Overview of the ICRP System of Internal and External Dosimetry

ICRP Symposium on Radiological Protection Dosimetry
Historical Review and Current Activities

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ICRP Dose Quantities

Absorbed dose, $D$
The fundamental dose quantity given by

\[ D = \frac{d\bar{\epsilon}}{dm} \]

where $d\bar{\epsilon}$ is the mean energy imparted to matter of mass $dm$ by ionizing radiation. The SI unit for absorbed dose is joule per kilogram (J/kg) and its special name is gray (Gy).

Equivalent dose, $H_T$
The dose in a tissue or organ $T$ given by:

\[ H_T = \sum_R w_R D_{T,R} \]

where $D_{T,R}$ is the mean absorbed dose from radiation $R$ in a tissue or organ $T$, and $w_R$ is the radiation weighting factor. Since $w_R$ is dimensionless, the unit for the equivalent dose is the same as for absorbed dose, J/kg, and its special name is sievert (Sv).
Effective dose, $E$

The tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body, given by the expression:

$$E = \sum_T w_T \sum_R w_R D_{T,R} \quad \text{or} \quad E = \sum_T w_T H_T$$

where $H_T$ is the equivalent dose in a tissue or organ, $T$, and $w_T$ is the tissue weighting factor. The unit for the effective dose is the same as for absorbed dose, J/kg, and its special name is sievert (Sv).
The Effective Dose

“Hypothetical” uniform exposure of the reference person yielding same total detriment

“Real” non-uniform exposure of the individual

This is the individual’s “effective dose” $E$
Dose coefficient – Internal Exposures
For adult workers, a dose coefficient is defined as either the committed equivalent dose in organ or tissue T per activity intake, $h_T(50)$, or the committed effective dose per intake, $e(50)$, where 50 is the dose-commitment period in years over which the dose is calculated. Note that elsewhere the term ‘dose per intake coefficient’ is sometimes used.
Dose Coefficient – External Exposures
A coefficient relating a dose quantity – organ equivalent dose or effective dose – to a physical quantity. For external exposure, the physical quantity ‘fluence’ or ‘air kerma’ is chosen.

Idealized environments of radionuclide contaminated air, water, or soils

Idealized occupational radiation fields
For $^{137}$Cs, Publication 30 assumes total body uniform distribution modeled as two compartments:

$$f_1 = 0.10 \quad \text{and} \quad f_2 = 0.9$$

$$\lambda_{eff_1} = \lambda_{b_1} + \lambda_{R} = \frac{ln2}{2 \, d} + \frac{ln2}{30 \, y \left(\frac{y}{365 \, d}\right)}$$

$$\lambda_{eff_2} = \lambda_{b_2} + \lambda_{R} = \frac{ln2}{110 \, d} + \frac{ln2}{30 \, y \left(\frac{y}{365 \, d}\right)}$$
\[ A_{TB}(t) = f_1 A_{blood}(0) \exp(-\lambda_{eff_1} t) + f_2 A_{blood}(0)\exp(-\lambda_{eff_2} t) \]

\[ \tilde{A}_{TB} = \int_{0}^{T=50y} A_{TB}(t) \, dt \]

\[ \tilde{A}_{TB} = \frac{f_1 A_{blood}(0)}{\lambda_{eff_1}} \left[ 1 - \exp(-\lambda_{eff_1} T) \right] + \frac{f_2 A_{blood}(0)}{\lambda_{eff_2}} \left[ 1 - \exp(-\lambda_{eff_2} T) \right] \]
Compartments Transfer Coefficient (d⁻¹)

