ASSESSMENT OF OCCUPATIONAL EXPOSURE DUE TO INTERNAL RADIATION SOURCES

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

DIRECT METHODS FOR INDIVIDUAL MONITORING

- 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 γ 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
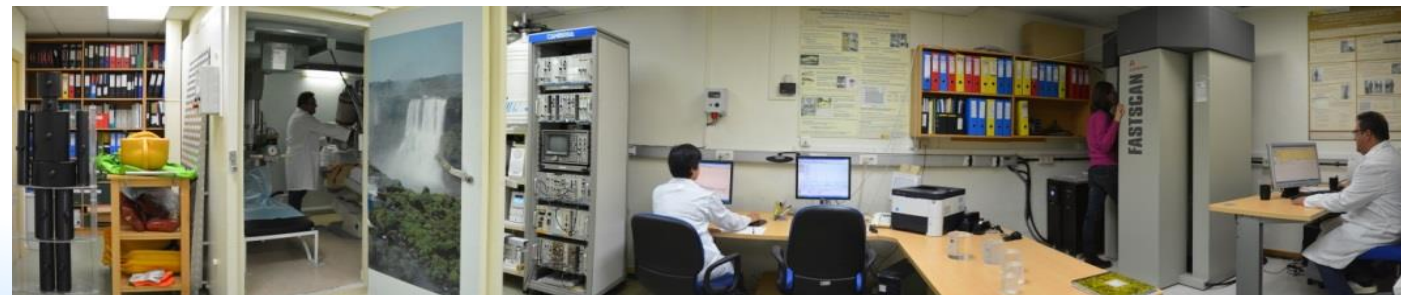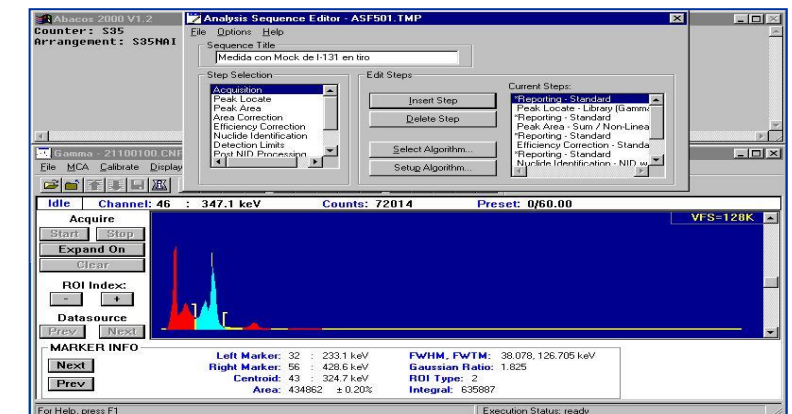
DIRECT METHODS FOR INDIVIDUAL MONITORING

- **DIRECT METHODS: IN VIVO MONITORING OF RADIONUCLIDES.**
  - ✓ **In-vivo monitoring system consist of:**

    - **Shielding** (reduction of the background)
    - **Detectors:**
      - Scintillators: NaI(Tl), Phoswich – high counting efficiency
      - 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

DIRECT METHODS FOR INDIVIDUAL MONITORING

- **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. ICRU Report 69

  - ✓ **In-vivo measurements of gamma emitters distributed in <u>total-body</u>:**

    - ▪ 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
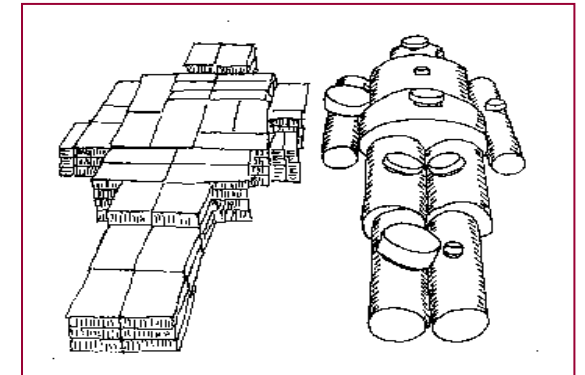

Brick Phantom

BOMAB Phantom (ANSI/HPS N13.35)

(BOMAB - Bottle Manikin Absorption Phantom)

Reference adult male

8

DIRECT METHODS FOR INDIVIDUAL MONITORING

- ## DIRECT METHODS: IN VIVO MONITORING OF RADIONUCLIDES.

