Assessment and interpretation of internal doses: uncertainty and variability

Francois Paquet, Mike Bailey, Rich Leggett, John Harrison
ICRP C2

This presentation has neither been approved nor endorsed by the Main Commission of ICRP
Internal exposures are managed by the use of the committed effective dose

\[ e(\tau) = \sum_T w_T \left[ \frac{h_T^M(\tau) + h_T^F(\tau)}{2} \right] \]
Calculating committed effective dose after internal contamination is a complex procedure
Intake → Deposition in tissues
Biokinetic models

Intake → Deposition in tissues
Generic biokinetic model

(ICRP 78, 1997)
Biokinetic models

Intake → Deposition in tissues → Transformations in tissues (Nb) → Emitted energy (Mev) → Absorbed dose in tissues (Gy) → Equivalent dose in tissues (Sv) → Effective dose (Sv)

Nuclear data

Fantoms and codes for radiation transport

Weighting factors for radiations $w_R$

Weighting factors for tissues $w_T$
Intake

Deposition in tissues

Transformations in tissues (Nb)

Emitted energy (Mev)

Absorbed dose in tissues (Gy)

Equivalent dose in tissues (Sv)

Effective dose (Sv)

Biokinetiс models

Dosimetric models
Complex procedure, limited to experts

ICRP has defined concepts and tools, to allow non-specialist to perform dose assessment

1. Dose per unit intake
2. Retention functions
Intake

Deposition in tissues

Transformations in tissues (Nb)

Emitted energy (Mev)

Absorbed dose in tissues (Gy)

Equivalent dose in tissues (Sv)

Effective dose (Sv)

Weighting factors for tissues $w_T$
Intake

Deposition in tissues

Transformations in tissues (Nb)

Emitted energy (MeV)

Absorbed dose in tissues (Gy)

Equivalent dose in tissues (Sv)

Effective dose (Sv)

Type

F

M

S

DPUI

µSv/Bq

0.6

2.1

6.8

For $^{234}$U

$Dose = Intake \times DPUI$

Weighting factors for tissues $w_T$

Equivalent dose in tissues (Sv)
<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$t_{1/2}$</th>
<th>Type</th>
<th>$f_i$</th>
<th>1 $\mu$m AMAD</th>
<th>5 $\mu$m AMAD</th>
<th>Ingestion</th>
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<tr>
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<tr>
<td>Ca-47</td>
<td>4.53d</td>
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<td>0.300</td>
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<td>Scandium</td>
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<td></td>
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<tr>
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<td>3.89h</td>
<td>S</td>
<td>1.0E-04</td>
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<tr>
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<td>3.93h</td>
<td>S</td>
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<td>1.0E-04</td>
</tr>
<tr>
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<td>1.0E-04</td>
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<td>6.4E-09</td>
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<td>1.0E-04</td>
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<tr>
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<td>3.35d</td>
<td>S</td>
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<td>7.3E-10</td>
<td>1.0E-04</td>
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<td>F</td>
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<tr>
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<td>S</td>
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<td>6.2E-08</td>
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<tr>
<td>Ti-45</td>
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<td>4.6E-11</td>
<td>8.3E-11</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.010</td>
<td>9.1E-11</td>
<td>1.4E-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td>0.010</td>
<td>9.6E-11</td>
<td>1.5E-10</td>
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</tr>
</tbody>
</table>

From ICRP 68, 1994
General procedures for assessing doses

Intake

Deposition in tissues

Transformations in tissues (Nb)

Emitted energy (Mev)

Absorbed dose in tissues (Gy)

Equivalent dose in tissues (Sv)

Effective dose (Sv)

Bioassays

Nuclear data

Fantoms and codes for particles transport

Weighting factors for radiations $w_R$

Weighting factors for tissues $w_T$

ICRP
INTERNATIONAL COMMISSION ON RADILOGICAL PROTECTION
General procedures for assessing doses

Intake → Deposition in tissues → Transformations in tissues (Nb) → Emitted energy (MeV) → Absorbed dose in tissues (Gy) → Equivalent dose in tissues (Sv) → Effective dose (Sv)

Retention function → Bioassays

Nuclear data

Fantoms and codes for particles transport

Weighting factors for radiations $w_R$

Weighting factors for tissues $w_T$
In this case, intake = Bq measured \times 10^5

Retention functions

Fig. A.10.3. $^{234}$U Inhalation Type S: predicted values (Bq per Bq intake) following acute intake.
General procedures for assessing doses

