RC-6

Internal Dosimetry
The science and art of internal dose assessment

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Abstract

Doses from intakes of radionuclides cannot be measured but must be assessed from monitoring, such as whole body counting or urinary excretion measurements. Such assessments require application of a biokinetic model and estimation of the exposure time, material properties, etc. Because of the variety of parameters involved, the results of such assessments may vary over a wide range, according to the skill and the experience of the assessor.

The refresher course gives an overview over the state of the art of the determination of internal dose. The first part of the course deals with the measuring techniques for individual incorporation monitoring i.e (i) direct measurement of activity in the whole body or organs, (ii) measurement of activity excreted with urine and faeces, and (iii) measurement of activity in the breathing zone or at the workplace, respectively. In the following part the biokinetic models used for the interpretation of the monitoring data are shortly described with special regard to the new models i.e. (i) the ICRP model for the human alimentary tract and (ii) the NCRP model for the biokinetics of radioactive materials in wounds. The third part of the course deals with the application of the models for the assessment of committed dose from incorporation monitoring data. This part is based mainly on the IDEAS General Guidelines, taking into account also the improvements of the guidelines provided by some follow-up projects.

Contents

1 Introduction

The determination of internal doses is an essential component of individual monitoring programmes for workers. It may also be needed for members of the public, who may have intakes of radionuclides in nuclear medicine and also in normal life following accidental releases of radionuclides into the environment. Assessment of internal doses can be divided into two phases, namely

- determination of the amount of radioactive material in the human body, in body organs or in wounds by direct measurements and/or by indirect methods such as excretion analysis or air monitoring,

- interpretation of the monitoring data in terms of intake and/or internal dose taking into account many influencing factors and assumptions, such as the physical and chemical characteristics of the radioactive substances, the mode of intake, the biokinetic and energy absorption processes, the individual parameters, etc.

The second phase is particularly important because of the number of variables and uncertainties involved. Although the International Commission on Radiological Protection (ICRP) and International Atomic Energy Agency (IAEA) have published extensive tables of dose per unit intake (dose coefficients), these are default values based on assumptions about the intake parameters that may not be valid in specific situations. Determination of the intake and the resulting internal dose can, therefore, be approached in many different ways, depending on the amount and quality of the data, the skill of the dosimetrist, computational tools available, and the assumptions made. When a set of bioassay data is given to two different dosimetrists, it is likely that these data will be interpreted differently, that different methods and dosimetric models will be applied, and therefore different numerical solutions will be obtained. Thus, it is important for laboratories dealing with internal dosimetry to undergo performance testing procedures in both phases of internal dosimetry to demonstrate the correctness of methods applied and also the consistency of the results with those obtained by other laboratories.

The refresher course gives an overview over the state of the art of the determination of internal dose with the main focus being put on the second phase. The first part of the course deals with the measuring techniques for individual incorporation monitoring i.e (i) direct measurement of activity in the whole body or organs, (ii) measurement of activity excreted with urine and faeces, and (iii) measurement of activity in the breathing zone or at the workplace, respectively. In the following part the biokinetic models used for the interpretation of the monitoring data are shortly described with special regard to the new models i.e. (i) the ICRP model for the human alimentary tract and (ii) the NCRP model for the biokinetics of radioactive materials in wounds. The third part of the course deals with the application of the models for the assessment of committed dose from incorporation monitoring data. This part is based mainly on the IDEAS General Guidelines, taking into account also the improvements of the guidelines provided by some follow-up projects, such as the CONRAD project.

2 Measuring techniques

This Chapter briefly describes the main measurement techniques, their advantages and their limitations for individual monitoring. In most cases, assessment of intakes of radionuclides may be achieved by body activity measurements, excreta monitoring, air sampling with personal air samplers, or a combination of these techniques. The choice of measurement technique will be determined by a number of factors including the radiation emitted by the radionuclide; the likely radiation dose; the biokinetic behaviour of the contaminant and the availability of equipment.

Routine monitoring programmes usually involve only one type of measurement if adequate sensitivity can be achieved. For some radionuclides, only one measurement technique is feasible, e.g. urine monitoring for intakes of tritium. For radionuclides, such as plutonium isotopes, that present difficulties for both measurement and interpretation, a combination of techniques may have to be employed. If different methods of adequate sensitivity are available, the general order of preference in terms of accuracy of interpretation is:

- body activity measurements;
- excreta analysis;
- personal air sampling and environmental measurements (workplace monitoring)

These techniques are, however, complementary and not mutually exclusive. Monitoring in relation to a particular task or event may often involve a combination of techniques so as to make the best possible evaluation of a novel or unusual situation. For example, a programme of both body activity and excreta measurements and, in some circumstances, personal air sampling may be used in combination with solubility studies on samples of airborne activity or source material from the workplace. Solubility studies will not necessarily give a good indication of the solubility characteristics of material in the lung but can provide valuable guidance for use in determining the most appropriate monitoring procedure [1].

In the workplace individuals may be exposed to a variety of radionuclides, as could occur in fuel reprocessing or manufacturing plants. In such circumstances it may be feasible to use a radionuclide that is readily detectable to assess the potential for exposure to other radionuclides in the plant. Thus screening for ^{144}Ce could be used to assess the potential for exposure to actinides. Similarly intakes of particulates may be complex mixtures and indicator radionuclides could be used in any assessment. Thus ^{241}Am may be present in inhaled fuel particles together with plutonium isotopes and external monitoring can be used to assess their intake.

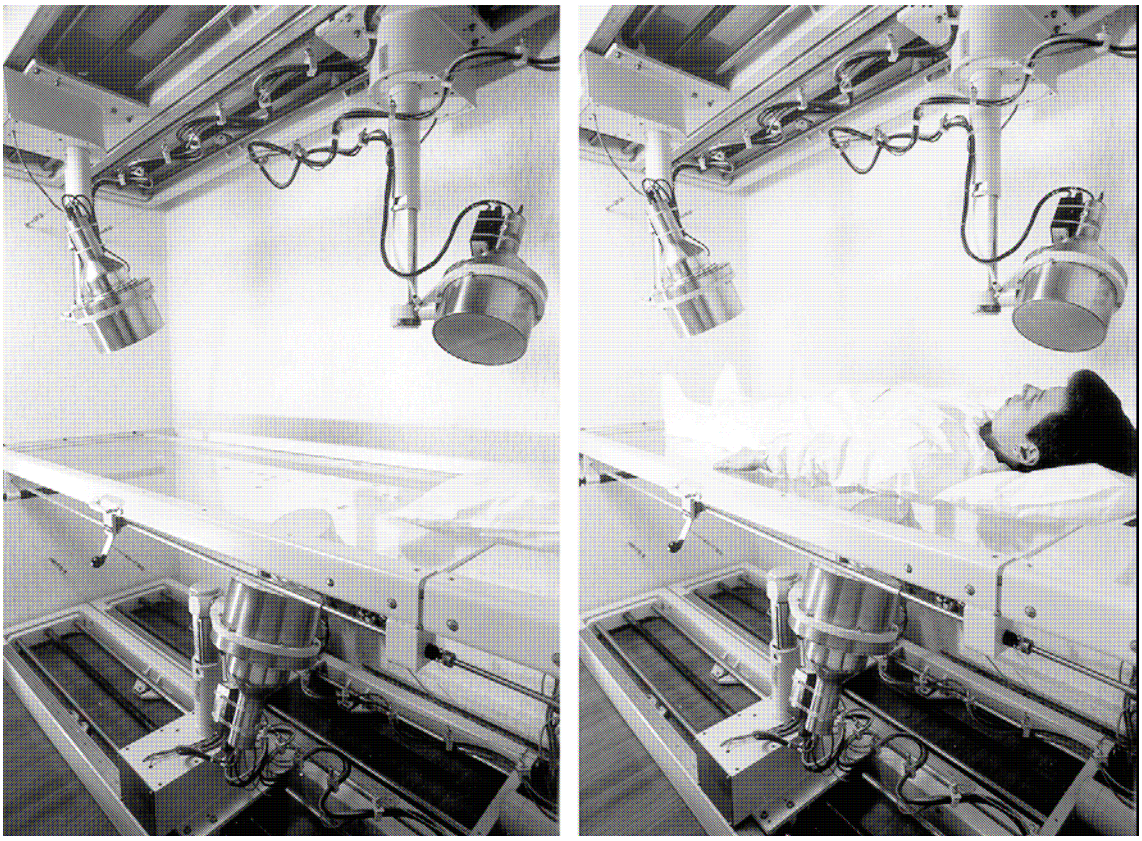
2.1 *In vivo* measurements

The IAEA has given guidance on the direct measurement of body content of radionuclides [2]. Advice has also been issued by ICRU [3] and by Landolt-Börnstein [4]. Direct measurement of body or organ content provides a quick and convenient estimate of activity in the body. It is feasible only for those radionuclides emitting radiation that can be detected outside the body.

Many facilities for the measurement of radionuclides in the whole body or in regions of the body consist of one or a number of high efficiency detectors housed in well-shielded, low-background environments. The geometrical configuration of the detectors is arranged to suit the purpose of the measurement, e.g. the determination of whole-body activity (Fig. 1) or of activity in a region of the body such as the thorax (Fig. 2) or the thyroid. The skull or knees may be used as a suitable site for measurement of radionuclides deposited in the skeleton and some radionuclides deposit preferentially in the liver where they can be detected. In special investigations, or in interpretation of unusual measurements, it may be advantageous to determine the distribution within the body either by profile scanning or by analysis of the relative response of detectors placed at different positions along the body.

Commonly encountered fission and activation products, such as ^{131}I, ^{137}Cs and ^{60}Co, can be detected with comparatively simple equipment at levels that are adequate for radiological protection purposes. Such simple equipment may consist of a single detector, viewing the whole body or a portion of the body, or, for iodine isotopes, a small detector placed close to the thyroid. The advantage of simple equipment is that it may be operated at the place of work, thereby avoiding the time required to visit a remote whole-body monitoring facility.

Figure 1: Stretcher type whole body counter with 4 NaI(Tl) scintillation detectors (Bicron 20 cm diam. × 10 mm crystals) for in vivo measurement of medium energy photon emitters (100 - 3000 keV) [4]



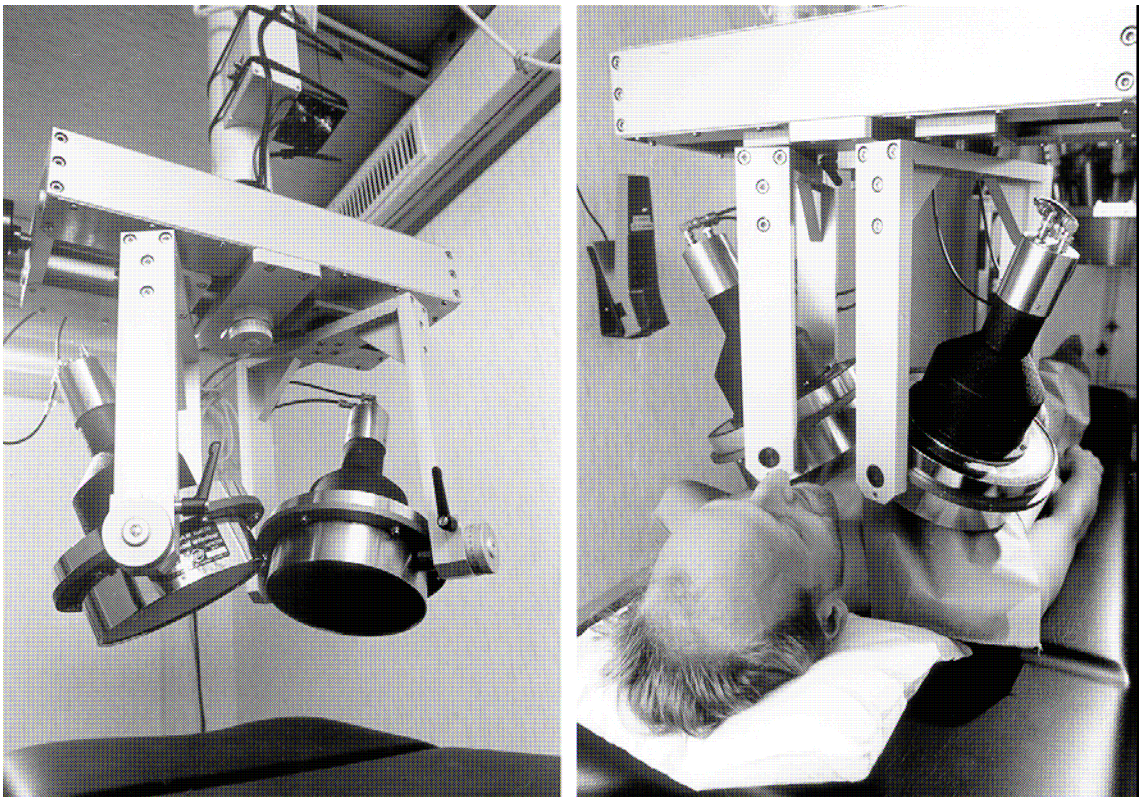
In principle, the technique can be used for radionuclides that emit: x or γ radiation; positrons, since they can be detected by measurement of annihilation radiation; energetic β particles that can be detected by measurement of bremsstrahlung (e.g. ^{90}Y for ^{90}Sr); and the α-emitters such as ^{235}U and ^{241}Am that can be detected by measurement of their characteristic 186 keV and 60 keV γ rays respectively, or α-emitters such as ^{238}Pu that can be detected by measurement of its characteristic 13, 17 and 20 keV x rays.

In contrast, high sensitivity techniques are needed for monitoring a few radionuclides at the levels that are required for protection purposes. Examples are the low energy photon emitters such as ^{210}Pb, ^{241}Am and isotopes of Pu in the lungs (Fig. 2) or in the skull (Fig. 3). In all situations when Pu isotopes are unaccompanied by ^{241}Am they are not detectable at the levels required for radiation protection purposes. If ^{241}Am is present then this can provide a valuable tracer for plutonium if the Pu: ^{241}Am ratio is known.

Up to the mid-1990s most body activity measurement facilities, whether high-sensitivity or simple systems, used thallium-activated sodium iodide detectors. These have the advantage that crystals of large volume can be manufactured and so provide high efficiency for detection of γ-rays. Interpretation of a γ-ray energy spectrum obtained from a mixture of radionuclides may, however, raise some difficulties. The components of the spectrum can be resolved by a multiple linear regression analysis technique, but this requires previous calibration of the detection equipment with standard sources of the required radionuclides dispersed in a matrix in such a way as to simulate the distribution and attenuation within the body. The increased availability of high-efficiency germanium detectors has lead to their increasing use, particularly in situations where workers may be exposed to

mixtures of unknown γ-ray emitting radionuclides. The superior energy resolving power of these detectors simplifies the interpretation of spectra obtained from complex mixtures of radionuclides although calibration is still needed.

Figure 2: Typical arrangement of 2 phoswich detectors (20 cm diam. 1 mm NaI(Tl) / 50 mm CsI(Tl) crystals) for in vivo measurement of low energy photon emitters such as ^{210}Pb, ^{241}Am and isotopes of Pu in the lungs [4]



The activity present in a wound can be detected with conventional γ detectors if the contaminant emits energetic γ-rays. In the case of contamination with α-emitting radionuclides, detection is much more difficult since the low energy x-rays that follow the α-decay will be severely attenuated in tissue; this effect is more important the deeper the wound. It is often necessary to localise the active material and this requires a well-collimated detector. Wound monitors must have an energy discrimination capability if a good estimate is to be made of contamination with mixtures of radionuclides.

The technology on which in vivo measurement systems are based is well-established. Nevertheless, there have been a number of recent developments that offer the promise of improved capabilities. Development work is being carried out on the optimisation of the area and thickness of detectors, with particular emphasis on the use of large detector arrays. Room temperature semiconductor arrays utilising either silicon or the compound semiconductor CdZnTe offer the possibility that bulky liquid nitrogen or electrical cooling systems may no longer be necessary [5-9].

Figure 3: Typical arrangement of 4 HPGe for in vivo measurement of low energy photon emitters such as ^{210}Pb, ^{241}Am and isotopes of Pu in the skull [74]

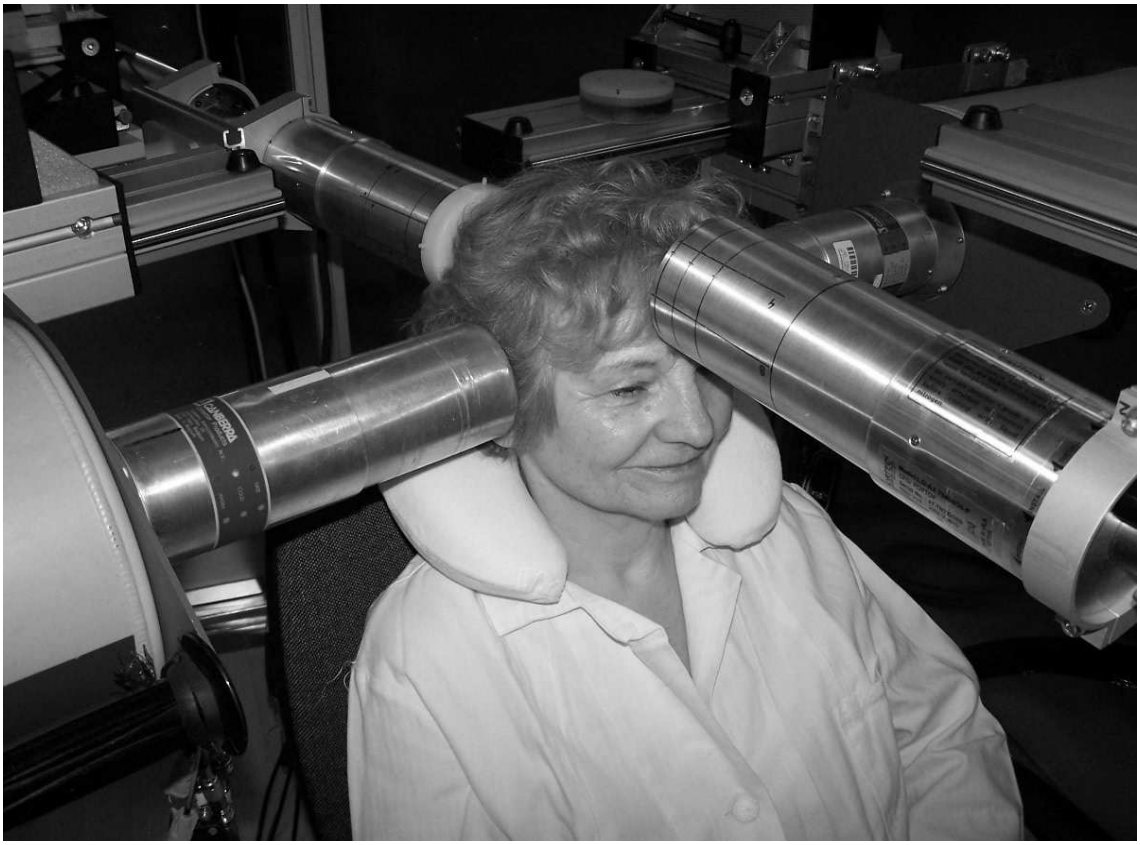


Figure 4: The BOMAB phantom for simulation of homogeneous activity depositions in the whole body [4]

