Brachytherapy: Sources and Dose Calculations

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Source Construction

- Source characteristics
  - Physical length
  - Active length
  - Linear intensity
  - Filtration
  - Activity
Amersham model 6711 $^{125}$I Seed

Dose Distribution - model 6711

Theragenics $^{103}$Pd Source
### List of Radionuclides

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Energy (MeV)</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radium-226</td>
<td>0.24 - 2.2</td>
<td>1600 years</td>
</tr>
<tr>
<td>Cobalt-60</td>
<td>1.25</td>
<td>5.26 years</td>
</tr>
<tr>
<td>Radon-222</td>
<td>0.78</td>
<td>3.83 days</td>
</tr>
<tr>
<td>Cesium-137</td>
<td>0.66</td>
<td>30 years</td>
</tr>
<tr>
<td>Palladium-103</td>
<td>0.021</td>
<td>17 days</td>
</tr>
<tr>
<td>Iodine-125</td>
<td>0.028</td>
<td>59.4 days</td>
</tr>
<tr>
<td>Gold-198</td>
<td>0.42</td>
<td>2.7 days</td>
</tr>
<tr>
<td>Iridium-192</td>
<td>0.47</td>
<td>73.83 days</td>
</tr>
<tr>
<td>Yttrium-90</td>
<td>Beta 2.3, Gamma 1.74</td>
<td>64 hours</td>
</tr>
<tr>
<td>Strontium-90</td>
<td>Beta 0.55</td>
<td>28 years</td>
</tr>
</tbody>
</table>

### Source Construction

- Cesium Pellet
- Cesium Wash
- Cesium Tube Source
- Iridium Wire
- Gold (Au) Seeds
- Iodine Seeds
Half - Lives

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half - Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{226}$Ra</td>
<td>1620 years</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>30 years</td>
</tr>
<tr>
<td>$^{198}$Au</td>
<td>2.7 days</td>
</tr>
<tr>
<td>$^{192}$Ir</td>
<td>73.83 days</td>
</tr>
<tr>
<td>$^{125}$I</td>
<td>59.4 days</td>
</tr>
<tr>
<td>$^{103}$Pd</td>
<td>16.97 days</td>
</tr>
</tbody>
</table>

Mean life

\[ \frac{N(t)}{N_0} = e^{-t} = e^{-\frac{t}{\lambda}} \]

\[ \lambda t = 1 \]

\[ t = T_{av} = \frac{1}{\lambda} \]

\[ T_{av} = T_{1/2} \cdot 0.693 = 1.44 \cdot T_{1/2} \]
Brachytherapy Source Strength Specification

• Sealed photon source
  – encapsulated so radioactive material can not be lost from physical or chemical stress under foreseeable circumstances. Usually double metal wall encapsulation, prevents escape of radioactive material and absorbs unwanted betas. All brachytherapy sources are sealed sources except $^{192}$Ir wire or hairpins, which have core exposed when cut. ISO considers $^{192}$Ir wire or hairpins to be a closed source.

Brachytherapy Source Strength Specification

• Mass- Early 20th century
• Activity- Early 20th century
• Apparent Activity- Mid 20th century
• Air Kerma Strength- Late 20th century

Mass

• Radium
  – Mme. Curie prepared first $^{226}$Ra standards, quantified amount by expressing mass of sample in g or mg.
Activity

• $^{226}\text{Ra}$ alpha decays to $^{222}\text{Rn}$, all photons are emitted by radon or radon daughter products.
• Radon seeds produced by collecting radon gas from decay of radium and encapsulating in gold tubing.
• Method needed to permit correlation of $^{222}\text{Rn}$ to $^{226}\text{Ra}$ clinical experience.

Activity

• Defined 1 Curie (Ci) to be the amount of radon in equilibrium with 1 g of radium.
• A 1 Ci radon seed has same activity as 1 g of radium.
• Early experiments indicated 1 Ci of radon emitted $3.7 \times 10^{10}$ alpha per second.
• 1 Ci defined as $3.7 \times 10^{10}$ disintegrations per second (d.p.s.).