1. Intake
2. Deposition in tissues
3. Transformations in tissues (Nb)
4. Emitted energy (Mev)
5. Absorbed dose in tissues (Gy)
6. Equivalent dose in tissues (Sv)
7. Effective dose (Sv)
8. Weighting factors for radiations $w_R$
9. Weighting factors for tissues $w_T$
10. Nuclear data
11. Fantoms and codes for particles transport
12. Bioassays
13. DPUI

Intake → Deposition in tissues → Transformations in tissues (Nb) → Emitted energy (Mev) → Absorbed dose in tissues (Gy) → Equivalent dose in tissues (Sv) → Effective dose (Sv) → DPUI

ICRP
INTERNATIONAL COMMISSION ON RADIATIONAL PROTECTION
Main ICRP publications on these topics

For workers

  dose coefficients and ALI for inhalation and ingestion.

*Publication 68* (ICRP, 1994)
  updated dose coefficients following 1991 Recommendations (Publication 60, 1991), HRTM (Publication 66, 1994),
  new skeletal data (Publication 70, 1995) and revised systemic biokinetic models.
  No ALI anymore.

*Publications 54 and 78* (ICRP, 1988, 1997)
  guidance on the design of monitoring programs and the interpretation of results,
  to estimate doses to workers following radionuclide inhalation or ingestion.
  Provide predicted values of measured quantities after intake.
Main ICRP publications on these topics

For the members of the public


age-specific dose coefficients for inhalation and ingestion for 91 elements, using up-to-date models and latest ICRP recommendations.

*Publications 88 and 95 (2001, 2004)*

Dose to embryo/fetus and infants
Progress and changes made during this period

In physiology and biokinetic models
  • New data on Reference man (ICRP 89, 2002)
  • Human Alimentary Tract Model (ICRP 100, 2006)
The Human alimentary tract model

The former model

**Diagram:**
- **INGESTION**
  - STOMACH
    - $\lambda_{ST}$
    - SMALL INTESTINE
      - $\lambda_{SI}$
      - UPPER LARGE INTESTINE
        - $\lambda_{ULI}$
        - LOWER LARGE INTESTINE
          - $\lambda_{LLI}$
          - EXCRETION
    - $\lambda$
  - BODY FLUIDS
Progress and changes made during this period

In physiology and biokinetic models
  • New data on Reference man (ICRP 89, 2002)
  • Human Alimentary Tract Model (ICRP 100, 2006)
  • New element specific systemic models, physiologically realistic
Systemic model for Iodine

The former model (ICRP 1994, 1997)

The new model

Three subsystems:
- circulating inorganic iodide;
- thyroidal organic iodine
- extrathyroidal organic iodine.
Systemic model for Strontium

The former model (ICRP 1989)

The new model

Figure 10-1. Structure of the biokinetic model for systemic strontium.

Abbreviations: exch = exchangeable, nonexch = non-exchangeable
Figure 12.6. Structure of the biokinetic model for systemic radon.
Abbreviations: RT-air = respiratory tract air; Blood-A = arterial blood; Blood-V = venous blood;
Breast-g = glandular breast tissue; Breast-a = adipose tissue in breast;
HATM = Human Alimentary Tract Model (ICRP, 2006).
Progress and changes made during this period

In physiology and biokinetic models

• New data on Reference man (ICRP 89, 2002)
• Human Alimentary Tract Model (ICRP 100, 2006)
• New element specific systemic models, physiologically realistic
• More realistic treatment of the biokinetics of radionuclide daughters
• New data supporting update of the Human Respiratory Tract Model
Particle transport model (ICRP 66 HRTM)

Anterior nasal
- Naso-oro-pharynx-larynx
- Bronchi
- Bronchioles
- Alveolar interstitial

Extrathoracic
- ET<sub>1</sub>
- ET<sub>2</sub>

Thoracic
- LN<sub>ET</sub>
- ET<sub>seq</sub>
- BB<sub>seq</sub>
- BB<sub>1</sub>
- bb<sub>1</sub>
- Al<sub>1</sub>, Al<sub>2</sub>, Al<sub>3</sub>

Clearance rates (d<sup>-1</sup>)
# Uranium absorption

<table>
<thead>
<tr>
<th>Compound</th>
<th>Absorption parameter values</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Default Type F</strong></td>
<td>( f_r ) ( s_r ) ( s_s ) ( (d^{-1}) )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0 \hspace{10pt} 100</td>
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Element-specific values for \( f_r \), \( s_r \) and \( s_s \)
## Uranium absorption

