td>0.950</td>
<td></td>
</tr>
<tr>
<td>25 × 25</td>
<td></td>
<td></td>
<td>0.955</td>
<td></td>
</tr>
</tbody>
</table>
Irregular field shapes

- Measure
- Analytical algorithm or Monte Carlo code
- Equivalent rectangles
  - Applicator insert field shape
  - Max dose in broadest region of field
  - Distant regions do not usually contribute significantly to output
  - Not sufficiently accurate for highly irregular fields – measure these!
Off-axis fields

- Often neglect this
- Flatness < 3%
- Can assume radial OAR

\[ OAR(E, CS, SSD_o, X, Y) = OAR_{meas} \left( E, CS, SSD_o, X = \sqrt{X^2 + Y^2}, Y = 0 \right). \]
Irregular field inserts: Equivalent rectangles
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. cerrobend cutout)
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 dmax 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?
Treating at extended SSD

• Electron output dose not follow a simple conventional inverse-square relationship
  – Lots of attenuation, scatter in air, collimation, foils, etc…

• Distance corrections take two forms:
  – Use of an “effective SSD” that can be used in an inverse-square fashion.
  – Use of an “air-gap factor” that can be used in addition to (on instead of) a conventional inverse-square factor
Electron source

- **Virtual Source** – An intersection point of the back-projections along the most probable directions of electron motion at the patient surface.

\[
\text{Gap Correction} = \left( \frac{\text{SSD}_{\text{Effective}} + d_{\text{max}}}{\text{SSD}_{\text{Effective}} + d_{\text{max}} + g} \right)^2
\]
Effective SSD is a function of field size (cone) and energy

<table>
<thead>
<tr>
<th>Effective SSD Values</th>
<th>6 x 6</th>
<th>10 x 10</th>
<th>15 x 15</th>
<th>20 x 20</th>
<th>25 x 25</th>
</tr>
</thead>
<tbody>
<tr>
<td>6MeV</td>
<td>118.90</td>
<td>82.16</td>
<td>88.60</td>
<td>90.03</td>
<td>90.99</td>
</tr>
<tr>
<td>9MeV</td>
<td>77.56</td>
<td>86.34</td>
<td>88.75</td>
<td>90.76</td>
<td>91.46</td>
</tr>
<tr>
<td>12MeV</td>
<td>117.13</td>
<td>86.34</td>
<td>89.28</td>
<td>90.53</td>
<td>91.48</td>
</tr>
<tr>
<td>16MeV</td>
<td>84.66</td>
<td>87.14</td>
<td>89.66</td>
<td>91.79</td>
<td>92.87</td>
</tr>
<tr>
<td>20MeV</td>
<td>80.17</td>
<td>83.72</td>
<td>88.63</td>
<td>91.59</td>
<td>92.91</td>
</tr>
</tbody>
</table>
Air-gap factor

\[ F_{SSD} = ISF_{SSD_{nom}} + g = \left( \frac{SSD_{nom} + d_m}{SSD_{nom} + d_m + g} \right)^2 \times f_{air} \]

May be combined into a single \( f_{air} \)

- \( f_{air} \) is a function of energy and field size
- Use square-root method for rectangular fields:

\[ f_{air_{LxW}} = \sqrt{f_{air_{LxL}} \times f_{air_{WxW}}} \]
Example air-gap factors for 9MeV beam

<table>
<thead>
<tr>
<th>Field Size (cm²)</th>
<th>100</th>
<th>105</th>
<th>110</th>
<th>115</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 × 2</td>
<td>1.000</td>
<td>0.882</td>
<td>0.743</td>
<td>0.611</td>
<td>0.505</td>
</tr>
<tr>
<td>3 × 3</td>
<td>1.000</td>
<td>0.946</td>
<td>0.878</td>
<td>0.792</td>
<td>0.715</td>
</tr>
<tr>
<td>4 × 4</td>
<td>1.000</td>
<td>0.942</td>
<td>0.902</td>
<td>0.862</td>
<td>0.815</td>
</tr>
<tr>
<td>6 × 6</td>
<td>1.000</td>
<td>0.978</td>
<td>0.954</td>
<td>0.940</td>
<td>0.915</td>
</tr>
<tr>
<td>10 × 10</td>
<td>1.000</td>
<td>0.984</td>
<td>0.972</td>
<td>0.961</td>
<td>0.955</td>
</tr>
<tr>
<td>15 × 15</td>
<td>1.000</td>
<td>0.988</td>
<td>0.978</td>
<td>0.970</td>
<td>0.963</td>
</tr>
<tr>
<td>20 × 20</td>
<td>1.000</td>
<td>0.987</td>
<td>0.975</td>
<td>0.971</td>
<td>0.963</td>
</tr>
<tr>
<td>25 × 25</td>
<td>1.000</td>
<td>0.987</td>
<td>0.982</td>
<td>0.974</td>
<td>0.970</td>
</tr>
</tbody>
</table>
Beware of different approaches

Approach 1:

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

\[ O(\text{SSD}) = O(\text{SSD}_o) \cdot \left[ \frac{\text{SSD}_o + R_{100}(E, FS)}{\text{SSD} + R_{100}(E, FS)} \right]^2 \cdot f_{\text{air}}(E, FS, \text{SSD}). \]