Activity

• Later experiments established amount of radon in equilibrium with 1 g of radium gives $3.61 \times 10^{10}$ d.p.s.
• Curie definition remains $3.7 \times 10^{10}$ d.p.s.
• milliCurie (mCi) is $3.7 \times 10^{7}$ d.p.s.
Apparent Activity

- Apparent activity - activity of a bare source that produces the same exposure rate at calibration distance as the specified source.
- Expressed in mCi for brachytherapy.
- Particularly useful for low energy photon sources, e.g., $^{125}$I, $^{103}$Pd.

mgRaeq

- Post WWII, other reactor produced isotopes began to be used as radium substitutes in radiotherapy.
- Source strength was expressed in mCi, but also needed a method to take advantage of clinical experience with radium.
- Used mgRaeq.

mgRaeq

- mgRaeq yields same exposure rate at calibration distance as 1 mg Ra encapsulated by 0.5mm Pt.
- The exposure rate at 1 cm from 1 mg Ra(0.5mm) is 8.25R/hr.
- Exposure Rate constant ($\eta$) is
  $\eta = 8.25 \frac{(R\cdot cm^2)}{(mg\cdot hr)} - Ra(0.5 mm\ Pt)$
  $\eta = 7.71 \frac{(R\cdot cm^2)}{(mg\cdot hr)} - Ra(1.0 mm\ Pt)$
mg-hours or mgRaeq-hours

- Number of mg or mgRaeq in implant times the duration of the implant in hours

Exposure Rate Constants

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$G_x (R \cdot cm^2/mCi \cdot hr)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{226}$Ra (0.5mmPt)</td>
<td>8.25</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>3.3</td>
</tr>
<tr>
<td>$^{192}$Ir</td>
<td>4.69</td>
</tr>
<tr>
<td>$^{198}$Au</td>
<td>2.38</td>
</tr>
<tr>
<td>$^{125}$I</td>
<td>1.51</td>
</tr>
<tr>
<td>$^{103}$Pd</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Conversion - mCi to mg Ra eq

$\text{# of mg Ra eq} = \left(\frac{G_x}{G_{Ra}}\right) \times \text{# of mCi}_x$
Conversion - mCi to mg Ra eq

Examples

\(^{137}\text{Cs}\)

\[
\text{# of mg Ra eq} = \left(\frac{3.3}{8.25}\right) \times \text{# of mCi}\text{\(^{137}\text{Cs}\)}
\]

\[
= 0.4 \times \text{# of mCi}\text{\(^{137}\text{Cs}\)}
\]

\(^{192}\text{Ir}\)

\[
\text{# of mg Ra eq} = \left(\frac{4.69}{8.25}\right) \times \text{# of mCi}\text{\(^{192}\text{Ir}\)}
\]

\[
= 0.569 \times \text{# of mCi}\text{\(^{192}\text{Ir}\)}
\]

1 mCi of \(^{137}\text{Cs}\)

\[-dN / dt = 3.7 \times 10^7 \text{ dps} = \text{dN} \]

\[
\text{N} = 3.7 \times 10^7 \text{ dps} / l
\]

\[
l = \frac{0.693}{T_{1/2}} = 0.693 / \left(30 \text{ y} \times p \times 10^7 \text{ s/y}\right)
\]

\[
l = 7.36 \times 10^{-10} \text{ s}^{-1}
\]

\[
\text{N} = 5.03 \times 10^{16} \text{ atoms of } \text{\(^{137}\text{Cs}\)}
\]

\[
A_0 = 6.023 \times 10^{23} \text{ atoms per } 137 \text{ g of } \text{\(^{137}\text{Cs}\)}
\]

Mass of 1 mCi =

\[
\left(\frac{5.03 \times 10^{16}}{6.02 \times 10^{23}}\right) \times 137 = 10 \text{ mg}
\]

Dose Rate Calculation - Seeds

\[
dD/dt = A G f B_w B_s f_{an} / d^2
\]

A = activity

G = exposure rate constant

f = f-factor - R to cGy conversion factor

B_w, B_s = attenuation and scattering in tissue

B_w, B_s = attenuation and scattering for source encapsulation and self attenuation

f_{an} = anisotropy factor
Attenuation and Scattering Functions

Tissue
\[ B_{tiss} = 1 + k_r (md)^a \]
\[ B_{tiss} = a + bd + gd^2 + Dd^3 \]

