Refresher Course

“Programmes for Internal Dose Monitoring”

Part 1: Basic Aspects and Essential Elements  K Henrichs
Part 2: Uncertainties in Assessments of Internal Doses and Advice on Monitoring  A. Hodgson
Dosimetry of incorporated radionuclides

\[ \text{DOSE in } T = \text{energy per mass unit transported to } T \times \frac{\text{# of disintegrations in } S}{\text{time integral of activity}} \]

Depending on:

- radiation type
- energy emitted
- masses
- geometry i.e. gender, age, health
- physical half-life,
- distribution & retention - element, compound - path of intake - AMAD, f1, … - age, gender

S = region containing radioactivity

T = region of interest
Dose coefficients ....

Biokinetics:
Reference models and parameters

Radiation transport:
anthropomorphic or voxel phantoms

Dose coefficients for reference persons
= Dose (Sv) per unit of activity (Bq)
compiled e. g. by ICRP (ICRP 72, 88, ..)

... help to quantify exposures for reference persons if intakes are known
Monitoring is …

- performed to
  • verify that each worker is protected adequately against risks from radionuclide intakes
  • document the protection complies with legal requirements

- retrospective:
  
  **Measure:**
  - room activity
  - body burden
  - excreta

  **Calculate:**
  - intake* using reference retention data
  - exposure using reference dose coefficients

  *additional uncertainty: unknown time of incorporation event

ISO 20553:

to a Risk of Internal Contamination with Radioactive Material
Distinguish …

<table>
<thead>
<tr>
<th>Monitoring Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Routine monitoring</strong></td>
<td>to quantify normal exposures, i.e. where there is no evidence to indicate that acute intakes have occurred or where chronic exposures cannot be ruled out.</td>
</tr>
<tr>
<td><strong>Special monitoring</strong></td>
<td>to quantify significant exposures following actual or suspected abnormal events.</td>
</tr>
<tr>
<td><strong>Confirmatory monitoring</strong></td>
<td>required to check the assumptions underlying the procedures previously selected.</td>
</tr>
<tr>
<td><strong>Task-related monitoring</strong></td>
<td>applies to a specific operation.</td>
</tr>
<tr>
<td><strong>Individual monitoring</strong></td>
<td>needed to assess the exposure of a single worker by measuring individual body activities, excretion rates or activity inhaled (using personal air samplers).</td>
</tr>
<tr>
<td><strong>Workplace monitoring</strong></td>
<td>provides exposure assessments for a group of workers assuming identical working conditions.</td>
</tr>
</tbody>
</table>
Necessity of monitoring:
classification of processes, workers …

Inputs:
- earlier monitoring results
- compounds, AMAD, dose coefficients,
- estimate of incorporation probabilities
- …

Risk assessment for each work process

Classification of each worker:
no / low / high risk

Criteria:
no risk: expected annual exposure likely to be < 1 mSv/a
low risk: expected annual exposure may exceed 1 mSv/a but likely < 6 mSv/a
high risk: annual exposure may exceed 6 mSv/a

Output:
Assignment of each worker to a spec. monit. procedure

Criteria:
no risk: no monitoring
low risk: collective or workplace monitoring
high risk: individual monitoring

Design of the monitoring programs

Exposure risk constant in time: routine monitoring
varying: task related or special monitoring

Inputs:
- radionuclide: emissions
- compounds: biokinetics, …
- AMAD, f1, ..
- avail. tech., detection limits

IRPA 11 Refresher Course 5b
Programmes for Internal Dose Monitoring” Part 1:Basic Aspects and Essential Elements K Henrichs
Radiation type and biokinetics determine measurement methods:

**in-vivo measurements:** for photon emitters ($\gamma$, X-ray)
- whole body counter: e. g. Cs-137, Co-60
- partial body counter: e. g. I, Te (thyroid), Am + Pu (lungs)
- typ. detection limit: 10 - 500 Bq

**in-vitro, excretion analysis:** for $\alpha$- and $\beta$-emitters
- urine, feces, nose blow e. g. Sr-90, H-3
- typ. detection limit: 1 mBq ($\alpha$-emitters)

**air-monitoring:**
- room: if sensitivity of individual methods is not sufficient
- personal: if high intakes are expected
Select method and interval to ensure …

- the detection of an annual dose > 1mSv:
  for in vivo measurements  \( e(50) \times DL / R(\Delta T) \times 365 / DT < 1 \text{ mSv/a} \)
  for in vitro measurements  \( e(50) \times DL / E(\Delta T) \times 365 / DT < 1 \text{ mSv/a} \)

  with  
  \( e(50) \) = dose coefficient, 
  \( DL \) = detection limit, 
  \( R(t) \) = retention at \( t \) since incorporation, 
  \( E(t) \) = excretion rate at \( t \) since incorporation, 
  \( \Delta T \) = time interval for routine monitoring.