  - ✓ **In-vivo measurements of gamma emitters in <u>lungs</u>**

    - In vivo measurement of radionuclides with long residence times in the lung (e.g. U oxides, insoluble Pu, ^{241}Am,: typical α emitters).

    - Detection of Xray, γ 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.
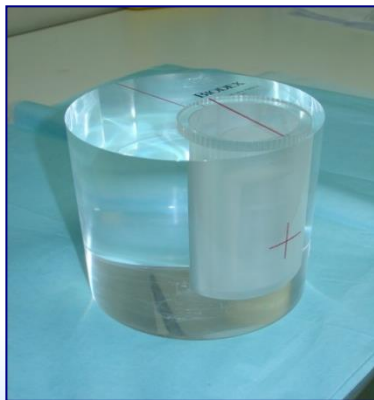

(LLNL Lawrence Livermore Nat Lab US)

(JAERI Japan Atomic Energy Agency)

DIRECT METHODS FOR INDIVIDUAL MONITORING

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

  ✓ **In-vivo measurements of radioiodine in <u>thyroid</u>**

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

  - **^{125}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}I or ^{129}I (mainly same emissions as ^{125}I, longer half life)

ANSI Thyroid Phantom,

Bottle of 20 ml with either ^{131}I or ^{125}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)

DIRECT METHODS FOR INDIVIDUAL MONITORING

IAEA

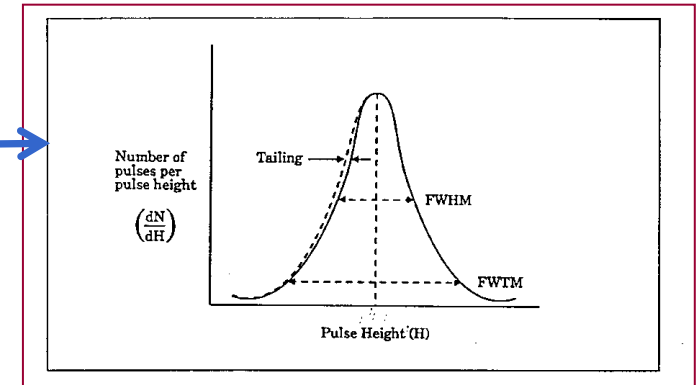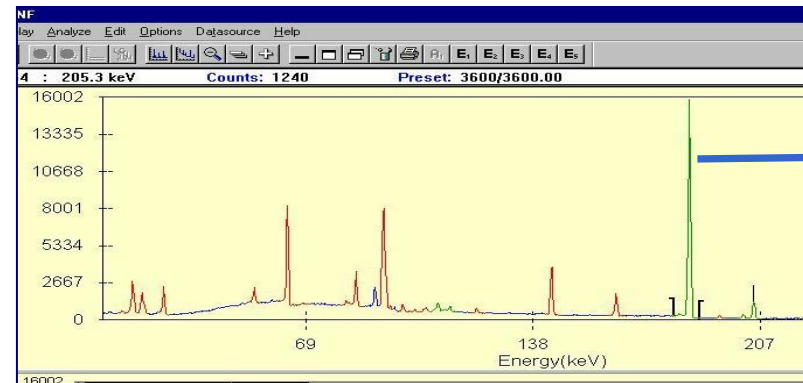- **Calibration of in-vivo monitoring systems:**

