Preparing for the ABR Part 2 Therapy Board Exam - Handout
Bonnie Chinsky, M.S. – 7/21/2014
Loyola University Medical Center

Disclaimer: The following is an overview of physics constants, equations, & concepts that might be helpful in preparing for the Part 2 exam that are not provided by the ABR on exam day. Visit http://www.theabr.org/ic-rp-calc for the list of constants provided on exam day. The accuracy of the information in this handout is not guaranteed nor is it intended for clinical use. Use at your own risk.

1. General
1.1. Important Constants

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 amu</td>
<td>1.66x10^{-27} kg = 931 MeV</td>
<td></td>
</tr>
<tr>
<td>1 Ci</td>
<td>3.7x10^{10} Bq = activity of 1g $^{226}$Ra</td>
<td></td>
</tr>
<tr>
<td>R-to-rad in air</td>
<td>0.876 rad/R = 0.876 cGy/R</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 U (air kerma strength)</td>
<td>cGy-cm²/h = µGy-m²/h</td>
<td></td>
</tr>
<tr>
<td>1 R</td>
<td>2.58x10^{-4} C/kg</td>
<td></td>
</tr>
<tr>
<td>1 mg Ra eq</td>
<td>8.25x10^{-4} R/h</td>
<td></td>
</tr>
</tbody>
</table>

1.2. Isotopes – γ Emitters

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\Gamma$ (R-cm²/mCi-h)</th>
<th>Avg. γ E (keV)</th>
<th>HVL in Pb (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{226}$Ra</td>
<td>8.25 (R-cm²/mg-h)</td>
<td>0.83 MeV</td>
<td>14</td>
</tr>
<tr>
<td>$^{192}$Ir</td>
<td>4.69</td>
<td>0.38 MeV</td>
<td>2.5</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>3.26</td>
<td>0.66 MeV</td>
<td>5.5</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>13.07</td>
<td>1.25 MeV</td>
<td>11</td>
</tr>
<tr>
<td>$^{125}$I</td>
<td>1.46</td>
<td>28 keV</td>
<td>0.025</td>
</tr>
<tr>
<td>$^{103}$Pd</td>
<td>1.48</td>
<td>21 keV</td>
<td>0.01</td>
</tr>
<tr>
<td>$^{198}$Au</td>
<td>2.38</td>
<td>0.41 MeV</td>
<td>2.5</td>
</tr>
</tbody>
</table>

1.3. Isotopes – β Emitters
- $^{90}$Sr (0.546 MeV, 28.8 y) $\rightarrow$ $^{90}$Y (2.28 MeV, 64 hr) $\rightarrow$ $^{90}$Zr
- $^{89}$Sr (1.46 MeV, 50 d) $\rightarrow$ $^{89}$Y
- Electron range in air: 4 m for 2 MeV

2. Radiation Protection
2.1. Dose Equivalent & Effective Dose Equivalent

$$H_E = \sum_T w_T H_T$$
$$= \sum_T w_T H_T \sum_R w_R D_T$$

$w_T$ = weighting factor for tissue, T (unitless)
$H_t$ = dose equivalent delivered to tissue T (Sv)
$w_R$ = relative weighting factor for radiation R (Sv/Gy)
$D_R$ = absorbed dose delivered to tissue T from radiation R (Gy)
$H_e$ = effective dose equivalent (Sv)
2.2. Permissible Doses

<table>
<thead>
<tr>
<th>Exposure Limits</th>
<th>Occupational</th>
<th>Public</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permissible Doses</td>
<td>50 mSv/y</td>
<td>1 mSv/y</td>
</tr>
<tr>
<td>Lens</td>
<td>150 mSv/y</td>
<td>Frequent</td>
</tr>
<tr>
<td>Extremities</td>
<td>500 mSv/y</td>
<td>Infrequent</td>
</tr>
<tr>
<td>Cumulative</td>
<td>Age (y) x 10 mSv/y</td>
<td>Lens, other</td>
</tr>
<tr>
<td>Fetal</td>
<td>5 mSv total</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transporting Radioactive Isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max surface (mrem/h)</td>
</tr>
<tr>
<td>Transport index</td>
</tr>
</tbody>
</table>

| Cancer Induction Probability | 5% per Sv (ICRP 60) |

2.3. Shielding

Primary: \( P = \frac{WUT}{d^2} B_P \)

Secondary \(_{\text{Scatter}}\): \( P = \frac{\alpha WT}{d_{\text{sec}}^2 d_{\text{sca}}^2} \frac{F}{400} B_S \)

Secondary \(_{\text{Leakage}}\): \( P = \frac{0.001WT}{d_l^2} B_l \)

- \( P \) = permissible dose
- \( W \) = workload (500-1000 Gy/Wk)
- \( T \) = occupancy factor
- \( \alpha \) = scatter-to-primary ratio off the scatterer at 1m
- \( F \) = field size at scatterer
- \( U \) = use factor
- \( U = 1 \)
- \( B_S = 1 \)
- \( B_P = 1 \)

**Rule of thumb:** If secondary & leakage barriers differ by at least 3 HVLs, the thicker of the 2 is enough. Otherwise, add 1 HVL to the thicker of the 2.

