INTERNAL DOSIMETRY
ITS EVOLUTION AND NEW TRENDS

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Introduction

Inhalation and ingestion are the major routes of intakes of radionuclides into the body, however other kinds of contamination can also occur. As an example wounds in the skin can also provoke the transport of radionuclides to the bloodstream. The big question on internal dosimetry remains in the way to evaluate such intakes as well as in the establishment of safe limits for intakes of radionuclides by workers and members of public.

The International Commission on Radiological Protection (ICRP) has been dealing with these problems for about forty years [ICRP59]. The intake and the internal doses can be quantitatively assessed through mathematical modeling especially made to simulate the human metabolism associated with in vivo and in vitro bioassay methods. These models are constantly being updated in order to permit good estimates of the intake, retention and excretion of radionuclides by the human body. Dosimetric procedures are also under frequent revision in order to establish derived limits to be used in the practice of control of workers and also to provide better interpretations of the results of measurements based on the modeling.

A general model has been developed by ICRP for purposes of estimating intakes, body or organ contents and/or excretion rates for most radionuclides by means of describing the distribution and retention of the radionuclide under consideration into the body. This model is formed by three main components: a respiratory tract model, a gastrointestinal (GI) tract model and "metabolic" or systemic models describing distribution and retention of radionuclides in organs as shown in Figure 1. The ^{238}U isotope is employed in most of the examples of this text to illustrate the evolution of the systemic models.

This text is concerned on some discussions on the developments and trends of metabolic models and dosimetry and their associated parameters, which have been adopted by ICRP to evaluate intakes of radionuclides.

The Evolution of Concepts in Internal Dosimetry:

The ICRP Publication 2

The first respiratory tract model was issued in the ICRP Publication no 2 in 1959 [ICRP59]. The variation of the deposition as a function of the particle size was not considered and compounds were classified according to the solubility in water (soluble and insoluble). The respiratory tract was divided into upper and lower respiratory passages. Deposition fractions and half-times associated with removal to the plasma and to the gastrointestinal tract were assigned according to the solubility.

The gastrointestinal model proposed at that time had many similarities with the one presently used by ICRP. It was divided into four compartments stomach, small intestine, upper large intestine and lower large intestine. First order kinetics was also considered with mean residence times of 1, 4, 8 and 18 hours respectively attributed to the four cited compartments. The translocation to the body fluids is assumed to be in the small intestine only A parameter called f_1 was defined as the fraction of stable element reaching the blood [ICRP59]. If $f_1 = 1$, the absorption to the blood is complete.

The first metabolic model was issued in the Publication no. 2 in 1959 [ICRP59]. An example for the uranium is shown in Figure 2. Although these simple biokinetic models recognize the main organ of deposition, they show no recycling of activity through the body organs At that time ICRP was concerned in relating concentrations of radionuclides in the air and water as a way to assess internal doses in the several body organs The objective was the establishment of Maximum Permissible Concentrations (MPC) for radionuclides in air and water related to maximum permissible weekly doses in body organs. The MPCs depend on several factors, such as: age, physical conditions, ingestion habits, hygiene, biochemical, physical and radioactive properties of elements and kind of contamination The concept of "critical organ" was introduced, i.e., the MPCs should consider the organ that accumulates the greatest concentration of radionuclides, the essentialness of the organ, the organ damaged by the route of entry and the most radiosensitive body organ

ICRP Publication no. 2 [ICRP59] used the following maximum weekly doses as primary limits

0 1 rem/week for gonads and whole body

0 6 rem/week for skin and thyroid

0 3 rem/week for soft tissues

In this way one could associate a Maximum Permissible Concentration (MPC) for air and water to a maximum dose rate, depending on the critical organ. The tables for Maximum Permissible Concentrations for air $(MPC)_a$ and water $(MPC)_w$ were recommended as the first occupational derived limits for the radiation protection due to intake of radionuclides [ICRP59].