Wall
\[ B_w = \exp(-mwtw) \]

Source
\[ B_s = \exp(-m_0 t_s) \]

Meisberger Coefficients

Ratio of in-water exposure to in-air exposure - Tissue attenuation/scattering

Meisberger, L.L., Keller, R., Shalek, R.J.,
Dose Rate Calculation - Linear Sources

Quantization Method - divide source into multiple point sources
Quantization Method

Dose Rate Calculation - Linear Sources
Sievert Integral
\[ \frac{dD(x, y)}{dt} = \left( \frac{\lambda_B}{L} \right) \exp(-\mu t) \sec \theta \left[ \mu \frac{L}{y} \right] \]

L = active length
y = perpendicular distance from source to calculation point
\( m = \) effective attenuation coefficient of wall
q= as defined in diagram

Sievert Integral Source Geometry
Comparison of linear source to point source

Ra filtered by 0.5 mm Pt

Linear source - Shalk & Stovall

<table>
<thead>
<tr>
<th>distance (cm)</th>
<th>cGy/mg-hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.50</td>
</tr>
<tr>
<td>0.50</td>
<td>1.00</td>
</tr>
<tr>
<td>1.00</td>
<td>1.50</td>
</tr>
<tr>
<td>1.50</td>
<td>2.00</td>
</tr>
<tr>
<td>2.00</td>
<td>2.50</td>
</tr>
<tr>
<td>2.50</td>
<td>3.00</td>
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<tr>
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<td>4.00</td>
</tr>
<tr>
<td>4.00</td>
<td>4.50</td>
</tr>
<tr>
<td>4.50</td>
<td>5.00</td>
</tr>
</tbody>
</table>

% difference between 1.5 cm Ra source and point Ra source

<table>
<thead>
<tr>
<th>distance (cm)</th>
<th>1.5 cm Ra</th>
<th>point</th>
<th>% diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>50.67</td>
<td>126.23</td>
<td>59.86%</td>
</tr>
<tr>
<td>0.50</td>
<td>20.26</td>
<td>31.51</td>
<td>35.71%</td>
</tr>
<tr>
<td>0.75</td>
<td>10.84</td>
<td>13.98</td>
<td>22.48%</td>
</tr>
<tr>
<td>1.00</td>
<td>6.67</td>
<td>7.85</td>
<td>15.05%</td>
</tr>
<tr>
<td>1.50</td>
<td>3.20</td>
<td>4.71</td>
<td>4.89%</td>
</tr>
<tr>
<td>2.00</td>
<td>1.85</td>
<td>1.95</td>
<td>4.89%</td>
</tr>
<tr>
<td>2.50</td>
<td>1.20</td>
<td>1.24</td>
<td>3.06%</td>
</tr>
<tr>
<td>3.00</td>
<td>0.83</td>
<td>0.85</td>
<td>2.38%</td>
</tr>
<tr>
<td>3.50</td>
<td>0.61</td>
<td>0.62</td>
<td>1.69%</td>
</tr>
<tr>
<td>4.00</td>
<td>0.47</td>
<td>0.47</td>
<td>0.81%</td>
</tr>
<tr>
<td>4.50</td>
<td>0.37</td>
<td>0.37</td>
<td>0.40%</td>
</tr>
<tr>
<td>5.00</td>
<td>0.30</td>
<td>0.30</td>
<td>-0.52%</td>
</tr>
</tbody>
</table>
Away & Along Tables

Young - Batho
Shalek - Stovall
Krishnaswamy

Young and Batho, British Journal of Radiology, 37, 38, 1962.

Young-Batho Source Geometry

Geometry of dose calculation for linear radium sources.
Shalek and Stovall, American Journal of Roentgenology, Radium Therapy and Nuclear Medicine, CII, 662, 1968.

ACR Standard on Brachy Physics
Manually-Loaded Temporary Implants Section IV.C.3.