  ✓**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
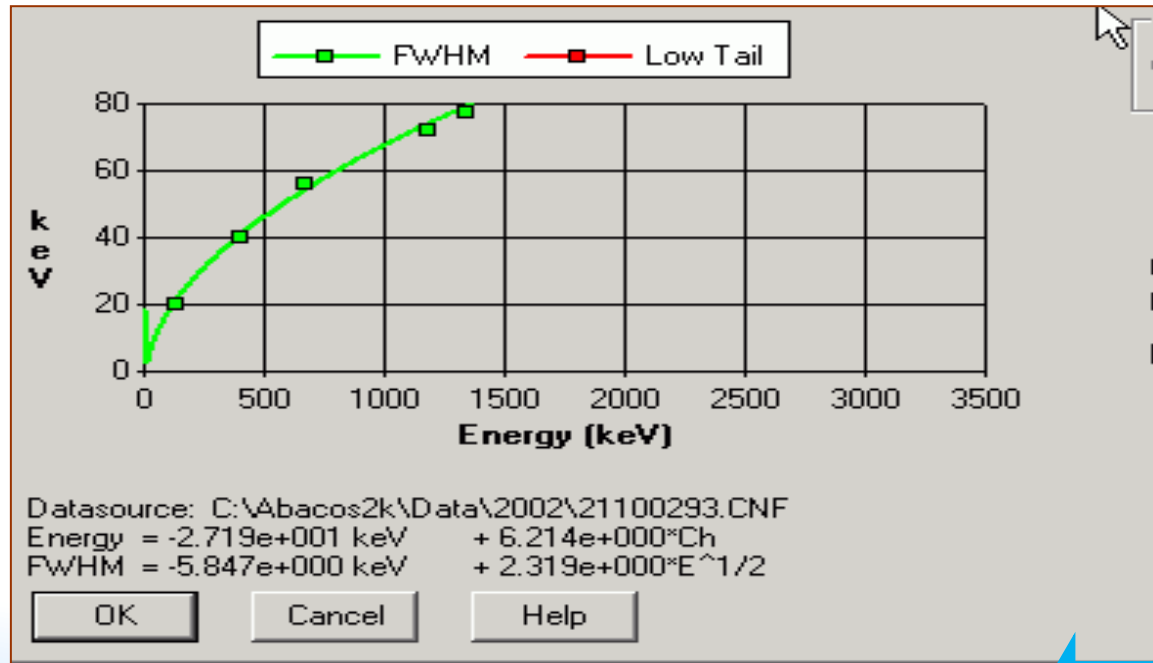

(BOMAB phantom ANSI /HPS N3,35)

Result of the in vivo measurement :
Gamma Spectrum - nº detected pulses (counts) vs. Energy (keV) of emitted photons
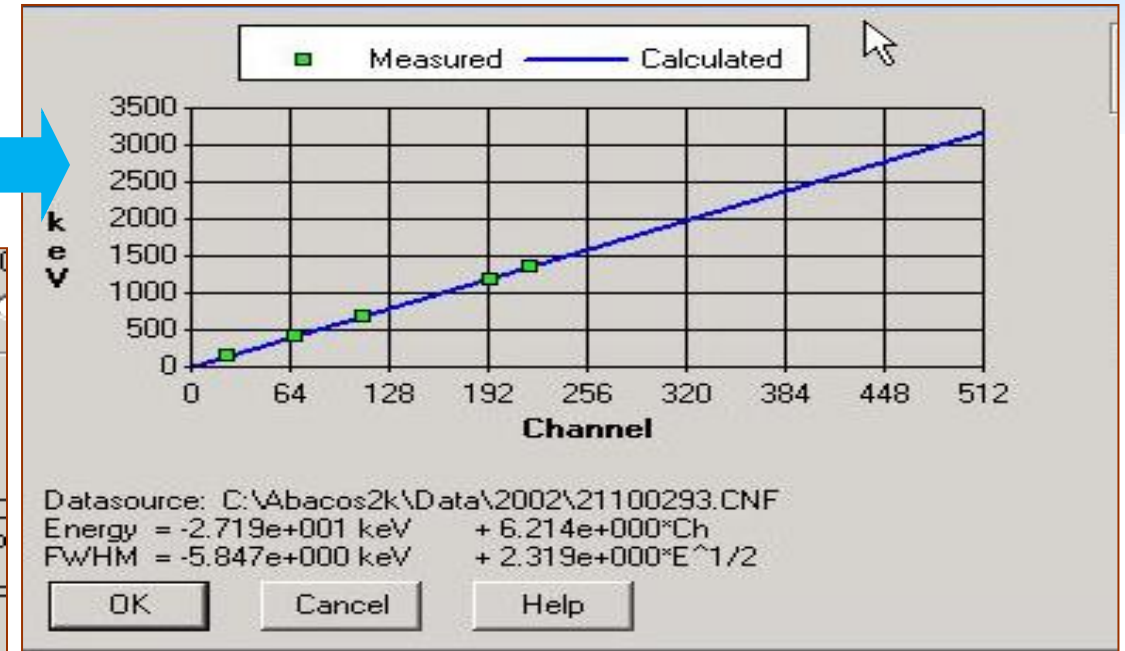
DIRECT METHODS FOR INDIVIDUAL MONITORING