**Skyshine**

- \( D = 0.249 \times 10^6 \frac{B_{xs}D_{io} \Omega^{1.3}}{d_l^2 d_s^2} \)
- \( H = 0.84 \times 10^{-5} \frac{B_{ns} \Phi_0 \Omega}{d_l^2} \)

**Typical TVLs (cm)**

<table>
<thead>
<tr>
<th>Energy (MV)</th>
<th>120kVp (CT)</th>
<th>6</th>
<th>10</th>
<th>15</th>
<th>18</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>35</td>
<td>40</td>
<td>44</td>
<td>45</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>0.09</td>
<td>5.5</td>
<td>5.6</td>
<td>5.7</td>
<td>5.7</td>
<td></td>
</tr>
</tbody>
</table>

2.4. Scatter & Secondary Particles

- Max energy of 90° Compton scattered photon = 0.511 MeV
- Photoneutron production energy threshold for photons = 10 MeV
2.5. Radioactive Seed Disposal

- Seeds can be discarded after 10 half-lives

3. Monitor Unit Calculations

3.1. General Equations

<table>
<thead>
<tr>
<th>SAD Setup (TPR/TMR/TAR):</th>
<th>SSD Setup (PDD):</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ MU = \frac{D}{S_c(r_c)S_p(r_d)TMR(r_d, d)OF (SAD + d_{max})^2} ]</td>
<td>[ MU = \frac{D}{S_c(r_c)S_p(r_d_{max})PDD(r, d)OF (SSD + d_{max})^2} ]</td>
</tr>
</tbody>
</table>

- \( r \) = field size at surface
- \( r_d \) = field size at calc point
- \( r_c \) = coll. setting at SAD
- \( d \) = depth of calc point
- \( d_{max} \) = depth of max dose
- \( OF \) = other factors – wedge, tray, off-axis

3.2. PDD to TAR/TMR Equations

| \( TAR(r_d, d) = \frac{PDD(r, d)(SSD + d_{max})^2}{100}BSF(r) \) | \( TMR(r_d, d) = \frac{PDD(r, d)(SSD + d_{max})^2}{100}S_p\left(r_{d_{max}}\right) \) |

3.3. PDDs at SSD1 to PDDs at SSD2

\[ PDD_{SSD_2} = PDD_{SSD_1} (\frac{SSD_2 + d_{max}}{SSD_2 + d})^2 (\frac{SSD_1 + d}{SSD_1 + d_{max}})^2 \]

3.4. SAR Equations

| \( SAR(d, r_d) = TAR(d, r_d) - TAR(d, 0) \) | SAR isolates scatter component from TAR values
| \( \overline{TAR} = TAR(d, 0) + SAR \) | Irregular fields: \( \overline{TAR} \) is obtained & used for MU calcs

3.5. Penumbra, Gap, & Collimator Rotation Equations

| \( P_d = \frac{s(SSD + d - SCD)}{SCD} \) | \( gap = \frac{d}{2} \left( \frac{L_1}{SSD_1} + \frac{L_2}{SSD_2} \right) \) | \( \tan \theta_{coll} = \frac{L/2}{SSD} \) |

- \( d \) = prescription depth
- \( SCD \) = source collimator distance
- \( L_{1,2} \) = size of field 1 or 2
- \( s \) = source focal spot size (=3mm for linac)
- \( \Theta_{coll} \) = collimator angle for CSI field