- maximum potential underestimation < 3

  i. e. assuming that a single intake occurred in the middle of the monitoring interval this requirement means:

  \[ \frac{R(\Delta T/2)}{R(\Delta T)} < 3 \]
  \[ \frac{E(\Delta T/2)}{E(\Delta T)} < 3 \]
## Reference levels …

<table>
<thead>
<tr>
<th>Level</th>
<th>Meaning</th>
</tr>
</thead>
</table>
| **Recording level**    | The recording level is the level at or above which monitoring results have to be recorded. It shall be set at a value corresponding to an annual dose no higher than **1 mSv**. Results falling below this level may be shown as “below recording level”.
| **Investigation level**| The investigation level is the level at or above which investigation has to be made into the uncertainty associated with the measurements in order to refine the monitoring result. It shall be set at a value corresponding to an annual dose no higher than **6 mSv**. |

… help that unnecessary, non-productive work can be avoided and resources can be used where they are most needed.
Important elements to ensure quality…

- the definition of maximum tolerated deviations from the predefined frequencies of measurements,
- clear rules for collecting samples of urine or feces
  24 hours sampling periods for urine, 3 days for feces
- regulations to avoid contaminations
  (as well for in vitro as for in vivo measurements)
- the definition of action levels for further investigations
- definition of assumptions as the basis for the interpretation of measurements
- confirmatory monitoring
  regularly and after any major modification
- intercomparisons for measurement (sampling, laboratory)
- intercomparisons for dose assessment
Refresher Course

Programmes for internal dose monitoring

Alan Hodgson (NRPB, UK)
Optimisation of Monitoring for Internal Exposure


Final report to be published as NRPB-W report. Obtainable as PDF from NRPB website - nrpb.org
Assessment of doses from monitoring measurements

- Assumed intake times
  - AMAD
  - Size distribution
  - Density
  - Physiological parameters
  - etc.

- Deposition Model

- Particle Transport Model

- Absorption Model

- Systemic Model
  - Uptake fractions
  - Rate constants
  - etc.

- DEPOSITION & CLEARANCE
  - RT & GI

- EFFECTIVE DOSE, \( E_{50} \)

- Lung & GI dose per unit intake

- Organ doses per unit intake

- INTAKE

- WB activity per unit intake

- Measured Whole Body activity

- Functions
  - SYSTEMIC UPTAKE(t)

- Organ doses (t)

- Parameters
  - Assumed intake times

- Models
  - Systemic Model
  - Absorption Model
  - Particle Transport Model
  - Deposition Model

- Quantities
  - Assumed intake times
  - AMAD
  - Size distribution
  - Density
  - Physiological parameters
  - etc.

- Functions
  - SYSTEMIC UPTAKE(t)

- Organ doses (t)

- Parameters
  - Assumed intake times

- Models
  - Systemic Model
  - Absorption Model
  - Particle Transport Model
  - Deposition Model

- Quantities
  - Assumed intake times
  - AMAD
  - Size distribution
  - Density
  - Physiological parameters
  - etc.
Assessing Intakes and Doses

- Human, animal, in-vitro studies
  - GIGAFIT
  - Absorption parameters
  - PLEIADES
  - Doses
  - Organ retention
  - Bioassay

- ICRP - HRTM Deposition, clearance and absorption parameters
- ICRP - Systemic model
Uncertainties in biokinetic modelling

Absorption Parameter Values
Alternative Representation of Absorption

\[
\begin{align*}
\text{Rapid dissolution} & \quad f_r \\
\text{Bound material} & \quad f_b s_r \quad f_b s_s \\
\text{Blood} & \quad (1-f_b)s_r \quad s_b \quad (1-f_b)s_s
\end{align*}
\]
...much simpler if exclude the ‘bound state’

\[ f_r \quad \text{Rapid dissolution} \]

\[ (1-f_r) \quad \text{Slow dissolution} \]