- **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(keV)= a*channel + b**

Datasource: C:\Abacos2k\Data\2002\21100293.CNF
Energy = -2.719e+001 keV   + 6.214e+000*Ch
FWHM = -5.847e+000 keV   + 2.319e+000*E^1/2

Datasource: C:\Abacos2k\Data\2002\21100293.CNF
Energy = -2.719e+001 keV   + 6.214e+000*Ch
FWHM = -5.847e+000 keV   + 2.319e+000*E^1/2

FWHM(keV)= 5.847 + 2.319E$^{1/2}$

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**

12

DIRECT METHODS FOR INDIVIDUAL MONITORING

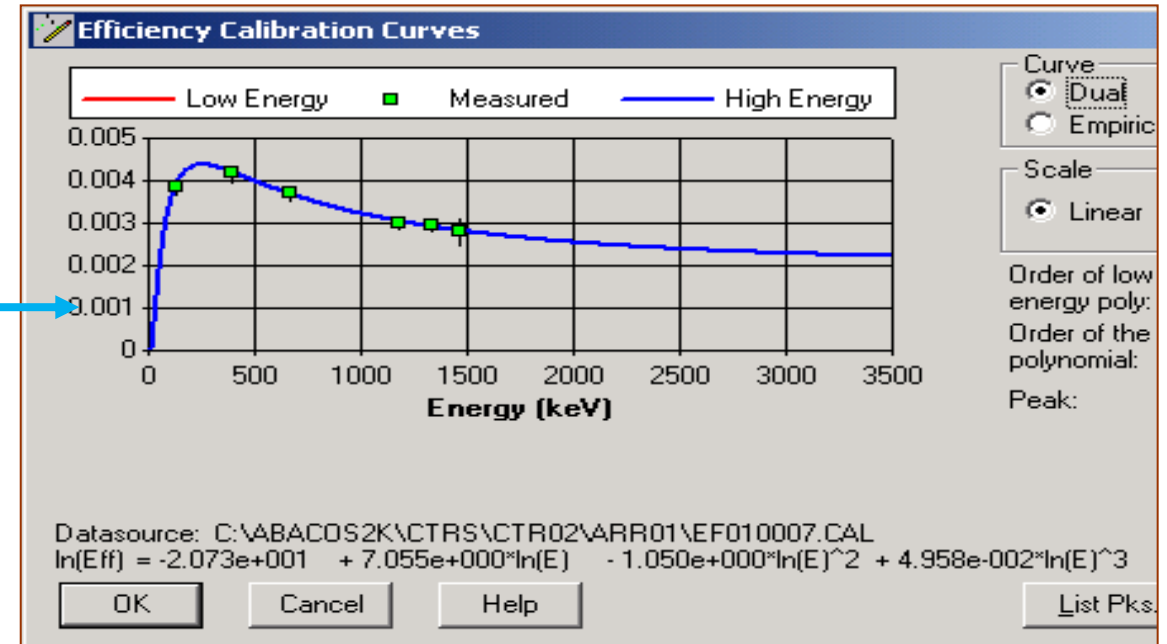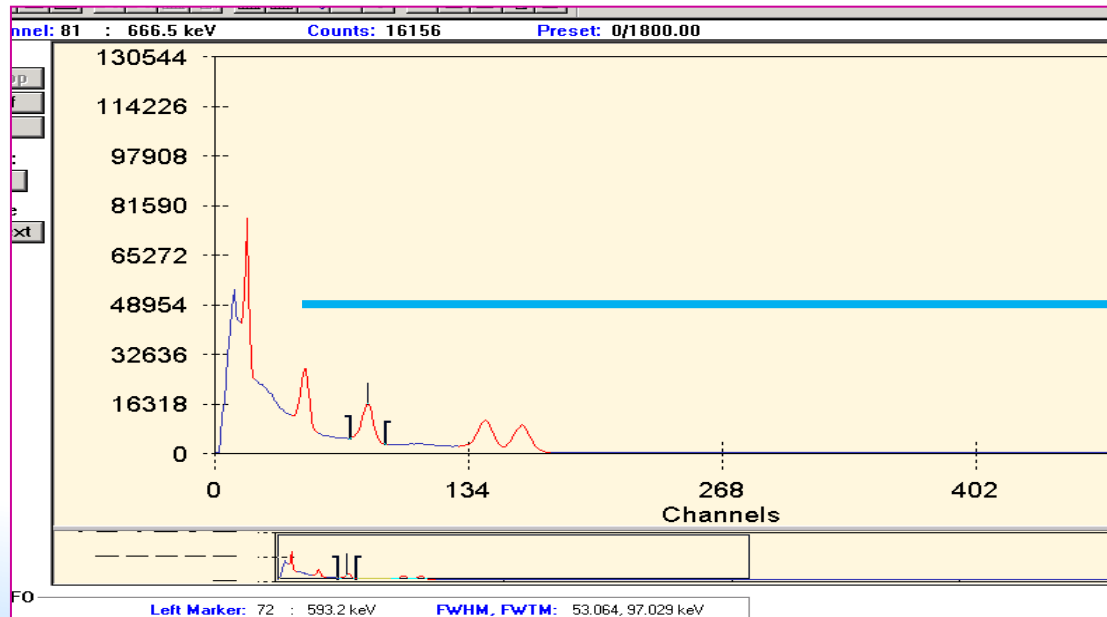- **Calibration of in-vivo monitoring systems:**
  - ✓ **Counting Efficiency calibration:**