<table>
<thead>
<tr>
<th>Compartments</th>
<th>Transfer Coefficient (d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood 1 to Liver 1</td>
<td>70</td>
</tr>
<tr>
<td>Blood 1 to Urinary bladder contents</td>
<td>60</td>
</tr>
<tr>
<td>Blood 1 to Right colon contents</td>
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<tr>
<td>Blood 1 to ST0</td>
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</tr>
<tr>
<td>Blood 1 to ST1</td>
<td>10</td>
</tr>
<tr>
<td>Blood 1 to ST2</td>
<td>4.0</td>
</tr>
<tr>
<td>Blood 1 to Cortical bone surf</td>
<td>6.0</td>
</tr>
<tr>
<td>Blood 1 to Trabecular bone surf</td>
<td>6.0</td>
</tr>
<tr>
<td>Blood 1 to Kidneys 1</td>
<td>9.0</td>
</tr>
<tr>
<td>Blood 1 to Kidneys 2</td>
<td>1.0</td>
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<tr>
<td>Blood 1 to Blood 2</td>
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<td>Blood 2 to Blood 1</td>
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<tr>
<td>Liver 1 to SI cont</td>
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<tr>
<td>Liver 1 to Blood 1</td>
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<tr>
<td>Liver 1 to Liver 2</td>
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</tr>
<tr>
<td>Liver 2 to Blood 1</td>
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</tr>
<tr>
<td>ST0 to Blood 1</td>
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<tr>
<td>ST1 to Blood 1</td>
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<tr>
<td>ST2 to Blood 1</td>
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<td>Cortical bone surf to Blood 1</td>
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<tr>
<td>Cortical bone surf to Cortical bone vol</td>
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<tr>
<td>Trabecular bone surf to Blood 1</td>
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<tr>
<td>Trabecular bone surf to Trabecular bone vol</td>
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<tr>
<td>Cortical bone vol to Blood 1</td>
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<tr>
<td>Trabecular bone vol to Blood 1</td>
<td>0.000493</td>
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<tr>
<td>Kidneys 1 to Urinary bladder contents</td>
<td>0.462</td>
</tr>
<tr>
<td>Kidneys 2 to Blood 1</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

surf = surface, vol = volume, SI = small intestine
Biokinetic Models - Numerical Solution

\[ \frac{dA_{i,j}(t)}{dt} = \sum_{k=1 \atop k \neq j}^{M} A_{i,k} \lambda_{i,k,j} - A_{i,j} \left[ \sum_{k=1 \atop k \neq j}^{M} \lambda_{i,j,k} + \lambda_{i}^{P} \right] + \sum_{k=1}^{i-1} A_{k,j} \beta_{k,i} \lambda_{i}^{P} \]

- \( M \) is the number of compartments describing the kinetics;
- \( \lambda_{i,j,k} \) is the fractional transfer rate of chain member \( i \) from compartment \( j \) (donor compartment) to compartment \( k \) (receiving compartment) in the biokinetic model;
- \( \lambda_{i}^{P} \) is the physical decay constant of chain member \( i \); and
- \( \beta_{k,i} \) is the fraction of the decays of chain member \( k \) forming member \( i \).
Time Integration of Organ Activity

Integration of organ activity over the dose commitment period $\tau$ and summation over all biokinetic compartments $j$ yields the time-integrated activity $\tilde{A}$

$$\tilde{A}_i(r_S, \tau) = \sum_j \int_0^\tau A_{i,j}(t) \, dt$$

Normalizing by the activity intake at $t = 0$, yields the time-integrated activity coefficient $\tilde{a}$

$$\tilde{a}_i(r_S, \tau) = \frac{\tilde{A}_i(r_S, \tau)}{\sum_j A_{1,j}(0)}$$

*The parameter $\tilde{a}$ is equivalent to the older term “residence time” in the MIRD schema*
ICRP Dose Coefficients for Equivalent Dose

The committed equivalent dose coefficient in target region \( r_T \) of the Reference Adult Male, \( h^M(r_T, \tau) \), and Reference Adult Female, \( h^F(r_T, \tau) \), for integration time \( \tau \) is given by

\[
h^F(r_T, \tau) = \sum_i \sum_{r_S} \tilde{a}_i(r_S, \tau) \ S^F_w (r_T \leftarrow r_S)_i
\]

\[
h^M(r_T, \tau) = \sum_i \sum_{r_S} \tilde{a}_i(r_S, \tau) \ S^M_w (r_T \leftarrow r_S)_i
\]

\( S \) coefficients, \( S^M_w (r_T \leftarrow r_S)_i \) and \( S^F_w (r_T \leftarrow r_S)_i \), are the radiation-weighted equivalent doses in target region \( r_T \) per nuclear transformation of chain member \( i \) in source region \( r_S \) [Sv (Bq s)^{-1}] for the male and female worker, respectively.
ICRP Dose Coefficients for Equivalent Dose

