UNIT 5
DIRECT METHODS FOR THE MONITORING OF INTERNAL EXPOSURES
DIRECT METHODS FOR INDIVIDUAL MONITORING

CONTENTS OF LECTURE

• METHODS FOR INDIVIDUAL MONITORING AND WORKPLACE MONITORING OF INTERNAL EXPOSURES

• DIRECT METHODS FOR INDIVIDUAL MONITORING: IN VIVO MONITORING OF RADIONUCLIDES.
  ✓ Whole-body and partial-body (organ) activity measurements.
DIRECT METHODS FOR INDIVIDUAL MONITORING

• METHODS FOR INDIVIDUAL MONITORING AND WORKPLACE MONITORING OF INTERNAL EXPOSURES

The doses due to intakes of radionuclides can not be obtained directly from measurements but must be assessed from:

DIRECT METHODS - monitoring of internal exposures

✓ In-vivo measurements of the retained activity $M(Bq)$ in total body or organs, using Whole/partial Body Counters

IN DIRECT METHODS - monitoring of internal exposures

✓ In-vitro measurements of the activity concentration in excreta samples $M(Bqd^{-1}, BqL^{-1})$

✓ Workplace monitoring – Air sampling. Activity concentration in the air $M(Bqm^{-3})$

Or by a combination of these methods
The choice of monitoring technique mainly depends on:

- Type of radiation and energy emitted by the radionuclide and its progeny
- The half life of the radionuclide and the chemical compound
- Metabolic behaviour of the contaminant inside the body: retention/excretion rate depending on the time after intake
- Total/partial (organ) deposition and excretion pathway of the contaminant
- Sensitivity and feasibility of the measurement method
DIRECT METHODS FOR INDIVIDUAL MONITORING

✓ DIRECT METHODS FOR INDIVIDUAL MONITORING: IN VIVO MONITORING OF RADIONUCLIDES.
✓ Whole-body and partial-body (organ) activity measurements

- In vivo measurements of x-rays and gamma emitter radionuclides internally deposited in the body, using $\gamma$ spectrometry.
- Measurement of the Activity retained in total body or in organs/tissues of the body $M$ (Bq) at the time of monitoring, $t_m$ (days) after the intake.
- The counting geometry (total body, lungs, thyroid, bone,...) depends on the biokinetics of the incorporated radionuclide and retention place at the monitoring time ($t_m$ in days) after the intake.
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• DIRECT METHODS: IN VIVO MONITORING OF RADIONUCLIDES.

✓ In-vivo monitoring system consist of:

  ▪ **Shielding** (reduction of the background)
  ▪ **Detectors:**
    o Scintillators: NaI(Tl), Phoswich – high counting efficiency
    o Semiconductors: HPGe – high spectral resolution, they need to be cooled (e.g. with liquid nitrogen)
  ▪ **Electronic instrumentation** processes the signals generated from the interaction of photons (from internal emitters) with the detector system. The result of a measurement is an energy spectrum
  ▪ **Gamma Spectrometry software**

✓ The objective: identification and quantification (activity, Bq) of the radionuclides inside the body
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• DIRECT METHODS: IN VIVO MONITORING OF RADIONUCLIDES.

Whole/partial body counting. NaI(Tl) and HPGe detectors. Gamma Spectrometry

| (1) Shielded room | (2) Whole Body Counter / Mobile Units |
DIRECT METHODS FOR INDIVIDUAL MONITORING

• DIRECT METHODS: IN VIVO MONITORING OF RADIONUCLIDES

✓ In-vivo measurements of gamma emitters distributed in total-body:
  ▪ Determination of fission and activation products and other radionuclides deposited in the whole body.
  ▪ Calibration Phantom: surrogate of the human body, fabricated with tissue-equivalent material, filled with a known radioactive source of radionuclides (e.g. $^{57}$Co, $^{37}$Cs, $^{60}$Co,...) covering the range of energy of interest (e.g. 100-3000 keV), e.g. BOMAB
**DIRECT METHODS FOR INDIVIDUAL MONITORING**

**DIRECT METHODS: IN VIVO MONITORING OF RADIONUCLIDES.**

- **In-vivo measurements of gamma emitters in lungs**
  - In vivo measurement of radionuclides with long residence times in the lung (e.g. U oxides, insoluble Pu, $^{241}$Am: typical $\alpha$ emitters).
  - Detection of Xray, $\gamma$ photons (typically $E < 200$ keV in case of actinides)
  - HPGe detectors (high spectral resolution) and Phoswich detectors

**Lung Calibration:**

- Livermore (LLNL, USA) phantom or JAERI (Japan) Phantom. Anthropomorphic simulators of the human torso of an adult male
- Pairs of lungs with radioactive sources, tissue equivalent material
- Set of chest plates of ribs, muscle and fat, with different chest thickness
- Counting Efficiency mainly depending on Energy and chest wall thickness.
DIRECT METHODS FOR INDIVIDUAL MONITORING

- DIRECT METHODS: IN VIVO MONITORING OF RADIONUCLIDES.