Blood
### Intake Uncertainties - Absorption Parameter Values

<table>
<thead>
<tr>
<th>Absorption Type*</th>
<th>Rapid Fraction ($f_r$)</th>
<th>Rapid Rate ($s_r$) d⁻¹</th>
<th>Slow Rate ($s_s$) d⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow</td>
<td>0.001</td>
<td>100</td>
<td>1 x 10⁻⁴ (t/2 ~ 7000 d)</td>
</tr>
<tr>
<td></td>
<td>(t/2 ~ 10 min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>0.1</td>
<td>100</td>
<td>5 x 10⁻³ (t/2 ~ 140 d)</td>
</tr>
<tr>
<td></td>
<td>(t/2 ~ 10 min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast</td>
<td>1</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(t/2 ~ 10 min)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*ICRP Publication 66 ‘Human Respiratory Tract Model for radiological protection’ (1994)*
ICRP Default Absorption Parameter Values

Deposition and lung retention of ‘default’ 5 µm particles

Fraction of inhaled

Type S

Type M

Days

0 60 120 180 240 300 360

0 0.01 0.02 0.03 0.04 0.05 0.06 0.07
Practical example

Acute Inhalation Exposure of Plutonium Nitrate
Plutonium Compounds: Exposure Limits and Assessment of Intake and Dose after Inhalation

N Stradling, A Hodgson, T Fell, E Ansoborlo, P Bérard, G Etherington and B Le Guen

NRPB Chilton, CEA Marcoule, CEA Saclay, EDF-GDF St Denis

NRPB-W52
Obtainable as PDF from NRBP website - nrpb.org
## Intake Uncertainties - Absorption Parameter Values

<table>
<thead>
<tr>
<th>Absorption Type*</th>
<th>Rapid Fraction ((f_r))</th>
<th>Rapid Rate (\text{half-time})</th>
<th>Slow Rate ((s_s)) (\text{half-time})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow</td>
<td>0.001</td>
<td>~ 10 min</td>
<td>~ 7000 d</td>
</tr>
<tr>
<td>Man C*</td>
<td>0.21</td>
<td>~ 3 d</td>
<td>~ 300 d</td>
</tr>
<tr>
<td>Man D*</td>
<td>0.20</td>
<td>~ 1.5 d</td>
<td>~ 430 d</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.1</td>
<td>~ 10 min</td>
<td>~ 140 d</td>
</tr>
</tbody>
</table>

*Values from volunteer studies using \(^{237+244}\text{Pu}\) (Etherington et al 2002; Hodgson et al 2002)
Lung Retention of inhaled Pu nitrate

Fraction of inhaled

Days

0 60 120 180 240 300 360

0 0.01 0.02 0.03 0.04 0.05 0.06 0.07

Type S
Type M
Man C
Man D
Pu Nitrate: Lung Monitoring after acute intake

Minimum detectable dose (Sv) after acute intake

<table>
<thead>
<tr>
<th>Days</th>
<th>Man C</th>
<th>Man D</th>
<th>Type M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>7</td>
<td>1.3</td>
<td>1.3</td>
<td>1.9</td>
</tr>
<tr>
<td>30</td>
<td>1.7</td>
<td>1.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

MDA: 3 kBq
Urinary Excretion of inhaled Pu Nitrate

Fraction of Inhaled

Days

0 60 120 180 240 300 360

Type S

Type M

Man D
## Pu Nitrate: Urine Assay

Minimum detectable dose (mSv) after acute intake

<table>
<thead>
<tr>
<th>Days</th>
<th>Man C</th>
<th>Man D</th>
<th>Type M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.12</td>
<td>0.07</td>
<td>0.014</td>
</tr>
<tr>
<td>7</td>
<td>0.09</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td>30</td>
<td>0.45</td>
<td>0.54</td>
<td>0.34</td>
</tr>
</tbody>
</table>

MDA: 1 mBq d⁻¹
Faecal Excretion of inhaled Pu Nitrate

![Graph showing the excretion of Pu nitrate in faeces over days. The graph plots fraction of inhaled radioactivity against days, with logarithmic scales for the y-axis showing fractions from $10^{-6}$ to $10^{-1}$. The x-axis represents days from 0 to 360.]
Pu Nitrate: Feecal Assay

