Internal dosimetry

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Lecture prepared in collaboration with Siria MEDICI, PhD – IRA/CHUV

EPFL

RBPA course **(PHYS-450)**

October 2025

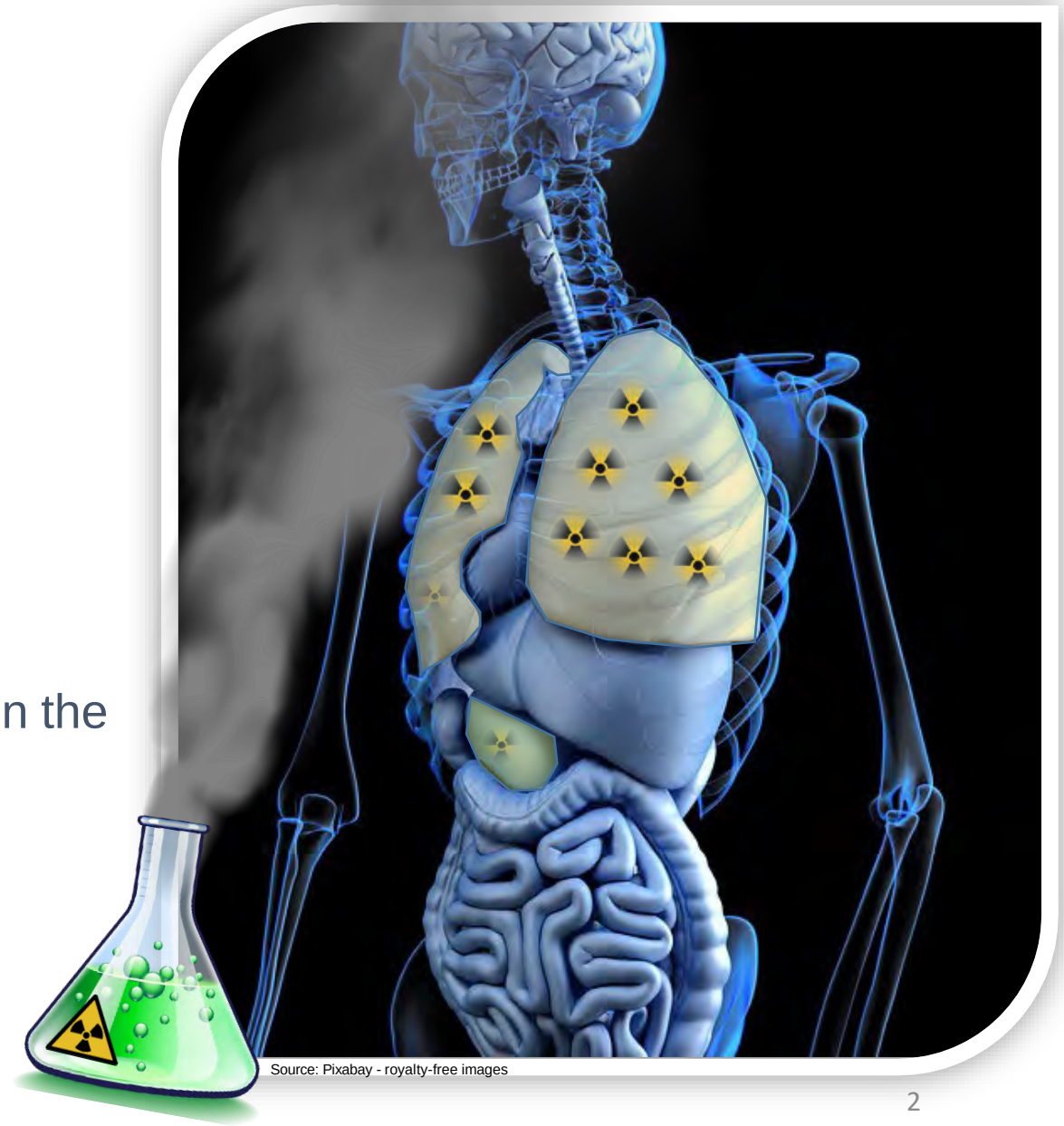
Objectives

Describe how the **incorporation** of a radioactive substance delivers a **dose** to a person

Explain how the **effective dose** delivered by a **radionuclide intake** can be estimated; in particular describe:

- what is a **compartmental model**
- how it is possible to **compute the dose** to a **tissue/organ**

Compute the **effective dose** received by a person when the **intake is known**



Source: Pixabay - royalty-free images

Radiation protection

First question:
What potential hazards are associated with the use of ionising radiation

Source: https://fr.123rf.com/

3

Glossary : sealed vs unsealed sources

sealed sources

Source: SUVA
https://www.suva.ch/fr-ch/prevention/par-danger/materiaux-rayonnements-et-situations-a-risque/rayonnement-et-radioactivite/rayonnement-ionisant/controle-de-letancheite-des-sources-de-rayonnements-scellees

sources whose construction prevents the dispersion of radioactive material under normal working conditions.

unsealed sources

Source: AI generated from a photo taken by IRA

sources whose construction does not allow to prevent the dispersion of radioactive material (ex : liquids, powders).

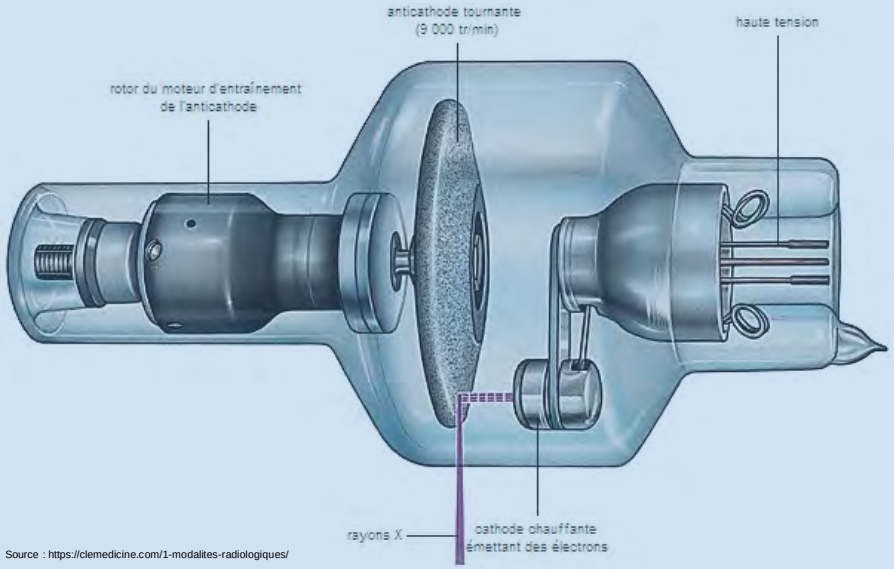
Exposure pathways

External exposure

Internal exposure

External exposition

Source: Scientific instruments - https://www.imagesco.com/geiger/radioactive-sources-int.html



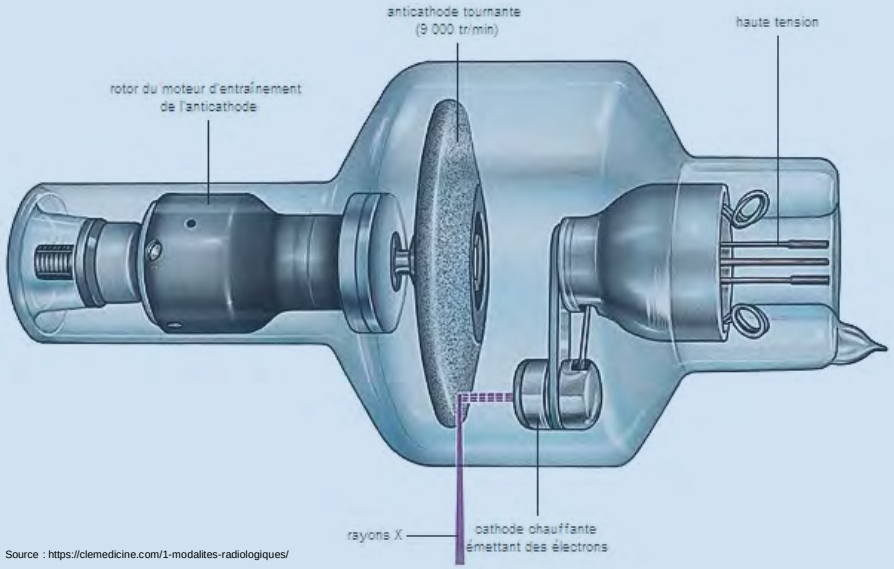
Source : https://clemedicine.com/1-modalites-radiologiques/

