The Relevance of Dose for Low-Energy Beta Emitters

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EU Scientific Seminar
Emerging Issues on Tritium and Low Energy Beta Emitters
Luxembourg, 13 November 2007
OUTLINE

Introductory comments on dose, radiation quality and RBE

ICRP system

Some issues for this symposium

Beta-decay of radionuclides
  Low-energy beta emitters

Unusual features of low-energy beta emitters

A few additional comments

Conclusions and recommendations
Introductory comments on ‘Dose’ (and radiation quality)

Absorbed Dose

- **Physical** quantity, precisely defined, no changeable parameters
- Absorbed dose is the quotient of deby $dm$, where $de$ is the mean energy imparted to matter of mass $dm$.
- Absorbed dose = Deposited Energy ÷ Mass $D = \frac{de}{dm}$
- Units: joule per kilogram = **gray** (Gy)

- Independent of type (quality) of ionizing radiation
- Approximately proportional to the average density of ionizations in the mass (volume) of interest

**BUT** **biological** effectiveness of a given absorbed dose depends on many additional factors, including:

- Type of radiation (i.e. radiation quality)
- Dose rate, dose fractionation
- Particular biological system, effect and level of interest
This symposium is particularly concerned with radiation quality

- of tritium ($^3$H) and other low-energy beta emitters, that is, with low energy electrons;

- and comparison with reference radiations, that is, mixed high- and low-energy electrons from gamma-rays or orthovoltage X-rays;

Also some additional special features of these beta emitters.

**Radiation quality**

Determined by the *track structure* of the radiation

- Microscopic features of the individual tracks
- Relationship between separate tracks, in time and space.
Low-LET reference radiation:

Sparsely ionizing on average, but \( \sim \frac{1}{4} \) of energy deposited via denser clusters of ionizations from low-energy secondary electrons (on scale of nanometres) (Magnified in diagram)

Very low dose from a single track (ave \( \sim 0.001 \) Gy to cell nucleus)

High-LET radiation:

Densely ionizing on average (especially for low-velocity ions, natural alpha-particles, etc)

High dose from a single track (\( \sim 0.2 - 0.5 \) Gy from single a-track)

LET = Linear Energy Transfer
All radiation tracks are highly structured on the scale of DNA.

**Opposing trends:** Alpha-particle has
-- low probability of hitting DNA (few tracks per Gy)
-- high probability of damage when it does hit.

Clustered ionizations from low-energy electron

Single ionization

Delta-ray electron

**Tracks in chromatin fibre**

1. Electron
   - Low LET tracks
2. Alpha-particle
   - High-LET track
   - ~25 nm
hprt mutation-induction by alpha-particles compared to X-rays in V79 cells

In general, biological effectiveness depends on:
--- radiation quality
--- dose
--- dose-rate
--- biological system

Relative Biological Effectiveness (RBE) of alpha-particles in this system is

\[ \text{Dose B} \approx 8 \text{ Dose A} \]

Example:

Relative Biological Effectiveness for Cell Inactivation by Ionizing Radiations

Goodhead, IJRB 65, 7-17 (1994)
Schematic dose responses for radiation risks

LET = Linear Energy Transfer
RBE\textsubscript{m} = Relative Biological Effectiveness (maximum)
w\textsubscript{R} = Radiation weighting factor
DDREF = Dose and Dose-Rate effectiveness Factor

Mod from Goodhead, Adv Radiat Biol 16, 7 (1992)
ICRP system developed for radiation protection

Dosimetry/risk system based on

- **Absorbed dose** \( (D_T) \) to each tissue or organ  
  (ie physical dose)  

- but with ‘subjective’ prescribed weighting factors for approximate dependence of human risks:

  1. **weighting for radiation quality:**  
     Equivalent dose to a tissue,  
     \[ H_T = S_R \cdot (w_R \cdot D_{T,R}) \]  
     Units: sievert (Sv) = J/kg

  2. **weighting also for tissue sensitivity:**  
     Effective dose to whole body,  
     \[ E = S_T \cdot (w_T \cdot H_T) \]  
     \[ = S_{T,R} \cdot (w_T \cdot w_R \cdot D_{T,R}) \]  
     Units: sievert (Sv) = J/kg
1. Primary ICRP risk estimates:

Risk per Gy from epidemiological data (mostly external, low LET; A-bomb, medical) (DDREF=2) \( \div W_R (= 1 \text{ low LET}; = 20 \text{ alphas}) \)