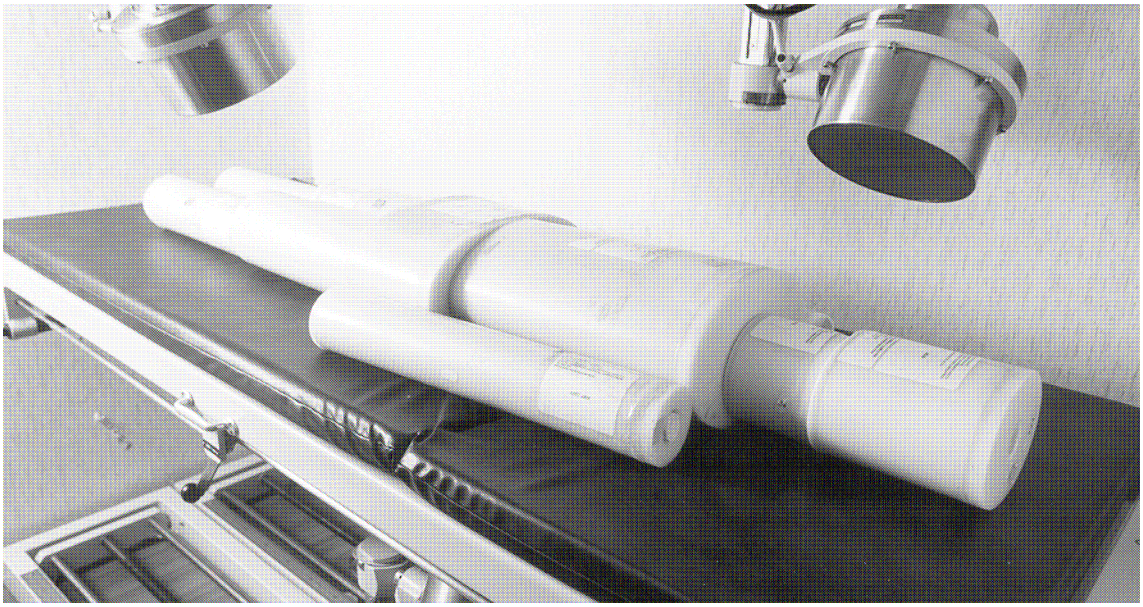
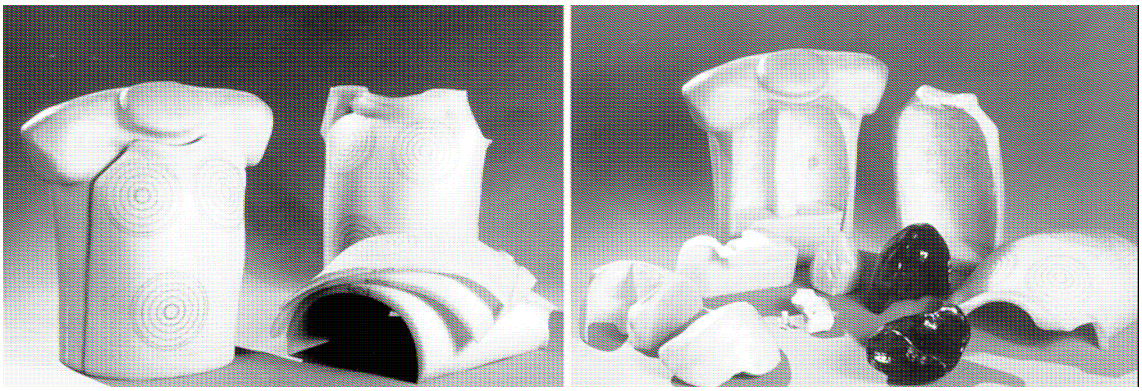


Figure 5: The LLNL chest phantom for simulation of homogeneous activity depositions in the lungs, tracheobronchial lymph nodes and in the liver [4]



Almost all laboratories continue to use physical phantoms such as the Bottle-Mannikin-ABsorption (BOMAB, Fig. 4) or Lawrence Livermore thorax phantoms (Fig. 5) for activity calibrations, but this approach has significant limitations with respect to the body size, body shape, and radionuclide distribution that can be modelled. These limitations could in principle be overcome using the numerical calibration techniques which have been developed over recent years. Mathematical voxel phantoms are constructed using data from computed tomography (CT) or magnetic resonance imaging (MRI scans on real subjects). Monte-Carlo simulations are then used to model photon transport from the phantom and the detection of photons by a simulated detector [11-13].

Figure 6: Voxel phantom for calibration of phoswich detectors in lung counting geometry (left) and in knee counting geometry (right) [13]

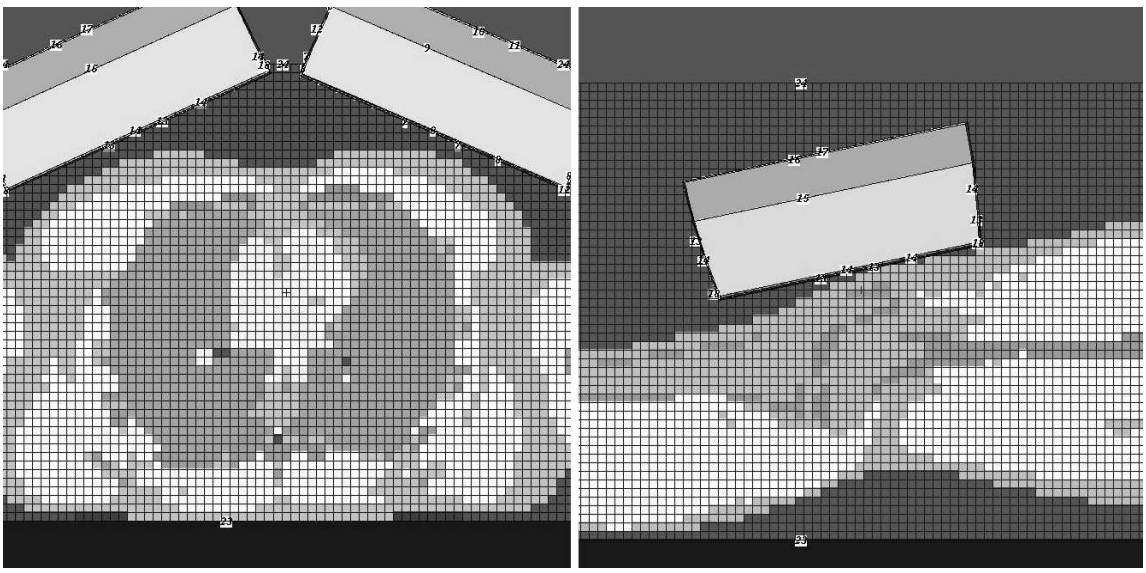


Table 1 lists some typical detection characteristics of a standard whole body counter (stretcher type with 4 NaI(Tl) scintillation detectors as shown in Fig. 1) for homogeneous depositions of some selected fission and activation products in the whole body. The lower limit of detection achieved by the whole body counter is compared to the value required for the detection of annual intakes corresponding to a

total committed effective dose of 1 mSv by means of routine incorporation monitoring. Table 2 shows the respective detection characteristics of a lung counter (4 HPGe detectors) for homogeneous depositions of some selected actinides in the lungs.

Table 1: Typical detection characteristics of a standard whole body counter (stretcher type with 4 NaI(Tl) scintillation detectors as shown in Fig. 1) for homogeneous depositions of some selected fission and activation products in the whole body (subject counting time t_S = 300 s; background counting time t_B = 1800 s) [4]

Nuclide	Detected photon radiation		Counting efficiency	Background count rate	Lower limit of detection [Bq]	
	Energy [keV]	Yield y [%]	η [%]	N_B/t_B [cps]	Required[1)]	Achieved
^{57}Co	123	86	1.5	14.0	20000	60
^{137}Cs	662	85	0.9	7.4	10000	73
^{134}Cs	796	85	0.81	4.9	6000	66
^{60}Co	1173	100	0.66	3.9	1000	62
^{22}Na	1275	100	0.61	4.0	200	67

1) for the detection of annual intakes corresponding to a total committed effective dose of 1 mSv by means of routine incorporation monitoring

Table 2: Typical detection characteristics of a lung counter (4 HPGe detectors) for homogeneous depositions of some selected actinides in the lungs; subject counting time t_S = 3000 s; background counting time t_B = 30000 s) [4]

Nuclide	Detected photon radiation		Counting efficiency[2)]	Background count rate	Lower limit of detection [Bq]	
	Energy [keV]	Yield y [%]	η [%]	N_B/t_B [cps]	Required[1)]	Achieved
^{239}Pu	17.1(L_β)	2.3	0.017	0.0088	2	1500
^{241}Am	59.6	35.9	0.47	0.0090	0.2	3.6
^{235}U	186	57	0.24	0.0041	3	3.0

1) for the detection of annual intakes corresponding to a total committed effective dose of 1 mSv by means of routine incorporation monitoring

2) Calibration with LLNL chest phantom for 25 mm chest wall thickness and 50/50 muscle/adipose tissue composition

2.2 *In vitro* measurements

In some cases, excreta monitoring may be the only measurement technique for those radionuclides which have no γ-ray emissions or which have only low energy photon emissions. Excreta monitoring programmes usually involve analysis of urine, although faecal analysis may also be required if the material is relatively insoluble. Other samples may be analysed for specific investigations. Examples

are the use of nose blow or nasal smears as routine screening techniques. Blood can be sampled in the case of suspected high level contamination, although activity concentrations are generally difficult to relate to body content or intakes (see also publications of IAEA [14-16]).

The collection of urine samples involves three considerations. Firstly, care must be taken to avoid adventitious contamination of the sample. Secondly, it is usually necessary to assess or estimate the total activity excreted in urine per unit time from measurements on the sample provided. For most routine analyses, a 24 h collection is preferred but, if this is not feasible, it must be recognised that smaller samples may not be representative. Where a 24 h sample is not easily collected then the first morning voiding is preferable for analysis [15]. The total daily excretion of creatinine, produced as a metabolic product in muscle metabolism, may be less variable than the volume of fluid lost in urine, although some individuals may still exhibit wide daily variations. For some radionuclides, adequate sensitivity can be achieved only by analysis of several days' excreta (e.g see Duke, [17]). Measurement of creatinine concentration in urine has frequently been used to estimate 24 h excretion of radionuclides from urine samples collected over part of a day. Tritium is an exceptional case for which it is usual to take only a small sample and to relate the measured activity concentration to the concentration in body water. Thirdly, the volume required for analysis depends upon the sensitivity of the analytical technique.

The analysis of faecal samples for routine monitoring involves uncertainty in interpretation owing to daily fluctuations in faecal excretion. Ideally, therefore, collection should be over a period of several days. However, this may be difficult to achieve in practice and interpretation may need to be based on a single sample. Faecal monitoring is more often used in special investigations, particularly following a known or suspected intake by inhalation of moderately soluble, Type M or insoluble, Type S compounds. In these circumstances measurement of the quantity excreted daily may be useful in the evaluation of clearance from the lungs and in the estimation of intake. Early results may be useful in identifying exposed individuals.

Table 3: Typical lower limits of detection for in vitro measuring techniques

Radionuclide	Measuring technique	Lower limit of detection
^{3}H	Liquid scintillation counter	100 Bq/l
^{14}C	Accelerator mass spectrometry (AMS)	0.1mBq/ml (mg samples)
^{131}I, ^{137}Cs	γ spectrometry	1 Bq/l
^{210}Po	Radiochemical separation and α spectrometry	30 mBq/l
U_{nat}	Radiochemical separation and α spectrometry	10 mBq/l
^{238}U, ^{232}Th	Inductively Coupled Plasma - Mass Spectr. (ICP-MS)	5-10 μBq per sample
^{239}Pu	Radiochemical separation and α spectrometry	1 mBq per sample
^{239}Pu	Thermal Ionization Mass Spectrometry (TIMS)	4 μBq per sample

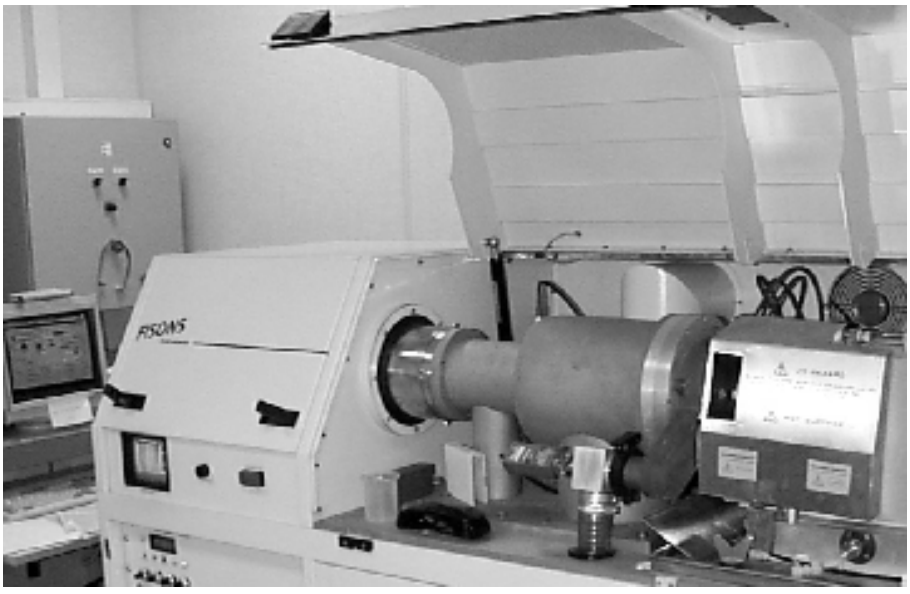
Radionuclides that emit γ-rays may be determined in biological samples by direct measurement with scintillation or semiconductor detectors. Analysis of α- and β-emitting radionuclides requires chemical separation followed by appropriate measurement techniques. Measurement of so-called total α or β activity may occasionally be useful as a simple screening technique, but there is no single method that will determine accurately all the α- and β-activity in the sample. The results cannot always be interpreted quantitatively, but can be useful for providing confirmation of satisfactory working

conditions, an unusual result indicating the need for further investigation which would include radiochemical analysis.

Measurement of activity in exhaled breath is a useful monitoring technique for some radionuclides such as ^{226}Ra and ^{228}Th since the decay chains of both these radionuclides include gases which may be exhaled [18,19]. It can also be used to monitor $^{14}CO_2$ formed in vivo from the metabolism of ^{14}C-labelled compounds [20, 21].

Increasing use is being made of mass spectrometric techniques for the analysis of excreta samples. Inductively Coupled Plasma - Mass Spectrometry (ICP-MS, Fig. 7) can achieve much lower detection limits for long-lived radionuclides than is possible with alpha spectrometry. For example, for ^{238}U and ^{232}Th, detection limits are in the region of 5-10 μBq per sample [22]. Measurement times are in the region of a few minutes, whereas an alpha spectrometry measurement typically takes several days. The more advanced mass spectrometric techniques such as multiple collector ICP-MS or sector field ICP-MS have the capability to detect very small changes in isotopic ratios and so can detect small amounts of depleted or enriched uranium in urine samples [23]. In the case of ^{239}Pu the use of Thermal Ionization Mass Spectrometry (TIMS), which has a minimum detection limit of about 4 μBq per sample, allows detection of an intake of Type S that would give rise to a committed effective dose of about 0.2 mSv. The more complicated technique of accelerator mass spectrometry (AMS) can be used to measure ^{14}C in small samples, mg-size, with low activities down to ~0.1mBq/ml with high accuracy (<2%). The AMS technique may need to be considered for routine monitoring in situations where exposure to [^{14}C]-compounds that deposit extensively in adipose tissue, or other tissues with very slow metabolic turnover, biological half-times of 60->150 d, is likely, since it must be expected that the elimination of ^{14}C from such tissues will occur by metabolism to [^{14}C]CO_2 and exhalation in the breath.

Figure 7: Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) device as used at IRSN, Fontenay aux Roses, France [24]



2.3 Personal air sampling and workplace monitoring

A Personal Air Sampler (PAS) is a portable device specifically designed for the estimation of intake by an individual worker from a measurement of concentration of activity in air in the breathing zone of the worker. A sampling head containing a filter is worn on the upper torso close to the breathing zone. Air is drawn through the filter by a calibrated air pump carried by the worker. Ideally, sampling

rates would be similar to typical breathing rates for a worker (~1.2 m^3 h^{-1}). However, sampling rates of current devices are only about 1/10 of this value. The activity on the filter may be measured at the end of the sampling period to give an indication of any abnormally high exposures. The filters can then be retained, bulked over a longer period, and the activity determined by radiochemical separation and high sensitivity measurement techniques. An estimate of intake during the sampling period can be made by multiplying the measured average air concentration by the air volume estimated to be inhaled by the worker during the period of intake. The difficulties in assessing intakes from PAS measurements were considered by Whicker [25]. Breathing zone measurements can vary significantly as affected by measurement conditions such as orientation of the sampler with respect to source, on which lapel (right or left) the sampler is worn, design of the air sampling head, particle size, local air velocities and directions, and sharp gradients in and around the breathing zone of workers.

Static air samplers (SAS) are commonly used to monitor workplace conditions, but can underestimate concentrations in air in the breathing zone of a worker. Marshall and Stevens [26] reported that PAS:SAS air concentration ratios can vary from less than 1 up to 50, depending on the nature of the work. Britcher and Strong [27] concluded from their review of monitoring data for Magnox plant workers that intakes assessed from PAS data were about an order of magnitude greater than those implied by SAS data. Nevertheless, if SAS devices are sited appropriately, a comparison of PAS and SAS measurements can be used to define a fixed PAS:SAS air concentration ratio which can be used in the interpretation of SAS measurements for dose assessment purposes. It should, however, be recognised that the use of SAS is a relatively indirect method for assessing doses, and use of the results to estimate individual dose requires a careful assessment of exposure conditions and working practices. Apart from their potential use for dose estimation, SAS devices can also provide useful information on radionuclide composition, and on particle size if used with a size analyser such as a cascade impactor.

Overall the use of PASs and SASs can be an important part of a comprehensive workplace monitoring programme and is able to provide an early indication of risk of exposure., However, experience of the use of PASs and SASs indicates that body activity measurements and/or excreta analysis are to be preferred for the assessment of individual intakes of airborne radionuclides and doses.

3 Biokinetic models

3.1 Overview

Knowledge of the behaviour of radioactive materials within the human body is essential for the assessment of intake or committed effective dose from measurements of activity in the body or in excreta. This Chapter gives a general description of the routes of intake of radionuclides into the body, and subsequent transfers within and out of the body. It also gives an overview of the current ICRP biokinetic models used to calculate body or organ content and daily urinary or faecal excretion at specified times after intake. See the original reports of ICRP [28-33] for details.

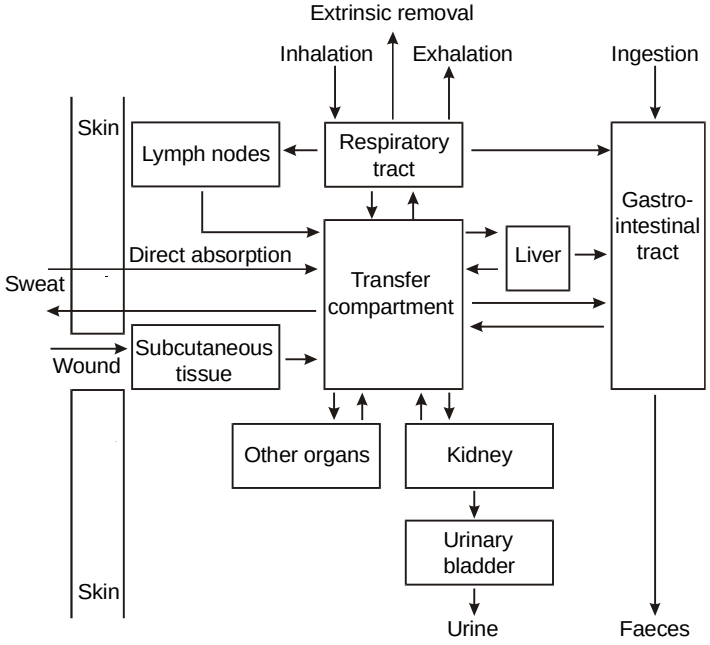
Figure 8 summarises the routes of intake, internal transfers, and excretion. The respiratory tract, the gastrointestinal (GI) tract, the intact skin, and wounds are the principal routes of entry to the body. A proportion of the activity is absorbed into blood and hence body fluids. Activity reaching body fluids (transfer compartment) in this way is known as systemic material. The activity then undergoes various transfers which determine its distribution within the body and its route and rate of elimination. The distribution of systemic activity in the body can be diffuse and relatively homogeneous, e.g. with tritiated water, or localised in certain organs or tissues, e.g. with iodine (thyroid), alkaline earth metals (bone), plutonium (bone and liver).