Internal exposition

Source : https://www.itnonline.com/content/pet-fludeoxyglucose-f18-injection-gains-fda-clearance

External exposition

Source: Scientific instruments - https://www.imagesco.com/geiger/radioactive-source-kit.html



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Internal exposition

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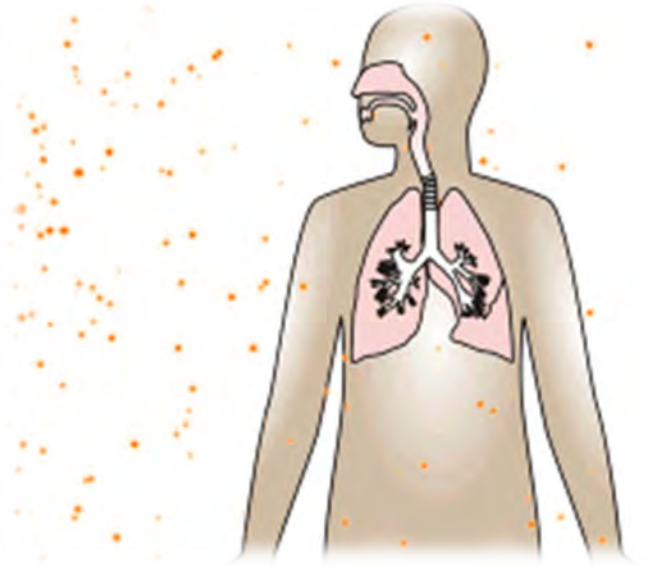
Internal exposure Pathways



Source : https://remm.hhs.gov/contamimage_top3.htm

Respiratory tract (inhalation)

This is the most common route in the event of a nuclear accident or atmospheric contamination (dust, aerosols, radioactive gases).

Example: inhalation of radioactive iodine, plutonium or radon.

Digestive tract (ingestion)

Through consumption of contaminated water, food.

Through contaminated hands.

Example: ingestion of caesium-137 or strontium-90 present in the food chain after a release.

Skin, wounds and (accidental) injections

Skin: Rarer, but possible if the skin is damaged (wounds, burns).

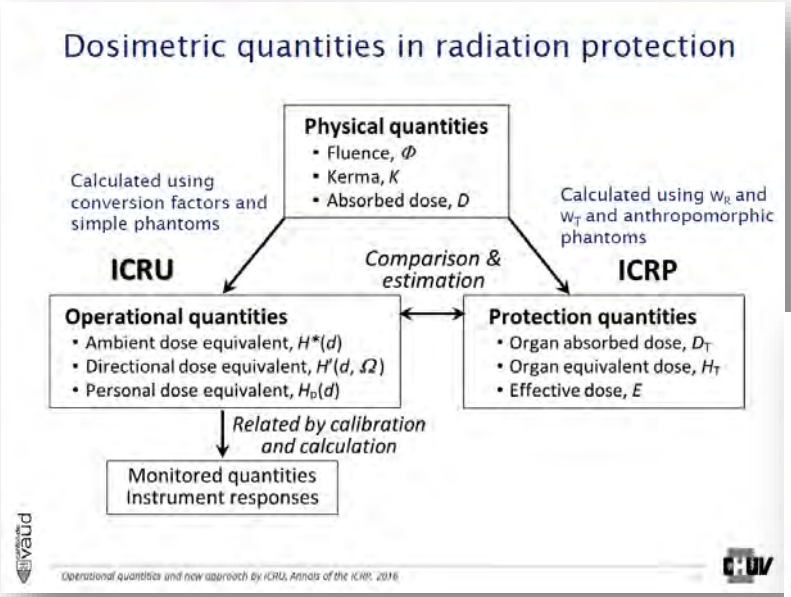
Some radioelements can pass through intact skin, but generally in very small quantities.