Nominal risk probability coefficients for cancer (and hereditary disease) for tissues and whole body (Sv\(^{-1}\))

\( = W_T \) (as 4 groups)

2. Hence, **Estimated** Risk for external radiation exposures:

Absorbed dose to tissues (Gy/Bq) \( \times W_R \)

Equivalent dose to tissues (Sv)

Nom. risk prob. coefft for tissue (Sv\(^{-1}\)) \( \times \)

Risk to Tissue

Effective dose to body (Sv) \( \times W_T \)

Nom. risk prob. coefft for body (Sv\(^{-1}\)) \( \times \)

Risk to Whole Body

For radiation protection, limits are set in terms of effective dose (or equivalent dose) as surrogates for whole-body risk (or tissue risk).

**Comment:** Complex, yet crude, system to achieve additivity of risk from all exposures; Convenient for rough planning purposes in radiological protection.
1. Primary ICRP risk estimates:

- **Epi data** (mostly external, low LET; A-bomb, medical)

  \[ x \ W_R \left(=1 \text{ low LET}; \right. \]
  \[ = 20 \text{ alphas} \]

  Nominal risk probability coefficients for cancer (and hereditary) \( (Sv^{-1}) \)

\[ = W_T \]

(as 4 groups)

2. ICRP Dose Coefficients for internal radionuclides:

(i.e. Dose per unit intake)

- Biokinetic models (intake ? tissues)
- Dosimetric models (decays ? absorbed dose)

  \[ x \ W_R \left(=1 \text{ low LET}; \right. \]

  Absorbed dose to tissues \( (\text{Gy/Bq}) \)

  \[ x \ W_R \left(=1 \text{ low LET}; \right. \]

  Equivalent dose to tissues \( (\text{Sv/Bq}) \)

  \[ S \times W_T \left(=1 \text{ low LET}; \right. \]

  Effective dose to body \( (\text{Sv/Bq}) \)

3. Hence, Estimated Risk from internal radionuclide exposure:

- Estimated intake \( (\text{Bq}) \) (ingestion, inhalation, absorption)

  \[ x \]

  Tissue dose coefft \( (\text{Sv/Bq}) \)

  \[ x \]

  Nom. risk prob. coefft for tissue \( (\text{Sv}^{-1}) \)

  \[ \rightarrow \]

  Risk to Tissue

- Body dose coefft \( (\text{Sv/Bq}) \)

  \[ x \]

  Nom. risk prob. coefft for body \( (\text{Sv}^{-1}) \)

  \[ \rightarrow \]

  Risk to Whole Body

For radiation protection, limits are set in terms of effective dose (or equivalent dose) as surrogates for whole-body risk (or tissue risk)

**Comment:** Complex, yet crude, system to achieve additivity of risk from all exposures; Convenient for rough planning purposes in radiological protection.
Hence, effective dose is used

- as primary quantity for dose-limits in radiation protection
  --- for prospective dose assessment, optimization and for demonstrating compliance

- as surrogate for risk (within the broad approximations of the ICRP system)

- for simple additivity of doses (and implied risks) from low-dose exposure scenarios, including
  - non-uniform irradiation of body or tissues
  - mixed radiation qualities
  - internal and external radiation sources
  - any temporal distributions of dose
    (i.e. dose-rate and dose fractionations)

Effective dose is not suitable for

- more accurate retrospective assessments of individual doses and risks

- use in epidemiological studies

- probability of causation in exposed individuals

[ICRP draft recommendations, Jan 2007]
Issues for this symposium could include:

- Appropriateness of ICRP specification of $w_R = 1$ for ALL photon and electron irradiations, including for low-energy beta emitters

- Under what circumstances should this value be used?
  (e.g. prospective planning and routine records in radiation protection when doses are well below dose limits, ....)

- What values of RBE should be used for particular low-energy beta-emitters when more accurate dose or risk assessments are required?
  (e.g. retrospective dose/risk assessments, prospective assessments/planning if approaching dose limits, epidemiology, compensation, litigation, ...)

- What other factors, in addition to radiation quality, may require consideration for particular low-energy beta-emitters?
  (e.g. non-uniformity of absorbed dose to target cells within a tissue, to critical sub-cellular components, ...)