    Counting Efficiency (Eff in counts/photon) depends on the energy E(keV) of γ photons:

    Ln Eff (c/ph) = Σ bᵢ (Ln E (keV))ⁱ

$$Eff\,(cps/Bq) = \frac{Area(n^{\circ}counts)_{E(keV)} \Big/ t(s)}{Activity(Bq)}$$

$$Eff\,(c/photon) = \frac{Area(n^{\circ}counts) \Big/ t(s)}{Activity(Bq) * I_{E}}$$

DIRECT METHODS FOR INDIVIDUAL MONITORING

- **In vivo monitoring of an exposed person allows the identification and quantification of the incorporated radionuclides by gamma spectrometry, and the <u>assessment of the Activity retained in the body</u>.**

    - ✓ **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 :**

$$Activ(Bq) = \frac{Area_{peak\ E(keV)}}{T(s) * Eff(c/ph) * I_e}$$

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

$$\sigma = Activ(Bq) * \sqrt{\frac{2^2}{cps * T(s)} + \frac{ErrEff^2}{Eff^2}}$$

DIRECT METHODS FOR INDIVIDUAL MONITORING

- **Naturally occurring radionuclides**

  - ✓ **Potassium-40** (^{40}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}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.

DIRECT METHODS FOR INDIVIDUAL MONITORING

- **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 radioiodine handling procedure (e.g. gamma cameras or thyroid probes).

DIRECT METHODS FOR INDIVIDUAL MONITORING
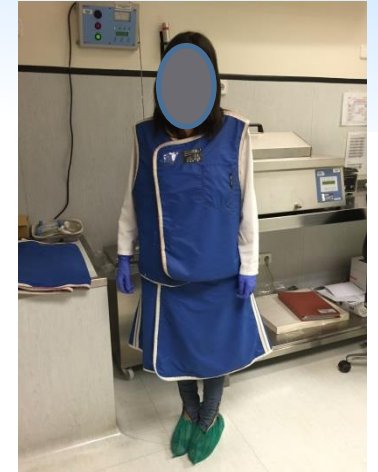
- **ISO 28218 Standard "Performance criteria for radiobioassay"**

  - ✓ **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.
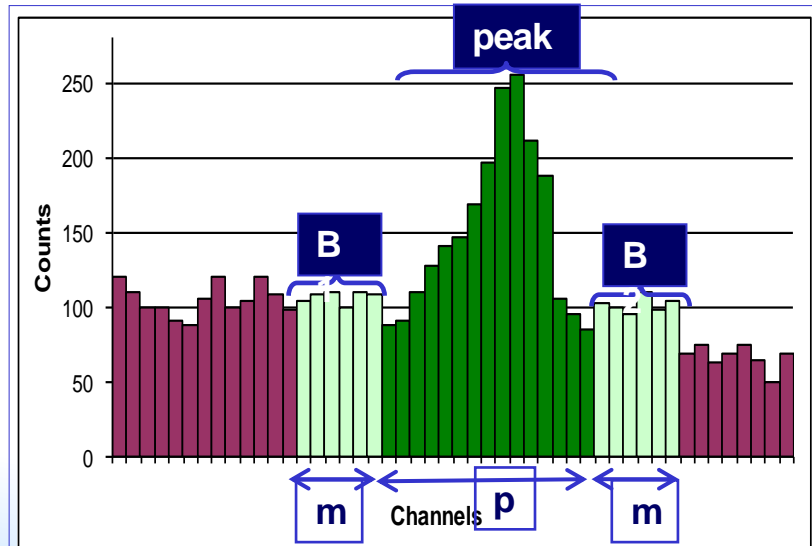
  - ✓ **Detection Limit (y#)**