The ICRP Publications 26 and 30:

Since then many new information on the effects of radiation in the body as well as about the uptake and retention of radioactive materials in body tissues and data concerning radioactive decays have been provided. The concept of dose in a "critical organ" was replaced by the calculation of the committed dose equivalent, $H_{50,T}$, averaged throughout a tissue (T) in the 50 years after intake of a radionuclide. Radiation induced effects were divided in two categories stochastic and non-stochastic. The limits were then established in a way to prevent non-stochastic effects and to limit the occurrence of stochastic effects to an acceptable level [ICRP77]. For stochastic effects ICRP recommended a system for limiting exposure based on the principle that the limit on risk should be equal whether the whole body is irradiated uniformly or whether there is non-uniform irradiation The limitation is no longer applied to an organ but to the whole body since several organs are irradiated following the entry of a radionuclide into the body. ICRP [ICRP77] recommended the annual limit of 0.05 Sv for the stochastic dose equivalent for the whole body irradiation and 0.5 Sv for the prevention of occurrence of non-stochastic effects in organs.

The basic limits recommended by ICRP for occupational exposure can be numerically evaluated through the following conditions:

$$\sum_T w_T \cdot H_{50,T} < 0\,05 \ \text{Sv} \qquad (1)$$

for stochastic effects and

$$H_{50,T} < 0\,5 \ \text{Sv} \qquad (2)$$

for non-stochastic effects The weighting factors w_T related to the probability of occurrence of stochastic effects per unit of dose equivalent have been derived [ICRP77]. These factors are shown in the second column of Table 1 These factors were recommended for protection of any worker independent of age or sex. For the remainder the ICRP Publication 26 recommended the five organs or tissues receiving the greatest dose equivalents not listed in the second column of Table 1, where a weighting factor of 0.06 was attributed for each organ For the special case of internal dosimetry, when the gastrointestinal tract is irradiated, the stomach, small intestine, upper large intestine and lower large intestine are considered as four separate organs.

The introduction of $H_{50,T}$, the establishment of the primary limits recommended by the Publication 26 [ICRP77] and the advent of new metabolic models allowed ICRP to supersede its Publication 2, issuing another publication specifically recommended for internal dosimetry, the ICRP Publication 30 [ICRP79] In this publication ICRP has proposed the annual limit on intake (ALI) of a radionuclide as a secondary limit to be used in practice. It is the greatest value of the annual intake which satisfies the limits The ALIs estimated

by ICRP take into account ingestion and inhalation of a specified radionuclide Daughters produced in the body after the intake were also taken into account

The respiratory tract model used in Publication 30 was developed by ICRP Task Group on Lung Dynamics [ICRP66]. It was divided in three main regions for aerosol depositions. the nasal passage, the trachea and bronchial tree and the pulmonary region. The pulmonary lymphatic system was also included. This model takes into account the deposition of particles in the regions as a function of the aerodynamic properties of the aerosol distribution. The deposition can be related to the activity median aerodynamic diameter (AMAD) [ICRP79]. ICRP has calculated the committed dose equivalents assuming AMAD= 1 mm as a default. Significant different values can be found for other values of AMAD.

The clearance of inhaled materials from the respiratory tract occurs mainly to the gastrointestinal tract and body fluids (transfer compartment) It is associated with processes of absorption and particle transport and are well described elsewhere [ICRP66], [ICRP79] In order to describe the clearance in a quantitative way, materials were classified as D, W and Y, which refers to their retention in the pulmonary region. Class D are materials in the range of half-times less than 10 days, Class W in the range of 10 to 100 days and Class Y greater than 100 days The importance of considering the lymphatic tissue remains on the retention of Class Y compounds. No retention was considered for Classes D and W. Since the clearance of materials from compartments is governed by first order kinetics, a set of first order differential equations with constant coefficients can describe the process of retention of radionuclides in the compartments [ICRP79].