- Appropriateness of ICRP $w_T$ values for ALL radiations, including low-energy beta emitters?
**ICRP-prescribed values of radiation weighting factor**

<table>
<thead>
<tr>
<th>Radiation type and energy range</th>
<th>Prescribed $w_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ICRP(1991)</strong></td>
<td>(ICRP2007 draft)</td>
</tr>
</tbody>
</table>
| Photons, all energies                                               | 1                | 1
| Electrons and muons, all energies                                   | 1                | 1
| Neutrons, energy $< 10$ keV                                         | 5                |
| 10 keV to 100 keV                                                   | 10               |
| $>100$ keV to 2 MeV                                                 | 20               |
| $>2$ MeV to 20 MeV                                                  | 10               |
| $>20$ MeV                                                           | 5                |
| Protons, other than recoil protons, $>2$ MeV                       | 5                | 2
| alpha particles, fission fragments, heavy nuclei                   | 20               | 20

★ Implies equal risk per unit effective dose to body
per unit equivalent dose to a tissue
per unit absorbed dose to a tissue

For **ALL** photon and electron irradiations

ICRP treats: absorbed dose from low-energy beta emitters (few keV)
*exactly as if* from orthovoltage X-rays (~100 keV)
or from high-energy gamma-rays (~1 MeV).
Beta decay of radionuclides:

Electron emission ($\beta^-$ decay):

$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + ^{0}_{-1}e + ^{0}_{0}\bar{\nu}$$

Positron emission ($\beta^+$ decay):

$$^{A}_{Z}X \rightarrow ^{A}_{Z-1}Y + ^{0}_{+1}e + ^{0}_{0}\nu$$

[where $\nu$ is neutrino]

Tritium $\beta^-$ decay:

$$^3_{1}H \rightarrow ^3_{2}He + e^- + \bar{\nu}$$

Electron emission spectrum:

- $E_{max} = 18.6$ keV
- $E_{ave} = 5.7$ keV
Some relevant low-energy beta\(^-\) -emitting radionuclides:

<table>
<thead>
<tr>
<th>(\beta^-)-decay</th>
<th>Electron energy (keV)</th>
<th>Electron range (µm)</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Average</td>
<td>Max</td>
</tr>
<tr>
<td>(^3)H \rightarrow (^3)He</td>
<td>18.6</td>
<td>5.7</td>
<td>~7</td>
</tr>
<tr>
<td>(^{14})C \rightarrow (^{14})N</td>
<td>157</td>
<td>~290</td>
<td></td>
</tr>
<tr>
<td>(^{35})S \rightarrow (^{35})Cl</td>
<td>167</td>
<td>~320</td>
<td></td>
</tr>
<tr>
<td>(^{106})Ru \rightarrow (^{106})Rh</td>
<td>39.4</td>
<td>~28</td>
<td></td>
</tr>
<tr>
<td>(^{210})Pb \rightarrow (^{210})Bi((\beta,a))</td>
<td>63.5</td>
<td>~64</td>
<td></td>
</tr>
</tbody>
</table>

Compare:

| \(^{90}\)Sr \rightarrow \(^{90}\)Y(\(\beta\)) | 546 | ~1950 |     |           | 29 y    |
| \(^{131}\)I \rightarrow \(^{131}\)Xe (+gamma) | 971 | ~4200 |     |           | 8 d     |
| \(^{137}\)Cs \rightarrow \(^{137}\)Ba (+gamma) | 1176 | ~5200 |     |           | 30 y    |
Unusual features of low-energy beta-emitters:

1) Increased average ionization density (LET)
2) Short electron tracks
3) Non-uniformity of dose
4) Cell (or nucleus) hit frequencies per unit dose (numbers of tracks)
5) Nuclear transmutations
6) Isotopic mass differences
7) Molecular forms

[8) Positron annihilation for β⁺-emitters]

Most of these features are not incorporated into conventional radiation protection dosimetry.
Average Linear Energy Transfer (LET), \( L = \frac{\text{Sum } e}{I} \)

Average energy restricted LET, \( L_{\Delta} = \frac{\text{Sum}(e<\Delta)}{I_{\text{total}}} \)

Lineal energy, \( y = \frac{\text{Sum } e}{2/3 \ d} \)
**Unusual features:**

1) Increased average ionization density on subcellular scale (by whatever measure)

### LET (Linear Energy Transfer) (keV/µm)

<table>
<thead>
<tr>
<th>LET</th>
<th>Tritium β</th>
<th>X-rays</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.7</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>[~12]</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>11.5</td>
<td>13.1</td>
</tr>
<tr>
<td>Dose-average LET</td>
<td>11.5</td>
<td>13.1</td>
</tr>
<tr>
<td>[L_{\text{inf},D}]</td>
<td>[0.31]</td>
<td></td>
</tr>
</tbody>
</table>