    - ▪ 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.

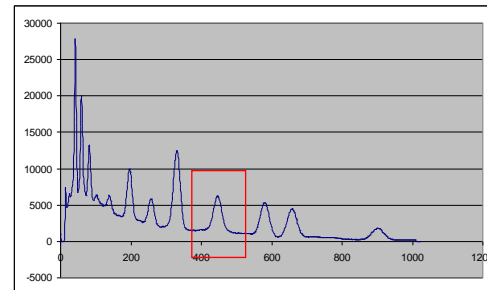# DIRECT METHODS FOR INDIVIDUAL MONITORING

- **Detection Limit (y#)**

  ISO 28218 – Annex B, "Detection Limit – Application examples"

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

$n_0 = B_1 + B_2$

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

ISO28218 Annex B Example B1: Direct measurement of an internal contamination (gamma emmitters) with WBC (lineal background)

DIRECT METHODS FOR INDIVIDUAL MONITORING

Detection Limit (y#)

ISO 28218

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

~ 1

Minimum Detectable Activity (MDA) - (ANSI 13.30)

MDA – Currie

$$MDA = \frac{L_D}{t.Eff.Ie} = \frac{K^2 + 2.L_C}{t.Eff.Ie}$$

$$B = \mu_B = \frac{N}{2.n}(B_1 + B_2)$$

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

$$L_C = k.\sqrt{\left(\frac{N}{2.n}\right)(B_1 + B_2) + \left(\frac{N}{2.n}\right)^2(B_1 + B_2)^2}$$

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

$\approx$

DIRECT METHODS FOR INDIVIDUAL MONITORING

- **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.

DIRECT METHODS FOR INDIVIDUAL MONITORING

- **Uncertainties - in vivo monitoring**

  ✓ 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:

  $$SF = \exp\sqrt{[\ln(SF_A)]^2 + [\ln(SF_B)]^2}$$

  where SF_A and SF_B are the scattering factors for Type A and B uncertainties, respectively.

DIRECT METHODS FOR INDIVIDUAL MONITORING

- **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])

| Source of uncertainty (type)	Lognormal scattering factor, K_{SF}		
	Low photon energy $E < 20$ keV	Intermediate photon energy 20 keV $< E < 100$ keV	High photon energy $E > 100$ keV
Counting statistics (A)	1,5	1,3	1,07
Variation of detector positioning (B)	1,2	1,05	<1,05
Variation of background signal (B)	1,5	1,1	<1,05
Variation in body dimensions (B)	1,5	1,12	1,07
Variation of overlaying structures (B)	1,3	1,15	1,12
Variation of activity distribution (B)	1,3	1,05	<1,05
Calibration (B)	1,05	1,05	1,05
Spectrum evaluation[a] (B)	1,15	1,05	1,03

[a] High purity germanium detector spectra.

Taken from ISO27048, Annex B, Table B.1

DIRECT METHODS FOR INDIVIDUAL MONITORING

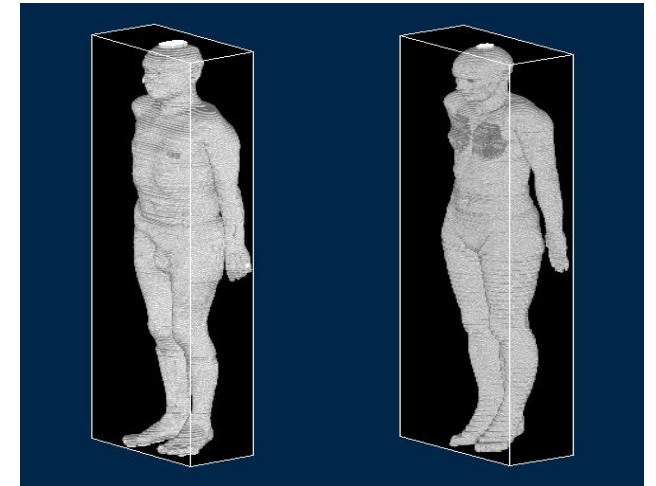- **Numerical calibration of in vivo monitoring**

