Radioactivity

Lecture 7
Dosimetry and Exposure Limits
Radiation Exposure - Radiology

The radiation impact on biological and genetic materials requires some protective measures!
Units for scaling the decay

Classical Unit: 1 Curie [Ci]

$$1 [Ci] = \frac{dN}{dt} = 3.7 \cdot 10^{10} \left[ \frac{\text{decays}}{s} \right]$$

Modern Unit: 1 Becquerel [Bq]

$$1 [Bq] = \frac{dN}{dt} = 1 \left[ \frac{\text{decay}}{s} \right]$$

The so-called dosimetry units (rad, rem) determine the amount of damage radioactive radiation can do to the human body. They depend on the kind and nature of the incident radiation (X-rays, γ-rays, α-particles, β-particle, or neutrons). It also depends on the energy loss of the particular radiation and the associated ionisation effects in the human body material.
Refresher example

You have a radioactive sample that emits one alpha particle per second. What is the activity of the sample in Bq and in Ci?

\[
\frac{dN}{dt} = 1 \left[ \frac{\text{decay}}{s} \right] = 1 \text{[Bq]}
\]

\[
1 \text{[Ci]} = \frac{dN}{dt} = 3.7 \cdot 10^{10} \left[ \frac{\text{decays}}{s} \right] = 3.7 \cdot 10^{10} \text{[Bq]}
\]

\[
1 \text{[Bq]} = \frac{1}{3.7 \cdot 10^{10}} \text{[Ci]} = 2.7 \cdot 10^{-11} \text{[Ci]}
\]

The nature of the radiation doesn’t make any difference on the activity!
Long lived $^{40}\text{K}$ radioactivity

$^{40}\text{K}$ has a half-life of $T_{1/2} = 1.28 \cdot 10^9$ years its natural abundance is 0.021 % of the elemental potassium abundance.

Potassium-Argon dating method

$^{40}\text{K}$ → $^{40}\text{Ar}$, $^{40}\text{Ca}$

$\beta^+ + \beta^- + \gamma$ 1.46 MeV

Potassium Concentrations

Source of data: U.S. Geological Survey Digital Data Series DDS-9, 1993
40K in Human Body

The human body contains ~ $7 \cdot 10^{20}$ radioactive $^{40}$K particles, $T_{1/2} = 1.25 \times 10^9$ y. What is the activity in Becquerel and Curie?

$$A(t) = \lambda \cdot N(t)$$

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.69}{1.25 \cdot 10^9 \text{[y]}} = \frac{0.69}{1.25 \cdot 10^9 \cdot 3.14 \cdot 10^7 \text{[s]}} = 1.53 \cdot 10^{-17} \text{[s}^{-1}]$$

$$A = 1.53 \cdot 10^{-17} \text{[s}^{-1}] \cdot 7 \cdot 10^{20} = 10700 \text{[s}^{-1}] = 10700 \text{[Bq]}$$

$$A = 10700 \text{[Bq]} = \frac{1.07 \cdot 10^4}{3.7 \cdot 10^{10}} \text{[Ci]} = 2.9 \cdot 10^{-7} \text{[Ci]} = 0.3 \text{[\mu Ci]}$$
Radiological Units

Amount of energy $E$ deposited by radiation into body part of mass $m$.  

**Dose:** 

$$D = \frac{E}{m}$$

*Unit Rad or Gray*

Radiation independent dose 

$$H = Q \cdot D$$

*Unit Rem or Sievert*

1 Gy = 1 J/kg; 1 rad = 0.01 Gy = 0.01 J/kg
Biological Impact Measures

Each kind of radiation has a different impact on body material through the kind of physical interaction during the stopping of the radiation and the amount of energy transferred to biological system. Each kind of radiation has a specific weighting factor $Q$ to determine the equivalent dose:

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>1</td>
</tr>
<tr>
<td>Neutrons: $E&lt;10$keV</td>
<td>5</td>
</tr>
<tr>
<td>Neutrons: $E&gt;10$keV</td>
<td>15</td>
</tr>
<tr>
<td>Protons</td>
<td>5</td>
</tr>
<tr>
<td>Alphas</td>
<td>20</td>
</tr>
</tbody>
</table>