Minimum detectable dose ($\mu$Sv) after acute intake

<table>
<thead>
<tr>
<th>Days</th>
<th>Man C</th>
<th>Man D</th>
<th>Type M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>7</td>
<td>8.6</td>
<td>8.4</td>
<td>14</td>
</tr>
<tr>
<td>30</td>
<td>80</td>
<td>74</td>
<td>115</td>
</tr>
</tbody>
</table>

MDA: 1 mBq d$^{-1}$
Summary: Pu Nitrate

Acute exposure

- Lung monitoring - *is of little practical value*
- Urine assay – *doses 0.1 mSv up to 7 d after intake*
- Faecal assay – *doses < 0.1 mSv up to 30 d after intake*
Uncertainties in biokinetic modelling

Particle size
Lung retention; ICRP Type M compound

Fraction of inhaled vs Days

- 10 µm
- 5 µm
- 1 µm

Days: 0 60 120 180 240 300 360

Fraction of inhaled: 0.12 0.10 0.08 0.06 0.04 0.02 0.00
Minimum Detectable Doses for Plutonium Nitrate

Days after intake

Dose, Sv

Minimum Detectable Doses for Plutonium Nitrate

Days after intake

Dose, Sv

Minimum Detectable Doses for Plutonium Nitrate

Days after intake

Dose, Sv

Minimum Detectable Doses for Plutonium Nitrate

Days after intake

Dose, Sv
Minimum Detectable Doses for Plutonium Dioxide

Dose, Sv

Days after intake

Range

Type S

Urine

Faeces

Minimum Detectable Doses for Plutonium Dioxide

Dose, Sv

Days after intake

Range

Type S

Urine

Faeces
Uncertainties in biokinetic modelling

Systemic retention half-time
Practical example

Acute and Repeated Inhalation Exposure to Cs-137
Assessment of Intake and Dose after Inhalation of Caesium-137 by Workers and Adult Members of the Public

N Stradling, A Hodgson, T Fell, T Smith, G Etherington, and T Rahola

NRPB Chilton, STUK Helsinki

NRPB-W51
Obtainable as PDF from NRPB website - nrpb.org
Absorption from Lungs and Body Retention of Caesium

Assumptions

• Absorption
  Default Type F- *but can vary between default Types F and M* (ICRP 78, 1997)

• Body Retention
  Half-times of 2 d (10%) and 110 d (90%)- *but longer term half-time can vary from about 50 d to 150 d* (ICRP 56, 1989)
Acute Intake: MDA 100 Bq Whole Body

Minimum dose (Sv)

Days

- F default
- F 50d
- F 150d
- M default
- M 50d
- M 150d

IRPA 11 Refresher Course 5b
Programmes for Internal Dose Monitoring” Part 1: Basic Aspects and Essential Elements

K Henrichs
Whole Body Monitoring: Acute Exposure to Type F compound

<table>
<thead>
<tr>
<th>Days</th>
<th>Dose (µSv) for systemic half-time of:</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 days</td>
<td>110 days</td>
</tr>
<tr>
<td>7</td>
<td>0.83</td>
</tr>
<tr>
<td>30</td>
<td>1.2</td>
</tr>
</tbody>
</table>

MDA of 100 Bq
Whole Body Monitoring: Acute Exposure to Type M compound

<table>
<thead>
<tr>
<th>Days</th>
<th>Dose (µSv) for systemic half-time of;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 days</td>
</tr>
<tr>
<td></td>
<td>110 days</td>
</tr>
<tr>
<td></td>
<td>150 days</td>
</tr>
<tr>
<td>7</td>
<td>5.5</td>
</tr>
<tr>
<td>30</td>
<td>7.1</td>
</tr>
<tr>
<td>90</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>MDA of 100 Bq</td>
</tr>
</tbody>
</table>
Acute Intake: MDA 1 Bq d^{-1} in Urine
Urine assay: Acute Exposure to Type F compound

<table>
<thead>
<tr>
<th>Days</th>
<th>Dose (µSv) for systemic half-time of:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 days</td>
</tr>
<tr>
<td>7</td>
<td>0.54</td>
</tr>
<tr>
<td>30</td>
<td>1.9</td>
</tr>
</tbody>
</table>