The gastrointestinal dosimetric model adopted by ICRP is based on the biological model developed by Eve [EV66] [DO66]. The GI tract was kept with the same four compartments: stomach, small intestine, upper large intestine and lower large intestine (ST, SI, ULI and LLI in Figure 3). First order kinetics was also used to simulate the metabolism of the contents. However the mean residence times were changed to 1, 4, 13 and 24 hours respectively. The mathematical descriptions of the mechanisms associated with ingestion and translocation from the respiratory tract were improved . It was proposed that the gastrointestinal absorption depends on the class of the compound for each element as done for the respiratory tract and it is given by the parameter f_1, already defined as the fraction of stable element reaching the body fluids [ICRP79].

The general characteristics of the metabolic model recommended by the ICRP [ICRP79] for most radionuclides are similar to that shown in Figure 2 Activity entering the blood or transfer compartment coming from the respiratory and gastrointestinal tracts is taken up by the various organs or excreted This general model still does not include recycling of radioactivity from organs back into the transfer compartment. Physiological parameters corresponding to a "Reference Man" representing a typical occupationally exposed adult, were employed in the calculations [ICRP75].

The ICRP Publication 60:

The ICRP Publication 26 was superseded by the Publication 60 [ICRP91], which took into account the new biological information related to the detriment associated with radiation exposures The quantity effective dose, E, was introduced as

$$E = \Sigma w_T \quad H_T \tag{3}$$

where w_T and H_T are the tissue weighting factor (shown in the third column of Table 1) and the equivalent dose for tissue T respectively. Explicit w_T values are now assigned to a number of organs (colon, stomach, liver, oesophagus, and urinary bladder) which were part of the remainder in Publication 26 [ICRP77] and 30 [ICRP79]. The quantity committed effective dose defined as

$$E(\tau) = \Sigma w_T \, . \, H_T(\tau) \tag{4}$$

is particularly employed in the case of internal dosimetry also for groups other than workers. The parameter τ is the time during which the dose is committed to the tissue T It varies according to the group. It is assumed 50 years for workers, 70 years for members of the public and infinity for patients. The method of treating the remainder has been modified somewhat from that used in ICRP Publication 30. The remainder is constituted of the following 10 organs. muscle, brain, small intestine, kidneys, pancreas, spleen, thymus, uterus, adrenals, extrathoracic airways. More detailed explanation can be found elsewhere [ICRP95].

For occupational exposures ICRP [ICRP91] recommends to limit the effective dose to 0 1 Sv in a five year period (average annual of 0.02 Sv) with a limit of 0.05 Sv in any single year and includes annual limits on the equivalent dose to skin and hands of 0 5 Sv and to the lens of the eye of 0.15 Sv. The annual limit on intake (ALI) for any radionuclide is obtained by dividing the annual average effective dose limit (0.02 Sv) by the committed effective dose, E(50), resulting from the intake of 1 Bq of that radionuclide.

Models Presently Adopted by ICRP

The ICRP Publication 66 Respiratory Tract Model·

The new ICRP respiratory tract model is presented in its Publication 66 [ICRP94] and shown in Figure 4. It is a physiologically based model and the respiratory tract is divided into two main regions: extrathoracic and thoracic. The extrathoracic region contains the anterior nose (ET_1) and the posterior nasal passages, the larynx, the pharynx and the mouth (ET_2) The thoracic region contains the bronchi, the bronchioles, and the alveolar-interstitium. The compartments with asterisks denote those where direct deposition of aerosol occurs,

and from which the mechanical transport of particles occurs in the clearance processes. The deposition fraction in ET_{seq} is assumed to be equal to 0 0005 of that in the region ET_2. Similarly it is assumed that a fraction equal to 0.007 of the total amount deposited in the BB and bb regions, goes to BB_{seq} and bb_{seq} respectively. The deposition in the AI region was divided as follows: 30% for AI_1, 60% for AI_2 and 10% for AI_3. The numbers near the arrows represent the removal rate in d^{-1} from the compartments.