✓ In-vivo measurements of radioiodine in thyroid

- \(^{131}\text{I}\): gamma emitter with a main photopeak of 364.5 keV. Calibration Source: \(^{131}\text{I}\) or \(^{133}\text{Ba}\) (mainly same emissions as \(^{131}\text{I}\), longer half life)

- \(^{125}\text{I}\): detection of the X-ray emissions of 27.1 keV or/and of the low-energy gamma photopeak of 35.5 keV. Calibration Source: \(^{125}\text{I}\) or \(^{129}\text{I}\) (mainly same emissions as \(^{125}\text{I}\), longer half life)

ANSI Thyroid Phantom,
Bottle of 20 ml with either \(^{131}\text{I}\) or \(^{125}\text{I}\) for thyroid calibration of an adult male
(ANSI/HPS N13.44-2014)

Livermore Thyroid Phantom,
Representing the neck and the thyroid gland of an adult male
(LLNL Lawrence Livermore Nat Lab US)
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- Calibration of in-vivo monitoring systems:
  ✓ Energy and FWHM Calibration
  ✓ Counting Efficiency calibration

- Calibration Phantom: simulating the body and/or the organs of interest, filled or labelled with appropriate radioactive sources of radionuclide(s), with known activity distributed in the simulated total-body or organ of interest

(BOMAB phantom ANSI /HPS N3,35)

Result of the in vivo measurement:
Gamma Spectrum - n° detected pulses (counts) vs. Energy (keV) of emitted photons
• Calibration of in-vivo monitoring systems:

✓ Energy calibration: Centroid of the peak in the spectrum is associated with the energy of the photons of the source: 

\[ E(\text{keV}) = a \times \text{channel} + b \]

FWHM: Full Width at Half Maximum of the spectral peak

✓ FWHM Calibration: FWHM of the peak in the spectrum depends on the energy of the photons from the calibration source

FWHM(keV) = 5.847 + 2.319E^{1/2}
Counting Efficiency (Eff in counts/photon) depends on the energy E(keV) of γ photons:

\[ \text{Ln Eff (c/ph)} = \sum b_i (\text{Ln E (keV)})^i \]

Efficiency Calibration Curves

\[ \text{Eff (cps/Bq)} = \frac{\text{Area (n\textdegree counts)/E(keV)}}{\text{t(s)}} \]

\[ \text{Eff (c/photon)} = \frac{\text{Area (n\textdegree counts)/t(s)}}{\text{Activity (Bq)} \times I_E} \]
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- In vivo monitoring of an exposed person allows the identification and quantification of the incorporated radionuclides by gamma spectrometry, and the assessment of the Activity retained in the body.

- **Identification of radionuclides**: Energy calibration allows the association of the channel of the photopeak in the spectrum with the Energy of the photons emitted by the contaminants inside the body.

- **Assessment of the Activity** of the radionuclides detected. Efficiency calibration is used:

  \[ \text{Activ (Bq)} = \frac{\text{Area}_{\text{peak E(keV)}}}{\text{T(s) * Eff(c/ph)*} I_e} \]

- **Uncertainty (Type A, counting statistics)**:

  \[ \sigma = \text{Activ (Bq)} * \sqrt{\frac{2^2}{\text{cps} * \text{T(s)}} + \frac{\text{ErrEff}^2}{\text{Eff}^2}} \]
Naturally occurring radionuclides

- Potassium-40 \(^{40}\text{K}\) is a naturally occurring radionuclide of potassium with an isotopic abundance of 0.0117%. It emits a 1.46 MeV (0.6%).

- Potassium is present in all living things, being physiologically necessary for their function.

- The human body generally contains between 2 and 5 kBq of \(^{40}\text{K}\) (closer to 5 kBq in young males), distributed throughout the body.