### Lineal energy (keV/µm)

<table>
<thead>
<tr>
<th>Site diameter</th>
<th>Frequency-mean ((\bar{y}_F))</th>
<th>Dose-mean ((\bar{y}_D))</th>
</tr>
</thead>
<tbody>
<tr>
<td>d = 5 µm</td>
<td>1.4</td>
<td>~1.7</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>~2.6</td>
</tr>
<tr>
<td>d = 1 µm</td>
<td>3.1</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td>5.0</td>
</tr>
<tr>
<td>d = 0.5 µm</td>
<td>4.1</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>7.3</td>
<td>5.4</td>
</tr>
<tr>
<td>d = 0.1 nm</td>
<td>4.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>9.2</td>
<td>-</td>
</tr>
<tr>
<td>d = 0.01 nm</td>
<td>7.8</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>18.0</td>
<td>17.7</td>
</tr>
</tbody>
</table>

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1) Increased average ionization density on subcellular scale
(by whatever measure)

**LET (Linear Energy Transfer)**

<table>
<thead>
<tr>
<th></th>
<th>Tritium β</th>
<th>X-rays</th>
<th>60Co gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track-average LET</td>
<td>4.7</td>
<td>6.3</td>
<td>1.7</td>
</tr>
<tr>
<td>$L_{100,T}$ (keV/µm)</td>
<td>11.5</td>
<td>13.1</td>
<td>9.4</td>
</tr>
<tr>
<td>Dose-average LET</td>
<td>11.5</td>
<td>13.1</td>
<td>9.4</td>
</tr>
<tr>
<td>$L_{100,D}$ (keV/µm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{\infty,D}$ (keV/µm)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Unusual features:**

Compare with protons of similar LET:

$\sim 10$ MeV protons have LET ($L_T$) = 4.7 keV/µm

For protons ICRP prescribes $w_R = 5$ (ICRP60, 1991)

$w_R = 2$ (ICRP draft recs, Jan 07)

(reduced partly on the basis of low penetration of external protons)
Two low-energy-electron tracks
(Typical of secondary e’s from X-, gamma-rays)

1 keV electron

0.5 keV electron

DNA

[ Nikjoo, Charlton, Goodhead
Electron track

300 eV electron

- = ionized molecule
- = excited molecule

2 nm

Clustered DNA damage

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Unusual features:

2) Short ranges of electrons (beta-particles)

Ranges of tritium beta-particles:

- Average: 0.56 µm
- Maximum: ~ 7 µm

Compare with:

- Typical cell diameters: ~ 7 µm to 30 µm
- Typical cell nucleus diameters: ~ 6 µm to 15 µm
- Chromatin fibre diameter: ~ 0.030 µm
- DNA diameter: ~ 0.0024 µm

Hence:

- Short range
  - does not mask increased LET of these electrons on scale of DNA and chromatin;
  - limits ability of single track to damage two distant targets on cellular scale;
  - can lead to non-uniformity of dose when emitters are inhomogeneously distributed.
3) Non-uniformity of absorbed dose

Occurs when β-emitters are non-uniformly distributed on scales of:

- tissue compartments (all low-energy β-emitters)
- individual cells (some low-energy β-emitters)
- cell compartments, eg nucleus vs cytoplasm (a few low-energy β-emitters)
- chromosomes or DNA (notably tritium)

Examples: Tritiated DNA precursors;
OBT in adipose tissue;
......
etc

NOTE: Also, mean ionization density may be increased in targets with bound tritium compared to uniform HTO. [Chen (2006): $\ddot{y}_D$ ratio ~ 1.7] Additional to enhancement of absorbed dose.
Unusual features:

4) Cell (or nucleus) hit frequencies per unit dose
   • Larger mean energy deposition by single $^3$H $\beta$ than from single track from Co gamma;

   • Hence, fewer hits from tritium than from Co gamma-rays (for equal average absorbed dose to tissue);

   • i.e. Fewer cells (or nuclei) are hit by $^3$H, but they are hit harder.