Removal of deposited material from the body occurs principally by urinary and faecal excretion. Urinary excretion is the removal in urine of material from the plasma and extracellular fluid. Faecal excretion has two components: systemic faecal excretion which represents removal of systemic

material via the GI tract; and direct faecal excretion of the material passing unabsorbed through the GI tract.

The models for the major routes of intake (inhalation and ingestion) are described in the following Sections. For some radionuclides, it is also necessary to consider direct uptake from contamination on the skin. There is no general model of entry of radionuclides through the skin because of the large variability of situations which may occur. Many factors must be taken into account: the chemical form of the compound, the location and the surface of the contaminated area as well as the physiological state of the skin. Intact skin is a good barrier against entry of a substance into the body. Generally, radionuclides do not cross the intact skin to any significant extent. However, a few elements may be transferred rapidly. The most important is tritiated water and this is the only case considered specifically by ICRP [28, 33]. However, absorption through skin is not included in the derivation of the dose coefficient for tritiated water (ICRP, [33]). Iodine may also be taken up through skin, but to a lesser extent.

Figure 8: Summary of the main routes in intake, transfers and excretion of radionuclides in the body



3.2 Human respiratory tract model

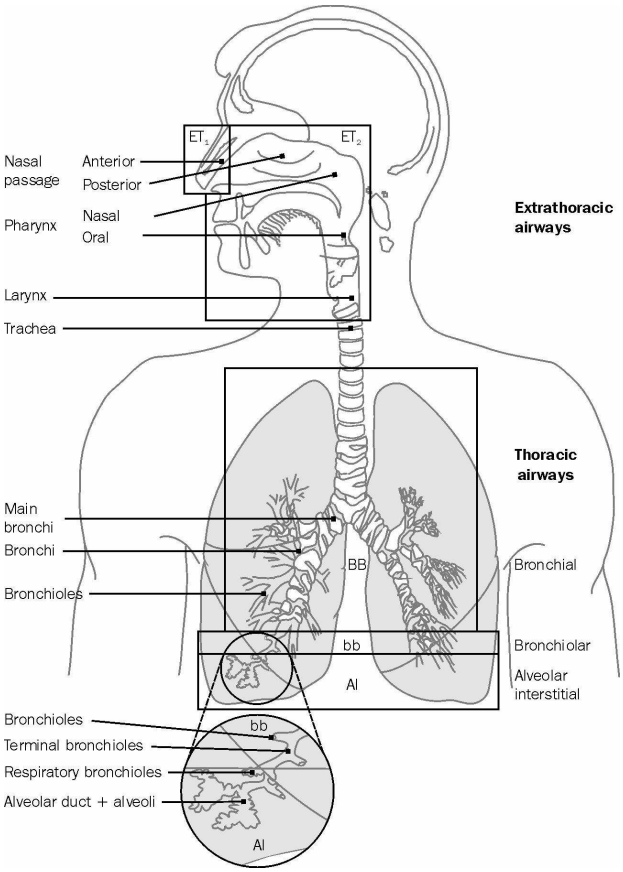
The Guide for the Practical Application of the ICRP Human Respiratory Tract Model (ICRP, [1]); Bailey *et al*, [34,35]) provides extensive guidance on the application of the HRTM to specific situations, such as those in which individual monitoring is carried out for intakes of radionuclides by inhalation.

In the model described in Publication 66 [31], the respiratory tract is represented by five regions (Fig. 9). The extrathoracic (ET) airways are divided into ET_1, the anterior nasal passage, and ET_2, which consists of the posterior nasal and oral passages, the pharynx and larynx. The thoracic regions are bronchial (BB: trachea and bronchi), bronchiolar (bb), and alveolar-interstitial (Al: the gas exchange region). Lymphatic tissue is associated with the extrathoracic and thoracic airways (LN_{ET} and LN_{TH} respectively).

Deposition

The deposition model evaluates fractional deposition of an aerosol in each region, for all aerosol sizes of practical interest (0.6 nm – 100 μm). For the ET regions, measured deposition efficiencies were related to characteristic parameters of particle size and airflow, and were scaled by anatomical dimensions to predict deposition under other conditions (e.g. gender, ethnic group). For the thoracic airways a theoretical model of gas transport and particle deposition was used to calculate particle deposition in each of the BB, bb, and AI regions, and to quantify the effects of the subject's lung size and breathing rate. To model particle deposition, the regions are treated as a series of filters, during both inhalation and exhalation. The efficiency of each is evaluated by considering aerodynamic (gravitational settling, inertial impaction) and thermodynamic (diffusion) processes acting competitively. Regional deposition fractions were calculated for aerosols having log-normal particle size distributions, with geometric standard deviations (σ_g) taken to be a function of the median particle diameter, increasing from a value of 1.0 at 0.6 nm to a value of 2.5 above about 1 μm (Publication 66, § 170 [31]). Deposition parameters are given for three reference levels of exertion for workers (sitting, light exercise, heavy exercise).

Figure 9: Respiratory tract regions defined in the Human Respiratory Tract Model [31]



For inhalation of radionuclides by workers, the reference subject is taken to be a normal nose-breathing adult male at light work. For occupational exposure the default value now recommended for the Activity Median Aerodynamic Diameter (AMAD) is 5 μm (Publication 68, [36]), which is considered to be more representative of workplace aerosols than the 1 μm default value adopted in Publication 30. Fractional deposition in each region of the respiratory tract of the reference worker is given in Table 4 for aerosols of 5 μm AMAD.

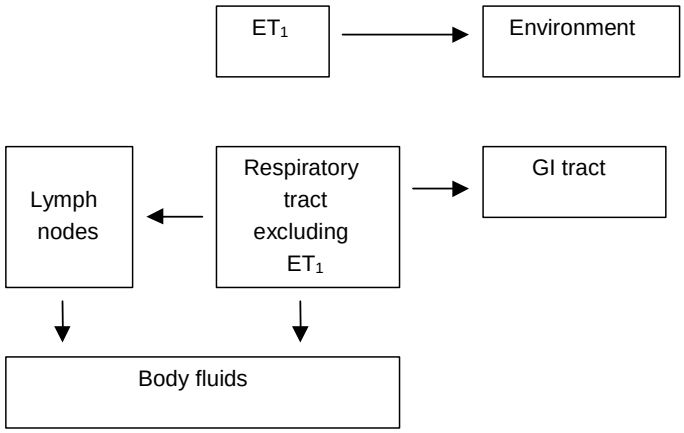
Table 4: Regional deposition of inhaled 5-μm AMAD aerosol in Reference Worker (%) (values are rounded) [31]

Region	Deposition (% of inhaled activity)
ET_1	34.0
ET_2	40.0
BB	1.8
bb	1.1
Al	5.3
Total	82.0

Clearance

The HRTM describes several routes of clearance from the respiratory tract (Fig. 10). Material deposited in ET_1 is removed by extrinsic means such as nose-blowing. In other regions clearance is competitive between the movement of particles towards the GI tract and lymph nodes (particle transport), and the absorption into blood of material from the particles in the respiratory tract. Removal rates due to particle transport and absorption to blood are taken to be independent.

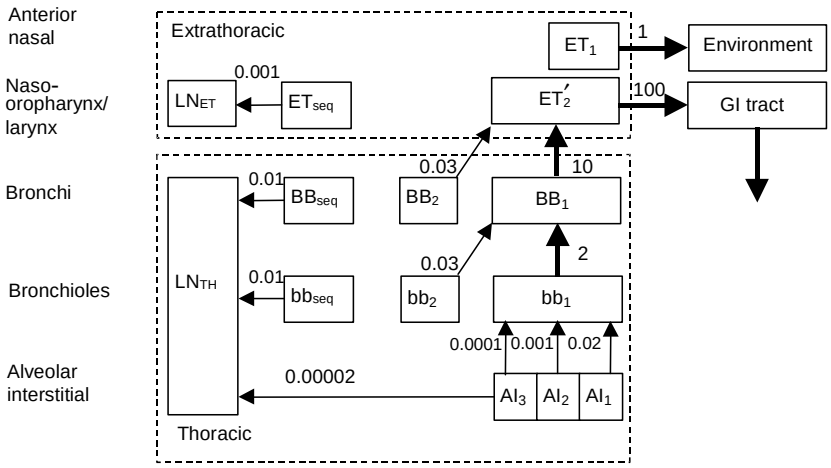
Figure 10: Routes of clearance from the respiratory tract [31]



It is assumed that particle transport rates are the same for all materials. A single compartment model is therefore provided to describe particle transport of all materials (Fig. 11). Reference values of rate constants were derived, so far as possible, from human studies, since particle transport rates are known to vary greatly among mammalian species. Figure 11 as it stands would describe the retention and clearance of a completely insoluble material. However, as noted above, there is in general simultaneous absorption into blood.

Absorption depends on the physical and chemical form of the deposited material. It is assumed to occur at the same rate in all regions (including the lymph nodes) except ET_1, where it is assumed that none occurs. Absorption is a two-stage process: dissociation of the particles into material that can be absorbed into body fluids (dissolution); and absorption into body fluids of soluble material and of material dissociated from particles (uptake). The clearance rates associated with both stages can be time-dependent.

Figure 11: Compartment model representing time-dependent particle transport from each respiratory tract region. Rates shown alongside arrows are reference values in units of d^{-1}. It is assumed that (i) the AI deposit is divided between AI_1, AI_2 and AI_3 in the ratio 0.3:0.6:0.1; (ii) the fraction of the deposit in BB and bb that is cleared slowly (BB_2 and bb_2) is 50% for particles of physical size <2.5 μm and decreases with diameter >2.5 μm, and the fraction retained in the airway wall (BB_{seq} and bb_{seq}) is 0.7% at all sizes; (iii) 0.05% of material deposited in region ET_2 is retained in its wall (ET_{seq}) and the rest in compartment ET_2' which clears rapidly to the GI tract. The model as shown above would describe the retention and clearance of a completely insoluble material. However, there is in general simultaneous absorption to body fluids of material from all the compartments except ET_1

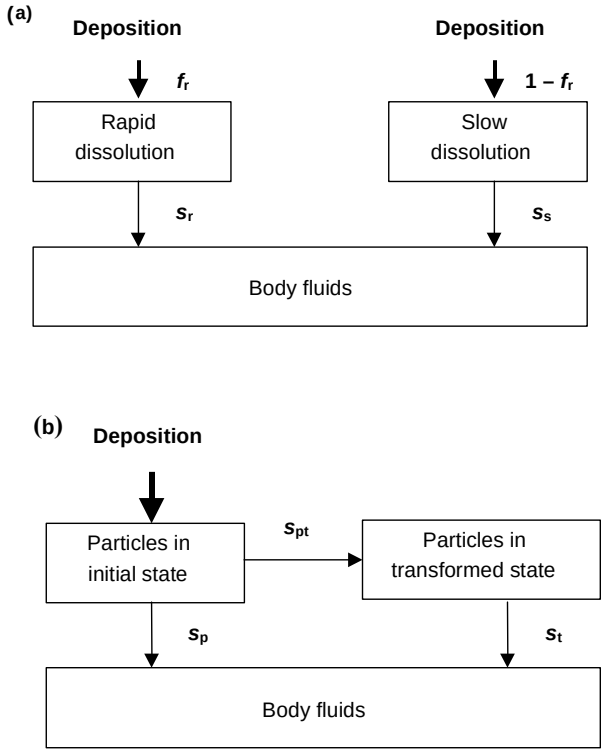


Dissolution

The simplest compartment model representation of time-dependent dissolution is to assume that a fraction (f_r) dissolves relatively rapidly, at a rate s_r, and the remaining fraction ($1 - f_r$) dissolves more slowly, at a rate s_s (Fig. 12(a)). In the HRTM provision is made for only two such states, to avoid undue complexity, as it is considered that there would rarely in practice be sufficient information available to justify more.

A limitation of the system in Fig. 12 (a), however, is that it can only readily represent an overall fractional dissolution rate that decreases with time. To overcome this, the HRTM uses an equivalent system with the same number of variables, but which gives greater flexibility, shown in Fig. 12 (b). In this, the material deposited in the respiratory tract is assigned to compartments labelled "Particles in initial state" in which it dissolves at a constant rate s_p. Material is simultaneously transferred (at a constant rate s_{pt}) to a corresponding compartment labelled "Particles in transformed state" in which it has a different dissolution rate, s_t. With this system, the initial dissolution rate is approximately s_p and the final dissolution rate is approximately s_t. Thus with suitable choice of parameters, including $s_t > s_p$, an increasing dissolution rate can be represented. The ratio of s_p to s_{pt} approximates to the fraction that dissolves rapidly.

Figure 12: Alternative compartment models representing time-dependent dissolution, followed by instantaneous uptake to body fluids. In the model shown in Fig. 12 (a), a fraction f_r of the deposit is initially assigned to the compartment labelled "Rapid dissolution", and the rest $(1 - f_r)$ of the deposit is initially assigned to the compartment labelled "Slow dissolution". In the model shown in Fig. 12 (b), all the deposit is initially assigned to the compartment labelled "Particles in initial state". For definition of symbols, see text.



If the dissolution rate decreases with time, as is usually the case, either system could be used, and would give the same results, with the following values:

$$s_p = s_s + f_r\,(s_r - s_s)$$

$$s_{pt} = (1 - f_r)\,(s_r - s_s)$$

$$s_t = s_s$$

In most circumstances the system in Fig. 12 (a) has advantages. In particular, it is simpler to understand, and it is generally more straightforward to estimate the values of the parameters in Fig. 12 (a) than those of Fig. 12 (b) from experimental data. The system shown in Fig. 12 (b) is that "formally" used in the HRTM, rather than that of Fig. 12 (a), only in that the default absorption parameter values (Table 2) are specified in terms of s_p, s_{pt} and s_t, rather than f_r, s_r and s_s.

Uptake

Uptake to body fluids of dissolved material can usually be treated as instantaneous. In some situations, however, a significant fraction of the dissolved material is absorbed slowly into body fluids because of binding to respiratory tract components. To represent time-dependent uptake, it is assumed that a fraction (f_b) of the dissolved material is retained in a "bound" state, from which it goes into body fluids at a rate s_b, while the remaining fraction ($1 - f_b$) goes to body fluids instantaneously. In the model, material in the "bound" state is not cleared by particle transport processes, but only by uptake to body fluids. Thus, only one "bound" compartment is required for each region. However, it is assumed by default that uptake is instantaneous, and this is reflected in the reference values.

The system shown in Fig. 11 applies to each of the compartments in the particle transport model shown in Fig. 10 except ET_1 where no absorption occurs.

It is recommended that material-specific rates of absorption should be used in the model for compounds for which reliable experimental data exist. For other compounds, default values of parameters are recommended, according to whether the absorption is considered to be fast (Type F), moderate (M) or slow (S) (corresponding broadly to inhalation Classes D, W and Y in ICRP Publication 30). Reference values for each are specified in terms of the parameters s_p, s_{pt} and s_t, and are given in Table 5. The "bound" state is not invoked for the default values, i.e., $f_b = 0$ for all three Types.

These absorption rates, expressed as *approximate* half-times, and the corresponding amounts of material deposited in each region *that reach body fluids* can be summarised as follows:

Type V: 100% absorbed instantaneously. Regional deposition does not need to be assessed for such materials, because in dose calculations they can be treated as if they were injected directly into body fluids.

Type F: 100% absorbed with a half-time of 10 minutes. There is rapid absorption of almost all material deposited in BB, bb, and AI, and 50% of material deposited in ET_2. The other 50% of material deposited in ET_2 is cleared to the GI tract by particle transport.

Type M: 10% absorbed with a half-time of 10 minutes and 90% with a half-time of 140 d. There is rapid absorption of about 10% of the deposit in BB and bb; and 5% of material deposited in ET_2. About 70% of the deposit in AI eventually reaches body fluids.

Type S: 0.1% absorbed with a half-time of 10 minutes and 99.9% with a half-time of 7000 d. There is little absorption from ET, BB, or bb, and about 10% of the deposit in AI eventually reaches body fluids.

For absorption Types F, M, and S, all the material deposited in ET_1 is removed by extrinsic means. Most of the deposited material that is not absorbed is cleared to the GI tract by particle transport. The small amounts transferred to lymph nodes continue to be absorbed into body fluids at the same rate as in the respiratory tract.

The choice between the default absorption Types F, M, and S is the most common one to be made in applying the HRTM.

ICRP Publication 66 does not give criteria for assigning compounds to absorption Types on the basis of experimental results. Guidance on the choice of default Type, and hence of the reference values of the absorption parameters, is given in ICRP Publication 68 [36] for occupational exposure and in ICRP Publication 71 [33] for exposure of the public (for the 31 elements covered).

In ICRP Publication 68, which gives inhalation dose coefficients for workers, compounds for which clearance was previously given as "inhalation Class" D, W or Y in ICRP Publication 30, were

generally assigned to "absorption Type" F, M or S respectively. A listing of the classifications is given in ICRP Publication 68, Annexe F [36].

Criteria for assigning compounds to absorption Types on the basis of experimental results were developed in ICRP Publication 71. They are described, with examples of their application, in [1] (Annexe C) which is based on ICRP Publication 71, Annexe D.

Table 5: Default absorption parameter values for Type F, M, and S materials (based on ICRP Publication 66, Table 18)[a] [31]

		Absorption type		
		F(fast)	M (moderate)	S (slow)
Initial dissolution rate (d^{-1})	s_p	100	10	0.1
Transformation rate (d^{-1})	s_{pt}	0	90	100
Final dissolution rate (d^{-1})	s_t	-	0.005	0.0001
Fraction dissolved rapidly	f_r	1	0.1	0.001
dissolution rate				
Rapid (d^{-1})	s_r	100	100	100
Slow (d^{-1})	s_s	-	0.005	0.0001
Fraction to bound state	f_b	0	0	0

[a]The model values s_p, s_{pt} and s_t in this table are *reference values i.*e., the recommended default values for use in the model. No "bound" state is assumed for default Types.

Gases and Vapours

For radionuclides inhaled as particles (solid or liquid) the HRTM assumes that total and regional depositions in the respiratory tract are determined only by the size distribution of the aerosol particles. The situation is different for gases and vapours, for which deposition in the respiratory tract depends entirely on the chemical form. In this context, deposition refers to how much of the material in the inhaled air remains behind after exhalation. Almost all inhaled gas molecules contact airway surfaces, but usually return to the air unless they dissolve in, or react with, the surface lining. The fraction of an inhaled gas or vapour that is deposited in each region thus depends on its solubility and reactivity.

As a general default approach the HRTM assigns gases and vapours to three classes, on the basis of the initial pattern of respiratory tract deposition (ICRP Publication 66, Chapter 6):

- Class SR-0 insoluble and non-reactive: negligible deposition in the respiratory tract.
- Class SR-1 soluble or reactive: deposition may occur throughout the respiratory tract. In the absence of information 100% total deposition is assumed, with the following distribution: 10% ET_1, 20% ET_2, 10% BB, 20% bb and 40% AI (ICRP Publication 66, Paragraph 221).
- Class SR-2 highly soluble or reactive: 100% deposition in the extrathoracic airways (ET_2).