- Potassium-40 is detected by most in vivo measurements of workers and members of the public, and its presence is clearly identified in the resulting gamma spectrum.
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- Radiopharmaceuticals in Nuclear Medicine

✓ ISO 16637 Radiological protection — Monitoring and internal dosimetry for staff members exposed to medical radionuclides as unsealed sources

- $^{131}$I: high risk of intake when handling unsealed sources. It is the largest cause of internal doses to nuclear medicine workers.

- Triage monitoring or
- Individual confirmatory monitoring (in vivo measurements or urine radiobioassay) recommended to confirm adequacy of protective measures and level of exposures.
  - on-site in vivo measurements of radionuclides in the body are recommended (e.g. for $^{99m}$Tc or $^{18}$F), in whole body counters near the nuclear medicine unit or by mobile body counters performing measurements.
  - Nuclear medicine units may use own devices to perform monitoring of workers involved in a radiiodine handling procedure (e.g. gamma cameras or thyroid probes).
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- ISO 28218 Standard “Performance criteria for radiobioassay”
  - Decision Threshold (y*)
    - Fixed value of the measurand by which, when exceeded by the result of an actual measurement of a measurand quantifying a physical effect, it is decided that the physical effect is present.
    - The decision threshold provides a way of distinguishing the difference between the count rate from the measurand under analysis and the count rate from the appropriate blank.
  - Detection Limit (y#)
    - Smallest true value of the measurand that is detectable by a measuring method.
    - The value of the detection limit indicates the ability of the laboratory to detect a radionuclide in a sample (urine, feces,…) or in a person.

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- Detection Limit ($y#$)

ISO 28218 – Annex B

$y^# = 2k_{1-\alpha}\sqrt{\left(\frac{1}{t\cdot\varepsilon}\right)^2 + \left(\frac{P}{2m}\cdot n_0 + \left(\frac{P}{2m}\right)^2 n_0\right) + k^2_{1-\alpha}\left(\frac{1}{t\cdot\varepsilon}\right)}$

1. $\varepsilon = 1 - k^2_{1-\alpha}\left(\frac{u(\varepsilon)}{(\varepsilon)}\right)^2$

$A_B = \frac{n_p - \frac{P}{2m} n_0}{t\cdot\varepsilon}$

ISO28218
Annex B
Example B1: Direct measurement of an internal contamination (gamma emmitters) with WBC (lineal background)
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Detection Limit ($y^\#$)

\[
y^\# = \frac{2k_{1-\alpha} \sqrt{\left(\frac{1}{t \cdot \varepsilon}\right)^2 \left(\frac{p}{2m} n_0 + \left(\frac{p}{2m}\right)^2 n_0\right)} + k_{2-1-\alpha}^2 \left(\frac{1}{t \cdot \varepsilon}\right)}{1 - k_{2-1-\alpha}^2 \left(\frac{u(\varepsilon)}{(\varepsilon)}\right)^2} \approx 1
\]

Minimum Detectable Activity (MDA) - (ANSI 13.30)

\[
MDA = \frac{L_D}{t \cdot \text{Eff.} \cdot Ie} = \frac{K^2 + 2L_C}{t \cdot \text{Eff.} \cdot Ie}
\]

\[
B = \mu_B = \frac{N}{2 \cdot n} (B_1 + B_2)
\]

\[
L_C = k \cdot \sqrt{B + \left(\frac{N}{2 \cdot n}\right)^2 (B_1 + B_2)} =
\]

\[
L_C = k \cdot \sqrt{\left(\frac{N}{2 \cdot n}\right) (B_1 + B_2) + \left(\frac{N}{2 \cdot n}\right)^2 (B_1 + B_2)^2}
\]

\[
MDA(Bq) = \frac{k^2 + 2k \cdot \sqrt{\left(\frac{N}{2 \cdot n}\right) (B_1 + B_2) + \left(\frac{N}{2 \cdot n}\right)^2 (B_1 + B_2)^2}}{t \cdot \text{Eff.} \cdot Ie}
\]

MDA - Currie

ISO 28218

Detection Limit ($y^\#$)

Minimum Detectable Activity (MDA) - (ANSI 13.30)
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• Uncertainties - in vivo monitoring

✓ Measurement uncertainties arise from counting statistics, characterised with a Poisson or Gaussian distribution (Type A uncertainties), and Type B uncertainties which contain all uncertainties other than Type A. Type B uncertainties cannot be determined empirically but rather are evaluated assuming a single lognormal distribution.