An additional and independent method should be used to validate the dose calculation results of the computerized planning systems. This validation should be consistent with the written prescription and completed before 50% of the dose is delivered.

Implant Doses

- Permanent Implant
  - \( D = (dD_0/dt) T_{av} \)
- Temporary Implant with \( T_{1/2} \gg T \)
  - \( D = (dD_0/dt) T \)
- Temporary Implant with \( T_{1/2} \ not \gg T \)
  - \( D = (dD_0/dt) T_{av} [1 - \exp(-T/T_{av})] \)
  - “milliCuries destroyed”
Temporary Implant $T_{1/2}$ not $>> T$

\[ D = \frac{dD}{dt} \int_{0}^{t} \exp(-\lambda t) \, dt \]
\[ D = \frac{dD}{dt} \left[ -\{\exp(-T)/l\} \right] \]
\[ D = \frac{dD}{dt} \left[ -\{\exp(-T)/l\} + \{1/l\} \right] \]
\[ D = \frac{dD}{dt} \left[ l \{1-exp(-lT)\} \right] \]
\[ D = \frac{dD}{dt} T_{av} \{1-exp(-T/T_{av})\} \]

milliCuries destroyed

\[ D = \frac{dD}{dt} T_{av} \{1-exp(-lT)\} \]
\[ D = \frac{dD}{dt} T_{av} \{1-exp(-lT)\} \]
\[ D = \frac{dD}{dt} T_{av} - (\frac{dD}{dt} T_{av}) \]
\[ D = \frac{dD}{dt} T_{av} - (\frac{dD}{dt} T_{av}) \]

Radiation Protection

- Time
- Distance
- Shielding
### Time

Dose is proportional to exposure time

Half the time equals half the dose

### Distance

For radiation protection purposes can assume dose follows inverse square law.

Dose at 1 cm = \(4 \times \text{Dose @ 2cm}\)

= \(0.25 \times \text{Dose @ 0.5cm}\)

### Photon Energies

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Energies (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{226})Ra</td>
<td>0.047 - 2.45 (ave 0.83)</td>
</tr>
<tr>
<td>(^{137})Cs</td>
<td>0.662</td>
</tr>
<tr>
<td>(^{192})Ir</td>
<td>0.136 - 1.06 (ave 0.38)</td>
</tr>
<tr>
<td>(^{198})Au</td>
<td>0.412</td>
</tr>
<tr>
<td>(^{125})I</td>
<td>0.0274 - 0.0355 (ave 0.028)</td>
</tr>
<tr>
<td>(^{103})Pd</td>
<td>0.0201, 0.023 (ave 0.021)</td>
</tr>
</tbody>
</table>
### Half-Value Layers

<table>
<thead>
<tr>
<th>Isotope</th>
<th>HVL (mm of Pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{226}$Ra</td>
<td>8.0</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>5.5</td>
</tr>
<tr>
<td>$^{192}$Ir</td>
<td>2.5</td>
</tr>
<tr>
<td>$^{198}$Au</td>
<td>2.5</td>
</tr>
<tr>
<td>$^{125}$I</td>
<td>0.025</td>
</tr>
<tr>
<td>$^{103}$Pd</td>
<td>0.008</td>
</tr>
</tbody>
</table>

### Radiation Protection Example $^{125}$I Calculation

Assume $^{125}$I prostate implant 10 cm to patient surface, 50 mCi total activity, tissue attenuates 95% of dose at 10 cm (5% transmission).

\[
\frac{dX_{\text{surface}}}{dt} = 1.51 \times 50 \times \left(\frac{1}{10}\right)^2 \times 0.05 = 38 \text{ mR/hr}
\]

\[
\frac{dX_{\text{1m}}}{dt} = 38 \text{ mR/hr} \times \left(\frac{10}{100}\right)^2 = 0.4 \text{ mR/hr}
\]

### AAPM Task Group 43

Task Group 43

• Incorporates latest data
• Incorporates SI units
  – Becquerel (Bq)
    • 1 Bq = 1 d.p.s = 2.7*10^{-11} Ci