• Any consequences? (Thresholds, Dose rate)

<table>
<thead>
<tr>
<th></th>
<th>$^3$H</th>
<th>Co gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{Z}_F$ (mGy)</td>
<td>4.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Hit frequency =1/$\tilde{Z}_F$ (mGy$^{-1}$)</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>$\tilde{Z}_F$</td>
<td>1.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Hit frequency =1/$\tilde{Z}_F$ (mGy$^{-1}$)</td>
<td>0.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

For sphere d = 7 µm

For sphere d = 12 µm

where $\tilde{Z}_F =$ mean specific energy

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Unusual features:

5) Nuclear transmutation

- Molecular changes result from transmutation of β-emitting radionuclide

- Conversion of $^3$H to $^3$He loses its chemical binding in molecule
  (e.g. deprotonation in a DNA base, potentially mutagenic?
  disruption of hydrogen bonding in DNA)

- Conversion of $^{14}$C to $^{14}$N in DNA base (potentially mutagenic?)

- Conversion of $^{35}$S to $^{35}$Cl alters the biomolecule
6) Isotopic mass difference ratio compared to stable isotope

- Affects physico-chemical properties

- Mass difference is very large for $^{3}\text{H}$ compared to normal $^{1}\text{H}$, by ratio of 3
  - (e.g. affect chemical reaction rates for uptake and clearance; differential diffusion;
    ‘buried tritium’:
    - differential binding of water in hydration shell of DNA – enrichment factor 2?
    - differential binding in proteins, other macromolecules – ” ” 1.4?

- Ratios are very small for most other $\beta$-emitters
Unusual features:

7) Molecular forms

- Different molecular compounds of β-emitters can influence uptake ratios, retention times and other biokinetic parameters

- Notable forms for $^3$H include:
  -- tritiated water
  -- organically bound tritium (OBT) – exchangable
    -- non-exchangable
  -- DNA precursors
8) Positron annihilation ($\beta^+$ emitters)

\[ e^+ + e^- \rightarrow 2 \text{ gamma} \quad \text{(High energies, >0.5 MeV each)} \]

- Delocalizes energy of $\beta^+$-emitters
Unusual features of low-energy beta-emitters:

1) Increased average ionization density (LET)
2) Short electron tracks
3) Non-uniformity of dose
4) Cell (or nucleus) hit frequencies per unit dose (numbers of tracks)
5) Nuclear transmutations
6) Isotopic mass differences
7) Molecular forms

[8) Positron annihilation for $\beta^+$-emitters]

- Most of these features are not incorporated into conventional radiation protection dosimetry.
- They may be incorporated in various ways into experimental measurements of RBE
A few additional comments
Low-energy electrons are an important component for dose deposition by all low-LET radiations (X, gamma, e); But especially so for tritium $\beta$-decay.

COMPARE:
Dose fraction deposited by electrons of energies 0.1 to 5 keV from:
- Tritium $\beta$ 77 %
- 220 kV X-rays 38 %
- Co gamma rays 34 %

NOTE: Low energy electrons are more efficient at:
- producing DNA double-strand breaks (DSB)
- producing a higher proportion of complex DSB (and other clustered damage)
Electron track

300 eV electron

● = ionized molecule
● = excited molecule

2 nm

Clumped DNA damage

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## Complexity of DNA Strand Breaks