For Classes SR-1 and SR-2, subsequent retention in the respiratory tract and absorption to body fluids are determined by the chemical properties of the specific gas or vapour. By default, reference values for an Absorption Type are used, normally Type F (absorption rate 100 d^{-1}) or Type V (instantaneous absorption).

Guidance on many of the more-commonly encountered radioactive gases and vapours is given in ICRP Publications 68 and 71 for workers and the public, respectively. For convenience, most of it is brought together in ICRP [1] in which some additional guidance is given.

3.3 Human alimentary tract model

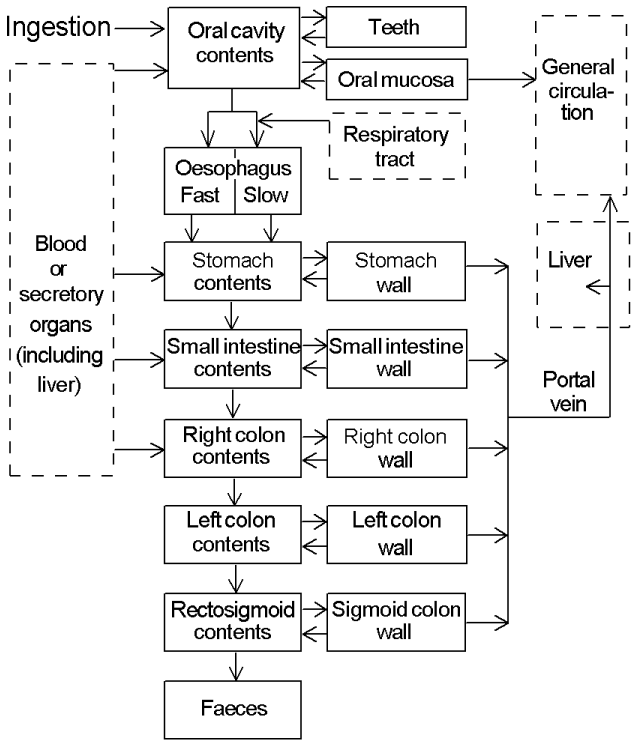
Material may reach the GI tract directly by ingestion, by transfer from the respiratory tract as described above, or by transfer from other body organs. The GI tract model defined in ICRP Publication 30 Part 1 (ICRP, [28]) was used in ICRP Publications 67, 68, 69, 71, 72 and 78 [30, 32, 33, 36-38] to describe the behaviour of radionuclides in the GI tract, and to calculate doses from radionuclides in the contents of the GI tract.

Recently the Publication 30 model of the gastrointestinal tract has been replaced by the Human Alimentary Tract Model (HATM) described in ICRP Publication 100 ([39]). The structure of the HATM is shown in Fig 13. Its main features can be summarised as follows:

- Inclusion of all alimentary tract regions. Doses are calculated for the oral cavity, oesophagus, stomach, small intestine, right colon, left colon and rectosigmoid (the sigmoid colon and rectum). Colon doses are combined as a mass-weighted mean to include the right colon, left colon and rectosigmoid.
- Gender-dependent parameter values for adults for dimensions and transit times of contents through the regions (age-dependent parameter values are also specified for use in future calculations of doses to members of the public).
- Transit times for food and liquids, as well as for total diet, for the mouth, oesophagus and stomach.
- A default assumption that absorption of an element and its radioisotopes to blood occurs exclusively in the small intestine, ie. The total fractional absorption, f_A coincides with the fractional absorption from the small intestine, f_{SI}.It is assumed there is no recycling from the wall to blood.
- Model structure to allow for absorption in other regions, where information is available.
- Model structure to allow for retention in the mucosal tissues of the walls of alimentary tract regions, and on teeth, where information is available.
- Explicit calculations of dose to target regions for cancer induction within each alimentary tract region, considering doses from radionuclides in the contents of the regions, and considering mucosal retention of radionuclides when this is taken into account.

The organs and fluids represented in Fig 13 by dashed boxes show connections between the HATM and the HRTM and systemic biokinetic models. First-order kinetics is assumed for all transfers in the HATM. This is a considerable simplification of the complex processes involved in transfer of material through the lumen of the alimentary tract but is expected to provide a reasonably accurate representation of the mean residence time of a radionuclide in each segment of the tract.

Figure 13: Structure of the HAT model. The dashed boxes are included to show connections between the HATM and the HRTM and systemic biokinetic models. f_A gives net transfer to blood and replaces the f_1 value of the gastrointestinal tract model. In general, uptake of radionuclides is assumed to occur from the small intestine.



Mucus and associated materials cleared from the respiratory tract enter the oesophagus via the oropharynx. For ingested food and liquids, the HATM specifies two components of oesophageal transit representing relatively fast transfer of 90% (mean transit time of 7 seconds for total diet) of the swallowed material and relatively slow transit of the residual 10% (40 seconds for total diet). It is assumed that the slower oesophageal transit times apply to all material cleared from the respiratory tract.

The oral cavity and oesophagus will receive very low doses from radionuclides in transit because of their short transit times (ICRP, ([39]). However, these regions were included for completeness, because a specific w_T is assigned to the oesophagus (ICRP, [40]), and because retention in the mouth, on teeth for example, can result in a substantial increase in dose to the oral mucosa. In general, the alimentary tract regions of greatest importance in terms of doses and cancer risk are the stomach and particularly the colon. While the small intestine may receive greater doses than the stomach, it is not sensitive to radiation-induced cancer and is not assigned a specific w_T value. Doses are calculated separately for the right colon, left colon and rectosigmoid. This partitioning of the colon for the purposes of dose calculations is predicated on the availability of transit time data. The rectum is taken to be part of the rectosigmoid, primarily because of difficulties in determining transit times separately. Mean transit times for the stomach and colon are about one-third greater in adult females than males. Slightly smaller masses in females (eg. 10% lower mass of colon tissue) will compound this gender difference.

In most cases, the values of f_A for ingestion will be the same as the f_1 values given previously for use with the Publication 30 model, since in most cases there is unlikely to be sufficient new information to warrant a revision in values. In addition, the general default assumption will be that absorption occurs solely from the small intestine, as in the Publication 30 model; that is, $f_{SI} = f_A$. However, the HATM allows absorption to be specified for other regions as well as the small intestine. As discussed in Publication 100 (ICRP ([39]) for the example of isotopes of iodine doses to alimentary tract regions and other tissues will in many cases be insensitive to assumptions regarding the site of absorption.

For inhaled particles reaching the alimentary tract after escalation from the respiratory tract, it is appropriate to take account of solubility in the lungs in specifying f_A values. For elements exhibiting a range in solubility according to their physicochemical form, there is evidence that the reduced solubility of Type M or S materials is also associated with reduced intestinal absorption. As discussed in Publication 71 (ICRP, ([33]), in many cases for which a single f_A value is specified for ingestion of an element, this is taken to apply to inhaled Type F materials and lower default values of 0.1 and 0.01 are applied to Types M and S. However, because of the need for realism in estimates of absorption for application to bioassay interpretation, attempts have been made wherever possible to use available data to specify f_A values for different forms rather than rely on defaults.

An important development in the HATM is the methodology used to calculate doses in the various regions from non-penetrating alpha and electron radiations. Thus, while the Publication 30 approach was to assume that the dose to the wall was one half of that to contents of the region, with an additional factor of 0.01 included for alpha particles to allow for their short range, the HATM takes explicit account of the location of the target tissue in the mucosal layer of the wall of each region. The targets relating to cancer induction are taken in each case to be the epithelial stem cells, located in the basal layers of the stratified epithelia of the oral cavity and oesophagus and within the crypts that replenish the single cell layer epithelium of the stomach and small and large intestines.

As discussed in Publication 100 (ICRP ([39]), the HATM generally results in substantially lower estimates of doses to the colon from beta-emitting radionuclides than obtained using the Publication 30 model. This is because the HATM takes explicit account of dose to the target region throughout the length of the colon, and of loss of energy in the colon contents and the mucosal tissue overlying the target stem cells (at a depth of 280 - 300 μm). This reduces energy deposition in the target tissue for electrons and results in zero dose in the target tissue from alpha particles. In the absence of retention of radionuclides in the alimentary tract wall, doses from ingested alpha emitters to all regions of the alimentary tract will be solely due to their absorption to blood and subsequent irradiation from systemic activity in soft tissues. For the stomach, the HATM and Publication 30 approaches give more similar estimates of doses from electron-emitting nuclides.

3.4 Absorption through intact skin

Generally, radionuclides do not cross the intact skin to any significant extent. Exceptions of practical importance are tritium oxide as liquid or vapour, organic carbon compounds and iodine as vapour or in solution.

There is no general model of entry of radionuclides through the skin because of the large variability of situations which may occur. Skin can become contaminated by contact with aerosols, liquids or surfaces contaminated with radionuclides. Clothing may be an important source of skin contamination and wet clothing may bring the contaminant into close contact with the skin thereby increasing the possibility of penetration through it. Many factors must be taken into account in dose assessment: the chemical form of the compound, the location and the surface of the contaminated area as well as the physiological state of the skin. Intact skin is a good barrier against entry of a substance into the body.

For skin contamination, both the radiation dose to the area of skin contaminated and the dose to the whole body as a result of absorption need to be considered. ICRP in Publication 60 [40] has

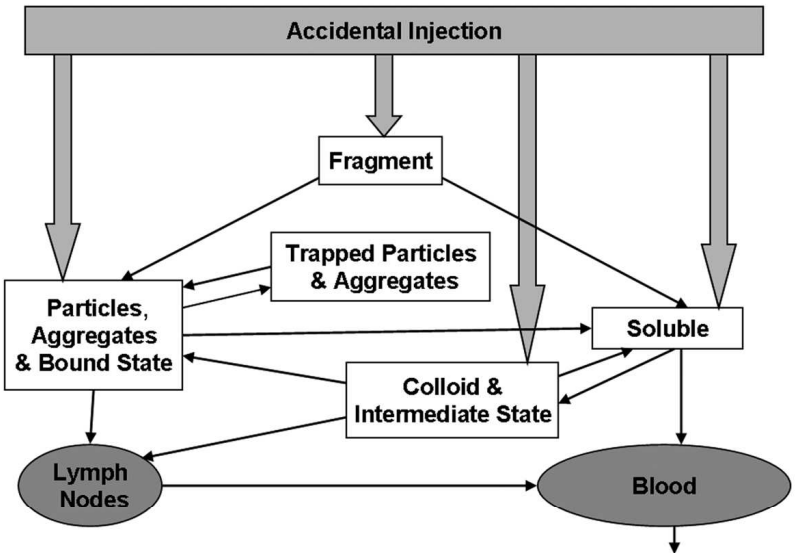
recommended that for skin contamination doses should be calculated to sensitive cells, assumed to be at a depth of 70 μm (as a reasonable average value). For deposited activity doses are to be calculated as an average to each cm^2 of skin tissue. This applies to activity distributed over the skin surface or aggregated in particles. No specific models are recommended by ICRP for calculating doses from β particles deposited on the skin and absorbed through it.

3.5 Wounds

To provide a means for calculating doses resulting from radionuclide-contaminated wounds, the National Council on Radiation Protection and Measurements, in collaboration with the ICRP, has developed a biokinetic and dosimetric model for exposure to radionuclides from contaminated wounds (NCRP, [41]), The model (Fig. 14) was formulated and parameterized largely using experimental animal data due to the lack of adequate human information. The model can be used to calculate radiation doses to the wound site from deposited radionuclides, and, when coupled with an element-specific systemic biokinetic model, can also be used to calculate committed doses to organs and tissues and committed effective doses as well as to predict urinary and fecal excretion patterns for bioassay interpretation.

The NCRP Wound Model (Fig. 14) was designed to predict the biokinetic behaviour of both soluble and insoluble radioactive materials, regardless of initial physical and chemical state. To do so, five compartments were designated to describe certain physical or chemical states of the radionuclide within the wound site. These comprise Soluble (S); Colloidal and Intermediate State (CIS), Particles; Aggregates and Bound State (PABS); Trapped Particles and Aggregates (TPA); and Fragments. In some cases, the compartments contain the radionuclide in its original physico-chemical form. In others, the originally deposited material changes state and moves from one compartment to another with time. Although using five compartments to represent the wound site appears complex, in most cases the model simplifies to two or three compartments depending on the physical and chemical form of the radionuclide specified. This two- or three-compartment representation was shown to be widely consistent with the experimental data describing wound site retention (NCRP, [41]).

Figure 14: NCRP wound model [41]



Four categories of retention were defined for radionuclides present in a wound initially in soluble form: Weak, Moderate, Strong and Avid, which refer generally to the magnitude of persistent retention in the wound. The criteria for categorization were: 1) the amount retained 1 d after deposition and 2) the rate of clearance of the remainder. In addition three other categories of deposit cover particles, colloids and fragments.

Release of radionuclide from the wound site occurs via the blood for soluble materials and lymph nodes (LN) for particulates. Further solubilisation of particles in LN also provides for radionuclide to the blood. The blood comprises the central compartment that links the wound model with the respective radioelement-specific systemic biokinetic model. Once the radionuclide reaches the blood, it behaves biokinetically as if it had been injected directly into blood, and in a soluble form. This is the same approach as is taken for the HRTM and HATM.

The presence of wounds, abrasions, burns or other pathological damage to the skin may greatly increase the ability of radioactive materials to reach subcutaneous tissues and then the blood and systemic circulation. Although much of the material deposited at a wound site may be retained at the site, and can be surgically excised, soluble (transportable) material can be transferred to the blood and hence to other parts of the body. These events occur only as a result of accidents, each event will, therefore, be unique and need to be assessed by occupational health physicists and medical staff.

To date, ICRP has not given advice on the interpretation of wound monitoring data following accidents involving radionuclides as each incident will be unique and general advice cannot be given. The biokinetic models that have been developed for various radionuclides are, however, applicable to the soluble component of any deposit in cuts or wounds that enters the blood circulation. The dose coefficients recommended by ICRP can be used in conjunction with the NCRP wound model parameter values to obtain organ and tissue doses and effective dose for radionuclides that have entered the blood from the wound site.

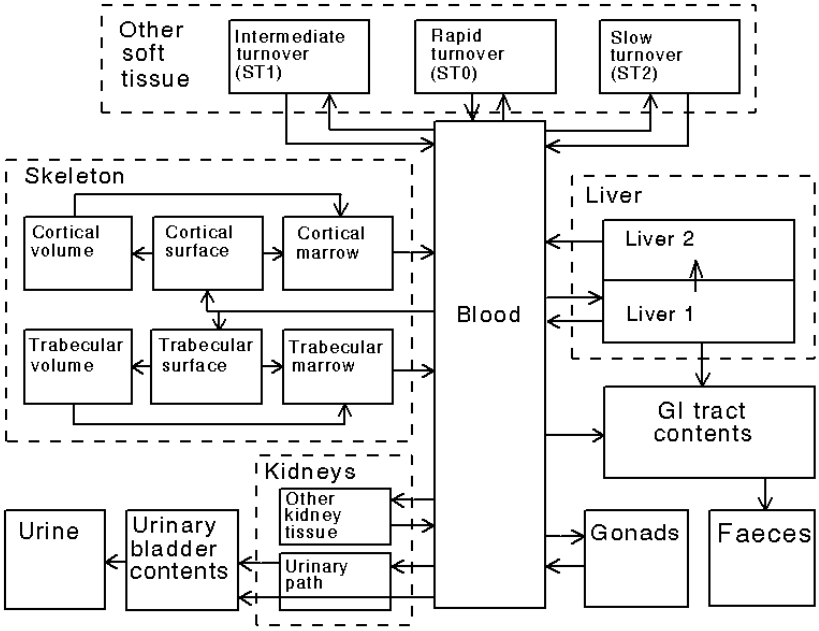
The application of the ICRP wound model for some real wound contamination cases has been discussed in the framework of the CONRAD project [42]. Good fits to the urine data have been obtained for four out of six cases. However, it was not possible to obtain a good fit with default wound retention categories for the two other cases. So further investigations are required. One suggestion to solve the problem was to assume a mixture of two default retention categories, either inside the ‘soluble category’ (weak, moderate, strong and avid) or inside the ‘insoluble category’ (colloid, particles or fragment). Another option would be to vary model parameter values. However, which parameters should be varied and to what extent are questions that still need to be answered.

3.6 Biokinetic Models for Systemic Activity

The fraction of an intake of a radionuclide entering the systemic circulation is referred to as the uptake. In Publication 30 ICRP reviewed information on the behaviour of radionuclides that had entered in the body. It recommended biokinetic models for radionuclides that had entered the blood for intakes by inhalation and ingestion. The ICRP 30 models applied specifically to workers and not to members of the public. More recently, Publications 56, 67, 69 and 71 revised the biokinetic models for selected radionuclides of 31 elements and these have been applied in the calculation of dose coefficients for both workers and for infants, children and adult members of the general population (ICRP [29, 30, 32, 33]. The models given in these Publications were primarily developed to provide age-dependent dose coefficients but the models for adults were also used in Publication 68 (ICRP, [36]) which gave updated dose coefficients for workers and in Publication 78 (ICRP, [38]) on the interpretation of bioassay data.

The biokinetic models recommended for adults are presently being reviewed by ICRP and will be published probably in 2009. A key feature of the updated models is that they will be applicable for both the calculation of doses and the interpretation of bioassay data.

Figure 15: Systemic model for plutonium and americium



Radionuclides entering the blood may distribute throughout the body (e.g. ^{3}H, ^{24}Na, ^{42}K, ^{137}Cs); they may selectively deposit in a particular tissue (e.g. ^{131}I in the thyroid; ^{90}Sr in bone) or they may deposit in significant quantities in a number of tissues (e.g. ^{239}Pu, ^{241}Am, ^{144}Ce). If a radionuclide that enters the blood is an isotope of an element that is required by the body then it will follow the normal metabolic pathways for that element (eg. ^{24}Na, ^{32}P, ^{42}K, ^{45}Ca, ^{59}Fe). If it has similar chemical properties to an element that is normally present then it will tend to follow the biokinetic pathways of that element, although its rate of transfer between the various compartments in the body may be different (e.g. ^{90}Sr and ^{226}Ra behave similarly to Ca, ^{137}Cs and ^{86}Rb similarly to K). For other radionuclides their behaviour in the body will depend upon their affinity for biological ligands and other transport systems in the body and, as a result, the extent of uptake and retention is largely unpredictable and must be assessed from the available human or animal data (eg. ^{95}Nb, ^{106}Ru, ^{239}Pu, ^{241}Am). Figure 15 illustrates the structure of the systemic model for plutonium and americium.

3.7 Excretion pathways

The biokinetic model adopted for the urinary bladder is described in Publication 67 (ICRP, [30]) and Publication 68 (ICRP, [36]). Although the model was developed for dosimetry, it is also applied in Publication 78 [38] to predict excretion. The number of voids per day is taken to be six. To represent the kinetics of the bladder in terms of first-order processes, the rate of elimination from the bladder is taken to be 12 d^{-1}. There is some degree of approximation in representing discrete events by a continuous process in this way. However, any inaccuracies introduced are likely to be small and will tend to cancel out when averaged over a daily measurement.

The activity present in the upper and lower large intestine includes material which entered the GI tract from the systemic circulation into the upper large intestine.

For bioassay interpretation it should be remembered that the transit time through the GI tract is subject to particularly large inter (and intra-) subject variations. Moreover, while for ease of computation transit through the GI tract is represented by a series of compartments that clear exponentially, in practice, the movement is more like "slug" flow. It is therefore unlikely that individual daily faecal clearance measurements in the first few days after intake will follow the predicted pattern, and so it is best to consider cumulative excretion over the first few days.