<table>
<thead>
<tr>
<th>Compound</th>
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</thead>
<tbody>
<tr>
<td><strong>Default Type F</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uranyl nitrate, UO$_2$(NO$_3$)$_2$</td>
<td>$f_r$ 1.0, $s_r$ 100 (d$^{-1}$), $s_s$ 0.005 (d$^{-1}$)</td>
<td>(F)</td>
</tr>
<tr>
<td>U-Tri-butyl-phosphate</td>
<td>0.9, 3, 0.002 (F)</td>
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<tr>
<td>Uranium peroxide hydrate</td>
<td>0.9, 0.9, 0.024 (F)</td>
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</tbody>
</table>

Element-specific values for $f_r$, $s_r$ and $s_s$
## Uranium absorption

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<tr>
<td></td>
<td>$f_r$</td>
<td>$s_r$ (d$^{-1}$)</td>
</tr>
<tr>
<td><strong>Default Type F</strong></td>
<td>1.0</td>
<td>100</td>
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<tr>
<td>Uranyl nitrate, UO$_2$(NO$_3$)$_2$</td>
<td>0.9</td>
<td>3</td>
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<tr>
<td>U-Tri-butyl-phosphate</td>
<td>0.97</td>
<td>12</td>
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<td>Uranium peroxide hydrate</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Default Type M</strong></td>
<td>0.1</td>
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Element-specific values for $f_r$, $s_r$ and $s_s$
## Uranium absorption

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<tr>
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<td>3</td>
</tr>
<tr>
<td>Uranium peroxide hydrate</td>
<td>0.9</td>
<td>0.9</td>
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<td><strong>Default Type M</strong></td>
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<td></td>
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<tr>
<td>Ammonium diuranate, ADU</td>
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<td>100</td>
</tr>
<tr>
<td>Uranium tetrafluoride</td>
<td>0.6</td>
<td>0.15</td>
</tr>
<tr>
<td>Uranium trioxide</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>U$_3$O$_8$</td>
<td>0.04</td>
<td>1</td>
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Element-specific values for $f_r$, $s_r$ and $s_s$
# Uranium absorption

<table>
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<th>Compound</th>
<th>Absorption parameter values</th>
<th>Type</th>
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<td>$f_r$</td>
<td>$s_r$ (d(^{-1}))</td>
</tr>
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<td>Uranyl nitrate, UO(_2)(NO(_3))(_2)</td>
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<td>100</td>
</tr>
<tr>
<td>U-Tri-butyl-phosphate</td>
<td>0.9</td>
<td>3</td>
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<tr>
<td>Uranium peroxide hydrate</td>
<td>0.9</td>
<td>0.9</td>
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<td><strong>Default Type M</strong></td>
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<tr>
<td>Ammonium diuranate, ADU</td>
<td>0.1</td>
<td>100</td>
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<td>0.8</td>
<td>0.7</td>
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<td>Uranium trioxide</td>
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<tr>
<td>U(_3)O(_8)</td>
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Element-specific values for $f_r$, $s_r$ and $s_s$
### Default parameter values

**Type F, M, S**

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<tr>
<th>Type</th>
<th>ICRP 66</th>
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<th>$s_s$ (d$^{-1}$)</th>
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<td></td>
<td>0.01</td>
<td>3</td>
<td>0.0001</td>
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Progress and changes made during this period

In physiology and biokinetic models
- New data on Reference man (ICRP 89, 2002)
- Human Alimentary Tract Model (ICRP 100, 2006)
- New element specific systemic models, physiologically realistic
- More realistic treatment of the biokinetics of radionuclide daughters
- New data supporting update of the Human Respiratory Tract Model

In dosimetry and monitoring
- Development of adult reference computational phantom, based on the new ref man (ICRP 110, 2009)
- New skeletal dosimetry (ICRP 116, 2010)
- Revised nuclear decay data (ICRP 107, 2008)
Progress and changes made during this period

In physiology and biokinetic models
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In dosimetry and monitoring
- Development of adult reference computational phantom, based on the new ref man (ICRP 110, 2009)
- New skeletal dosimetry (ICRP 116, 2010)
- Revised nuclear decay data (ICRP 107, 2008)
- Concept of dose per content
Intake

Bioassays

Dose per content

Effective dose (Sv)

Deposition in tissues

Transformations in tissues (Nb)

Emitted energy (MeV)

Absorbed dose in tissue (Gy)

Equivalent dose in tissue (Sv)

Weighting factors for tissues $w_T$

Weighting factors for radiations $w_R$

Fantoms and codes for particles transport

Nuclear data

ICRP
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Progress and changes made during this period (con’t)

In ICRP recommendations

- Adoption of the use of realistic phantoms (ICRP 103, 2007)
- Changes in weighting factors (ICRP 103, 2007)
- Changes in calculation of equivalent dose (ICRP 103, 2007)
Calculation of effective dose