The committed equivalent dose coefficients for tissue $T$ in the Reference Adult Male, $h_T^M(\tau)$, and Reference Adult Female, $h_T^F(\tau)$, are thus given as:

$$h_T^F(\tau) = \sum_{r_T} f(r_T, T) \ h^F(r_T, \tau)$$

$$h_T^E(\tau) = \sum_{r_T} f(r_T, T) \ h^E(r_T, \tau)$$

where the target region fractional weights $f(r_T, T)$ are the proportions of the equivalent dose in tissue $T$ associated with target region $r_T$.

For example, the colon (target tissue $T$) is composed of three target regions ($r_T$) – right colon, left colon, and rectosigmoid colon. However, the liver is composed of only one target region ($f = 1$).
As defined in *Publication 103*, the committed effective dose coefficient, $e(\tau)$, is then:

$$e(\tau) = \sum_T w_T \left[ \frac{h^M_T(\tau) + h^F_T(\tau)}{2} \right]$$
Specific Absorbed Fractions with the ICRP System

The radiation-weighted S coefficient [Sv (Bq-s)⁻¹] for a radionuclide is calculated as:

\[
S_w(r_T \leftarrow r_S) = \sum_R w_R \sum_i E_{R,i} Y_{R,i} \Phi(r_T \leftarrow r_S, E_{R,i})
\]

- \(E_{R,i}\) is the energy of the \(i^{\text{th}}\) radiation of type \(R\) emitted in nuclear transformations of the radionuclide;
- \(Y_{R,i}\) is the yield of the \(i^{\text{th}}\) radiation of type \(R\) per nuclear transformation, [(Bq s)⁻¹];
- \(w_R\) is the radiation weighting factor for radiation type \(R\); and
- \(\Phi(r_T \leftarrow r_S, E_{R,i})\) is the specific absorbed fraction (SAF), defined as the fraction of energy \(E_{R,i}\) of radiation type \(R\) emitted within the source tissue \(r_S\) that is absorbed per mass in the target tissue \(r_T\) (kg⁻¹).
**Adult Specific Absorbed Fractions - Previous**

ICRP Publication 30  
*Appendix I of ICRP Publication 23 – MIRD Phantom*

**Subsequent ICRP Publications**  
*Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources (ORNL TM-8381)*
Adult Specific Absorbed Fractions - Current

Publication 110 Reference Phantoms
Examples of the many challenges within C2 Task Groups 95 and 96

- First-time use of fractional values of electron absorbed fractions
- Discernment of “wall sources” for the Publication 100 alimentary tract organs
- Integration of phantom-derived SAFs with those derived from stylized models of the alimentary tract and respiratory tract
- Interpretation of ICRP Publication 89 Reference Masses – inclusive or exclusive of blood content
- Computation of blood sources – example of a distributed organ
- Treatment of progeny in-growth with unique systemic biokinetics
- First-time consideration of coefficients giving effective dose per bioassay content
Pediatric Specific Absorbed Fractions

ICRP Series of Pediatric Reference Phantoms
- Derived from UF/NCI hybrid phantom series
- Photon and Electron SAFs currently being completed
- QA to start within ICRP TG 96
- Support – U.S. Environmental Protection Agency
Pregnant Female Specific Absorbed Fractions

ICRP Series of Fetal and Pregnant Female Phantoms
- Derived from UF hybrid phantom series developed for the SOLO Project
- Primary photon and electron SAFs beginning currently
- QA to be completed under TG 96
- Support – U.S. Environmental Protection Agency

Models at 8 week to 38 weeks post-conception
ICRP Dose Coefficients - External

Publication 74 (1996)
- Based upon review of published dose coefficients
- Mixture of stylized and voxel phantoms

Publication 116 (2010)
- Based upon new MC calculations using the Publication 110 phantom
- Extensive benchmarking of various MC transport codes
ICRP Task Group 90
Age-Dependent Dose Coefficient for Env. Exposures
Thank you for your attention