Electron therapy
Class 1: fundamentals

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

Slide acknowledgements: Karl Prado, Rebecca Howell, Kent Gifford, Rajat Kudchadker, Ken Hogstrom and Khan’s book
Electron therapy

1. Fundamentals
2. MU calculations
3. Dose calculations
4. Special procedures
Characteristics of clinical electron beams

X-Ray Contamination

Surface Dose

Depth of 90% Dose

Depth of 80% Dose

Varian 2100C SN 241 Electron (15X15)
Percent Depth Dose

PDD

Depth (mm)

0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00

0.0 20.0 40.0 60.0 80.0 100.0 120.0 140.0

- 16 MeV
- 12 MeV
- 9 MeV
- 6 MeV
- 20 MeV
Why treat with electrons?

- Region of fairly uniform dose, then rapid falloff
- Treat superficial targets
- Avoid dose to deep and/or adjacent tissues
Clinical context: Why treat with electrons?
Head and neck

- Fields for postoperative irradiation of a patient with advanced cancer of the laryngopharynx
- Electrons used for off-cord reduction

Head & Neck
Posterior Strips (9 & 12 MeV)
Insert Positioning
Parotid

- 46-year-old lady with T2, N0 mucoepidermoid carcinoma of the left parotid gland.
No Bolus
Non-Beveled Bolus
Beveled Bolus
(16 MeV)
Pediatric CNS

- 3-year-old boy presented in fall of last year with tremors and found to have a large mass in the right parietal lobe with craniotomy. Biopsy confirming choroid plexus carcinoma. There is evidence of leptomeningeal disease both intracranially as well as in the spine.
Pediatric CNS (12 MeV)
Transverse CNS
Bi-Lateral Chestwall

• 70-year-old, postmenopausal female that had a left modified radical mastectomy in 07/01, and right modified radical mastectomy in 06/02 along with adjuvant chemo and radiotherapy.
Bi-Lat Chest Wall Electron (5 & 7 MeV)
Bi-Lat Chestwall Skin Rendering
Intact Breast

- 54 years old and has a T1, N0 invasive carcinoma of the right breast which is ductal in origin, nuclear grade III. She underwent segmental mastectomy with negative sentinel node evaluation.
Breast Boost
(20 MeV)
Mesothelioma

- Extrapleural pneumonectomy (EPP) followed by RT
- Heart, liver, lung, kidney, cord, esophagus
Mesothelioma

- 180cGy to 5400cGy
- Abdomen block to shield stomach and liver
- Start heart block at 1980cGy
- Block cord at 4140
Why treat with electrons?

- Region of fairly uniform dose, then rapid falloff
- Treat superficial targets
- Avoid dose to deep and/or adjacent tissues
LINAC in e- Mode

- Scattering Foil
- Monitor ionization chambers
- Field defining Light
- Collimator System
  - $2^\circ$ e$^-$ collimation = cone, downstream of photon collimators placed close to skin to dec. e$^-$ scatter in air
  - $3^\circ$ e$^-$ collimation = cutout downstream of cone custom shape field to match Rx site

Khan, Figure 4.8B
Electron scattering system
Electron Cones

- Always use a electron cone.
Electron Cones

• Available cone sizes for the Varian 21EX:
  – 6x6, 10x10, 15x15, 20x20, 25x25

25x25 (18lbs)
Electron Cutout
Electron Cutout

- Further field shaping with cut-out.
Cone Interlock
Energy loss

Two Types of Electron Interactions

1. Collisional Interactions (ionization and excitation):
   Incident electron interacts with atomic electrons in the absorbing medium

2. Radiative Interactions:
   Incident electron interacts with atomic nuclei in the absorbing medium.
Electron Stopping Power

- **Stopping Power** - Energy lost per unit path length in the medium $\rightarrow$ MeV/cm
  - Stopping power depends on the density of the absorbing medium. Thus......