Approach 2:

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

Output tabulated as O(E,CS,FS,SSD)

Approach 3:

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

CF(E,FS,SSD) – corrects for SSD
Output is O(E,CS,FS)
### Approach 2: Output factors and SSD effects included in a single factor

<table>
<thead>
<tr>
<th>SSD</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.986</td>
<td>0.989</td>
<td>0.948</td>
<td>0.916</td>
<td>0.861</td>
</tr>
<tr>
<td>101</td>
<td>0.963</td>
<td>0.962</td>
<td>0.919</td>
<td>0.889</td>
<td>0.824</td>
</tr>
<tr>
<td>102</td>
<td>0.940</td>
<td>0.936</td>
<td>0.891</td>
<td>0.862</td>
<td>0.789</td>
</tr>
<tr>
<td>103</td>
<td>0.918</td>
<td>0.911</td>
<td>0.864</td>
<td>0.836</td>
<td>0.755</td>
</tr>
<tr>
<td>104</td>
<td>0.897</td>
<td>0.887</td>
<td>0.837</td>
<td>0.811</td>
<td>0.722</td>
</tr>
<tr>
<td>105</td>
<td>0.877</td>
<td>0.863</td>
<td>0.812</td>
<td>0.787</td>
<td>0.690</td>
</tr>
<tr>
<td>106</td>
<td>0.856</td>
<td>0.842</td>
<td>0.790</td>
<td>0.762</td>
<td>0.655</td>
</tr>
<tr>
<td>107</td>
<td>0.836</td>
<td>0.821</td>
<td>0.769</td>
<td>0.737</td>
<td>0.622</td>
</tr>
<tr>
<td>108</td>
<td>0.817</td>
<td>0.800</td>
<td>0.748</td>
<td>0.713</td>
<td>0.590</td>
</tr>
<tr>
<td>109</td>
<td>0.799</td>
<td>0.781</td>
<td>0.729</td>
<td>0.689</td>
<td>0.560</td>
</tr>
<tr>
<td>110</td>
<td>0.781</td>
<td>0.762</td>
<td>0.709</td>
<td>0.667</td>
<td>0.530</td>
</tr>
<tr>
<td>111</td>
<td>0.765</td>
<td>0.744</td>
<td>0.691</td>
<td>0.642</td>
<td>0.502</td>
</tr>
<tr>
<td>112</td>
<td>0.749</td>
<td>0.727</td>
<td>0.673</td>
<td>0.618</td>
<td>0.475</td>
</tr>
<tr>
<td>113</td>
<td>0.734</td>
<td>0.710</td>
<td>0.655</td>
<td>0.595</td>
<td>0.449</td>
</tr>
<tr>
<td>114</td>
<td>0.719</td>
<td>0.694</td>
<td>0.638</td>
<td>0.573</td>
<td>0.423</td>
</tr>
<tr>
<td>115</td>
<td>0.705</td>
<td>0.678</td>
<td>0.621</td>
<td>0.551</td>
<td>0.399</td>
</tr>
<tr>
<td>116</td>
<td>0.689</td>
<td>0.661</td>
<td>0.604</td>
<td>0.531</td>
<td>0.379</td>
</tr>
<tr>
<td>117</td>
<td>0.674</td>
<td>0.645</td>
<td>0.588</td>
<td>0.512</td>
<td>0.359</td>
</tr>
<tr>
<td>118</td>
<td>0.660</td>
<td>0.629</td>
<td>0.571</td>
<td>0.493</td>
<td>0.340</td>
</tr>
<tr>
<td>119</td>
<td>0.645</td>
<td>0.614</td>
<td>0.556</td>
<td>0.475</td>
<td>0.321</td>
</tr>
<tr>
<td>120</td>
<td>0.631</td>
<td>0.599</td>
<td>0.540</td>
<td>0.458</td>
<td>0.303</td>
</tr>
</tbody>
</table>
Approach 3: Field-size dependent CF

After eqs~5cm, CF has steep gradients

For 5<eqs<10cm, CF has shallow gradient

For eqs>10cm, CF is fairly flat at ~1.23
Remember to do a sanity test(s)

• If we prescribe 200cGy to 80% isodose, SSD=100cm, how many MUs?
• If we increase SSD to 110cm SSD, how many MUs?
• What happens to MU if field size set to 5cm?
• What is the effect of energy?
• What do we do if we see an answer 2MU or 2000MU?
Calculations to include bolus

- When bolus is used, the depth-dose curve shifts “upstream” by a distance equal to the bolus thickness (e.g. if 1 cm bolus is used, the depth of $d_{max}$ shifts by a distance of 1 cm toward the skin surface)

- The output at this shorter distance is:

$$O_{SSD,b} = O_{SSD} \times \left( \frac{SSD + d_m}{SSD + d_m - b} \right)^2$$

Where $b$ is the bolus thickness in CD, and SSD is the nominal SSD

BEWARE: SSD to skin or bolus surface?
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 d_{max} 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%
Tissue Inhomogeneities

- Electron beam dose distribution can be significantly altered in the presence of tissue inhomogeneities; bone, lung, air cavities.
- Difficult to determine dose distribution within and around small inhomogeneities because of enhanced scattering effects.
- For LARGE and UNIFORM slabs, dose distribution beyond an inhomogeneity using the coefficient of equivalent thickness (CET) method.
The attenuation by a given thickness, $z$ of the inhomogeneity is equivalent to $z \times CET$.