  - ✓ **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.
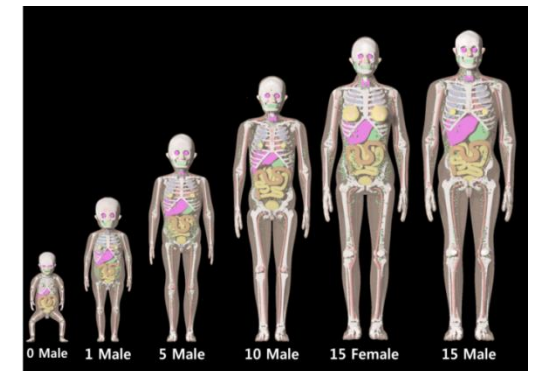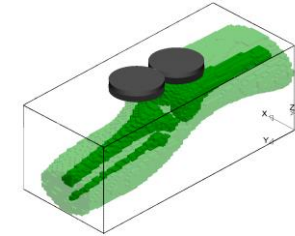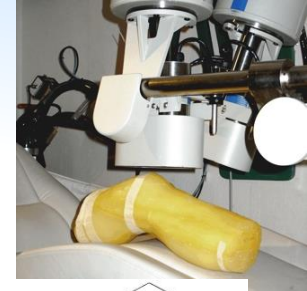
Reference paediatric phantoms, ICRP publication 143

DIRECT METHODS FOR INDIVIDUAL MONITORING

- **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

DIRECT METHODS FOR INDIVIDUAL MONITORING

- **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.

AMERICAN NATIONAL STANDARD / HEALTH PHYSICS SOCIETY. ANSI/HPS N.13.35. Specifications for the Bottle Manikin Absorption Phantom. Revision 09 (2009).

AMERICAN NATIONAL STANDARD / HEALTH PHYSICS SOCIETY. ANSI/HPS N13.30. Performance Criteria for Radiobioassay (2011).

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

EUROPEAN COMMISSION - RADIATION PROTECTION REPORT SERIES No.188 - Technical Recommendations for Monitoring Individuals for Occupational Intakes of Radionuclides (ec.europa.eu/energy/sites/ener/files/rp_188.pdf). EC RP 188 (2018).

INTERNATIONAL COMMISSION OF RADIATION UNITS AND MEASUREMENTS. Direct Determination of the Body Content of Radionuclides. ICRU Report 69, Journal of the ICRU 3 (1), (2003).

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Adult Reference Computational Phantoms. ICRP Publication 110. Ann. ICRP 39(2) (2009).

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Paediatric Computational Reference Phantoms. ICRP Publication 143. Ann. ICRP 49(1).(2020).

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. RADIATION PROTECTION – Monitoring of Workers Occupationally Exposed to a Risk of Internal Contamination with Radioactive Material. ISO 20553:2006. (ISO:Geneva) (2006)

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. RADIATION PROTECTION – Performance criteria for radiobioassay. ISO 28218:2010 (ISO: Geneva) (2010).

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. RADIATION PROTECTION – Dose assessment for the monitoring of workers for internal radiation exposure ISO 27048:2011 (ISO: Geneva) (2011).

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. RADIATION PROTECTION – Monitoring and internal dosimetry for staff exposed to medical radionuclides as unsealed sources. ISO 16637:2016 (ISO: Geneva) (2016).

[Griffith 1986] Griffith R. V., Anderson A. L., Dean, P. N., Fisher, J.C. and Sundbeck, C. W. Tissue-Equivalent Torso Phantom for Calibration of Transuranic-Nuclide Counting Facilities. Radiobioassay and Internal Dosimetry WorkShop, (Department of Energy: Albuquerque, New Mexico)(1986).

[Shirotani 1987] Shirotani, T. Development of realistic chest phantom for calibration of in-vivo plutonium counting facilities. Japan Atomic Energy Research Institute. JAERI-M 87-081 (1987).