3.8 Biokinetic functions

The ICRP biokinetic models outlined above allow for the calculation of biokinetic functions for the interpretation of incorporation monitoring data, i.e. the time dependence of the activity content of the whole body or an organ under investigation (retention function) or the time dependence of the activity excreted via urine or faeces (excretion function). Typically the biokinetic functions are calculated for a single intake by inhalation, ingestion and injection. For protracted intakes the biokinetic functions should be integrated (if given as a continuous function) or obtained by superposition (if tabulated at discrete times).

There are a number of publications which give biokinetic functions for radionuclides using the current ICRP Models, including: IAEA [15]; ICRP [43]; Phipps *et al* [44]; Potter [45]; Ishigure *et al* [46].

4 Dose assessment

4.1 State of the art

The biokinetic models outlined above are used for the assessment of internal dose from the monitoring data. There are some broad guidelines for routine, special and task-related individual monitoring recommended by ICRP in Publication 54 [47] and Publication 78 [38]. These guidelines leave most of the assumptions open, this resulting in many different approaches for the interpretation of monitoring data as demonstrated by the 3rd European Intercomparison Exercise on Internal Dose Assessment [48].

The 3rd European Intercomparison Exercise gave special consideration to the effects of the new models and the choice of input parameters on the assessment of internal doses from monitoring results. It also took into account some aspects which had not been considered in previous exercises, such as air monitoring, natural radionuclides, exposure of the public, artificially created cases and artificially reduced information. Seven case scenarios were distributed, dealing with ^{3}H, ^{90}Sr, ^{125}I, ^{137}Cs, ^{210}Po, ^{238}U and ^{239}Pu, and covering different intake scenarios and all monitoring techniques. Results were received from 50 participants, 43 representing 18 European countries and 7 from five countries outside Europe. Most participants attempted more than half of the cases. Thus on average there were 35 responses per case with a total of about 240 answers, giving a good overview of the state of the art of internal dosimetry. The results in terms of intake and committed effective dose appeared to be log-normally distributed with the geometric standard deviation ranging from 1.15 for the cases dealing with ^{3}H and ^{137}Cs, up to 2.8 for the cases dealing with α-emitters (Table 6). These figures reflect to large differences in the individual results which varied in the worst case over a range of five orders of magnitude. A key feature of the exercise was a Workshop, involving most of the participants, at which each case and the various approaches taken to assessing it were discussed. Several reasons for the differences in the results were identified, including different assumptions about the pattern of intake, and the choice of model.

Table 6: Statistical evaluations of the E(50) results of the 3rd European Intercomparison Exercise on Internal Dose Assessment (excluding outliers) [48]

Case number	Radionuclide	Geometric mean (mSv)	Geometric standard dev.	Number of results[(a)]
1	^{3}H	0.00529	1.16	41 (7)
2	$^{90}Sr/^{90}Y$	0.093	1.78	38 (4)
3	^{125}I	0.441	1.53	38 (2)
4	^{137}Cs	0.198	1.15	43 (6)
5	^{210}Po	3.18	1.25	20 (1)
	^{238}U (+daughters)	0.355	2.31	20 (0)
	^{232}Th (+daughters)	0.157	2.8	20 (0)
6(A)	^{239}Pu	240	2.4	32 (3)
7	^{239}Pu	347	2.16	30 (2)

[(a)] number of outliers in brackets

The most important conclusion of the 3rd European Intercomparison Exercise was the need to develop agreed guidelines for internal dose evaluation procedures in order to promote harmonisation of assessments between organisations and countries, which has special importance in the European Union, because of the mobility of workers between member states. This was the reason to launch the IDEAS project in the 5th EU Framework Programme (EU Contract No. FIKR-CT2001-00160).

The IDEAS project reviewed the "Science and art of internal dose assessment". Based on this review "General guidelines for the estimation of committed effective dose from incorporation monitoring data" were developed which cover all aspects of internal dosimetry [49].

For testing of the IDEAS Guidelines a new intercomparison exercise was organised jointly by the International Atomic Energy Agency (IAEA) and the IDEAS project [50]. Full details of the intercomparison exercise are provided by Hurtgen [51] and by the IAEA [52]. Six cases were selected to cover a wide range of practices in the nuclear fuel cycle and medical applications. These cases were: (1) acute intake of HTO, (2) acute inhalation of the fission products ^{137}Cs and ^{90}Sr, (3) acute inhalation of ^{60}Co, (4) repeated intakes of ^{131}I, (5) intake of enriched uranium and (6) single intake of Pu isotopes and ^{241}Am. Four of the cases (1, 2, 5 and 6) are real, and all except case 5 have been published. Cases 3 and 4 were artificially constructed.

Table 7: Statistical evaluations of the E(50) results of the IDEAS/IAEA intercomparison exercise [50-52] (excluding outliers)

Case number	Radionuclide	Geometric mean (mSv)	Geometric standard dev.	Number of results[(a)]
1	^{3}H	25.8	1.06	46 (12)
2	^{137}Cs	0.66	1.16	52 (6)
	^{90}Sr	7.22	1.94	48 (10)
3	^{60}Co	5.0	1.4	56 (6)
4	^{131}I	2.57	1.07	50 (13)
5	Enriched Uranium	36.8	2.4	38 (3)
6	^{241}Am	52	2.1	32 (3)
	^{239}Pu	140	1.58	31 (5)

[(a)] number of outliers in brackets

Because of the easy access to the cases via the Internet, and the worldwide promotion of the intercomparison exercise by the IDEAS group and the IAEA, there were a large number of

participants from all over the world. Participants were free to undertake only those cases relevant to their work. Of the 74 participants who assessed at least one case, 36% provided an answer to all six cases. The highest participation (84%) was for the cobalt and iodine cases and the lowest (57%) was for the americium part of case 6. The statistical procedure used in the previous exercise [46] was applied to identify outliers in each set of results. Table 7 summarises results (committed effective doses, E(50)) excluding outliers. The results were discussed with the participants during a workshop held by the Agency in April 2005.

As can be seen from Tables 6 and 7, the geometric standard deviation of the results tends to be smaller for the IDEAS/IAEA intercomparison exercise than for the 3rd European Intercomparison Exercise. The cases of the two intercomparisons cannot be compared with each other, but there seems to be an improvement. Actually, the IDEAS/IAEA intercomparison exercise showed that the IDEAS Guidelines have a positive influence on the harmonisation of reported intakes and doses. An important finding was the lower occurrence of outlying values among those who applied the Guidelines than among those who did not. However, even very detailed guidelines cannot help if unrealistic assumptions or simple mistakes are made. There is still a need for adequate training, experience and quality control.

Some 20% of participants used the IDEAS Guidelines correctly and reached results that can be considered accurate. In view of this, more effort should be put into the promotion and correct application of such guidelines in the international internal dosimetry community, together with dedicated training. So the IDEAS guidelines should be described in more detail also in this refresher course.

The disillusioning experience with the past intercomparison exercises was also recognised by the International Standardization Organization (ISO). Because of the substantial differences between national regulations, concepts, and dose assessment procedures the ISO recently initiated projects to standardize the monitoring of workers, the requirements for measuring laboratories and the processes for the quantitative evaluation of monitoring data [53]. The anticipated approaches correspond widely to the IDEAS Guidelines.

4.2 General requirements

As pointed out in the previous section, the intercomparison exercises have shown that there is a wide variety of evaluation procedures, depending on the experience and the skill of the assessor as well as on the hardware and software tools available. However, for a given set of internal monitoring data in terms of body/organ activity and/or urine/faecal activity there should be one standard estimate for the intake and the committed equivalent dose. This standard estimate is defined by the monitoring data, the biokinetic models for the description of the metabolism, dosimetric models, and – if available – some additional information, such as time of intake, route of intake, aerosol size, respiratory tract absorption Type, gastro-intestinal (GI) tract absorption factor (f_1 value) and previous internal exposures.

So the aim of the IDEAS guidelines [49] is to enable all assessors to derive the best estimate for any given set of incorporation monitoring data taking into account the following principles:

- Harmonisation: by following the procedures any two assessors should obtain the same estimate of dose from a given data set
- Accuracy: the “best” estimate of dose should be obtained from the available data
- Proportionality: the effort applied to the evaluation should be proportionate to the dose – the lower the dose, the simpler the process should be.

4.2.1 Harmonisation

A well-defined procedure is needed and for this reason the process is defined here primarily by means of a series of flow-charts. So far as possible, the process has been made widely applicable, i.e., it does not assume that the assessor has the use of sophisticated bioassay interpretation software. For routine monitoring situations, where typically there is only one measurement relating to each intake, it is reasonably straightforward to define a procedure. However, in special monitoring situations, where typically there is more than one measurement and quite possibly more than one type of measurement (urine, faeces…) different options for data handling can easily lead to different evaluated doses, even when the same model, parameter values and software are used. Another range of options, and opportunities for different evaluated doses, arises in situations where it is appropriate to consider changing parameter values from the ICRP defaults. Proposals are made here for a systematic approach to dose assessment in all these situations.

4.2.2 Accuracy

It is recognised that the uncertainties associated with assessed internal dose can be considerable, especially for actinides which are difficult to detect in the body and have relatively high dose coefficients (Sv Bq^{-1}). If the initial estimate of dose exceeds 1 mSv, it could well be that the possibility of a substantially higher dose (e.g. 6 mSv) cannot easily be excluded. It is then important to make best use of the available information. To do so may well involve changing parameter values from their ICRP default values and guidance is therefore needed on which parameter values might reasonably be varied according to the circumstances.

4.2.3 Proportionality

The effort applied to the evaluation of incorporation monitoring data should broadly correspond to the expected level of exposure, and the complexity of the case. On the one hand, if the exposure is likely to be very low with respect to the dose limits, simple evaluation procedures with a relatively high uncertainty may be applied. On the other hand, if the monitoring values indicate the exposure to be close to or even above the dose limits, more sophisticated evaluation procedures will need to be applied. These take account of any case-specific information available, so that the uncertainty and bias on the best estimate are as low as reasonably achievable.

4.3 Levels of task

With respect to operational radiation protection the following structure of "Levels of task" has been proposed by the IDEAS Guidelines [49]:

- Level 0: Annual dose (committed effective dose from intakes of radionuclides that occur in the accounting year) <0.1 mSv. No evaluation of dose needed.

- Level 1: Simple, "reference" evaluation, with ICRP defaults used for all parameter values, except where there is better *a priori* information available, e.g. for inhalation intakes information on the particle size distribution (dose from the intake typically 0.1 – 1 mSv).

- Level 2: Sophisticated evaluation using additional information to give more realistic assessment of dose: typically a special assessment of an accidental intake. Comparisons are made of the model predictions ("the fit") with the data, to choose between alternative parameter values, or to find optimum parameter values (*a posteriori*). At this Level, the parameters adjusted typically relate to the material (for inhalation intakes the AMAD and absorption Type), and the time of intake if unknown (dose from the intake typically 1 – 6 mSv).

- Level 3: More sophisticated evaluation, which applies to cases where there are comprehensive data available, as would be the situation after an accident. The evaluation is an extension of Level 2, typically to parameters relating to the subject (e.g. for inhalation intakes the HRTM particle transport rates). The fundamental approach at this Level is to adjust the model parameter values systematically, in a specific order ("step-by-step" approach), until the goodness of fit is acceptable (i.e. the fits obtained to all the data are not rejected by the specified criteria) (dose typically > 6 mSv).

Level 0 is the lowest level and it refers to cases where the effective annual dose would be most likely below 0.1 mSv, even if there should be similar intakes in each monitoring interval of the year. At this level there is no need to evaluate the measured values explicitly, and the effective dose can be set to zero in analogy to the rounding of doses in external dosimetry. However, the measured value should be recorded with respect to further assessments in the future.

According to the above definition a measured quantity M can be allocated to Level 0, if $M < M_C$, where

$$M_C = \frac{10^{-4} \cdot m(T/2)}{e(50)} \cdot \frac{T}{365} \qquad (1)$$

where, M_c is the "critical" monitoring quantity, T is the monitoring interval (in days) for the monitoring quantity considered, $m(T/2)$ is the corresponding retention or excretion function (per unit intake) for the monitoring quantity at time t = T/2, and $e(50)$ is the effective dose coefficient (in Sv/Bq).

The critical monitoring quantity M_C defined by the equation (1) is typically above, or close to, the lower limit of detection (LLD) for the fission and activation products whereas it is below the LLD for the actinides considered. So in the case of the actinides, any significant monitoring value is likely to result in a dose of more than 0.1 mSv and thus has to be evaluated. In the case of the fission and activation products, however, there might be significant monitoring values which result in a dose of less than 0.1 mSv. Thus, Level 1 applies typically to those radionuclides, which are easy to measure and which have low effective dose coefficients (i.e. ^{3}H, ^{137}Cs etc).

4.4 Understanding exposure situations

Workplace information should be gathered in order to understand the exposure situations, e.g., radionuclides that may have been incorporated (including equilibrium assumptions for the natural series), chemical form, presumed particle size (typically 1 or 5 μm), likely time, pattern and pathway of any intake.

If no special information is available, the following default parameter values could be used (reference procedure):

- Mode of intake: Single intake
- Time of intake: Mid-point of the monitoring interval, i.e. the mid-point of the time range between the date of the measurement being considered and the date of either the previous measurement or the beginning of monitoring

Inhalation:

- Absorption Type and f_1 value: defaults according to ICRP publications.
- Particle size: 5 μm AMAD

Ingestion:

- f_1 value: defaults according to ICRP.

In the case of exposures that lead to effective dose estimates higher than about 0.1 mSv (i.e. above Level 0 of the IDEAS guidelines), it is desirable to use parameter values in the calculation of tissue and organ equivalent dose that are more specific to the conditions of exposure and to the individual. By using such workplace specific parameters a more realistic dose assessment can be obtained.

For the interpretation of direct and indirect measurements in terms of the intake and resulting effective dose, data on the time pattern and pathway of intake, the chemical and physical form of the radionuclides and on previous intakes are needed. In many cases however the information may not be available.

The time pattern of intake is a main source of uncertainty in the interpretation of bioassay data. Assumptions about the time of intake and of whether the intake was acute, lasted for a short period of time or extended for a long time is a major point in the reliability of the interpretation of the bioassay data. For example, in some cases the retention and excretion functions diminish by orders of magnitude within a few days, therefore the choice of the time pattern of intake can influence the assessed dose within the same range.

Inhalation is the main pathway of intake in the workplace. The characterisation of the intake in terms of aerosol size and absorption type are needed for the application of the *m(t)* values to estimate the intake. The *m(t)* values are the calculated values of the measured quantities for unit intake at time t after the intake. The aerosol size will influence deposition in the HRTM and as a consequence the transfer of unabsorbed particles to the GI tract. In some working environments more than one particle size is detected. The rate of absorption of a radionuclide to blood is very important for interpreting bioassay data. It is a critical parameter in interpreting urine excretion data. The differences between the true absorption rates and the default parameters which have been assigned to the compound being inhaled are sources of errors that can be very large, especially when deriving intakes from urinary excretion bioassay data.

Further uncertainty is added when the activity of a radionuclide in the body could not be measured directly but is derived from progeny radionuclides. Contributions from intakes from natural sources, especially in the diet, may also contribute to the uncertainty of a bioassay result.

4.4.1 Knowledge of radionuclides handled

For many elements there are a number of radionuclides that could be present in the workplace with quite different physical characteristics. At the same time their behaviour after entry into the body can also be very variable depending upon the physical and chemical form present. Some examples are given below for uranium and plutonium to illustrate the potential for exposure to complex mixtures.

Tables 8-10 show the composition of natural and enriched (3.5% and 92.8%) uranium in terms of activity. Note that the composition in terms of mass is completely different. The Tables illustrate the diversity and complexity of uranium compounds found in the workplace.

Table 8: Isotopic composition of natural uranium

Isotope	% Isotopic composition[a]	% Alpha activity	Alpha activity[b] Bq/g
U-238	99.2745	48.16	1.23E+04
U-236	0.0000	0.00	0.00E+00
U-235	0.7200	2.25	5.76E+02
U-234	0.0055	49.59	1.27E+04
Total alpha activity, Bq/g			2.564E+04
Alpha activity ratio U-234/U-238			1.030
Alpha activity ratio U-235/U-238			0.047

[a] Composition is given as weight % of total U isotopes
[b] Alpha activity per gram uranium

Table 9: Isotopic composition of enriched (3.5 %) uranium

Isotope	% Isotopic composition[a]	% Alpha activity	Alpha activity[b] Bq/g
U-238	96.471	14.73	1.20E+04
U-236	0.0000	0.00	0.00E+00
U-235	3.5000	3.44	2.7992E+03
U-234	0.02884	81.84	6.6679E+04
Total alpha activity, Bq/g			8.1478E+04
Alpha activity ratio U-234/U-238			5.556
Alpha activity ratio U-235/U-238			0.233

[a] Composition is given as weight % of total U isotopes
[b] Alpha activity per gram uranium

Table 10: Isotopic composition of enriched (92.8 %) uranium

Isotope	% Isotopic composition[a]	% Alpha activity	Alpha activity[b] Bq/g
U-238	6.06	0.039	7.51E+02
U-236	0.34	0.428	8.16E+03
U-235	92.8	3.89	7.42E+04
U-234	0.79	95.64	1.82E+06
Total alpha activity, Bq/g			1.91E+06
Alpha activity ratio U-234/U-238			2452
Alpha activity ratio U-235/U-238			99.8

[a] Composition is given as weight % of total U isotopes
[b] Alpha activity per gram uranium

Table 11: Isotopic composition of Pu and Am in spent nuclear fuel from reprocessing plant

Isotope	% Isotopic composition, Pu+Am a	% Pu-Alpha activity	% Total-Alpha activity
Pu-238	0.30	38.47	38.47
Pu-239	78.65	36.56	36.56
Pu-240	14.64	24.95	24.95
Pu-241	5.55	-	-
Pu-242	0.860	0.02	0.02
Pu-244	0	0	0
Am-241	0	-	0

(a) Composition is given as weight % of total Pu isotopes + Am-241

Table 12: Isotopic composition of Pu and Am in spent Light Water Reactor fuel

Isotope	% Isotopic composition, Pu+Am [b]	% Pu-Alpha activity	% Total-Alpha activity	% Total activity
Pu-238	2.23 (0.69)	81.53	72.86	2.75
Pu-239	54.05 (3.08)	7.17	6.41	0.24
Pu-240	23.18 (0.67)	11.25	10.05	0.38
Pu-241	12.98 (1.42)	-	-	96.23
Pu-242	5.94 (1.32)	0.05	0.04	0.0
Am-241	1.62 (1.22)	-	10.64	0.40
Pu-241 activity/Total Pu a activity				29
Pu-241 /(Pu-239+Pu-240) [a] activity				155
Am-241 activity/Pu-241 activity				0.004

(a) Light Water Reactors consitute >80% of all commercial reactors, the remaining 20% being evenly divided between Pressurised Heavy Water Reactors (PHWR) of the CANDU type and Gas Cooled (Magnox) Reactors. This data is compiled from six sets of data covering various LWR sub types and reactor power outputs. The composition is for spent Low Enriched Uranium fuel (LEU).

(b) Composition is given as mean atom % of total Pu isotopes + Am-241. Sample Standard Deviations in parentheses.

The plutonium composition of some materials encountered in the nuclear industry are given in Tables 11 and 12 which show the composition of Pu and Am radionuclides in the reprocessing of spent fuel (Pu-nitrate, Pu oxides) and fuel from a light water reactor (LWR). Again there are widely different chemical characteristics and composition [55].

4.4.2 Time(s)and pattern of intake

A principal source of uncertainty in the interpretation of bioassay data is the determination of the time of intake. In general, the time will not be known beforehand, especially in the case of routine monitoring when it is required to estimate an intake from a measurement made at the end of a monitoring interval. If an unusual occurrence triggered special bioassay monitoring, then the time of that occurrence is usually taken as the time of intake.