3.6. Beam Characteristics – Photons & Electrons

Note: approximate values for 10x10; values vary between linacs

<table>
<thead>
<tr>
<th>6 MV</th>
<th>10 MV</th>
<th>15 MV</th>
<th>18 MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2.8</td>
<td>2.9</td>
<td>3.5</td>
</tr>
<tr>
<td>10</td>
<td>2.9</td>
<td>3.0</td>
<td>3.6</td>
</tr>
<tr>
<td>15</td>
<td>3.0</td>
<td>3.1</td>
<td>3.7</td>
</tr>
<tr>
<td>18</td>
<td>3.1</td>
<td>3.2</td>
<td>3.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6 MeV</th>
<th>9 MeV</th>
<th>12 MeV</th>
<th>16 MeV</th>
<th>20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>2.3</td>
<td>2.9</td>
<td>3.6</td>
<td>2.1</td>
</tr>
<tr>
<td>49</td>
<td>78</td>
<td>82</td>
<td>89</td>
<td>91</td>
</tr>
<tr>
<td>67</td>
<td>74</td>
<td>77</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>0.84</td>
<td>0.88</td>
<td>0.89</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>12</th>
<th>16</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>2.3</td>
<td>2.9</td>
<td>3.6</td>
</tr>
<tr>
<td>78</td>
<td>82</td>
<td>89</td>
</tr>
</tbody>
</table>

**Electron Beam Properties:**

- \( d_{90} \) (cm) = \( E(\text{MeV})/4 \)
- \( d_{80} \) (cm) = \( E/3 \)
- range = \( E/2 \)
- \( E_x = E \left( 1 - d/R_p \right) \)
- \( E_0 = 2.4R_{50} \)
- Pb shield thickness: 0.5mm/MeV; Cerrobend 20% thicker
3.7. **Heterogeneity Corrections**

\[
CF = \frac{TAR(d_1 + \rho_2d_2 + d_3)}{TAR(d_1 + d_2 + d_3)}
\]

CF corrects the dose calculation for heterogeneities. The MU will be increased by a factor of 1/CF.

3.8. **Wedges**

3.8.1. **Hinge Angle**

\[
\theta_{wedge} = \frac{\theta_{hinge}}{2}
\]

\(\theta_{wedge}\) = wedge angle
\(\theta_{hinge}\) = hinge angle = angle between central axes of wedge fields

3.8.2. **Universal Wedge Angle**

\[
\tan \theta_{simulated} = B \cdot \tan \theta_{universal}
\]

\(B\) = weight of wedged field = \(D_{\text{wedge}}/D_{\text{tot}}\)
\(D_{\text{wedge}}\) = dose from universal wedged field
\(D_{\text{tot}}\) = total dose prescribed

3.9. **Timer Error**

\[
M_1 = n \dot{M}(t_{\text{short}} + \Delta t) = \dot{M}(t_{\text{tot}} + n\Delta t)
\]

\[
M_2 = \dot{M}(t_{\text{tot}} + \Delta t)
\]

\[
\Delta t = \frac{t_{\text{tot}}(M_2 - M_1)}{M_1 - nM_2}
\]

\(\dot{M}\) = charge collection rate  
\(n\) = number of short measurements (≥10)
\(t_{\text{short}}\) = short measurement time  
\(\Delta t\) = timer error  
\(t_{\text{tot}} = nt_{\text{short}}\) = total measurement time
\(M_1\) = total charge collected over \(n\) short measurements
\(M_2\) = total charge collected over 1 measurement session of length \(t_{\text{tot}}\)

3.10. **Patient Thickness vs. Dose Uniformity**

<table>
<thead>
<tr>
<th>Energy</th>
<th>Max:Midline Dose 30cm Thickness</th>
<th>See Khan 3rd ed. p. 211-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{60}\text{Co})</td>
<td>1.4</td>
<td>Dose ratios start at 1.0 for 10cm thickness</td>
</tr>
<tr>
<td>4MV</td>
<td>1.25</td>
<td>Dose ratios increase approximately as thickness squared</td>
</tr>
<tr>
<td>10MV</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>24MV</td>
<td>1.05</td>
<td></td>
</tr>
</tbody>
</table>

3.11. **Compensators, Bolus, & Spoilers**

- Compensators – account for missing tissue while maintaining buildup region
- Spoilers – increase angular spread of phase space of electrons; degrade electron beam energy
- Bolus – shift PDD buildup region toward skin surface

\[
t_c = TD \frac{\tau}{\rho_c}
\]

\(t_c\) = photon compensator thickness
\(TD\) = tissue deficit (cm)
\(\tau\) = thickness ratio, function of distance between compensator & absorber
\(\rho_c\) = density of compensator material
4. Dosimetry

4.1. TG-51

Overview: The TG-51 protocol yields absorbed dose in water in Gy at the point of measurement in absence of the ion chamber. Must be performed in a water phantom of at least 30 x 30 x 30 cm.