  – Air Kerma Strength (U)
    • 1 U = 1 mGy m^2/hr = 1 cGy cm^2/hr

Becquerel

• 1 Bq = 1 d.p.s.
• 1 Bq = 2.7*10^{-11} Ci = 2.7*10^{-8} mCi
• SI unit
• “21st century Activity”

Task Group 43

Line source
\( \frac{dD(r,q)}{dt} = S_L \left[ \frac{G_s(r,q)}{G_s(r_0,q_0)} \right] g_s(r) F(r,q) \)

Point source
\( \frac{dD(r,q)}{dt} = S_L \left[ \frac{G_p(r,q)}{G_p(r_0,q_0)} \right] g_p(r) F(r,q) \)
### Air Kerma Strength

\[ S = \frac{dK}{dt}d^2, \quad U \]

1 U = 1 mGy m²/h = 1 cGy cm²/h

Brachytherapy source strength specified in terms of air kerma rate at a point in air along the perpendicular bisector of the source. Product of air kerma rate times distance (usually 1 meter) to point.

### Kerma

- **Kinetic Energy**
- **Released to Material**

### Kerma

- Indirectly ionizing radiations (photons and neutrons) deposit energy through two step process:
  - 1st step: photon or neutron releases kinetic energy to medium through interactions with electrons (photons) or nuclei (neutrons), *kerma*
  - 2nd step: kinetic energy released is deposited downstream (collisional kerma), *dose*, or re-irradiated as bremsstrahlung (radiative kerma)
Kerma

- Kerma created by photons interacting with air.
- At brachytherapy energies, amount of energy re-irradiated as bremsstrahlung is essentially zero.
- **Air Kerma**
  - \( K = X(W/e) \)
  - \( X \) = exposure
  - \( (W/e) \) = average energy to create an ion pair

Air Kerma

- SI unit
- “21st century Exposure”
Air Kerma Strength

\[ K = X(W/e)\left(\frac{m_{in}/r}{m_{en}/r}\right) \]

\[ m_{en}/r = (m_{in}/r)(1-g) \]

\[ g = 0 \]

\[ K = X(W/e) \]

\[ S_k = \frac{(dX(r)/dt)(W/e)d^2}{(dX(R/h)/dt)(0.876 \text{ cGy}/R)(1\text{m}^2)} \]

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Air Kerma Strength

- Product of air kerma rate times distance squared, usually 1 m, to point of specification.
- \( S_k = (dK(r)/dt)r^2 \), units are in U
  - 1U = 1 mGy \cdot m^2/hr or 1 cGy \cdot cm^2/hr
- AAPM task group 43 protocol specifies air kerma strength on perpendicular bisector of source at 1cm

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Air Kerma Strength

- 1U = \( (dK(r)/dt)r^2 \)
- 1U = \( (dX(r)/dt)(W/e)r^2 \)
- 1U = \( (dX(r)/dt)(0.876 \text{ cGy}/R)r^2 \)
- Example - \(^{226}\text{Ra}\)
  - 1mg \(^{226}\text{Ra}\)(0.5mm Pt)
    \[ = [8.25 \text{ (R-cm}^2/\text{mg-hr})](0.876 \text{ cGy}/R)r^2 \]
    \[ = 7.227 \text{ cGy cm}^2/\text{hr} = 7.227 \text{ mGy m}^2/\text{hr} \]
    \[ = 7.227U \]
  - 1U = 0.138 mg Ra (0.5mm Pt)
Air Kerma Strength Conversions

1 mGy m²/h
= 0.348 mCi for ¹³⁷Cs
= 0.243 mCi for ¹⁹²Ir
= 0.486 mCi for ¹⁹⁸Au
= 0.787 mCi for ¹²⁵I
= 0.773 mCi for ¹⁰³Pd

Total Reference Air Kerma - TRAK

- Reference Air Kerma Rate is air kerma rate at 1 m in units of mGy/hr
- European nomenclature for quantity numerically equal to Air Kerma Strength (mGy·m²/hr)
- RAKR times the duration of the implant is
  - Total Reference Air Kerma - mGy @ 1 m
  - “21st century mg-hrs”