Where,

$$\text{CET} = \frac{(\text{Electron Density})_{\text{inhomogeneity}}}{(\text{Electron Density})_{H_2O}}$$

- Dose at a point beyond the inhomogeneity is determined by calculating effective depth, $d_{\text{eff}}$, along the ray joining the point and the virtual source of the electrons.
- May include correction because of ISF
Coefficient of Equivalent Thickness (CET)

- **Bone**
  - \( \text{CET}_{\text{Compact Bone}} \approx 1.65 \)
  - \( \text{CET}_{\text{Spongy Bone}} \approx 1.1 \), can assume unity
  - CET method is in good agreement with in vivo measurements in patients for dose behind the mandible.

- **Lung**
  - Studies show considerable variation of CET with depth in the lung.
  - CET is only a rough approximation for lung inhomogeneity
Question

- We calculated 250 MU for an electron treatment (6 MeV, 0.5 cm bolus) to the scalp. The physician wants to know why we didn’t consider the bone in the calculation, and if we did, what effect would it have on the MU and PDD. What should we tell them?
Raphex Question: T61, 2002

• 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
Raphex Question: T60, 1999

• How much dose is delivered at the 90% PDD level from an electron beam in 100MU. OF=1.05cGy/MU.

A. 110cGy
B. 106cGy
C. 100cGy
D. 95cGy
E. 90cGy
An electron cone has an output of 1.13cGy/MU. The MU setting to deliver 200cGy at the 93% isodose level is _____MU?

A. 243  
B. 215  
C. 190  
D. 177  
E. 165
A 12MeV electron field delivers 200cGy at the 90% isodose level. The output of the cone and insert is 1.02cGy/MU. The MU setting is____.

A. 176  
B. 184  
C. 218  
D. 227  
E. 250
A lesion of a maximum depth of 3cm is treated with 12MeV electrons (PDD data below). 1 cm of bolus is placed on the skin. If 200cGy is delivered to the distal edge of the tumor, the skin dose and maximum tissue doses are?

Use the PDD Data below:

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDD</td>
<td>90</td>
<td>95</td>
<td>98</td>
<td>100</td>
<td>80</td>
<td>40</td>
<td>5</td>
</tr>
</tbody>
</table>
A 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 d_{max} 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%
Extended SSD, rectangular field

- Dose prescription: 180 cGy to 100% isodose
- Electron energy: 9 MeV
- Applicator: 15x15 cm²
- Field size: 5x12 cm²
- SSD: 110 cm

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

\[ O(\text{SSD}) = O(\text{SSD}_0) \cdot \left[ \frac{\text{SSD}_0 + R_{100}(E, FS)}{\text{SSD} + R_{100}(E, FS)} \right]^2 \cdot f_{\text{air}}(E, FS, \text{SSD}). \]
What if we:

• Add 1cm bolus:

\[ O_{SSD, b} = O_{SSD} \times \left( \frac{SSD + d_m}{SSD + d_m - b} \right)^2 \]

• What would be the change in dose at Rmax if we added 4x11 cm² skin collimation?
Effect of Oblique Incidence on Dose Distribution

- The broad electron beam can be represented as a large number of pencil beams placed adjacent to each other.

- When a beam is obliquely incident on the patient’s surface:
  - Points at shallow depths receive greater side scatter from adjacent pencil beams, which have traversed a greater amount of the material.
  - Points at greater depths receive less scatter.
Beam obliquity factor

\[
D(f + g, d) = D_0(f, d) \left( \frac{f + d}{f + g + d} \right)^2 \times OF(\theta, d)
\]
<table>
<thead>
<tr>
<th>$\frac{Z/R_p}{b}$</th>
<th>(22)</th>
<th>(18)</th>
<th>(15)</th>
<th>(12)</th>
<th>(9)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\theta = 30^\circ)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>1.00</td>
<td>0.98</td>
<td>0.98</td>
<td>1.00</td>
<td>0.94</td>
<td>1.01</td>
</tr>
<tr>
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Field flatness and symmetry

- Plane perpendicular to beam axis
- Uniformity index (ICRU): \( \frac{A_{dose}}{A_{geom}} > 90\% \)
- Specifies dose < 103\% of CAX value
- Depth: e.g. 95\% beyond dmax (AAPM TG#25)
- Area: 2cm inside geometrical 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
Homework, I’m afraid

- Feel free to create an Excel table
- Please include all working (OF used, etc) so I can understand what happened if you don’t get the correct answer (partial points may be possible!)
- Always use a sanity check: What answer do we expect for:
  - 200cGy, 80%, 100cm SSD?
  - 200cGy, 90%, 100cm SSD?
  - 200cGy, 90%, 110cm SSD?