Since the bioassay function that gives the predicted measurement depends on the time since the intake it follows that the estimate of intake will vary, depending on when it is assumed the intake took place. If the time of the intake is known then the assessment is straightforward. However, if the time of intake is unknown then a judgement has to be made when it occurred. In ICRP Publication 54 [47] and ICRP Publication 78 [38] it is argued that in the absence of any information, the time of intake is equally likely to have occurred before the end of the monitoring interval, and therefore suggests that in these situations, a value of t=T/*2* should be used, i.e. the intake is assumed to have occurred at the mid pint of the monitoring interval.

If a significant intake and effective dose is calculated, using this assumption, then a more realistic determination may be required. Sometimes a review of workplace monitoring data, such as airborne or surface contamination levels can indicate a likely time for the intake to have occurred. Similarly, if other workers in the same workplace have exhibited positive routine bioassay samples, a review of the data and monitoring schedules for the individual workers may help determine the time of intake for all. Of course, an individual worker may be able to recall the incident that led to the intake. In addition, if several bioassay results are available, perhaps including different types of measurement, a comparison of these results with the m(t) tables may help in narrowing the choice of the time the intake occurred.

While the mid point assumption is a pragmatic and simple approach, it does not result in an unbiased estimate of the intake. If this assumption is applied regularly, to an individual worker, it is subject to bias and will tend to overestimate the worker's real intake. It is always preferable to avoid bias, and it can be demonstrated that this can be avoided by assuming a constant chronic intake. If a software program is being used to estimate the intake, then this method can be simply applied by selecting the intake regime to be constant and chronic throughout the monitoring interval. Theoretical considerations aside, however, the choice of an appropriate method of estimating intakes is also dependent on broader considerations such as ease of implementation, and in many situations, the mid-point method is adequate, considering the other uncertainties involved in dose assessment.

4.4.3 Intake pathways

Although intakes by inhalation alone are the most frequent in the workplace, intakes by ingestion and uptake through wounds and intact skin cannot be excluded. Sometimes the worker touches the mouth with contaminated hands and ingestion occurs. If the pathway of intake is not known and several bioassay results are available, including different types of bioassay measurements, a comparison of these results with the *m(t)* tables may help in determining the pathway of intake. In some facilities simultaneous intakes by inhalation and ingestion can occur. In principle, results from the ingestion and inhalation tables can be combined to give predicted values of *m(t)*. Alternatively, it can be modelled by assuming inhalation with a large AMAD (> 5 μm).

If the radionuclide activity can be assessed by direct measurements, lung counting can be used to differentiate between inhaled and ingested material. However, if this is not possible and the radionuclide is in an insoluble form, interpretation of activities excreted in faecal and urine samples in terms of intake is quite problematic. Both the ingested material and the inhaled material deposited in the upper respiratory tract will clear through the faeces in the first few days after intake. Consequently, it is important to initiate excreta sampling as soon as possible after the intake, continuing for an

extended period. Material in the faeces after the second week will be exclusively from the respiratory tract, and can be used, together with the appropriate values of *m(t)*, to correct the earlier faecal samples for this component. In the monitoring of workers chronically exposed to long–lived, insoluble radionuclides, activities in the faeces after a 15 days' absence from work will mostly reflect the delayed clearance from inhaled material (IAEA, [14, 16]).

4.4.4 Particle size/chemical composition

Although recent reviews of reported measurements of AMAD in workplaces (eg. Dorrian and Bailey [56]) support the ICRP publication 66/68 default value of 5 μm for occupational exposure, they also show that a wide range (about 1–20 μm) has been observed. If the airborne contamination in the workplace has been well characterised, it may be possible to use a more realistic value based on measurements of the activity size distribution. Alternatively, if there are suitable early measurement data available, an "effective" AMAD can be inferred a posteriori from the measurements. The main effect of the aerosol AMAD is to determine the relative amounts deposited (i) in the upper respiratory tract (extrathoracic airways, ET, bronchi, BB, and bronchioles, bb, in the HRTM), which (if not absorbed into blood) is mainly cleared rapidly to the alimentary tract and hence to faeces within a few days, and (ii) in the lower respiratory tract (alveolar-interstitial, AI, region in the HRTM), which is mainly cleared slowly from the lungs. For a relatively insoluble (Type M or S) material inhaled by a Reference Worker, the ratio of cumulative faecal excretion over the first 3 days to lung activity on day 3 increased almost linearly from about two at 1 μm AMAD to twelve at 10 μm AMAD. Hence the observed ratio could be used to infer the "effective" AMAD. It is referred to as "effective", because the ratio will be determined not only by the aerosol size, but also by the subject's breathing pattern (especially if it involves mouth-breathing) and inter-subject variation in deposition under any given set of conditions. Because it takes account of these, it is preferable for dose assessment than *a priori* measurements of the AMAD.

4.5 Handling of monitoring data

Care must be taken to ensure that a measurement result, *M(t)*, and the respective biokinetic function *m(t)* are comparable. Thus, *M(t)* must not be influenced significantly by previous intakes which are not covered by *m(t)*. Thus, all evaluations should be carried out using net measured values, *N(t),*

$$N(t) = M(t) - P(t) \qquad (2)$$

where *P(t)* is the contribution from previous intakes to the actual measured value *M(t)* under investigation.

Note that in the following the measured values *M(t)* are always considered to be net measured values without contributions from previous intakes.

When only a single bioassay measurement is available, a point estimate of the intake is made. If multiple measurements are available, a best estimate of intake may be obtained by applying a statistical fitting method.

4.5.1 Single data point

Special monitoring

For special or task-related monitoring when the time of intake is known, the intake can be estimated from the measured results using the predicted values of measured quantities. If only a single measurement is made, the intake, *I*, can be determined from the measured quantity, *M*, by:

$$I = \frac{M}{m(t)} \qquad (3)$$

where *m(t)* is the predicted value of the measured quantity for unit intake and *t* is the time of the measurement after the intake.

The intake can be multiplied by the dose coefficient to give the committed effective dose; this can then be compared with the dose limit or any pre-determined investigation level based on dose. If the measurement indicates that an investigation level (or a dose level) has been exceeded, further investigation is required.

Routine monitoring

For routine monitoring, it is normally assumed that intake took place as single inhalation in the middle of the monitoring interval of T days. For a given measured quantity, M, obtained at the end of the monitoring interval, the intake is:

$$Intake = \frac{M}{m(T/2)} \tag{4}$$

where *m(T/2)* is the predicted value of the measured quantity for unit intake by inhalation occurring at the mid-point of the monitoring interval. The dose from intake in the monitoring interval is obtained by multiplying the intake by the dose coefficient. The dose or intake can be compared with the pro-rata fraction of the dose limit or of the activity corresponding to that limit. Alternatively, the dose or intake can be compared with pre-determined investigation levels.

4.5.2 Multiple data sets

Usually, the bioassay data for an intake estimate will consist of results for different samples collected at different times, and even from different monitoring techniques, e.g., urine data and faecal data, and perhaps also direct measurements.

To determine the best estimate of a single intake, when the time of intake is known, it is first necessary to calculate the predicted values, $m(t_i)$, for unit intake of the measured quantities, where t_i is the time of the i^{th} measurement M_i. It is then required to determine the best estimate of the intake, *I*, such that the product $I\ m(t_i)$ "best fits" the measurement data (M_i, t_i). In cases where multiple types of bioassay data sets are available, it is recommended to assess the intake and dose by fitting predicted values to the different types of measurement data simultaneously. For example, if urine and faecal data sets are available then, the intake is assessed by fitting predicted values to both data sets simultaneously.

Numerous statistical methods for data fitting are available [IAEA, 16]. The two accepted scientific approaches are the maximum likelihood method and the Bayesian approach. These two methods are most widely applicable and can be applied to the cases where it is assumed that the measurements are log-normally distributed as recommended in IDEAS General Guidelines [49]. Other methods, such as the least squares method are special cases of the maximum likelihood method under certain assumptions. The standard equations given for the least squares method apply to cases where the measurements are normally distributed and therefore do not strictly apply to the IDEAS General Guidelines.

The maximum likelihood method is discussed in detail in the IDEAS General Guidelines. Simple equations are given there for the intake that can be applied without the use of sophisticated software.

4.5.3 Number and type of data required for assessment of dose

The reliability of the dose assessment depends on the number and type of the monitoring data. Thus, there are minimum requirements for the type and number of monitoring data, depending on the involved radionuclide and the dose range. Such requirements have been suggested by the IDEAS guidelines [49]. Recently the requirements have been updated within the framework of the CONRAD project [42].

Table 13: Suggested minimum number and type of data required for the assessment of dose for some categories of radionuclides [42]

Category of radionuclide	Type of monitoring	Number of required monitoring data		
		D < 1 mSv (minimum requirement)	1 mSv < D < 6 mSv[a]	D > 6 mSv[b]
All type of α emitters with significant γ component (^{235}U, ^{241}Am, etc.)	Urine	-	2	3
	Faeces	1	2	3
	Whole body, critical organ or wound site	-	2	4
All type of α emitters without significant γ component (^{210}Po, ^{239}Pu, etc.)	Urine	-	3	5
	Faeces	1	3	5
All type of β emitters with significant γ component (^{60}Co, ^{131}I, ^{137}Cs, etc.)	Whole body, critical organ or wound site	1	2	4
	Urine	-	2	4
F-type β emitters without significant γ component (^{3}H, ^{14}C, etc.)	Urine	1	4	8
M/S-type β emitters without significant γ component (^{90}Sr, etc.)	Urine	1	2	4
	Faeces	-	2	4
Pure γ emitters (^{123}I, etc.)	Whole body or critical organ	1	2	4
	Urine	-	2	4

[a] The monitoring data should cover a time range of 30 d; if the effective half-life is ,30 d, the monitoring data should cover a time range corresponding to the effective half-life.

[b] The monitoring data should cover a time range of 60 d; if the effective half-life is ,30 d, the monitoring data should cover a time range corresponding to twice the effective half-life.

Table 13 shows the updated requirements for some selected radionuclides. Ideally the measurements should be distributed appropriately over the relevant time range given in Table 13. Note that the table is only a provisional first attempt which is not prescriptive at all. More work and input from those with practical experience are required to give comprehensive guidance on this issue.

4.5.4 Data processing before use

Some types of measurement data may need processing before use. Examples include:

- "Lung". Generally, the combined activity in lungs and thoracic lymph nodes is referred to as 'lung' activity, and it is this quantity that is calculated by internal dosimetry software. Where estimates of lung and lymph node activity are given separately, they should be summed. "Chest" measurements may also include counts from activity in liver and skeleton for radionuclides that concentrate in these tissues, and their contributions will have to be subtracted.

- Faeces. The transit time through the GI tract is subject to large inter (and intra-) subject variations. Moreover, while for ease of computation transit through the GI tract is represented by a series of compartments that clear exponentially, in practice, the movement is more like "slug" flow. It is therefore unlikely that individual daily faecal clearance measurements in the first few days after intake will follow the predicted pattern, and so it is best to consider cumulative excretion over the first few days.

- Urine. If the data are given in terms of Bq/litre then this can be normalised to daily excretion rates by assuming 1.6 litres of urine are excreted per day (reference value for man, ICRP Publication 89 [46].

- Plutonium. Assume that "Pu" (if not qualified) refers to total Pu alpha-activity (^{238}Pu, ^{239}Pu, and ^{240}Pu). Assume that "^{239}Pu" (if not qualified) actually represents ^{239}Pu+^{240}Pu, because these cannot be separated by alpha spectrometry. If ^{241}Pu is not measured then assume a typical ratio to total plutonium alpha activity, for use as default. See table of typical plutonium isotopic ratios, which should be used with caution as default in those cases where no specific information is available.

- Uranium. Excretion data (especially faecal) may need correction for dietary intakes of uranium. Doses need to be included for isotopes in addition to those measured. In particular, for enriched uranium ^{235}U may be measured, while the highest dose comes from ^{234}U. See table of typical uranium isotopic ratios for depleted, natural, high- and low-enriched uranium.

4.5.5 Assessment of uncertainty on data

The uncertainties on the data are of great importance for the evaluation for several reasons:

- They enable an objective decision to be made on whether a measured value is due to a new intake, or due to previous intakes that already have been evaluated.

- They enable an objective decision to be made on whether a measured value is consistent with previous evaluations, or if it indicates the previous evaluations to be wrong.

- They can have a strong influence on all evaluations using weighted fitting procedures (i.e. where there is more than one data point).

- They enable rogue data to be identified objectively.
- They enable objective (statistical) criteria (goodness-of-fit) to be calculated, which are used to determine whether the predictions of the biokinetic model (with a given set of parameter values) used to assess the intake and dose are inconsistent with the data.
- They enable statistics, such as the χ^2, to be calculated, which are used to compare the fits to the data of different models/parameter values.

Generally, the uncertainties in the measurement are difficult to estimate. When activity levels are low and close to the limit of detection, uncertainties due to counting statistics may dominate the overall uncertainty. For radionuclides that are easily detected and present in sufficient quantity, uncertainties due to counting statistics will be small compared to other sources of uncertainty. Consideration must also be given to systematic uncertainties in other parts of the measurement procedure, e.g. calibration, or correction for body size of *in vivo* measurements. These uncertainties apply to the measurement of activity in the sample or person. With excretion measurements, the activity in the sample is used to provide an estimate of the subject's average excretion rate over 24 hours for comparison with the model predictions. If the samples are collected over periods less than 24 hours then they should be normalised to an equivalent 24-hour value. This introduces additional sources of uncertainty relating to biological (inter-and intra-subject) variability and sampling procedures, which may well be greater than the uncertainty in the measured sample activity.

Table 14: Default values for the components of log-normal uncertainty for in vivo measurements of radionuclides emitting low, intermediate and high photon energy radiation [49]

Source of uncertainty (Type)	Log-normal scattering factor 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[1)] (B)	1.15	1.05	1.03

1) HPGe detector spectra

Typically, the components of uncertainty are grouped into two categories: Type A comprises those components which can be described by the Poisson distribution (i.e. counting errors). Type B comprises all other components (i.e. variation of background signal, variation of the subject positioning during *in vivo* measurement, variation of body dimensions, overlaying structures, distribution of activity within the body during *in vivo* measurement, variation of the biokinetic behaviour, uncertainty of the calibration standard and the variation of the recovery for an in vitro measurement). The Type B components cannot be expressed in terms of Poisson statistics, and thus there is a problem in combining the Type B and the Type A components in order to derive the total uncertainty of the data point.

Table 14 lists preliminary values for the various components of uncertainty of *in vivo* counting as suggested by the IDEAS guidelines [49]. The uncertainty is given in terms of the scattering factor (SF) assuming that the distributions of the counting results can be approximated by log-normal distributions. The SF is the geometric standard deviation of the distribution. For example, the SF due to counting statistics is given as SF = 1.5 for low photon energy counting. This means that the scattering of the measured values due to counting statistics would result in 67% of the values to be in between $x_{50}/1.5$ and $x_{50}*1.5$, where x_{50} is the median of all the measured values.

Table 15: Default values for the total type A and type B log-normal uncertainty for in vivo measurements of radionuclides emitting low, intermediate and high photon energy radiation

Uncertainty type	Log-normal scattering factor SF		
	Low photon energy E < 20 keV	Intermediate photon energy 20 keV < E < 100 keV	High photon energy E > 100 keV
Total type A	1.5	1.3	1.07
Total type B	2.06	1.25	1.15
Total	2.3	1.4	1.2

Based on the experience gained in the IDEAS project as well as on general considerations, the following general approach for the calculation of the total uncertainty may be applied.

$$SF = \exp\left[\sqrt{\sum_i \ln^2(SF_i)}\right] \quad (5)$$

where, SF is the total scattering factor, and SF_i is the scattering factor due to component i. When applying this approach on the SF values given in Table 14, the values in Table 15 are derived for the total scattering factors.

The measured activity, A and its Type A uncertainty, σ_A are given in terms of measured quantities by:

$$A = C_n \left(N_G - \frac{N_B}{R_B} \right)$$

$$\sigma_A = C_n \sqrt{N_G + \frac{N_B}{R_B^2}} \tag{6}$$

where, N_G is the number of measured counts, N_B is the number of measured background counts, R_B is the ratio of background count time to sample count time, and C_n is the normalisation factor converting counts to activity.

The SF for Type A uncertainties is given by:

$$SF_A = \exp\left[\frac{\sigma_A}{A} \right] \tag{7}$$

The SF for Type B uncertainties is given by:

$$SF_B = \exp\left[\frac{\sigma_{C_n}}{C_n} \right] \tag{8}$$

where σ_{C_n} is the uncertainty on the normalisation factor.

Basically, the Type A component decreases with increasing activity and/or increasing counting time, whereas the Type B components can be considered to be independent of the activity involved or counting time. Thus, at low activity values or low counting times, respectively, the total uncertainty is governed by the Type A component, whereas at high counting times the Type B components are predominant.

Typical values for Type B scattering factors for various types of in vitro measurement from different studies are given in Table 16. In practice routine urinary excretion data from plutonium workers is often found to have a log-normal distribution with a SF of about 1.3 to 2.0 (Moss *et al*, [57] and Riddell *et al*, [58]). However, Moss *et al*. [57] showed that when the sampling method and analytical procedures are carefully controlled for true 24 h urine samples, over 5 days, then the SF is significantly less (1.1).

The SF values listed in the Tables 14 – 16 represent some preliminary figures derived from some selected sources and judgements. The subject has been investigated in more detail in the framework of the CONRAD project using more information from practical experience [42]. These investigations revealed the SF values for in vivo measurements to be widely consistent with practical experience. The SF factors for faecal measurements in Table 16 were slightly adjusted.

Table 16: Default values for the log-normal scattering factor SF for various types of in vitro measurement from different studies (Type B errors). Ranges are given in parentheses [42, 49]

Quantity	Log-normal scattering factor SF
True 24-hr urine	1.1[(a)]
Activity concentration of ^{3}H in urine	1.1[(b)]
Simulated 24-hr urine, creatinine or specific gravity normalized.	1.6[(b)] (1.3[(c)] - 1.8[(d)])
Spot urine sample	2.0[(a)]
Faecal 24-hr sample	3 (2 - 4)[(b)]
Faecal 72-hr sample	1.9 (1.5 – 2.2)[(e)]

(a) Value given by Moss *et al*, [49] based on plutonium in urine measurements of workers at Los Alamos.
(b) Value based on judgement and experience.
(c) At Los Alamos, Type B uncertainties, in terms of the coefficient of variation, for urine samples normalised using volume and specific gravity has been found to be 30% (i.e. a SF of 1.3).
(d) Value given by Riddell *et al*, [50] based on plutonium in urine measurements of Sellafield workers. Because sampling procedures and measurements techniques have improved over the years recent measurements are likely to have a SF less than 1.8.
(e) SF values for 72-hr faecal samples are consistent with 24-hr faecal samples.

4.5.6 Criteria for rejecting fit

In assessing intakes and doses, the underlying starting assumption is that:

- the structure of the biokinetic model is a realistic representation of the physical and biological processes, and
- the model parameter values are correct.

Estimates of bioassay quantities will be unbiased only if these conditions are met. These assumptions are analogous to the null hypothesis in classical statistics. In cases where the model predictions are inconsistent with the data (i.e. fits are inadequate) this indicates that either the model parameter values or the structure of the model is incorrect. The classical statistical approach is to reject the model and to repeat the assessment with different model parameter values or with a new model structure so that the predictions are not inconsistent with the data. Before the model structure itself can be rejected, it is necessary to first consider changes to the model parameter values. In the IDEAS guidelines only changes to the parameter values are considered, not to the model structure.