In radiology, in particular for medical applications, this is refined by the introduction of body-part specific weighting factors for the different kind of radiation particles or waves!
**Equivalent Dose to Effective Dose**

\[ H = Q \cdot D \quad E = \sum W_T \cdot D \]

---

**Ionising radiation - Protection Dose quantities in SI units**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>SI unit or modifier</th>
<th>Derivation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorbed dose (D_T)</td>
<td>gray (Gy)</td>
<td>joule/kg</td>
<td>Energy absorbed by irradiated sample of matter - a physical quantity.</td>
</tr>
<tr>
<td>Radiation weighting factor - (W_R)</td>
<td></td>
<td>Dimensionless factor</td>
<td></td>
</tr>
<tr>
<td>Equivalent dose (H_T)</td>
<td>sievert (Sv)</td>
<td>joule/kg</td>
<td>Biological effect of radiation type (R) with weighting factor (W_R). Multiple radiation types require calculation for each, which are then summed.</td>
</tr>
<tr>
<td>Tissue weighting factor - (W_T)</td>
<td></td>
<td>Dimensionless factor</td>
<td>Biological effect on tissue type (T) having weighting factor (W_T). Particular irradiation. Effective dose = summation of organ doses to those parts irradiated. Complete (uniform) irradiation. If whole body irradiated uniformly, the weightings (W_T) summate to 1. Therefore, Effective dose = Whole body Equivalent dose.</td>
</tr>
<tr>
<td>Effective dose (E)</td>
<td></td>
<td>joule/kg</td>
<td></td>
</tr>
</tbody>
</table>
# Weighting Factors

## Tissue Weighting Factors (ICRP 60)

<table>
<thead>
<tr>
<th>Organ or Tissue</th>
<th>$W_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonads</td>
<td>0.20</td>
</tr>
<tr>
<td>Red bone marrow</td>
<td>0.12</td>
</tr>
<tr>
<td>Colon</td>
<td>0.12</td>
</tr>
<tr>
<td>Lung</td>
<td>0.12</td>
</tr>
<tr>
<td>Stomach</td>
<td>0.12</td>
</tr>
<tr>
<td>Bladder</td>
<td>0.05</td>
</tr>
<tr>
<td>Breast</td>
<td>0.05</td>
</tr>
<tr>
<td>Liver</td>
<td>0.05</td>
</tr>
<tr>
<td>Oesophagus</td>
<td>0.05</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.05</td>
</tr>
<tr>
<td>Skin</td>
<td>0.01</td>
</tr>
<tr>
<td>Bone surface</td>
<td>0.01</td>
</tr>
<tr>
<td>Remainder</td>
<td>0.05(^2,3)</td>
</tr>
</tbody>
</table>
Dose units in Radiology

The Sievert (Gray) is a measure of biological effect.

1 Gray (Gy) = 1 Joule/kg  (Energy/mass)

1 Sievert (Sv) = 1 Gray x Q, where Q is a "quality factor" based on the type of particle.
  Q for electrons, positrons, and x-rays = 1
  Q = 3 to 10 for neutrons, protons dependent upon the energy transferred by these heavier particles.
  Q = 20 for alpha particles and fission fragments.

Converting older units:

1 rad = 1 centigray = 10 milligrays ( 1 rad = 0.01 Gy = 10 mGy )

1 Gy = 100 rad

1 rem = 1 centisievert = 10 millisieverts ( 1 rem = 0.01 Sv = 10 mSv )

1 Sv = 100 rem

Nominal background radiation absorbed dose of 100 mrad/year = 1 mGy/yr.
Nominal background radiation dose biological equivalent of 100 mrem/year = 1mSv/yr.
Occupational whole body limit is 5 rem/yr = 50 mSv/yr.
2.5 mrem/hr or 25 uSv/hr is maximum average working level in industry.