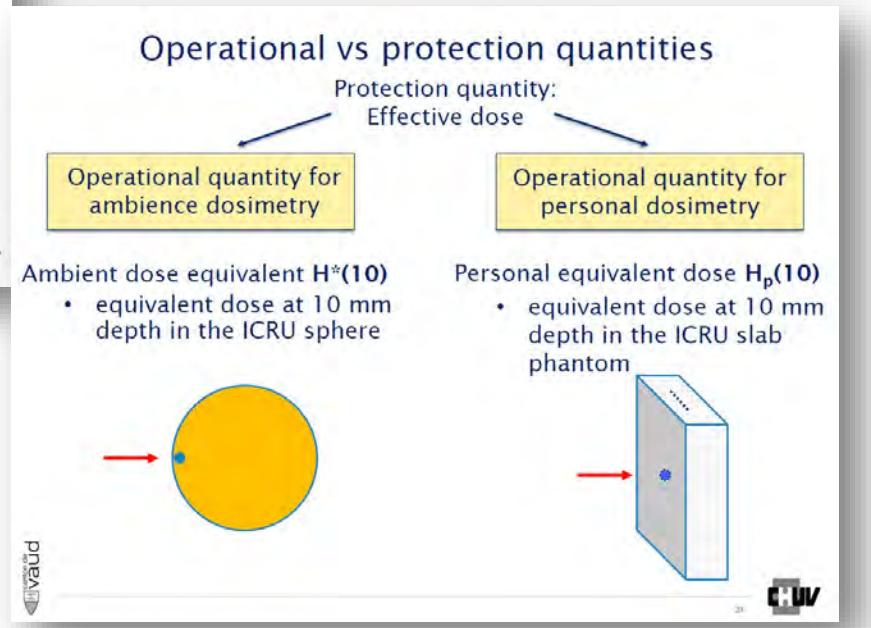
Direct contamination through penetration through an open wound, cut, or accidental injection in a medical/industrial setting.

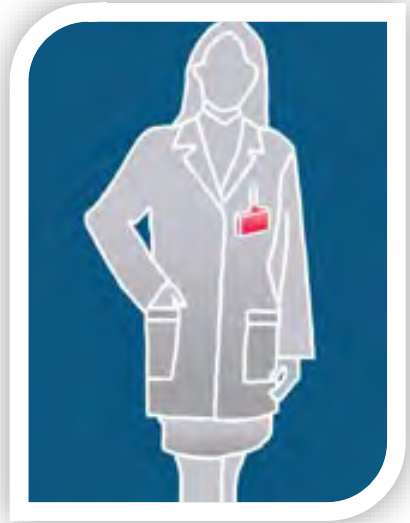
External exposure

What's the associated dosimetric quantity?

This question refers to previous lecture on "**Introduction to dosimetry**"