The mechanical clearance of the particles accounts for the surface transport (fast process of mucociliary clearance to the GI tract from the bronchial and bronchiolar regions and a slower clearance process from the AI region). The retention of particles in the airway wall is represented in the model by the sequestration compartments. It is assumed a direct aerosol deposition in the delayed clearance compartments BB_2 and bb_2 and in the sequestration compartments BB_{seq} and bb_{seq}. It is assumed that the sequestered particles are cleared to the lymph nodes (LN). These mechanical clearance processes compete with the translocation of the material to the blood, which is represented by a two-stage process: (i) the dissociation of the particles, and (ii) the absorption of the dissociated material. More comprehensive information can be found in ICRP Publication 66 [ICRP94]. The names F (fast), M (moderate) and S (slow) were chosen to represent Types of compounds replacing the corresponding Classes D, W and Y in ICRP Publication 30 [ICRP79] However whereas D, W and Y define overall clearance, F, M, and S refer only to absorption into blood. ICRP recommends the use of specific translocation rates for each compound keeping constant the parameters associated with the mechanical clearance processes. When these rates are not available ICRP recommends the use of default values.

Evolution of Systemic Models:

The last series of systemic models proposed by ICRP can be found in Publications 56 [ICRP89], 67 [ICRP93] and 69[ICRP95]. These very sophisticated physiologically based models have been used to describe the metabolisms of alcaline earths, lead, plutonium, amencium, thorium, uranium, etc. Age-specific applications have also been considered for 6 age-groups, which are: 3 months, 1 year 5 years, 10 years, 15 years and adult, which allows to estimate doses for members of the public Figure 5 shows the application for uranium These biokinetic models present recycling. The activity entering blood is retained by bone surfaces and soft tissues or excreted. The bone was divided into cortical and trabecular portions, which were divided into bone surface and bone volume. According to ICRP[ICRP95] a fraction of the activity leaving the plasma is deposited on bone surfaces. Another fraction returns to plasma and the rest migrates to exchangeable bone. A portion of activity leaving exchangeable bone volume is assumed to return to bone surfaces and the rest migrates to regions of bone that loses activity to plasma more slowly. These processes are represented by the pathways leaving the EXCH and NONEXCH compartments respectively. The compartments ST0, ST1 and ST2 serve to provide the balance of the model in terms of material distribution. The liver was assumed to have two

compartments LIVER1 which presents a faster half-time. A portion of the activity leaving liver is assumed to return to plasma and the remainder goes to LIVER2, from which it is removed with a longer half-time For the particular case of uranium the red blood cells (RBC) compartment is also represented.

It must be pointed out that some age-specific biokinetic models proposed are still non-recycling models Examples are tritiated water, organically bound tritium, carbon, niobium, iodine, cesium, cerium Specific excretion models representing the liver-gallbladder and bladder-kidney functions are also intrinsically taken into account

Trends in Internal Dosimetry:

A complete revised metabolic and dosimetric model describing the embryo and the fetus will be issued soon by ICRP The dose commitment to the fetus should consider the radiation emitted by nuclear transformations in the maternal tissues and contents of walled organs, in the fetal tissues and in the child's tissues following birth Important points will be considered like: a) acute and continuous intakes before and during pregnancy, b) continuity in doses delivered to embryo, fetus and newborn through the transfer of radionuclides to fetal circulation and subsequent distribution and retention by growing fetal tissues up to the childhood, c) accumulation in tissues for specific cases, like iodine in fetal thyroid, actinides in liver and in fetal skeleton, etc and average dose in the remainder tissues. The fetal target tissues are lungs, thyroid, bone marrow, spleen, liver, thoracic tissue, gastrointestinal tract and brain.