- Mass Stopping Power = Stopping power divided by density $\rightarrow$ MeVcm$^2$/g

\[
\frac{\text{MeV}}{\text{cm}} \times \frac{\text{cm}^3}{\text{g}} = \frac{\text{MeV} \cdot \text{cm}^2}{\text{g}}
\]
Stopping Power

- **Two Components:**
  1. Collisional Stopping Power
  2. Radiative Stopping Power

\[
\left( \frac{S}{\rho} \right)_{\text{Total}} = \left( \frac{S}{\rho} \right)_{\text{Col}} + \left( \frac{S}{\rho} \right)_{\text{Rad}}
\]
Collision Stopping Power:
- Tapers off with increasing energy
- Higher for Lower Z
- ~2MeV/cm for water for E>1MeV

Radiative Stopping Power:
- Large increase with increasing energy
- Higher for higher Z
Restricted Collisional Mass Stopping Power

- Energy lost by a charged particle in a medium is not always equal to the energy absorbed in a target, especially when the target is small with respect to the range of secondary electrons produced, some of the secondary electrons (δ-Rays) do not deposit dose locally.

- **Restricted Collisional Mass Stopping Power** → The energy $(E)$ lost by an electron per unit path length $(\ell)$ as a result of collision interactions with atomic electrons in which the energy loss is less than $\Delta$.

  - Basically it is the collisional stopping power without the high energy δ-rays.

\[
\frac{L}{\rho}_{\text{col},\Delta} = \frac{dE}{\rho d\ell}_{\text{col},\Delta}
\]
Absorbed Dose

\[ D = \int_{\Delta}^{E_0} \Phi_E \cdot \left( \frac{L}{\rho} \right)_{col,\Delta} \cdot dE \]

Restricted collision mass stopping power
Electron Scattering

- Multiple-coulomb scattering interactions between incident electrons and (mostly) nuclei of the medium
- Scattering power $\propto Z^2E^{-2}$

Figure 1. Bubble chamber photograph of a 9.3-MeV electron pencil beam propagating through propane.

From AAPM Summer School 1991
Effect of scattering on depth-dose curves

(2) With scatter and angle

(3) + angle

(2) + scatter

(3) Experimental
Characteristics of clinical electron beams

- Surface Dose
- Depth of 80% Dose
- Depth of 90% Dose
- X-Ray Contamination
Some PDD descriptors

$R_{50}$ = the depth (cm) at which the dose is 50% of the maximum dose.

$R_p$ = the depth (cm) of the point where the tangent to the descending portion of the curve intersects the extrapolated background.

X-Ray Contamination
Energy specification
Mean Energy, $E_0$

- The **MEAN ENERGY** of an electron beam, at the phantom surface is given by:

\[
\bar{E}_0 = C_4 \cdot R_{50}
\]

- $C_4$ as defined by TG21 is **2.33 MeV/cm**
- $C_4$ according to more recent Monte-Carlo calculations is **2.4 MeV/cm**
Most probable energy

\[(E_p)_0 = C_1 + C_2 R_p + C_3 R_p^2\]

According to the Nordic Association of Medical Physics:

- \(C_1 = 0.22\) MeV
- \(C_2 = 1.98\) MeV cm\(^{-1}\)
- \(C_3 = 0.0025\) MeV cm\(^{-2}\)
- (in practice, OK to ignore beam divergence)
Energy at Depth, \((E_p)_z\)

\[
\bar{E}_z = \bar{E}_0 \left(1 - \frac{z}{R_p}\right)
\]

Where:
- \(z\) is depth in tissue
- \(R_p\) is the practical range

(same equation for \((E_P)_Z\))
Characteristics of Clinical Electron Beams

- Depth of the 80% Dose:
  - Equal to approximately $E_{\text{nom}}/2.8$:

<table>
<thead>
<tr>
<th>$E_{\text{nom}}$</th>
<th>$E_{\text{nom}}/2.8$</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2.14</td>
<td>2.20</td>
</tr>
<tr>
<td>9</td>
<td>3.21</td>
<td>3.30</td>
</tr>
<tr>
<td>12</td>
<td>4.28</td>
<td>4.30</td>
</tr>
<tr>
<td>16</td>
<td>5.71</td>
<td>5.50</td>
</tr>
<tr>
<td>20</td>
<td>7.14</td>
<td>7.00</td>
</tr>
</tbody>
</table>