Dose Rate Constant

L = (dD(r₀, q₀)/dt)/Sₖ

Dose rate to water at a point along perpendicular bisector of source 1 cm from the source for source strength of 1U.
**Geometry Factor**

\[ G_p(r, q) = \frac{1}{r^2} \quad \text{point source} \]

\[ G_l(r, q) = \frac{b}{L \; r \; \sin q} \quad \text{line source if } q \text{ not } 0^\circ \]

\[ G_l(r, q) = \frac{1}{(r^2 - \frac{L^2}{4})} \quad \text{line source if } q = 0^\circ \]

\( L = \text{active length} \)

\( b = q_2 - q_1 \) in radians

Accounts for variation in relative dose due to distribution of activity within the source, ignoring photon absorption and scattering.

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**Derivation of Geometry Factor**

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**TG43 Source Geometry**

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Sievert Integral Source Geometry

Geometry of dose calculation for linear radium sources.

Comparison Sievert to TG 43

Graph showing comparison between Sievert and TG 43.
5 cm Active Length Source Geometry Factor

<table>
<thead>
<tr>
<th>r (cm)</th>
<th>0.000</th>
<th>0.200</th>
<th>0.400</th>
<th>0.600</th>
<th>0.800</th>
<th>1.200</th>
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<tbody>
<tr>
<td>0.050</td>
<td>0.100</td>
<td>0.500</td>
<td>1.099</td>
<td>4.000</td>
<td>3.641</td>
<td></td>
</tr>
<tr>
<td>0.175</td>
<td>0.875</td>
<td>0.564</td>
<td>1.306</td>
<td>2.315</td>
<td></td>
<td></td>
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<tr>
<td>0.225</td>
<td>1.125</td>
<td>0.408</td>
<td>0.790</td>
<td>1.936</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.250</td>
<td>1.250</td>
<td>0.354</td>
<td>0.640</td>
<td>1.806</td>
<td></td>
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<tr>
<td>0.275</td>
<td>1.375</td>
<td>0.311</td>
<td>0.529</td>
<td>1.702</td>
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<td></td>
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<tr>
<td>0.350</td>
<td>1.750</td>
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<td>0.327</td>
<td>1.488</td>
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<td></td>
</tr>
<tr>
<td>0.400</td>
<td>2.000</td>
<td>0.179</td>
<td>0.250</td>
<td>1.395</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.475</td>
<td>2.375</td>
<td>0.137</td>
<td>0.177</td>
<td>1.298</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.525</td>
<td>2.625</td>
<td>0.116</td>
<td>0.145</td>
<td>1.251</td>
<td></td>
<td></td>
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Point Source Radial Dose Functions

\[ g(r) = \frac{(dD(r,\theta,\phi)/dt)G_x(r,\theta,\phi)/ (dD(r,\theta,\phi)/dt)G_x(r,\theta,\phi)}{q} \]

\( X \) is P or L depending if a point or line source geometry function

Accounts for the effects of absorption and scatter in tissue in the transverse plane of the source. Similar in concept to Meisberger technique, but radial dose function is normalized at 1 cm.
Relative Dose vs Distance

All isotopes normalized at 1 cm

0.001
0.01
0.1
1
10
100

0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0

distance (cm)

relative dose

I-125(6711)
I-125(6702)
Pd-103
Ir-192

Anisotropy Function

\[ F(r, q) = \frac{(dD(r, q)/dt) \cdot G(r, q_0)}{(dD(r, q_0)/dt) \cdot G(r, q)} \]

Accounts for anisotropy of dose distribution around the source, including effects of absorption and scatter in medium, i.e., self filtration in source, oblique filtration in walls, scattering and absorption in tissue

Anisotropy Factor

The ratio of dose rate at distance r, averaged with respect to solid angle, to dose rate on perpendicular bisector at same distance, \( f_{an}(r) \). Valid for randomly oriented point sources.
<table>
<thead>
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<th>Anisotropy Constant</th>
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<td>Anisotropy factor, ( f_{an}(r) ), averaged over distance yields anisotropy constant ( f_{an} ). Used at all distance and angles for point sources considered in Task Group 43 report. Anisotropy constant not recommended by TG43 update.</td>
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