Incorporation RN or external irradiation

Male phantom 73 kg

Equivalent dose males

Effective dose males

Effective dose female

Equivalent doses females

Effective dose females

Averaged equivalent dose

$W_T$ for males

$W_T$ for females

$W_R$
Progress and changes made during this period (con’t)

In ICRP recommendations

- Adoption of the use of realistic phantoms (ICRP 103, 2007)
- Changes in weighting factors (ICRP 103, 2007)
- Changes in calculation of equivalent dose (ICRP 103, 2007)

- Need to provide dose coefficients for Radon (ICRP 2009)
These new data and recommendations supported a revision of the past reports and provision of new dose coefficients with guidance on monitoring programs and data interpretation.

Done for external dosimetry (ICRP 116, 2010)
Need to be done for internal dosimetry
Revision of the reports on internal exposure

Division of the work in two parts:

- Revision of models and dose coefficients for workers (OIR series)

- Revision of models and dose coefficients for members of the public (Age dependant series, Embryo and fetus, maternal transfer,..)
The OIR series
5 volumes

OIR Part 1  (ICRP Publication 130)

• Control of occupational exposures to radionuclides
• Biokinetic and dosimetric models
• Methods of individual and workplace monitoring
• Monitoring programmes
• General aspects of retrospective dose assessment

To be published today!!
The OIR series
5 volumes

OIR Part 2 to 5

For each element section:

- Chemical forms in the workplaces
- Principal radioisotopes, physical half-lives and decay modes
- Review of data on inhalation, ingestion and systemic biokinetics
- Structure of biokinetic models and parameter values
- Monitoring techniques and typical detection limits
- Dose coefficients, reference bioassays functions and dose per content functions in printed document and/or electronic annexes
The OIR series
5 volumes

OIR Part 2
Hydrogen (H), Carbon (C), Phosphorus (P), Sulfur (S), Calcium (Ca), Iron (Fe), Cobalt (Co), Zinc (Zn), Strontium (Sr), Yttrium (Y), Zirconium (Zr), Niobium (Nb), Molybdenum (Mo) and Technetium (Tc).

OIR Part 3
Ruthenium (Ru), Antimony (Sb), Tellurium (Te), Iodine (I), Caesium (Cs), Barium (Ba), Iridium (Ir), Lead (Pb), Bismuth (Bi), Polonium (Po), Radon (Rn), Radium (Ra), Thorium (Th) and Uranium (U).

OIR Part 4
Lanthanides series, actinium (Ac), protactinium (Pa) and transuranic elements.

OIR Part 5
Fluorine (F), Sodium (Na), Magnesium (Mg), Potassium (K), Manganese (Mn), Nickel (Ni), Selenium (Se), Molybdenum (Mo), Technetium (Tc) and Silver (Ag) and most of the others.
Uncertainty and variability in dose calculation

Uncertainty: lack of knowledge of a central value for a population

Variability: difference between members result from physiological or environmental factors

Variability may induce uncertainty!!
Uncertainty in dose calculation

Depends on uncertainties:

- in measurement of activity
- in exposure scenario (route, time, RN, form,..)
- in biokinetic and dosimetric models
Uncertainties in biokinetic models

on parameter values AND on model structure

From R.W. Leggett (1992) and ICRP publication 67 (1993)
Uncertainties in biokinetic models

Depends on available information to derive biokinetic models

- Human data
  (available for Essent. elts + Cs, Pb, Ra, U, Am, Pu,..)
Uncertainties in biokinetic models

- Human data
- Human data on chemically similar elements (Ln)
Uncertainties in biokinetic models

- **Human data**

- **Human data on chemically similar elements (Ln)**

  Ca, Sr, Ba, Ra chemically and physiologically similar... but
  Na and K chemically similar but physiologically different
  Cs and K chemically similar but different kinetics
Uncertainties in biokinetic models

- Human data
- Human data on chemically similar elements
- Animal data

Need extrapolation
Uncertainties in biokinetic models

- Human data
- Human data on chemically similar elements
- Animal data
- Animal data AND chemically similar elements
There are many sources of uncertainty but:

Reference models and parameter values are fixed by convention and are not subject to uncertainty.

They are intended to be used for optimisation and demonstration of compliance with dose limits.

In case where models are used for other scientific purposes, uncertainties and variability may be taken into account.
Conclusions

Determination of internal doses is a complex procedure

Many tools available to directly assess dose from activity measurements

Based on the use of biokinetic and dosimetric models

No uncertainty for calculation of effective dose