- Depth of 90% is approximately $E_{\text{nom}}/3.2$

<table>
<thead>
<tr>
<th>$E_{\text{nom}}$</th>
<th>$E_{\text{nom}}/3.2$</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1.88</td>
<td>2.00</td>
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<tr>
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<td>2.81</td>
<td>3.00</td>
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<td>12</td>
<td>3.75</td>
<td>4.00</td>
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<tr>
<td>16</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>20</td>
<td>6.25</td>
<td>6.10</td>
</tr>
</tbody>
</table>
Characteristics of clinical electron beams

- Depth of maximum dose ($R_{100}$):
  - For $E < 12\text{MeV}$, $R_{100}$ equal to approximately $E/4$
  - Remember PDD very flat for higher energy beams

- Practical Range:
  - Equal to approximately $1/2$ nominal energy:

<table>
<thead>
<tr>
<th>$E_{\text{nominal}}$</th>
<th>$E_{\text{nom}}/2$</th>
<th>$R_p$</th>
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<tbody>
<tr>
<td>6</td>
<td>3.0</td>
<td>3.15</td>
</tr>
<tr>
<td>9</td>
<td>4.5</td>
<td>4.58</td>
</tr>
<tr>
<td>12</td>
<td>6.0</td>
<td>6.04</td>
</tr>
<tr>
<td>16</td>
<td>8.0</td>
<td>7.66</td>
</tr>
<tr>
<td>20</td>
<td>10.0</td>
<td>10.13</td>
</tr>
</tbody>
</table>

- Energy loss is about $2 \text{MeV/cm}$
Electron Depth Dose Curves:
The approximate 4,3,2 rule of thumb

\[ R_{100} \approx \frac{E_0}{4} \]

\[ R_{80-90} \approx \frac{E_0}{3} \]

\[ R_p \approx \frac{E_0}{2} \]
Entrance dose

- Surface dose increases with increasing energy
  - At lower energies electrons are more easily scattered through larger angles.

<table>
<thead>
<tr>
<th>Enom</th>
<th>Surface dose (%)</th>
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<tbody>
<tr>
<td>6</td>
<td>72</td>
</tr>
<tr>
<td>9</td>
<td>78</td>
</tr>
<tr>
<td>12</td>
<td>83</td>
</tr>
<tr>
<td>15</td>
<td>87</td>
</tr>
<tr>
<td>18</td>
<td>91</td>
</tr>
</tbody>
</table>
X-ray contamination

- Increases with energy
- Varies with accelerator design
- Defined at $R_p + 2$ cm

<table>
<thead>
<tr>
<th>$E_{\text{nom}}$</th>
<th>X-ray %</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.7%</td>
</tr>
<tr>
<td>9</td>
<td>1.2%</td>
</tr>
<tr>
<td>12</td>
<td>1.9%</td>
</tr>
<tr>
<td>16</td>
<td>3.7%</td>
</tr>
<tr>
<td>20</td>
<td>5.9%</td>
</tr>
</tbody>
</table>
ELECTRON BEAM CENTRAL AXIS DEPTH DOSE

Khan, figure 14.1
Raphex Question: T64-67, 2003

• Match the electron energy with the feature described below:

A. 6MeV

T64. Has Highest Surface Dose.

B. 9MeV

T65. Has Range of 6cm in tissue.

T66. Has 90%dd at 2.7cm.

C. 12MeV

T67. Has sharpest falloff between 80% and 20%.

D. 16MeV

Bonus: Has highest dose beyond the practical range

E. 20MeV
Raphex Question: T54, 1999

• An electron beam of how many MeV would be most suitable to treat a volume extending to a depth of 3cm of area 10x10cm?

A. 3
B. 6
C. 10
D. 15
E. 20
Raphex Question: T46, 2001

- Compared with 6MeV electrons, 16MeV electrons have:

  a) A greater surface dose.
  b) A lower bremsstrahlung tail.
  c) A sharper fall-off between 80% and 20% isodose levels
Raphex Question: T58, 2002

- Which of the following is true regarding electron beams? The surface dose:

A. Is about the same as that of a photon beam with the same energy
B. Is lower for a beam with a scattering foil than for a scanned beam.
C. Is about the same as that of a superficial x-ray beam.
D. Increases as energy increases
Raphex Question: T68, 2003

The dose beyond the practical range is primarily due to:

A. Very low energy electrons.
B. The highest energy electrons in the spectrum.
C. Characteristic x-rays generated in tissue.
D. Bremsstrahlung.
What energies do you think we might use?