Many more important tasks are being conducted by the ICRP. Some examples are: (i) The gastrointestinal tract is being revised by the ICRP New information on anatomy (inclusion of oesophagus as a target), physiology and radiation induced cancer risk are being considered, which will make possible to form a complete Alimentary Tract Model (ii) Compound specific parameters are being compiled to be included in the new respiratory tract model to allow more realistic descriptions of the absorption processes from the respiratory tract into the blood (iii) ICRP also intends to review parameters associated with the Reference Man (iv) Revision of the ICRP Publication 30, which is the major task for the Internal Dosimetry for the next years More data in modeling and excretion parameters are needed.

Some trends can also be seen on the development of phantoms based on computerized tomographic (CT) scans These are called "VOXEL Phantoms" The name VOXEL indicates an element of volume and it is based on the term pixel, used to define an element of a computer screen The organs are described by parallelograms instead of equations representing three dimensional geometric figures These phantoms can be applied in calculations of specific absorbed energy fractions (SAF) by the several body organs, through a more realistic anthropomorphic representation. Some adult phantoms [VE89],[DI96] and a seven year old child and a eight month old baby are also available However, these phantoms present some problems like

not all organs and tissues of interest can be visualized (not enough resolution to distinguish active and inactive bone marrows). They need to be harmonized with reference persons (a set of phantoms for the several age-groups are unlikely to be available before the year 2000, for the new ICRP Publication 30)

Table 1: Comparison between organ and tissue weighting factors proposed by ICRP Publications 26 and 60

Organ or Tissue	Weighting Factor	
	wT (ICRP26)	wT (ICRP60)
Gonads	0.25	0.20
Breast	0.15	0.05
Red Bone Marrow	0.12	0.12
Lungs	0 12	0.12
Bone Surface	0 03	0 01
Thyroid	0.03	0.05
Bladder	-	0.05
Colon	-	0.12
Liver	-	0.05
Oesophagus	-	0 05
Skin	-	0.01
Stomach	-	0.12
Remainder	0.30	0.05
Total	1.00	1.00

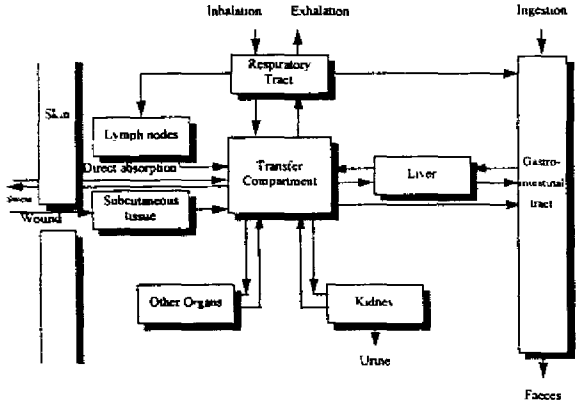


Figure 1: A General Biokinetic Model Showing Routes of Intake, Transfers and Excretion