### Photon Beams: energies between ⁶⁰Co and 50MeV

\[
D_w^Q = M k_Q N_{d,w}^{60Co} \\
M = M_{raw} P_{ion} P_{pol} P_{elec} P_{TP} \\
P_{ion} = \frac{1 - V_H/V_L}{M_{raw}^H/M_{raw}^L - V_H/V_L}
\]

\[
P_{pol} = \frac{|M_{raw}^- - M_{raw}^+|}{M_{raw}^+ - M_{raw}^-} \\
P_{TP} = \frac{273.2 + T}{273.2 + 22.0} \frac{760}{P}
\]

\[D_w^Q = \text{dose to water for beam of quality } Q \text{ determined by } \%dd(10)\]

\[M = \text{uncorrected chamber reading} \]

\[k_Q = \text{quality conversion factor} \]

Correction factors: \(P_{ion} = \text{recombination} \quad P_{pol} = \text{polarity} \quad P_{elec} = \text{electrometer} \quad P_{TP} = \text{temperature-pressure} \)

### Electron Beams: energies between 4 and 50MeV

\[
D_w^Q = M k_{ecal} k_{R_{50}}^Q N_{d,w}^{60Co} \\
d_{ref} = 0.6 R_{50} - 0.1 \text{ cm}
\]

\[
p_{gr}^Q = \frac{M_{raw}(d_{ref} + 0.5 r_{cav})}{M_{raw}(d_{ref})} \\
R_{50} = \begin{cases} 1.029 l_{50} - 0.06 & 2 \leq l_{50} \leq 10 \text{ cm} \\ 1.059 l_{50} - 0.37 & l_{50} > 10 \text{ cm} \end{cases}
\]

\[
k_{ecal} = \text{photon-electron quality conversion factor (chamber dependent)} \\
k_{R_{50}}^Q = \text{electron quality conversion factor (chamber and beam energy dependent)} \\
p_{gr}^Q = \text{electron gradient correction factor} \\
d_{ref} = \text{reference depth} \\
r_{cav} = \text{cylindrical ion chamber radius} \\
R_{50} = \text{depth of 50% dose with respect to maximum} \\
l_{50} = \text{depth of 50% ionization with respect to maximum after upstream shift of 0.5r_{cav}}
\]

4.2. Cross-Calibration of Parallel Plate Chamber for Electron Dosimetry

- Determine depth of \(d_{ref}\) (cm)
- Measure charge collected with cylindrical & parallel plate chambers with measurement point at \(d_{ref}\)
- Calculate \(k_{ecal} N_{d,w}^{60Co} = (M k_{ecal} k_{R_{50}}^Q N_{d,w}^{60Co})^{cyl}/(M k_{R_{50}}^Q)^{pp}\)

4.3. Measuring Electron PDD Curves

- Measure ionization curve
- Shift curve upstream if necessary
- Correct for inverse square
- Determine average electron energy with depth
- Scale curve by stopping power ratios at each depth

5. Radiation Biology

5.1. Biological Effective Dose

\[
BED = N d \left(1 + \frac{d}{\alpha/\beta}\right) \\
N = \text{number of fractions} \\
d = \text{dose per fraction} \\
\alpha/\beta = \text{linear quadratic factors; 3 for typical tumors, 10 for normal tissue}
\]
6. Film

6.1. Optical Density

\[ OD = \log_{10} \left( \frac{l_0}{I} \right) \]

- \( OD \) = optical density
- \( l_0 \) = incident light intensity
- \( I \) = transmitted light intensity

7. Brachytherapy

7.1. TG-43 Dose Calculation Formalism

\[ D = S_k \wedge \frac{G(r, \theta)}{G(r_0, \theta_0)} g(r) F(r, \theta) \]

- \( S_k \) = air-kerma strength (U)
- \( \wedge \) = dose-rate constant at \((r_0, \theta_0)\) (cGy/U)
- \( G(r, \theta) \) = geometry factor (-)
- \( g(r) \) = radial dose function (-)
- \( F(r, \theta) \) = anisotropy function (-)
- \( r \) = radius from center of mass of source (cm)
- \( \theta \) = angle between source axis & calculation point (°)
- \( r_0 = 1 \text{cm} \quad \theta_0 = 90° \)

\[
G(r, \theta) = \begin{cases} 
1/r^2 & \text{point source approximation} \\
\beta/L r \sin \theta & \text{line source approximation}
\end{cases}
\]

- \( \beta \) = angle subtended by source (radians)
- \( L \) = length of source

\[
g(r) = \frac{\hat{D}(r, \theta_0) G(r_0, \theta_0)}{\hat{D}(r_0, \theta_0) G(r, \theta_0)}
\]

\[
F(r, \theta) = \frac{\hat{D}(r, \theta_0) G(r, \theta_0)}{\hat{D}(r_0, \theta_0) G(r, \theta_0)}
\]

A special thanks to Ryan T. Flynn, PhD for his help preparing this handout.