Choice: 6, 9, 12, 15, 18MeV
Bolus or no bolus?
Electron Isodose Curves

• Isodose Curves – Scattering of electrons very important factor in SHAPE of isodose curve.
• As the beam penetrates the medium, the beam expands rapidly below the surface due to scattering!

• Spread of isodose curve depends on:
  1. Isodose Level
  2. Energy
  3. Field Size
  4. Collimation
Electron Isodose Curves

Low Energy Electron Beams
• ALL isodose levels bulge out!

High Energy Electron Beams
• LOW isodose levels bulge out
• HIGH isodose levels show lateral constriction, which becomes worse with decreasing field size

7 MeV

18 MeV
External electron shielding

- Thickness of shielding should give < 5% transmission.
  - If weight or thickness no problem, can use more than minimum required.
- When placing shields directly on patient use minimum thickness to achieve desired reduction in dose.
  - Eye shields
  - Internal shields

- Rule of Thumb: Minimum thickness of Pb for blocking electrons in mm is given by electron energy INCIDENT in the lead divided by 2.

\[ mm_{Pb} = \frac{E_o (MeV)}{2} \]
Internal Shielding

• Internal shielding can be useful to protect structures beyond target volume.

• Commonly used for:
  – Buccal mucosa, lip, eye lid lesions.

• Electron backscatter from the lead can enhance dose near the shield.
  – Magnitude of the Increase: 30-70% in the range of 1 to 20 MeV, having higher value for lower energies.
Internal Shielding

- Electron back scatter Factor (EBF) – The quotient of dose at interface with lead in place to that with homogeneous polystyrene phantom at the same point.

\[
EBF = 1 + 0.735e^{(-0.052 \bar{E}_z)}
\]

where,

\[
\bar{E}_z = \bar{E}_0 \left(1 - \frac{z}{R_p}\right)
\]
Internal Shielding

- To dissipate the effect of elect of electron backscatter from Pb shield, place suitable amount of low Z absorber between lead shield and preceding tissue interface.
- Typically want to reduce transmission of the backscattered electron intensity to $\leq 10\%$.

- Thickness of Low Z ($\rho=1$) material required to absorb the backscattered electrons is determined using the data in the figure below:
Internal Shielding Example:

- A buccal mucosa lesion is treated with a 9MeV electron beam incident externally on the cheek.
- Assuming the thickness of the lesion is 2cm, calculate:
  a) The thickness of lead required to shield the oral structures beyond the cheek.
  b) Magnitude of electron backscatter.
  c) Thickness of bolus or Al to absorb the backscattered electrons.
Internal Shielding Example:

a. The thickness of lead required to shield the oral structures beyond the cheek.
   - Incident Energy = 9MeV
   - Need to calculate energy at depth = 2cm

\[
\bar{E}_z = \bar{E}_0 \left(1 - \frac{z}{R_p}\right) = 9 \left(1 - \frac{2}{4.5}\right) = 5MeV
\]

- **Recall: Rule of Thumb**: Minimum thickness of Pb for blocking electrons in mm is given by electron energy INCIDENT in the lead divided by 2.

\[
mm_{Pb} = \frac{5}{2} = 2.5
\]
Internal Shielding Example:

b. Magnitude of electron backscatter.

\[ EBF = 1 + 0.735 e^{(-0.052 E_z)} \]

\[ EBF = 1 + 0.735 e^{(-0.052(5MeV))} = 1.57 \]

The lead shield causes a 57% increase in dose at the tissue interface.
Internal Shielding Example:

c. Thickness of bolus or Al to absorb the backscattered electrons.