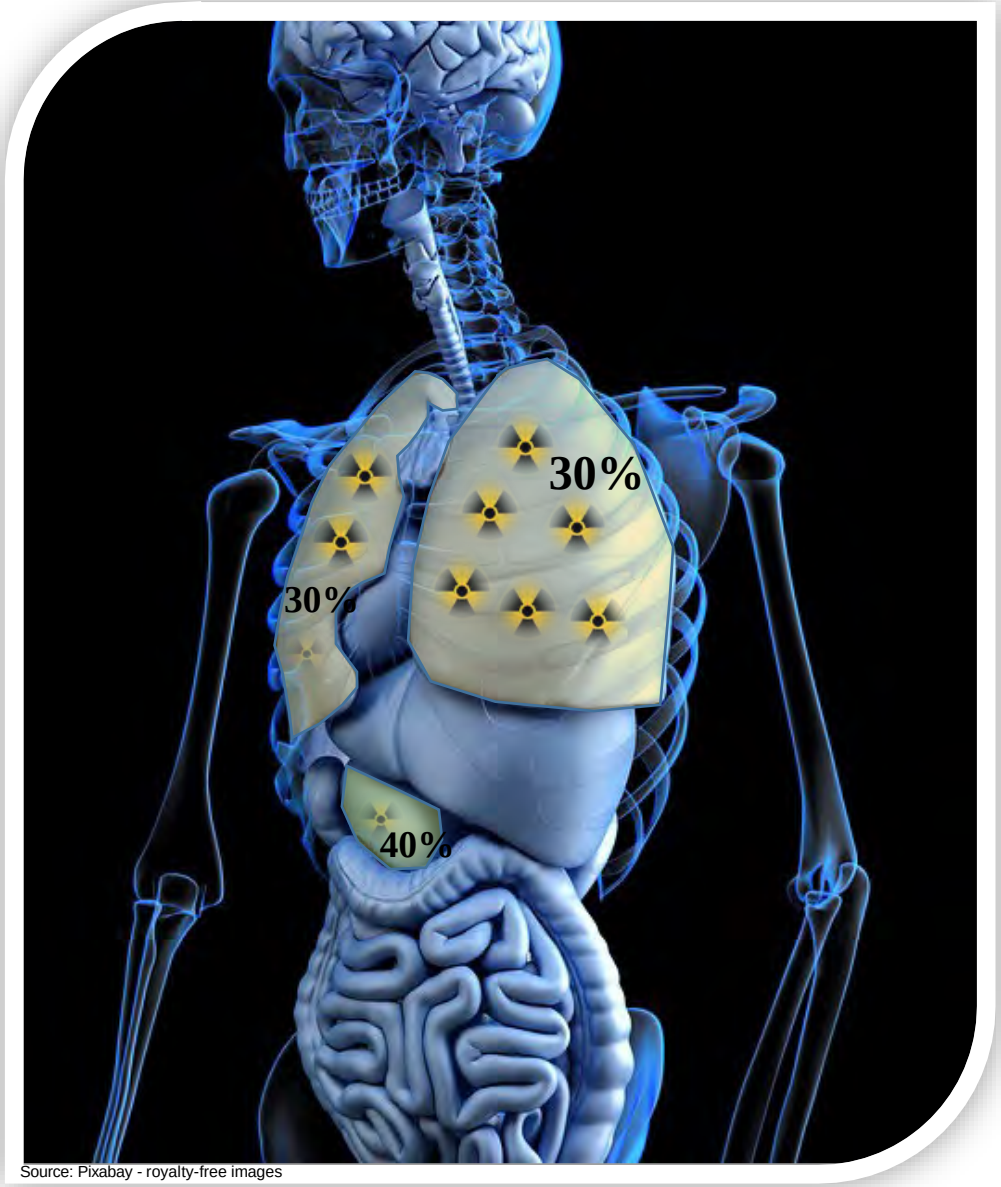




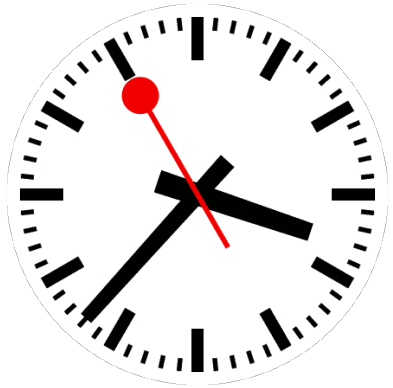
Individual monitoring in case of internal irradiation

Incorporation of a radioactive substance leads to internal exposure

What's the associated dosimetric quantity?