MDA of 1 Bq d⁻¹
Urine assay: Acute Exposure to **Type M** compound

<table>
<thead>
<tr>
<th>Days</th>
<th>Dose (µSv) for systemic half-time of:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 days</td>
</tr>
<tr>
<td>7</td>
<td>6.9</td>
</tr>
<tr>
<td>30</td>
<td>12</td>
</tr>
<tr>
<td>90</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>110 days</td>
</tr>
<tr>
<td>12</td>
<td>22</td>
</tr>
<tr>
<td>29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150 days</td>
</tr>
<tr>
<td>15</td>
<td>31</td>
</tr>
<tr>
<td>36</td>
<td></td>
</tr>
</tbody>
</table>

MDA of 1 Bq d⁻¹
Intake Model for Repeated Exposure

- Maximum
- Mid-point
- Random
- Uniform chronic
- Minimum

Monitoring interval

Bq

7 d

Bq

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Programmes for Internal Dose Monitoring" Part 1:Basic Aspects and Essential Elements  K Henrichs
### Whole Body Monitoring: Repeated Exposure to Type F compound

<table>
<thead>
<tr>
<th>Days</th>
<th>Mid-point intake</th>
<th>Maximum dose (µSv) for systemic half-time of;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>110 days</td>
<td>50 days</td>
</tr>
<tr>
<td>90</td>
<td>2.1</td>
<td>2.7</td>
</tr>
<tr>
<td>180</td>
<td>2.8</td>
<td>9.3</td>
</tr>
<tr>
<td>360</td>
<td>4.9</td>
<td>115</td>
</tr>
</tbody>
</table>

**MDA of 100 Bq**
### Urine assay: Repeated Exposure to Type F compound

<table>
<thead>
<tr>
<th>Days</th>
<th>Mid-point intake 110 days</th>
<th>Maximum dose (µSv) for systemic half-time of;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>50 days</td>
</tr>
<tr>
<td>90</td>
<td>4.1</td>
<td>2.4</td>
</tr>
<tr>
<td>180</td>
<td>5.5</td>
<td>8.4</td>
</tr>
<tr>
<td>360</td>
<td>9.6</td>
<td>102</td>
</tr>
</tbody>
</table>

MDA of 1 Bq d⁻¹
Whole Body Monitoring: Repeated Exposure to Type M compound

<table>
<thead>
<tr>
<th>Days</th>
<th>Mid-point intake 110 days</th>
<th>Maximum dose (µSv) for systemic half-time of; 50 days</th>
<th>110 days</th>
<th>150 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>7.9</td>
<td>13</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>180</td>
<td>10</td>
<td>27</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td>360</td>
<td>16</td>
<td>36</td>
<td>40</td>
<td>30</td>
</tr>
</tbody>
</table>

MDA of 100 Bq
## Urine assay: Repeated Exposure to Type M compound

<table>
<thead>
<tr>
<th>Days</th>
<th>Mid-point intake</th>
<th>Maximum dose (µSv) for systemic half-time of;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>50 days</td>
</tr>
<tr>
<td>90</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>180</td>
<td>29</td>
<td>49</td>
</tr>
<tr>
<td>360</td>
<td>43</td>
<td>198</td>
</tr>
</tbody>
</table>

MDA of 1 Bq d⁻¹
Cs-137: Repeated Intake: Whole Body

Error (cf default Type F)

- F 50d
- F 150d
- M default
- M 50d
- M 150d

Monitoring interval (days)
Cs-137: Urine Assay: Repeated Intake

Error (cf Type F default)

Monitoring interval (days)

F 50d
F 150d
M default
M 50d
M 150d
Summary - Inhalation of Cs

Acute exposure

- **WBM and urine assay can be used for assessing doses less than 1 mSv irrespective of absorption parameter values**

Repeated exposure

- **WBM can be used to assess doses of less than 1 mSv y⁻¹ with monitoring interval of 180 d, irrespective of absorption parameter values**

- **Urine assay can be used to assess doses of less than 1 mSv y⁻¹ with monitoring interval of 180 d provided background levels are low (say less than 10 Bq d⁻¹) and default Type M biokinetics can be excluded**