It is important to remember that it is not possible to prove that the null hypothesis is true. Test statistics are used to indicate that the null hypothesis is false. The criteria for rejecting the null hypothesis, (i.e. stating the fit is inadequate), needs to be defined before the assessment is carried out.

A comprehensive discussion of all the possible statistics that can be used to quantify whether a fit is inadequate is beyond the scope of this refresher course. Only the *chi-squared* test statistic, χ_0^2 is considered here.

If it is assumed that each measurement, M_i, is taken from a log-normal distribution with a scattering factor of SF_i then for n measurements, χ_0^2 is defined as:

$$\chi_o^2 = \sum_{i=1}^{n} \left(\frac{\ln(M_i) - \ln[I\, m(t_i)]}{\ln(SF_i)} \right)^2 \qquad (9)$$

The product $I\, m(t_i)$ is the predicted value.

The above formulae do not apply to data that are reported as below the lower limit of detection (<LLD).

When fitting predicted values to different types of data simultaneously, the overall χ_0^2 is equal to the sum of the calculated χ_0^2 values for each data set.

If the predictions are inconsistent with the data, then the calculated value of χ_0^2 is inconsistent with the theoretical *chi-squared* (χ^2) distribution with (n-1) degrees of freedom. The expected value of χ^2 is equal to the number of degrees of freedom (i.e. n-1).

The actual number of degrees of freedom when varying l parameters for a linear model (with respect to its parameters) is n-l. In this case the biokinetic model is not linear with respect to most of its parameters, other than the intake. If the fit is rejected assuming n-1 degrees of freedom then the fit would also be rejected if the actual number of degrees of freedom is less. For cases where there are comprehensive data so that $n>>l$, it is proposed to assume n-1 degrees of freedom for each step of the procedure given in the flow charts.

The probability of observing a larger χ^2 value than χ_0^2 for (n-1) degrees of freedom is given by the p-value, which can be obtained from Statistical Tables. The p-value is the fraction of the theoretical χ^2 distribution that lies above the calculated χ_0^2 value. So if the p-value is very small, the calculated χ_0^2 value is very much larger than expected and therefore it can be concluded that the predictions are likely to be inconsistent with the data and the assumed uncertainties.

The χ^2 test uses the assumed uncertainties. If the assumed uncertainties are overestimated then χ_0^2 is too small. The converse is also true; if the assumed uncertainties are underestimated then χ_0^2 is too large. This is one of the reasons why it is important to assess realistic scattering factors.

The IDEAS guidelines propose that the fits to the data are judged to be inadequate if:

- the probability that χ^2 is greater than χ_0^2 is 5% or less (i.e. if p-value < 0.05). In other words the fit is inadequate at the 5% level of significance, or if
- the fit displayed graphically looks unreasonable by eye.

It is also acknowledged that whether or not the fit displayed graphically looks unreasonable by eye is a subjective judgement. Generally, however, a fit would be considered unreasonable if all, or a long series, of data were systematically underestimated or overestimated.

4.6 Special aspects

4.6.1 Handling of data below limits of detection

It is recommended to keep records on the original counting statistic and associated information (duration of the measurement, background effect count rate, duration of the background effect measurement, assessed uncertainty of estimated activity, etc) for all data, including results, assessed as less than a decision threshold (ISO [59-61]). The substitution of the original data by an expression "less than the decision threshold" or "less than the detection limit" is not recommended. All original data may be involved into the dose assessment with taking into account the uncertainty associated with each result. Details of processing of such data are given in ISO standards (ISO [62, 63]).

If data are reported as being below the lower limit of detection (LLD) and only the LLD value is recorded then it is recommended to use the maximum likelihood method to obtain the best estimate of intake. It can be shown that this method leads to an unbiased estimate of the intake (Marsh [64]).

If the application of this method is not possible because of the lack of available software, then several other simplifying assumptions are possible. One such assumption is to treat each LLD value as a positive value at that measurement. This will clearly lead to an overestimate of the intake, but there is no simple method to quantify the degree of overestimation. In the example cases studied in the IDEAS project, it was found that that setting the LLD values to positive values at LLD/2 gave similar results as the application of the Maximum Likelihood Method. It is acknowledged that this method has no strong foundation in mathematics, and may not be universally applicable, but, in the interest of harmonisation and proportionality, it is recommended by the IDEAS guidelines, that if the maximum likelihood cannot be applied, then LLD data should be treated in this way.

4.6.2 Handling of data influenced by chelation therapy

Generally, it can be assumed that data of Pu and Am content in urine are affected by DTPA therapy. If DTPA has been effective in reducing systemic uptake then systemic organ retention and systemic faecal excretion will also be affected. Lung data are not affected by DTPA therapy.

The method of Jech *et al* [65] is proposed here: exclude urinary excretion data that have been affected by DTPA. Following La Bone [66, 67] it is proposed that data up to 100 days following chelation should be excluded. The alternative approach is to use a model for the urinary excretion of the chelated actinide, to compensate for the enhanced excretion (Hall method, La Bone, [67]). This is preferable, when an early assessment is required, because it makes more use of the available information, but the IDEAS partners were unable to propose a suitable formula at that time. Thus, in the framework of the CONRAD project a generic model considering the effects of DTPA treatment was developed [66, 68, 69]. At present the proposed model is tested with real data and it is expected to come up with a practical procedure for handling of data influenced by DTPA in the near future.

4.6.3 Identification of rogue data

A systematic basis to identify outliers and criteria to exclude them are needed. Outliers above and below the trend of the other data have different significance. A point above the trend might indicate another intake. A point below is more likely to result from a transcription or measurement error.

The problem of deciding how to identify outliers is not straightforward. Ideally, outliers should be identified before fitting model predictions to the data. If not, then the assessor faces a dilemma when the model does not fit the data: should the model parameters be varied to obtain a fit, or should the data that does not fit be rejected. So ideally, the trend of the data should be obtained first by, for example, fitting a sum of exponentials to the data and then using a statistical test to reject the data. In

practice, it is realised that this procedure could be time consuming, and many assessors will rely on judgement when deciding to reject certain data. Specifically, care must be taken in excluding data, particularly if a group of data at early or late times does not appear to be predicted by the model, then model parameters should be varied in preference to excluding data.

For measurement data suspected of being "rogue" a check should be made on whether inclusion or exclusion significantly affects the intake and dose. If it does not, there is no point in expending effort on justifying excluding it: it should be included. If it does have an effect, then a statistical test should be carried out to determine if it is an outlier. If it is an outlier then it should be excluded.

To identify outliers the following statistical test is proposed by the IDEAS guidelines. A measurement value is an outlier if it is more than a factor of SF^3 away from the trend of the other data, where SF is the scattering factor. If the data set is limited after excluding outliers, then further measurements may be required for assessment of dose.

4.7 Structured approach to dose assessment

The IDEAS General Guidelines provide a structured approach to the assessment of internal doses from monitoring data. It consists of a series of "Stages", broadly corresponding to the Levels of task given in Section 4.3. Each Stage consists of a series of "Steps", and is presented diagrammatically in a flow chart, with a brief explanation of each Step in the text. Detailed descriptions of all aspects of the evaluation process are given in the final report on the IDEAS General Guidelines [49].

Stage 1: Level 0 and for higher exposures

Level 0 refers to cases where it is expected that the annual dose (committed effective dose from intakes of radionuclides that occur in the accounting year) is likely to be below 0.1 mSv, even if there were similar intakes in each and every monitoring interval during the year. At this level there is no need to evaluate the intake or dose from the measured values explicitly. The effective dose can be reported as zero, by analogy with the rounding of doses in external dosimetry. However, the measured value should be recorded, because it may provide information useful for further assessments in the future.

Stage 2. Level 1, and for higher exposures: Check on significance of new measurement and consistency with previous evaluations

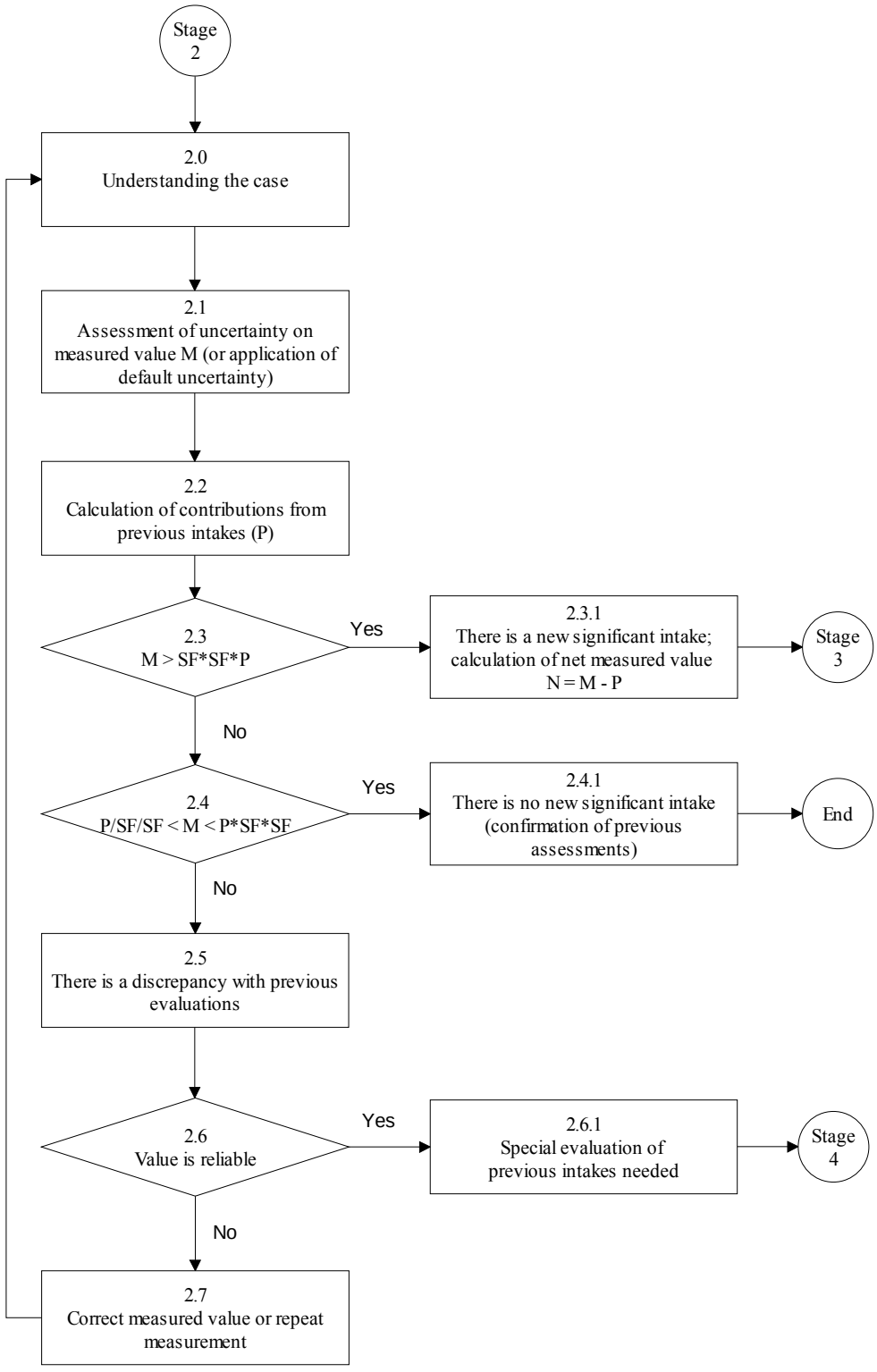
This stage will be presented here in detail in order to illustrate the structure of the approach (see Fig. 17). Level 1 refers to cases where it is expected that the dose from the intake is likely to be above 0.1 mSv. At this level the intake or dose from the measured values should be calculated explicitly. Before starting the assessment of intake and dose, however, it is recommended to plot the data and to do some simple hand calculations in order to understand the case. In addition, the statistical significance of the measured value M should be estimated. This includes the assessment of uncertainty on M as well as the calculation of the contributions from previous intakes to M in order to decide whether M is:

- due to a new intake,
- due to a previous intake, or
- if it is inconsistent with previous assessments.

Step 2.0: Understanding the case. Plot the data (including those from previous measurements if available) and do some simple hand calculations.

Step 2.1: Assessment of the uncertainty on M. Realistic estimates of the overall uncertainty on each data point are required. Here they are expressed as a total "scattering factor" (SF).

Figure 17: Stage 2. Check on significance of new measurement and consistency with previous evaluations



Step 2.2: Calculation of the contributions P from previous intakes. The contributions (P) from all previous intakes of the radionuclide considered are calculated, taking into account all pathways of intake, and all intakes of mixtures where the radionuclide was involved.

Step 2.3: New intake confirmed if $M > SF^2 * P$, then assume a new intake has occurred. If an intake has not occurred then there is only a 2.5% probability of a false positive (i.e. assuming a new intake when an intake has not occurred). Calculate the net value ($N = M – P$) of the radionuclide by subtracting P from the measured value M and go to Stage 3, in order to check whether the next stage of the task is Level 2 or Level 3

Step 2.4: New intake not confirmed. If $P/SF^2 < M < P*SF^2$, then the measured value M is consistent with the intakes assessed previously, and there is probably no new intake (i.e., there is no evidence for a new intake). The evaluation stops and the measured value M is recorded together with all relevant information (radionuclide, activity, type of measurement, type of monitoring etc).

Step 2.5: Discrepancy with the previous evaluations. If $M < P/SF^2$, then there is a discrepancy with the previous assessments. The reason for the discrepancy could be (i) the measured value M is not reliable and/or (ii) the previous assessments are wrong. For example, an intake occurring near the end of the previous monitoring interval is likely to have been overestimated based on an assumed intake at the mid-point.

Step 2.6: Check on the reliability of M. For whole body counting possibilities for errors include: external contamination, mismatching of calibration and actual activity distribution (i.e. lung activity calculated with whole body efficiency, or lung activity calculated in the presence of residual GI tract activity etc.). For excretion measurements possibilities include contamination of the sample, incomplete collection of the sample, errors in sample processing, etc..

Step 2.6.1: Reassess previous intakes. If it cannot be demonstrated that M is unreliable, then reassess the previous intake(s), i.e. go to the appropriate “Special procedure” at Stage 4.

Step 2.7: Check the measurement M. If it can be demonstrated that M is wrong, make corrections or repeat the measurement if possible and return to Step 2.0.

Stage 3. Standard evaluation procedure at Level 1

Having determined the measured value (M) to be due to a new intake, the intake and dose are evaluated from the net value $N = M – P$ using *a priori* parameter values. If the dose is assessed to be above 1 mSv, the evaluation should be repeated according to Stage 4, in which the parameter values chosen *a priori* may be adjusted, if necessary to obtain an acceptable fit to the data. The standard evaluation procedure should be applied only for routine monitoring. Case or site specific parameter values should be assigned as far as they are available.

Stage 4. Identification of pathway of intake for special evaluation above Level 1

Special procedures are needed for the evaluation when there is evidence for a committed effective dose of more than 1 mSv or in all cases of special monitoring. In all these cases the evaluation procedures depend to some extent on the pathway of intake. Thus, in Stage 4 the pathway of intake has to be identified.

Stage 5. Special procedure for inhalation cases above Level 1

The special procedure is grouped in three subsequent stages. In the first stage (5A), a simple evaluation is carried out using parameter values chosen *a priori*: before the evaluation is carried out. The procedure is very similar to the "Standard procedure" (Stage 3). The main difference is that in a special procedure there should be more than one measurement. In the second stage (5B), procedures are applied for varying the two main factors related to the inhaled material: the AMAD and absorption Type, and also the time of intake, if not known, using the measurement data (*a posteriori*). In the third stage (5C), an advanced evaluation is carried out. It applies to cases where there are comprehensive data available. The fundamental approach of this stage is that the model parameter values are adjusted systematically, in a specific order, until the goodness of fit is acceptable (i.e. the fits obtained to all the data are not rejected by the specified criteria).

Similar procedures have been defined for ingestion cases (Stage 6) and for mixed inhalation and ingestion cases (Stage 7). For more information see the final report on the guidelines [49].

5 Dissemination of the IDEAS Guidelines

5.1 ICRP

The guidelines were developed in close collaboration with the ICRP Committee 2 Task Group on Internal Dosimetry (INDOS) [70], which is developing a Guidance Document on internal dose assessment. The draft ICRP Guidance Document (GD) is following similar principles, and a similar structured approach to assessments based on the IDEAS Guidelines, but will relate to revised ICRP biokinetic models currently under development by INDOS. The information provided in the GD will be a significant development from that given in publications 54 and 78 on the interpretation of bioassay measurement data. The draft GD has been published on the ICRP web site in 2006 and many comments were received following the publication. The comments were used to refine the draft GD and the IDEAS Guidelines as well. In 2007, however, it was decided to cancel the development of the GD and to include only some essentials of the GD into the OIR series.

5.2 EURADOS/IAEA

The EURADOS Working Group 7 *Internal Dosimetry* organizes in cooperation with the International Atomic Energy Agency (IAEA) and the Czech Technical University in Prague a Regional Training Course on Advanced Methods for Internal Dose Assessment entitled *Application of IDEAS Guidelines and dissemination of CONRAD internal dosimetry results.* The course will be held on 2-6 February 2009 in Prague, Czech Republic. The purpose of the course is to provide the participants with advanced methodologies for internal dose assessment and practical skills to implement the IDEAS Guidelines in the field of monitoring of intake of radionuclides and to provide training in principal concepts and methods used for internal dose assessment of exposure due to intakes of radionuclides, with information on CONRAD Internal dosimetry results. It is anticipated to hold more such courses in future for further dissemination of the IDEAS Guidelines.

5.3 ISO

The disillusioning experience with the past intercomparison exercises was also recognised by the International Standardization Organization (ISO). Because of the substantial differences between national regulations, concepts, and dose assessment procedures the ISO recently initiated projects to standardize the monitoring of workers, the requirements for measuring laboratories and the processes for the quantitative evaluation of monitoring data [53]. The anticipated standards include the need for a monitoring programme and the design of a monitoring programme, i.e. the methods and intervals, decision levels and approaches for dose assessments. These approaches correspond widely to the

IDEAS Guidelines. There is a similar level of task structure with the same decision levels and evaluation procedures, this being of great importance for the harmonisation of internal dosimetry worldwide.

6 Supporting software

There are several commercial computer codes for the evaluation of incorporation monitoring data, such as IMBA Expert^{TM} [71, 72], IMIE [73, 74] or IDEA System [75]. IDEA System has been developed in the Karlsruhe Research Centre especially for assisting dosimetrists in applying the IDEAS Guidelines and other relevant recommendations for incorporation monitoring and internal dosimetry. IDEA System (Internal Dose Equivalent Assessment System) gives guidance to the user with respect to (i) planning of monitoring (estimation of potential exposures, decision on the requirements of monitoring, definition of optimum measuring techniques and monitoring intervals), (ii) performing routine and special monitoring, and (iii) evaluation of primary monitoring results. According to the IDEAS Guidelines the overall aims of the software can be summarized as: harmonization, accuracy and proportionality. The harmonization covers (i) the decision on the requirement of incorporation monitoring, (ii) the methods applied for incorporation monitoring and (iii) the methods applied for the evaluation of incorporation monitoring results. IDEA System provides well-defined procedures for all these three topics, which are consistent with the IDEAS Guidelines. The software is intended to be a dynamic tool for incorporation monitoring and for interpretation of monitoring data according to the overall aims mentioned above. So the software is continuously extended and adjusted taking into account the progress of monitoring techniques, the development of biokinetic models and the special needs and requirements of the users. The software provides the following features for evaluation of monitoring data:

- Standard evaluation (Level 1 of IDEAS Guidelines) with default parameters (single inhalation in the middle of monitoring interval; default absorption type and AMAD); automatic correction for contributions from previous intakes; automatic check of consistency with previous evaluations
- Standard evaluation (Level 2 of IDEAS Guidelines) with case or site specific parameters for single or chronic intakes by inhalation, ingestion or injection; automatic correction for contributions from previous intakes; automatic check of consistency with previous evaluations
- Special evaluation (Level 2 or 3 of IDEAS Guidelines) with individual adjustment of model parameter values (fitting of time of intake, absorption type, particle size, or f_1-value)
- Special evaluation using direct internal dosimetry (integration procedure; calculation of cumulated activity for ^{3}H in urine, Iodine isotopes in the thyroid or Caesium isotopes in the whole body)

The software has been tested in the frame of several national and international intercomparison exercises, where real and artificial incorporation cases were analysed by a large number of participants. In all artificial cases, where the answer in terms of intake or dose is known, the IDEA System software provided correct results.

