Current Approach to Radiation Quality Specification in Radiation Protection

DoReMi Radiation Quality Workshop
Brussels, 9 – 10 July 2013

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Modern radiation protection is based on the principles (ICRP Publication 26):

- **Principle of justification:**
  No practice shall be adopted unless it produces a net benefit.

- **Principle of optimisation**
  All exposures shall be As Low As Reasonably Achievable, economic and social factors taken into account.

- **Principle of limitation**
  Doses to individuals shall not exceed limits.

Assessment of radiation risks for individuals or groups of individuals is not a objective of radiation protection.
The practical (regulatory) implementation of the principles of limitation and optimisation requires the definition of appropriate radiation protection quantities including their specific units, (and the availability of methods to assess these quantities in real exposure situations).
Effective Dose (Equivalent):

The concept is restricted to the control of stochastic effects and is based on the assumption that:

- at low doses - the total radiation detriment to the exposed person is given by the sum of radiation detriments to single organs.
- organ dose equivalent is linearly correlated with detriment.

The applicability of this quantity and its underlying concept requires the use of a linear dose–risk relationship without a threshold (LNT model).
The quantity enables the necessary summation of doses from internal emitters and external radiation fields to provide a single numerical value for limitation and optimization.
Weighting factors

- Radiation weighting factors, $w_R$
  Take account of differences in biological effectiveness of different types of ionizing radiation

- Tissue weighting factors, $w_T$
  Sex-and age averaged, relative contribution of individual tissues to total detriment of stochastic effects for low-LET irradiations:

  \[ \text{all } w_T < 1 \text{ and } \sum w_T = 1 \]

Selection of values for weighting factors by ICRP is based on scientific knowledge available.
<table>
<thead>
<tr>
<th><strong>ICRP 60</strong> (1991)</th>
<th>0.01</th>
<th>bone surface, skin</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0.05</td>
<td>bladder, breast, liver, oesophagus, thyroid, remainder</td>
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<tr>
<td></td>
<td>0.12</td>
<td>bone marrow, colon, lung, stomach</td>
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<tr>
<td></td>
<td>0.2</td>
<td>gonads</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>ICRP 103</strong> (2007)</th>
<th>0.01</th>
<th>bone surface, skin, brain, salivary glands</th>
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<tbody>
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<td></td>
<td>0.04</td>
<td>bladder, liver, oesophagus, thyroid</td>
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<tr>
<td></td>
<td>0.08</td>
<td>gonads</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>bone marrow, colon, lung, stomach, breast, remainder</td>
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</tbody>
</table>
## Radiation weighting factors (ICRP 103)

<table>
<thead>
<tr>
<th>Radiation</th>
<th>$w_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>1</td>
</tr>
<tr>
<td>Electrons and muons</td>
<td>1</td>
</tr>
<tr>
<td>Neutrons</td>
<td>new continuous function</td>
</tr>
<tr>
<td>Protons and charged pions</td>
<td>5 $\rightarrow$ 2</td>
</tr>
<tr>
<td>Alpha particles, heavy ions and fission products</td>
<td>20</td>
</tr>
</tbody>
</table>

All values for $w_R$ relate to the radiation incident on the body or emitted from incorporated radionuclides.

Note: apart from the continuous function for neutrons $w_R$ assumes only 3 different values!
It should be noted that the concepts behind the two types of weighting factors are very different:

- Radiation weighting factors, with values between 1 and 25, are based on RBE evaluations and judgement with the assumption that the stochastic effects of a given type of radiation can be scaled to those of a reference radiation.
- Tissue weighting factors with values < 1 are based on relative detriment factors for different organs and are used to evaluate a weighted average of equivalent doses.
Radiation weighting factor for neutrons

\[ \bar{Q}_E = \frac{H_E}{\sum w_T D_T} \]

Secondary $\gamma$-radiation

Animal experiments

\[ Q(E) = \sum w_T \]

ICRP 60

ICRP 103

Neutron energy / MeV

Radiation weighting factor
Before the 1990 recommendations of the International Commission on Radiological Protection (ICRP 60), all dose-equivalent quantities were defined in terms of the quality factor, $Q(L)$, that was applied to the absorbed dose at a point. The weighted absorbed dose was called the dose equivalent, $H$. Averaging over an organ or a tissue, $T$, provided the mean organ or tissue dose equivalent, $H_T$.

The tissue weighted sum of organ and tissue dose equivalents was called effective dose equivalent, $H_E$. 
Effective dose

ICRP 60 introduced in 1990 a modified concept to take into account the differences in the effects of different types of radiation.

For radiation protection purposes, the absorbed dose is averaged over an organ or tissue, $T$, and this absorbed dose average is weighted for the radiation quality in terms of the radiation weighting factor, $w_R$, for the radiation incident on the body providing the mean organ or tissue equivalent doses.