- From Figure 14.40, a 5MeV beam 10mm of polystyrene or bolus required to reduce the transmission of backscattered electrons to 10% transmission.
- Using equation \( \rho_{Al} t_{Al} = \rho_{bolus} t_{bolus} \), the equivalent amount of Al is 4mm (\( \rho_{Al} = 2.7 \text{g/cm}^3 \)).
Raphex Question: T70, 2003

• The thickness of lead required to shield a 6MeV electron beam is approximately ___mm.

A. 0.5
B. 3
C. 6
D. 12
E. 24
Problems of Adjacent Electron Fields

- **Adjacent Electron Fields**
  - Abutting at surface – Hot spots in junction region.
  - Separated at surface – Cold spots in junction region.

- Electrons are typically used to treat lesions close to skin surface.
  - Hot spot may be more acceptable than cold spot.
Problems of Adjacent Electron Fields

- Adjacent electron Fields with different gaps at surface.

- As gap decreases from 1.5cm to 0.5cm, cold spot is reduced, but hot spot is increased.

Khan, Figure 14.30
Problems of Adjacent Electron/Photon Fields

- Adjacent Electron/Photon Fields
  - Hot spot on Photon side
  - Cold spot on electron side

- The extent of the hot and cold spots depends on the electron beam SSD
  - When SSD is increased:
    - Electron profile becomes less flat as a result of increased electron scattering by air.
    - Hot and Cold spots spread out over larger areas without large change in magnitude.

Due to outscattering of electrons from electron field.
Adjacent Electron/Photon Fields

- Adjacent Electron/photon fields.
  A. SSD = 100
  B. SSD = 120

Hot/cold spot covers larger area when electron field at extended SSD.
Raphex Question: T59, 2002

• Regarding electron field junctions, which of the following is true? When the light fields of two adjacent electron fields are matched on the skin:

A. The dose variation across the junction will be within 5% if the electrons have the same energy and light fields abut.
B. There will always be hot and cold spots because of the shape of electron penumbra.
C. The formula: \( \text{gap} = \left( \frac{\text{depth}}{\text{sad}} \right) \times \left( \frac{C_1+C_2}{2} \right) \) gives the best match.
D. Overlapping the fields by 0.5 cm generally gives the best match.
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.
Effect of Oblique Incidence on Dose Distribution

- Increased dose at shallow depths
- Decreased dose at deeper depths

In Reality as obliquity increases, the air gap between the skin surface and the cone end increases.

The depth dose at a point in an obliquely incident beam is effected by both “pencil scatter effect” and “beam divergence”.

Expected consequence of oblique incidence
Surface Irregularities
Raphex Question: T59, 1999

• An electron enters a patient’s surface obliquely. If the MU are calculated for normal incidence, ALL of the following can be expected EXCEPT:

A. Surface dose increases.
B. Depth of $d_{max}$ decreases.
C. Depth of 90% isodose decreases.
D. Depth of 50% isodose increases.
Raphex Question: T61, 1999

When treating with high energy electron beams, one of the problems with using bolus over part of the field is:

A. Calculating the thickness necessary.
B. Finding an appropriate material.
C. Dose inhomogeneity at the edge of the bolus.
D. The production of Bremsstrahlung.
Output – effect of field size
PDD - effect of field size

Varian 2100's 6MeV Electrons
Central Axis Depth Dose @ 100cm SSD

Varian 2100's 20MeV Electrons
Central Axis Depth Dose @ 100cm SSD
How small can I make a field?

- If a field produced by a lead cutout is smaller than the minimum size required for maximum lateral dose build-up, dose in open portion is reduced.

- The ICRU suggested Rp as the lower limit for field diameter.
  - Lateral scatter equilibrium is achieved if field size created by the cutout is $> R_p (E/2)$.

- Khan showed lateral scatter equilibrium is achieved if $R_{eq} > 0.88 \sqrt{E_{p,0}}$

(should be $> E/2$)

(will talk about square vs circle later)
Raphex Question: T60, 2002

- Electron output (cGy/MU) depends on all of the following EXCEPT:

  A. Cone or applicator size.
  B. SSD.
  C. Size of custom insert.
  D. Dose Rate at $d_{\text{max}}$
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.
Characteristics of clinical electron beams

- Surface Dose
- Depth of 90% Dose
- Depth of 80% Dose
- X-Ray Contamination

Thank you!