Table 17 compares, as an example, the results of IDEA System in terms of effective dose with the mean results of all participants of the IDEAS/IAEA Intercomparison Exercise [50-52]. The cases no. 3 and no 4 were artificial cases with the real value of the effective dose being known. In case no. 3, whole body counting data and urine excretion data were given for an incorporation of ^{60}Co. The data were analysed by IDEA System at Level 2 by fitting the absorption type for a single intake of ^{60}Co aerosols with 5 µm AMAD (Fig. 18). This evaluation resulted in an inhaled activity of 414 kBq ^{60}Co (50 % type W and 50 % type S; particle size 5 µm AMAD) corresponding to an effective dose of 4.98 mSv (Fig. 19). The absorption type fractions correspond exactly to the real values. Also the potential error (empirical scattering factor) reflects properly the scattering factor used for randomising the data when creating this artificial case. Figure 20 compares the whole body counting data with the fitted retention function. As can be seen from this and all other artificial cases, there is a very good agreement of the real values and the results provided by the IDEA System software.

Table 17: Test of the IDEA System software in the frame of the IDEAS/IAEA Intercomparison Exercise [50-52] (bold: artificial cases with the real value being known)

Case No	Involved Radionuclide	Effective Dose		
		Real value (mSv)	GM of the results of all participants (mSv)	Result of IDEA System (mSv)
1	^{3}H	not known	25.8	25.1
2	^{90}Sr	not known	7.22	8.6
2	^{137}Cs	not known	0.66	0.62
3	**^{60}Co**	**5.0**	**5.0**	**4.98**
4	**^{131}I**	**2.54**	**2.57**	**2.54**
5	Enriched Uranium	not known	36.8	9.7
6	^{239}Pu	not known	140	118

Figure 18: Evaluation of Case No. 3 of the IAEA/IDEAS Intercomparison Exercise (whole body counting data and urine excretion data; evaluation at Level 2 by fitting the absorption type assuming a single intake of ^{60}Co aerosols with 5 µm AMAD)

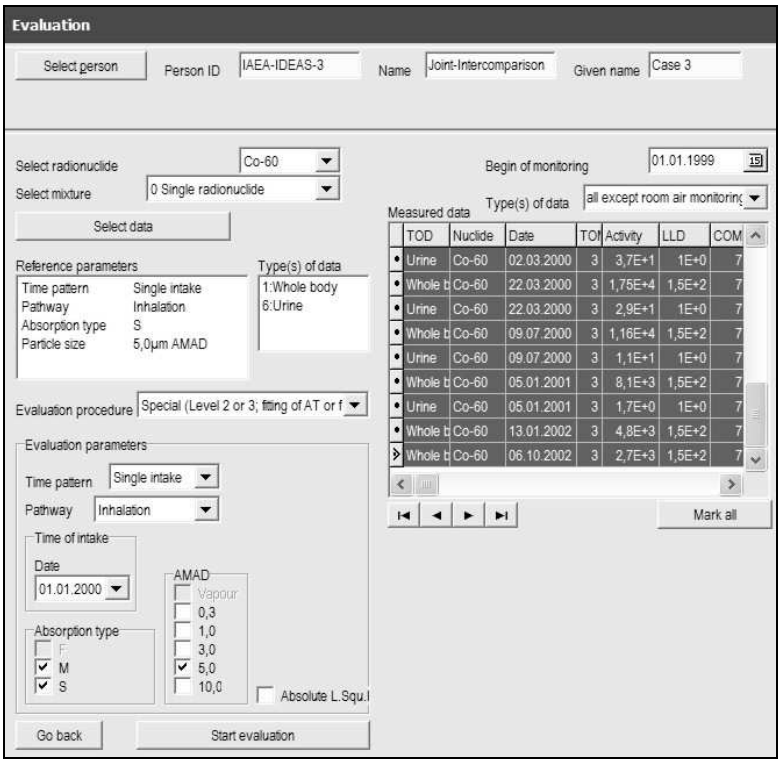


Figure 19: Results of the evaluation of Case No. 3 of the IAEA/IDEAS Intercomparison Exercise: single intake by inhalation of 414 kBq ^{60}Co; 50 % type W and 50 % type S; particle size 5 µm AMAD; effective dose and organ dose values in column D(QD); relative dose values in terms of dose limit fractions in column DR(QD); potential error 1.56 (empirical scattering factor)

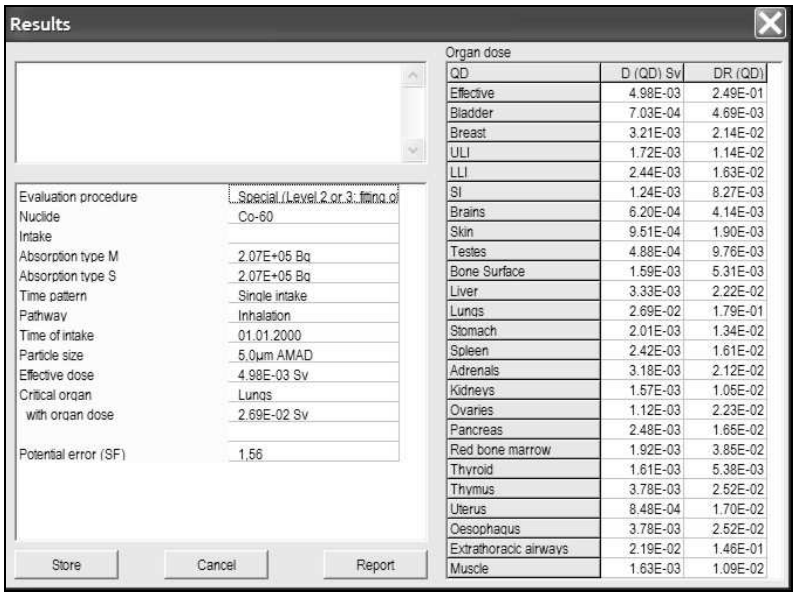
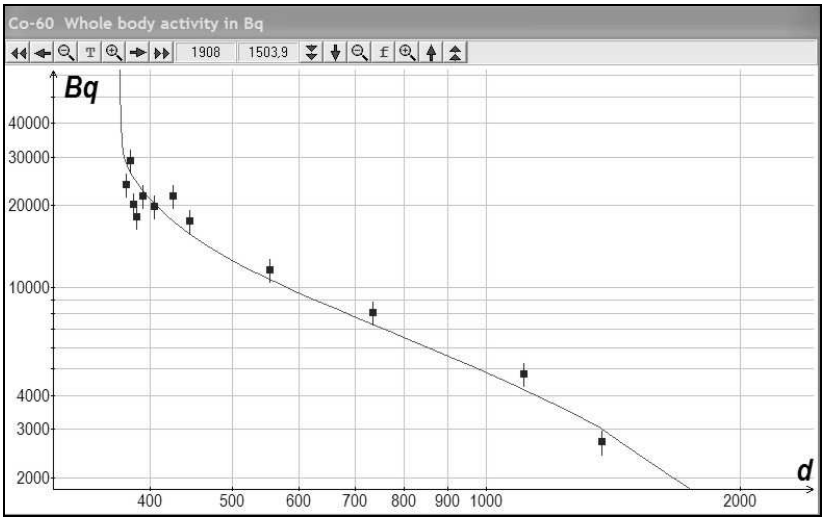


Figure 20: Results of the evaluation of Case No. 3 of the IAEA/IDEAS Intercomparison Exercise: whole body counting data with fitted retention function



The IDEA System software can be applied for all evaluation stages according to the IDEAS Guidelines except the "high end" stages 5C, 6C and 7C, where the biokinetic models have to be modified. For these stages other software such IMBA Expert^{TM} [71, 72] or IMIE [73, 74] may be used. However, IDEA System provides also many other tools for internal dosimetry, such as the assessment of the effective dose to the offspring due to intakes of the mother. For more information see the website www.idea-system.com.

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8 Glossary

Absorbed dose

The physical dose quantity given by

$$D = \frac{d\bar{e}}{dm}$$

where de is the mean energy imparted by ionising radiation to the matter in a volume element and dm is the mass of the matter in the volume element. The SI unit for absorbed dose is joule per kilogram (J kg^{-1}) and its name is Gray (Gy).

Absorption

Movement of material to blood regardless of mechanism. In the respiratory tract, it generally applies to dissociation of particles and the uptake into blood of soluble substances and material dissociated from particles

Absorption type

Classification of inhaled materials according to the absorption rate into the body fluids. The absorption types are defined in ICRP 66 and 71 as follows

Type F materials (deposited materials that are readily absorbed into body fluids from the respiratory tract; fast rate of absorption)

Type M materials (deposited materials that have intermediate rates of absorption into body fluids from the respiratory tract; moderate rate of absorption)

Type S materials (deposited materials that are relative insoluble in the respiratory tract; slow rate of absorption)

Type V materials (deposited materials that are assumed, for dosimetric purposes, to be instantaneously absorbed into body fluids from the respiratory tract - applied only to certain gases and vapours - very rapid absorption.)

Accuracy of measurement

The characteristics of an analysis or determination that ensure that both the bias and precision of the resulting quantity remains within specified limits

Activity

Physical quantity for the number of disintegrations per unit time (s) of a radioactive material. The SI-unit of the activity is Becquerel (Bq): 1 Bq = 1 s^{-1}

Activity Median Aerodynamic Diameter (AMAD)

Physical parameter for the description of the particle size of radioactive aerosols. Fifty percent of the activity in the aerosol is associated with particles of aerodynamic diameter (d_{ae}) greater than the AMAD. The AMAD is used for particle sizes for which deposition depends principally on inertial impaction and sedimentation: typically those greater than about 0.5 μm. For smaller particles, deposition typically depends primarily on diffusion, and the activity median thermodynamic diameter (AMTD) - defined in an analogous way to the AMAD, but with reference to the thermodynamic diameter of the particles - is used.

Bioassay

Any procedure used to determine the nature, activity, location or retention of radionuclides in the body by direct (*in vivo*) measurement or by indirect (*in vitro*) analysis of material excreted or otherwise removed from the body.

Biokinetic model

A mathematical model describing the intake, uptake and retention of a radionuclide in various organs or tissues of the body and the subsequent excretion from the body by various pathways.

Biokinetic function

A mathematical function describing the time course of the activity in the body (retention function) or the activity excreted via urine or faeces (excretion function) following a single intake at time t = 0. In general, the retention functions represent the body or organ activity at the time t after the intake, whereas the excretion functions represent the integral of the excretion rate from t – 1d until t.

Biological half-life

The time taken for the quantity of a material in a specified tissue, organ or region of the body (or any other specified biota) to halve as a result of biological processes.

Clearance

The net effect of the biological processes by which radionuclides are removed from the body or from a tissue, organ or region of the body

Note: The *clearance rate* is the rate at which this occurs.

Committed Effective Dose ($E(\tau)$)

The sum of the products of the committed equivalent doses in organs or tissues and the appropriate organ or tissue weighting factors (w_T), where τ is the integration time in years following the intake. The integration time is 50 y for workers.

Committed Equivalent Dose ($H_T(\tau)$)

The time integral of the equivalent dose rate in a particular tissue or organ that will be received by an individual following intake of radioactive material into the body, where τ is the integration time in years following the intake. The integration time is 50 y for workers.

Compartment

Pool of radioactive materials in the body which can be characterised by first order kinetics; a compartment can be an organ (as for example the liver), a part of an organ (as for example the RES of the liver), a tissue (as for example the bone), a part of a tissue (as for example the bone surface) or another substance of the body (as for example the body fluids)

Contamination

The activity of radionuclides present on surfaces, or within solids, liquids or gases (including the human body), where the presence of such radioactive material is unintended or undesirable

Critical value

The maximum value for the result of a single measurement in a monitoring programme where it is safe to assume that the corresponding annual committed effective dose will not exceed a predefined dose level

Decision threshold

The value that allows a decision on whether or not the physical effect quantified by the measurement is present

Deposition

The initial processes determining how much of a material in inhaled air remains in the respiratory tract after exhalation. Deposition of material may occur during both inhalation and

exhalation. The distribution of the deposition of inhaled materials in the different regions of the respiratory tract depends on factors including the Activity Median Aerodynamic Diameter (AMAD) and the breathing pattern of the subject.

Dose Coefficient

Committed equivalent dose in organ or tissue T per unit intake $h_T(\tau)$ or committed effective dose per unit intake $e(\tau)$, where τ is the time period in years over which the dose is calculated. The integration time is 50 y for adults

Effective Dose (E)

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

$$E = \sum_T w_T \cdot H_T$$

where H_T is the equivalent dose in tissue or organ, T, and w_T is the weighting factor for tissue T.

Equivalent dose (H_T)

The equivalent dose, $H_{T,R}$, in tissue or organ T due to radiation R, is given by:

$$H_{T,R} = w_R \cdot D_{T,R}$$

where $D_{T,R}$ is the average absorbed dose from radiation R in tissue T and w_R is the radiation weighting factor which is based on the quality of the radiation emitted by the source. Since w_R is dimensionless, the unit is the same as for absorbed dose, J kg^{-1}, and its name is Sievert (Sv). The total equivalent dose, H_T, is the sum of $H_{T,R}$ over all radiation types

$$H_T = \sum_R w_R \cdot D_{T,R}$$

Event

Any unintended occurrence, including operating error, equipment failure or other mishap, the consequences or potential consequences of which are not negligible from the point of view of protection or safety

Excretion analysis

Procedure for the assessment of the activity in the urine or faeces or in the exhaled air. The excretion analysis includes radiochemical separation, preparation of measuring samples and

the evaluation of the measuring samples by spectrometric or other techniques (i.e. α-spectrometry or ICP-MS)

Excretion function

The fraction of an intake excreted per day after a given time has elapsed since the intake occurred

Excretion rate

In general, the excretion rate is the amount of activity which is excreted via urine or faeces during 24 hours, with the decay of the radionuclide having been corrected for the end of the 24 hour sampling period. A special case is HTO where the excretion rate in general is given in terms of the activity concentration in the excreted material.

Fractional absorption in the gastrointestinal tract (f_1)

The f_1 value is the fraction of an element directly absorbed from the gut to body fluids.

Human Respiratory Tract Model (HRTM)

Biokinetic model for describing the deposition, translocation and absorption of inhaled materials in the human respiratory tract; published in ICRP Publication 66; the HRTM defines the following regions:

Extrathoracic (ET) airways.

The anterior nose (ET_1) and the posterior nasal passages, mouth, pharynx and larynx (ET_2).

Bronchial (BB) region.

The trachea and bronchi.

Bronchiolar (bb) region.

The bronchioles and terminal bronchioles.

Alveolar-interstitial (AI) region.

The respiratory bronchioles, alveolar ducts and sacs with their alveoli, and the interstitial connective tissue.

Intake

The activity of radioactive material entering the body, the principal routes being inhalation, ingestion or through intact or wounded skin (note in the case of inhalation of aerosols the intake is greater than the amount which is deposited in the body).

Acute intake

An intake occurring within a time period short enough that it can be treated as instantaneous for the purposes of assessing the resulting committed dose.

Chronic intake

An intake over an extended period of time, such that it cannot be treated as a single instantaneous intake for the purposes of assessing the resulting committed dose.

In vitro analyses

Analyses including measurements of radioactivity present in biological samples taken from an individual

Note 1: These include urine, faeces and nasal samples. In special monitoring programmes, samples of other materials such as blood and hair may be taken.

Note 2: These analyses are sometimes referred to as indirect measurements

In vivo measurement

Measurement of radioactivity present in the human body carried out using detectors to measure the radiation emitted.

Note 1: Normally the measurement devices are whole-body counters or partial-body (e.g. lung, thyroid) counters.

Note 2: Sometimes also referred to as direct measurements

Minimum detectable activity (MDA)

The minimum detectable activity (frequently also referred to as detection limit or lower limit of detection) is an *a priori* calculated value, which specifies the minimum body contribution that can be detected by a defined measurement procedure. The detection limit is complementary to the decision threshold, i.e. when considering the detection limit the wrong decision that there exists only a background effect when there is in fact a contribution from the body (Type II error), occurs with a well-defined probability β. Thus, the detection limit is closely related to the decision threshold defined by the Type I error probability α. By definition the detection limit is given in terms of body or organ activity and it can be compared directly with guideline values. See also ISO 2000a, 2000b, 2000c, 2005a, 2005b.

Minimum significant activity (MSA)

The minimum significant activity (frequently also referred to as decision threshold or critical level) is an *a posteriori* calculated value at which the decision can be made, whether the registered pulses include contributions from the measured sample or are solely due to background. If this decision rule is observed, a wrong decision that there is a contribution from the measured sample when actually only a background effect exists (Type I error), occurs with a well-defined probability α. By definition the decision threshold is given in terms of pulses but for practical application it is frequently transferred to the corresponding activity value. See also ISO 2000a, 2000b, 2000c, 2005a, 2005b.

Monitoring

The measurement of dose or contamination for the purpose of the assessment or control of exposure to radiation or radioactive material, and the interpretation of the results

Categories of monitoring programme

following ISO/IEC 20553 four different categories of monitoring programme are distinguished, namely confirmatory monitoring programmes, routine monitoring programmes, special monitoring programmes, and task-related monitoring programmes

Types of monitoring

according to ISO/IEC 20553 two different types of monitoring, individual monitoring and workplace monitoring, feature in each category of monitoring; a further type of monitoring, collective monitoring, is regarded as a particular form of workplace monitoring

Monitoring interval

The time period between two routine monitoring measurements

Occupational exposure

Exposure to radiation incurred at work as the result of situations that can reasonably be regarded as the responsibility of the operating management.

Quality assurance

Planned and systematic actions necessary to provide adequate confidence that a process, measurement or service will satisfy given requirements for quality, for example, those specified in a licence

Quality control

Part of *quality assurance* intended to verify that systems and components correspond to predetermined requirements

Quality management

All activities of the overall management function that determine the quality policy, objectives and responsibilities, and implement them by means such as quality planning, quality control, quality assurance and quality improvement within the quality system

Recording level

A level of dose, exposure or intake (specified by the employer or the regulatory authority) at or above which values of dose, exposure or intake received by workers are to be entered in their individual exposure records

Retention function

A function describing the fraction of an intake present in the body or in a tissue, organ or region of the body after a given time has elapsed since the intake occurred

Scattering factor

Geometric standard deviation of the distribution of measured data for a given type of measurement

Time of measurement

in the case of *in vitro* analysis, the time at which the biological sample (e.g. urine, faeces) was taken from the individual

in the case of *in vivo* measurements, the time at which the *in vivo* measurement begins

Transfer compartment

The compartment introduced for mathematical convenience into most of the biokinetic models used in ICRP and IAEA publications to account for the translocation of the radioactive material through the body fluids from where they are deposited in tissues.

Uptake

The processes by which radionuclides enter the body fluids from the respiratory tract, gastrointestinal tract or through the skin, or the fraction of an intake that enters the body fluids by these processes.