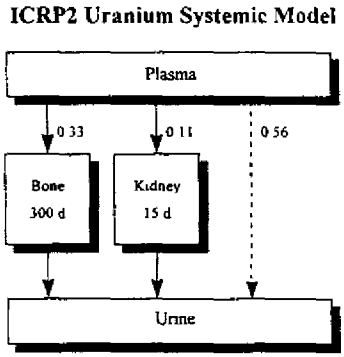
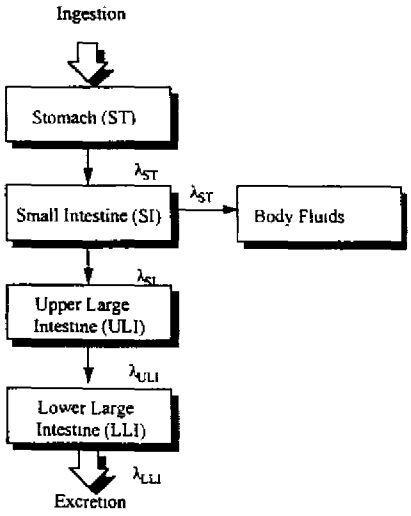
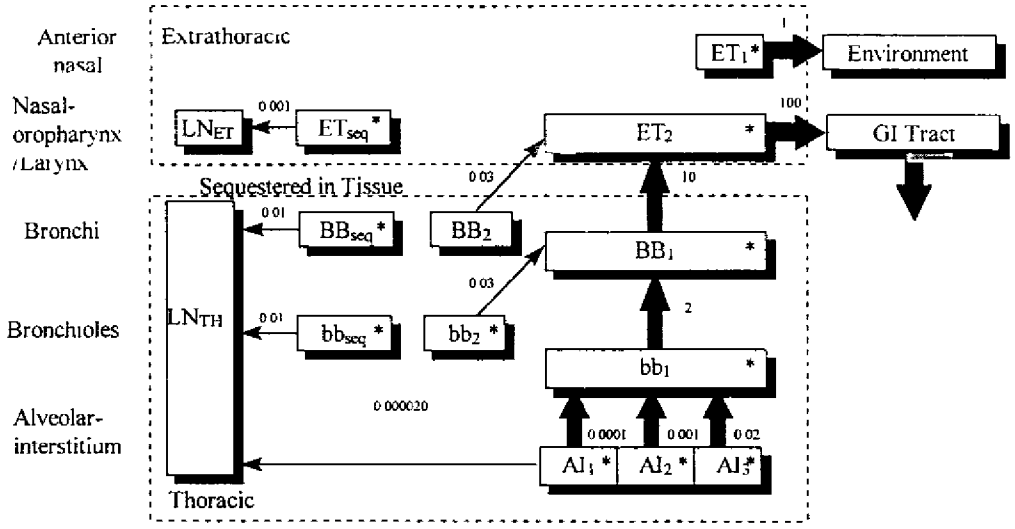


Figure 2 The Uranium Systemic Model Proposed by ICRP Publication 2 (1959)



Section of GI tract	Mass of Walls* (G)	Mass of Contents* (G)	Mean residence time (Days)	λ day^{-1}
Stomach (ST)	150	250	1/24	24
Small Intest. (SI)	640	400	4/24	6
Upper Large Intest. (ULI)	210	220	13/24	1.8
Lower Large Intest. (LLI)	160	135	24/24	1

Figure 3 The Gastrointestinal Tract Model Proposed by ICRP Publication 30 (1979)



Compartments with asterisks are those where direct deposition occurs

Figure 4. The Respiratory Tract Model Proposed by ICRP Publication 66 (1994)

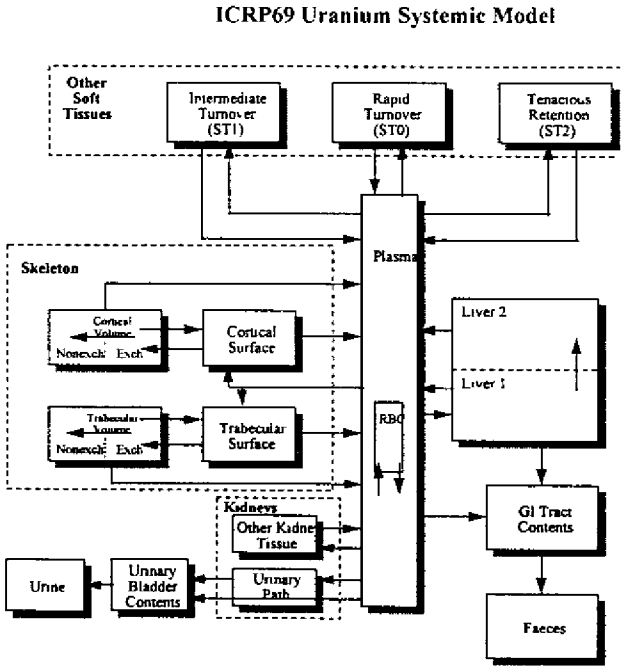


Figure 5. The Uranium Systemic Model Proposed by ICRP Publication 69

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