✓ In vivo measurements: common sources of Type B uncertainty include variations of
  (1) detector/person positioning,
  (2) background signals,
  (3) body dimensions,
  (4) overlying structures,
  (5) activity distribution,
  (6) calibration process and
  (7) spectrum evaluation.
The IDEAS Guidelines and ISO 27048 standard describe and analyse the components of uncertainties in in vivo bioassay measurements and propose a method for quantification of measurement uncertainties by applying a "scattering factor" (SF = geometric standard deviation of the lognormal distribution).

In cases where the Type A uncertainties are relatively small (less than 30%), both Type A and Type B uncertainties can be approximated by lognormal distributions. The total SF for the lognormal distribution describing the overall uncertainty for measurement M is given by:

$$SF = \exp\left[\ln(SF_A)^2 + \ln(SF_B)^2\right]$$

where SF_A and SF_B are the scattering factors for Type A and B uncertainties, respectively.
### Uncertainties - ISO 27048:2011 - Scattering Factors for in vivo monitoring

**Table B.1 — Typical values for the components of lognormal uncertainty for in vivo measurements of radionuclides emitting low, intermediate and high photon energy radiation (taken from [21][24])**

<table>
<thead>
<tr>
<th>Source of uncertainty (type)</th>
<th>Lognormal scattering factor, $\kappa_{SF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low photon energy $E &lt; 20$ keV</td>
</tr>
<tr>
<td>Counting statistics (A)</td>
<td>1.5</td>
</tr>
<tr>
<td>Variation of detector positioning (B)</td>
<td>1.2</td>
</tr>
<tr>
<td>Variation of background signal (B)</td>
<td>1.5</td>
</tr>
<tr>
<td>Variation in body dimensions (B)</td>
<td>1.5</td>
</tr>
<tr>
<td>Variation of overlaying structures (B)</td>
<td>1.3</td>
</tr>
<tr>
<td>Variation of activity distribution (B)</td>
<td>1.3</td>
</tr>
<tr>
<td>Calibration (B)</td>
<td>1.05</td>
</tr>
<tr>
<td>Spectrum evaluation$^a$ (B)</td>
<td>1.15</td>
</tr>
</tbody>
</table>

$^a$ High purity germanium detector spectra.

Taken from ISO27048, Annex B, Table B.1
• Numerical calibration of in vivo monitoring

✓ Numerical calibration techniques may be used as an alternative tool for in vivo measurement calibrations.

✓ Simulation of transport of photons from a numeric phantom to a mathematical-3D model of the detectors to be calibrated, using radionuclide decay data describing photon energies and yields.

✓ Generation of calibration factors for a wide range of scenarios. Flexible computational models of human bodies varying in gender, body height and mass have been used to study the morphology-induced variation of the detector efficiency.

Reference paediatric phantoms, ICRP publication 143
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• Numerical calibration of in vivo monitoring

✓ Measurements can be accurately simulated for both sexes, adults and children of different ages, for different statures (including different chest wall thicknesses), for any radionuclide distribution within the body, and for any detector type.

✓ Several codes for Monte Carlo simulations of radiation transport are available and have been applied to in vivo monitoring (e.g. EGSnrc, GEANT4, VMC and MCNP).

Reference Voxel phantoms
Adult male and female. ICRP Publication 110.
JM Gómez-Ros,
EURADOS Voxel School
• Numerical calibration of in vivo monitoring

✓ A higher degree of computational competence is required of the user.

✓ Currently, numerical techniques are rarely used for routine calibrations of *in vivo* measurements.

✓ Adequate **validation procedures** should be implemented which could be complex and need to be verified after any change of detectors.

✓ Validation of the method can be achieved by (i) validation of the modelling of the detector (counting geometry, materials, dead layer) and (ii) performing appropriate intercomparisons with physical phantom measurements using traceable radionuclide sources.
REFERENCES - UNIT 5 - DIRECT METHODS FOR INDIVIDUAL MONITORING


AMERICAN NATIONAL STANDARD / HEALTH PHYSICS SOCIETY. ANSI/HPS N44.3-1973 (R1984); Thyroid radioiodine uptake measurements using a neck phantom. McLean, VA: HPS; (2014).


REFERENCES - UNIT 5 - DIRECT METHODS FOR INDIVIDUAL MONITORING