Exposure rate from Naturally Occurring Radioactive Material; an empirically derived conversion factor for Ra-226 decay series:  1.82 microR/ hour = 1 picoCurie/gram.
### Annual Average Total Effective Dose Equivalent to the U.S. Population

<table>
<thead>
<tr>
<th>Source</th>
<th>Value (mrem)</th>
<th>Conversion (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Background, Radon</td>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>Cosmic and Terrestrial source</td>
<td>56</td>
<td>0.6</td>
</tr>
<tr>
<td>Medical and Dental X-Rays</td>
<td>54 (+~100)</td>
<td>0.55</td>
</tr>
<tr>
<td>Internal Source, $^{40}$K</td>
<td>40</td>
<td>0.4</td>
</tr>
<tr>
<td>Tobacco Smoking</td>
<td>280</td>
<td>2.8</td>
</tr>
<tr>
<td>Other Consumer Products</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total, All Population</strong></td>
<td><strong>640</strong></td>
<td><strong>6.4</strong></td>
</tr>
<tr>
<td><strong>Total, Non-Smokers</strong></td>
<td><strong>360</strong></td>
<td><strong>3.6</strong></td>
</tr>
</tbody>
</table>
Radiation doses and regulatory limits
(in mRem= 0.001Rem= 0.00001 Sv 0.01mSv= 10μSv)

Annual Nuclear Worker Dose Limit (NRC): 5,000 mSv = 50 mSv
Whole Body CT: 1,000 mSv = 10 mSv
Average U.S. Annual Dose: 620 mSv = 6 mSv
U.S. Avg. Natural Background Dose: 310 mSv = 3 mSv
Annual Public Dose Limit (NRC): 100 mSv
From Your Body: 40 mSv
Cosmic Rays: 30 mSv
Chest X-Ray: 10 mSv
Safe Drinking Water Limit (EPA): 4 mSv
Trans-Atlantic Flight: 2.5 mSv
## Comparing the Risks: Radiation, Smoking, and Driving

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Dose</th>
<th>Chance of Death</th>
<th>Equivalent to</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Number of</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cigarettes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Smoked</td>
</tr>
<tr>
<td>Bone Marrow From Leukemia</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{131}$I treatments for thyrotoxicosis</td>
<td>15 rem</td>
<td>$3 \times 10^{-4}$</td>
<td>2200.0</td>
</tr>
<tr>
<td>Chest radiograph</td>
<td>10 mrem</td>
<td>$2 \times 10^{-7}$</td>
<td>1.5</td>
</tr>
<tr>
<td>Skull examination</td>
<td>78 mrem</td>
<td>$1.6 \times 10^{-6}$</td>
<td>11.4</td>
</tr>
<tr>
<td>Barium enema</td>
<td>875 mrem</td>
<td>$17.5 \times 10^{-6}$</td>
<td>128.0</td>
</tr>
</tbody>
</table>

A full set of dental X-rays using a high energy X-ray machine and E-speed film has a relative cancer risk equivalent to that of smoking ~2-3 cigarettes.
Internal $\gamma$ Glowing from $^{40}\text{K}$

On average, 0.27% of the mass of the human body is potassium K of which 0.021% is radioactive $^{40}\text{K}$ with a half-life of $T_{1/2}=1.25 \cdot 10^9$ [y]. Each decay releases an average of $E_{\text{avg}} = 0.5$ MeV $\beta$- and $\gamma$-radiation, which is mostly absorbed by the body but a small fraction escapes the body.