Note: ICRU defined operational quantities which are used for radiation monitoring of exposure to external radiation still use $Q(L)$. 
The reason for replacing the quality factor, i.e. the $Q-L$ relationship, with $w_R$ values in the definition of the organ-equivalent doses and the effective dose was that the ICRP Commission believed:

"that the detail and precision inherent in using a formal $Q-L$ relationship to modify absorbed dose to reflect the higher probability of detriment resulting from exposure to radiation components with high LET is not justified because of the uncertainties in the radiological information".
Mean organ dose

Organ equivalent dose (ICRP 60)

\[ H_T^M = w_R \cdot D_T^M \quad H_T^F = w_R \cdot D_T^F \]

Organ dose equivalent (ICRP 26)

\[ \overline{H}_T^M = \overline{Q} \cdot D_T^M = \frac{1}{m^M} \int \int Q(L) \cdot D(L) \, dL \, dm \]
\[ \overline{H}_T^F = \overline{Q} \cdot D_T^F = \frac{1}{m^F} \int \int Q(L) \cdot D(L) \, dL \, dm \]
Human body averaged mean quality factors ($q_E$) ISO exposure (data from Sato et al.)
Organ equivalent dose, $H_T$, and organ dose equivalent from the GCR He-4 component (ISO exposure)
Determination of Effective Dose: Reference Values

For internal emitters: committed effective dose
NCRP Report 104 (1990)
The Relative Biological Effectiveness
Of Radiations of Different Quality
Radiation Quality Parameters
Quantification of radiation quality

- The general approach to quantify radiation quality for radiation protection is multiply absorbed doses (in an organ or tissue) with weighting or quality factors.
- This requires on one side suitable physical parameters describing the energy deposition pattern.
- On the other side relevant radiobiological (and epidemiological) data are required.
- RBE data used in the evaluation of quality factors come mainly from cell radiobiology and to a lesser extent from cancer induction and life shortening studies (mainly on mice).
**RBE, quality factor and radiation weighting factor**

**RBE**

a broad range of values for a given radiation depending on the biological endpoint considered, the dose and dose rate, the reference radiation and the experimental conditions.

**Q(L)**

a value of radiation quality depending on LET of the radiation at the point of interest. Nominal value at low doses which is derived from various radiobiological experiments on cells at low doses.

**w_R**

a single value depending only on the type (and energy for neutrons) of radiation incident on the human body. Nominal value at low doses which is based on radiobiological data.
LET dependance of radiation quality factor, \( Q \), (ICRP 60) and of \( RBE_{\text{max}} \) for total chromosomal exchanges (Cucinotta et al., Rad. Res. 170, 127-138 (2008))
Quality factor $Q(L)$

(concept introduced by “RBE” Committee in 1963)

$L, LET$ $[\text{keV/\mu m}]$ unrestricted linear energy transfer by a charged particle in water (not in tissue)

$Q(L)$ point quantity,
values mainly derived from single cell experiments and judgements

diagram showing $Q(L)$ for different types of particles: electrons, protons, $\alpha$-particles, and heavy ions.
Quality Factor Comparison

\[ Q(L), Q(y) \]

\[ \text{LET or } y \ (\text{keV/}\mu\text{m}) \]

\[ \text{Quality Factor} \]

\[ 10^0, 10^1, 10^2, 10^3 \]

\[ \text{LET or } y \ (\text{keV/}\mu\text{m}) \]

\[ \text{Quality Factor} \]

\[ 10^0, 10^1, 10^2, 10^3 \]

\[ \text{LET (keV/}\mu\text{m}) \]

\[ 10^0, 10^1, 10^2, 10^3 \]

\[ \text{Proton} \]

\[ Q_{\text{NASA}} \ (\text{Proton}) \]

\[ Q_{\text{NASA}} \ (\text{^{12}C}) \]

\[ Q_{\text{NASA}} \ (\text{^{56}Fe}) \]

Taken from Sato, T. et al.,

*Comparison of mean quality factors for astronauts calculated using the Q-functions proposed by ICRP, ICRU, and NASA, Adv. Space Res. (2013)*

\[ Q_{\text{NASA}} \] is based on the track structure Parameter \( Z^2/\beta^2 \)
Comparison of Effective Quality Factors

Effective Quality Factors based on $Q(L)$, $Q_{NASA}$ and $Q(y)$ for Male

- Low Energy: $Q(L) \leq Q(y) < Q_{NASA}$
- High Energy: $Q(y) < Q(L) < Q_{NASA}$

$Q_{NASA}$ is larger than the others for lighter particles
$Q(y) < 1$ for low LET particles such as high-energy protons

Taken from Sato et al
In the ICRP concept for radiation protection, differences in radiation quality are taken into account only in a very simplified way. (However, for the application in the regulatory context, radiation weighting factors have no uncertainty!)

This is partly explained by the conservative approach taken in radiation protection, but basically due to the paucity and considerable uncertainties of radiobiological data of relevance for the assessment of RBE values for stochastic effects in humans.
Different radiation quality parameters provide comparable results, except for high energy ions.

The ICRP of using weighted organ absorbed doses for radiation protection appears adequate for the purpose of risk limitation and optimization for many exposure situations. Exceptions include exposure to incorporated radionuclides emitting short-ranged radiation (e.g. Tritium, Auger emitters) and cosmic radiation.

There is an obvious need for the improvement of epidemiological and radiobiological knowledge and data.