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>% No Break</th>
<th>SSB</th>
<th>SSB+</th>
<th>2SSB</th>
<th>DSB</th>
<th>DSB+</th>
<th>DSB++</th>
<th>SSB Complex</th>
<th>DSB Compl. Total</th>
<th>SS DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>73.9</td>
<td>22.4</td>
<td>1.86</td>
<td>0.09</td>
<td>1.39</td>
<td>0.27</td>
<td>0.015</td>
<td>8.0%</td>
<td>17%</td>
<td>17</td>
</tr>
<tr>
<td>0.3</td>
<td>66.4</td>
<td>26.6</td>
<td>3.29</td>
<td>0.43</td>
<td>2.38</td>
<td>0.85</td>
<td>0.092</td>
<td>12.3%</td>
<td>28%</td>
<td>11</td>
</tr>
<tr>
<td>0.5</td>
<td>68.7</td>
<td>25.4</td>
<td>2.78</td>
<td>0.47</td>
<td>1.86</td>
<td>0.79</td>
<td>0.070</td>
<td>11.3%</td>
<td>29%</td>
<td>13</td>
</tr>
<tr>
<td>1.0</td>
<td>68.9</td>
<td>25.2</td>
<td>2.75</td>
<td>0.50</td>
<td>1.81</td>
<td>0.71</td>
<td>0.081</td>
<td>11.4%</td>
<td>32%</td>
<td>13</td>
</tr>
<tr>
<td>1.5</td>
<td>70.5</td>
<td>24.3</td>
<td>2.39</td>
<td>0.40</td>
<td>1.68</td>
<td>0.63</td>
<td>0.074</td>
<td>10.3%</td>
<td>29%</td>
<td>14</td>
</tr>
<tr>
<td>4.5</td>
<td>80.6</td>
<td>17.6</td>
<td>0.90</td>
<td>0.18</td>
<td>0.52</td>
<td>0.17</td>
<td>0.013</td>
<td>5.8%</td>
<td>26%</td>
<td>26</td>
</tr>
<tr>
<td>10</td>
<td>81.1</td>
<td>17.4</td>
<td>0.78</td>
<td>0.13</td>
<td>0.47</td>
<td>0.13</td>
<td>0.014</td>
<td>5.0%</td>
<td>23%</td>
<td>30</td>
</tr>
<tr>
<td>20</td>
<td>81.3</td>
<td>17.2</td>
<td>0.75</td>
<td>0.12</td>
<td>0.46</td>
<td>0.13</td>
<td>0.012</td>
<td>4.8%</td>
<td>23%</td>
<td>30</td>
</tr>
<tr>
<td>50</td>
<td>81.8</td>
<td>16.9</td>
<td>0.70</td>
<td>0.12</td>
<td>0.44</td>
<td>0.12</td>
<td>0.009</td>
<td>4.6%</td>
<td>22%</td>
<td>31</td>
</tr>
<tr>
<td>100</td>
<td>81.8</td>
<td>16.9</td>
<td>0.60</td>
<td>0.11</td>
<td>0.47</td>
<td>0.11</td>
<td>0.008</td>
<td>4.1%</td>
<td>20%</td>
<td>30</td>
</tr>
<tr>
<td>4.0</td>
<td>58.1</td>
<td>25.0</td>
<td>6.1</td>
<td>1.28</td>
<td>3.76</td>
<td>3.86</td>
<td>1.90</td>
<td>61%</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>53.3</td>
<td>23.1</td>
<td>6.8</td>
<td>1.90</td>
<td>4.01</td>
<td>6.14</td>
<td>4.81</td>
<td>73%</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Nikjoo/Goodhead/O’Neill/Terrissol/Wilson/Bolton/Watanabe: IJRB 71,467(‘97); Rad Res 148,485(‘97) & 156,577(‘02); Rad Prot Dosim 99,77(‘02)
Table D-3--- Low Dose RBE studies of Low-Let Radiation

(Bond et al 1978)

<table>
<thead>
<tr>
<th>System</th>
<th>Radiation</th>
<th>RBE = alpha ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tradescantia stamen hair mutation</td>
<td>X gamma</td>
<td>2.1</td>
</tr>
<tr>
<td>Lymphocyte chromosome aberrations</td>
<td>X e</td>
<td>3.2</td>
</tr>
<tr>
<td>Mouse oocyte killing</td>
<td>$^{3}\text{H}$ gamma</td>
<td>2.9-4.2</td>
</tr>
</tbody>
</table>

$^a$Effect = alpha.D + $\beta$.D$^2$, RBE is equivalent to RBE$_M$

- Very poor justification!!

Lymphocyte dicentric aberrations remain the mainstay of such claims, with heavy reliance on simple curve-fitting extrapolations.

Comment

Table commonly referred to as justification for claim of RBE = 2 of orthovoltage X-rays compared to $^{60}\text{Co}$ gamma rays!! (eg ICRP60)
Conclusions

- General expectation that low-energy beta emitters will have greater biological effectiveness than standard reference radiations
  Supported from many directions, experimental and theoretical.

- The magnitude and practical implications need consideration.

- Some special features of low-energy beta emitters may be overlooked in routine RBE experiments

- There may be issues with use of standard tissue weighting factors for all low-energy beta emitters
  e.g. access to target cells, or excesses therein (radiation quality differences)
Some recommendations

• Use available information (experimental and theoretical) to establish the likely effectiveness of low-energy beta emitters for human risk relative to reference radiations

• Consider special cases of potential practical relevance e.g. extreme inhogeneity

• Determine yields and complexity of DNA damage from tritium beta-emitters, including when bound to cellular DNA, in comparison with a reference radiation

• Seek agreement on a standard reference radiation of practical convenience and relevance to established human risks