Calculate, how many radioactive $^{40}\text{K}$ atoms are in your body system!
$^{40}\text{K}$ in your body

- mass of the body: $m_{\text{body}}$
- mass of potassium K in the body: $m_K = 0.0027 \cdot m_{\text{body}}$
- mass of radioactive $^{40}\text{K}$ in the body: $m_{^{40}\text{K}} = 0.00021 \cdot m_K = 5.67 \cdot 10^{-7} \cdot m_{\text{body}}$

40 g of $^{40}\text{K} \equiv 6.023 \cdot 10^{23}$ atoms

$$m_{^{40}\text{K}} = 5.67 \cdot 10^{-7} \cdot m_{\text{body}} \quad [\text{g}] = \frac{6.023 \cdot 10^{23} \cdot 5.67 \cdot 10^{-7} \cdot m_{\text{body}}}{40} \quad [\text{particles}] = N_{^{40}\text{K}}$$

$$\frac{N_{^{40}\text{K}}}{m_{\text{body}}} = 8.54 \cdot 10^{15} \quad [\text{particles / g}]$$

to calculate $N_{^{40}\text{K}}$, you need the body mass $m_{\text{body}}$ in gramm.

for 80 kg body: $N_{^{40}\text{K}} = 6.83 \cdot 10^{20} \quad [\text{particles}]$
Calculate the absorbed body dose over an average human lifetime of $t = 70 \text{ y}$ for this source of internal exposure.

* **Dose:** \[ D = \frac{E_{\text{absorbed}}}{m_{\text{body}}} = t \cdot A^{(40\text{K})} \cdot \frac{E_{\text{avg}}}{m_{\text{body}}} \]

* **Activity:** \[ A^{(40\text{K})} = \lambda \cdot N^{40\text{K}} = \ln 2 / T_{1/2} \cdot N^{40\text{K}} \]

\[
D = 70 \text{[y]} \cdot \frac{\ln 2}{1.25 \cdot 10^9 \text{[y]}} \cdot (8.54 \cdot 10^{15} \text{[g}^{-1}] \cdot m_{\text{body}}) \cdot \frac{0.5 \text{[MeV]}}{m_{\text{body}}}
\]

\[
D = 1.66 \cdot 10^{11} \text{[MeV/kg]} = 2.63 \cdot 10^{-2} \text{[J/kg]} = 2.63 \cdot 10^{-2} \text{[Gy]}
\]

**with:** \[ 1\text{[eV]} = 1.602 \cdot 10^{-19} \text{[J]} \]
Exposure to other natural or man-made radioactivity

Tobacco contains $\alpha$-emitter $^{210}$Po with $T_{1/2}=138.4$ days. Through absorption in bronchial system smoking adds 280 mrem/year to the annual dose of US population.

Medical radioactivity

\[ \frac{D}{h} = \frac{3000 \mu R}{3600s} = \frac{3000 \cdot 10^{-6} \cdot 10^{-2} Gy}{3600s} = 8.33 \cdot 10^{-9} \frac{Gy}{s} = \frac{0.511 \text{MeV}}{60kg} \cdot A = \frac{0.511 \cdot 1.602 \cdot 10^{-13} J}{60kg} \cdot A = 1.36 \cdot 10^{-15} \text{Gy} \cdot A \]

\[ 8.33 \cdot 10^{-9} \frac{Gy}{s} \cdot A = 6.11 \cdot 10^6 Bq = 6.11 \text{MBq} \]

\[ N(^{18}F) = \frac{A}{\lambda(^{18}F)} = \frac{A}{\ln 2} \cdot T_{1/2}(^{18}F) = \frac{6.11 \cdot 10^6}{\ln 2} \cdot 109.7 \cdot 60s = 5.8 \cdot 10^{10} \cdot 18F \]

\[ M(^{18}F) = N(^{18}F) \cdot \frac{18g}{6.022 \cdot 10^{23}} = 1.7 \cdot 10^{-12} g = 1.7 pg \]

Certainly much more ... taken about 4 hours after infusion and distributed via blood flow over entire body.
Developments

1980-1982
Medical Radiation: 0.53 mSv per capita per year
Non-medical Radiation: 3.1 mSv per capita per year
Cardiovascular Radiation Collective Effective Dose: 6,700 person-Sv
Medical Radiation Collective Effective Dose: 123,000 person-Sv

2006
Medical Radiation: 3.0 mSv per capita per year
Non-medical Radiation: 3.2 mSv per capita per year
Cardiovascular Radiation Collective Effective Dose: 356,000 person-Sv
Medical Radiation Collective Effective Dose: 899,000 person-Sv