Source: Pixabay - royalty-free images

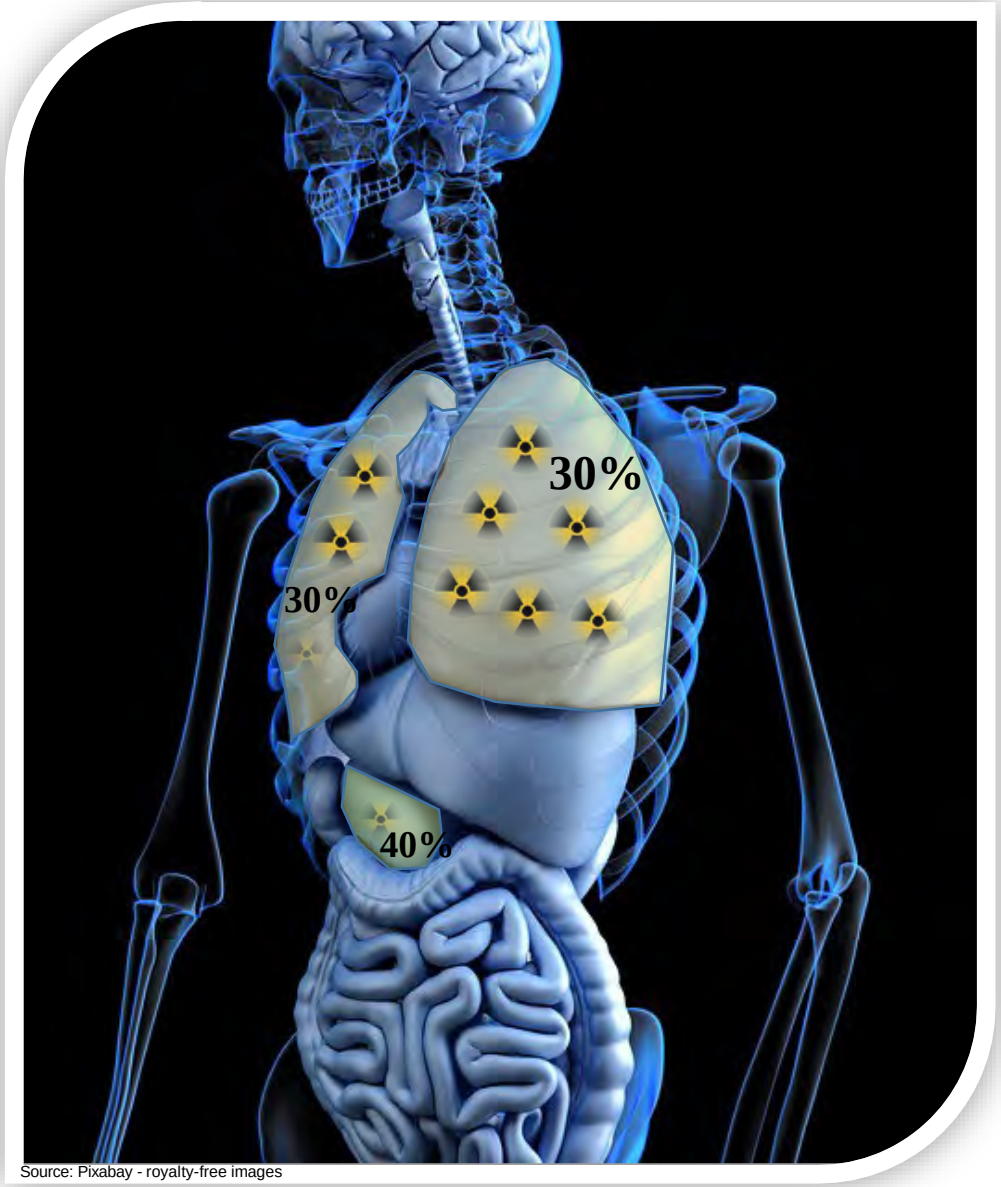


2 minutes by yourself
5 minutes in a group of 3

Individual monitoring in case of internal irradiation

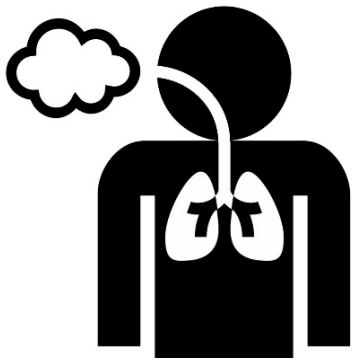
Incorporation of a radioactive substance leads to internal exposure

➔ **committed effective dose – E_{50}**



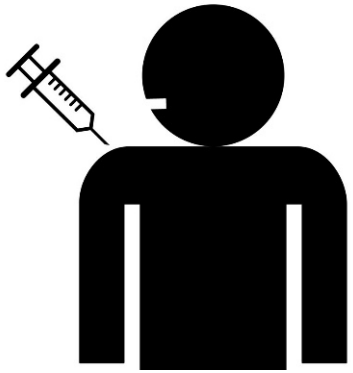
Source: Pixabay - royalty-free images

Committed effective dose E_{50}

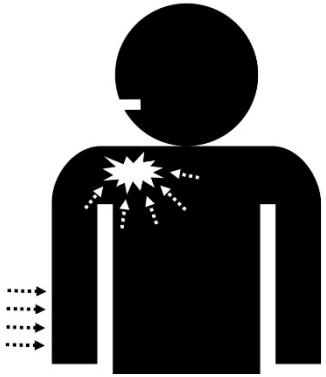


Inhalation

Ingestion

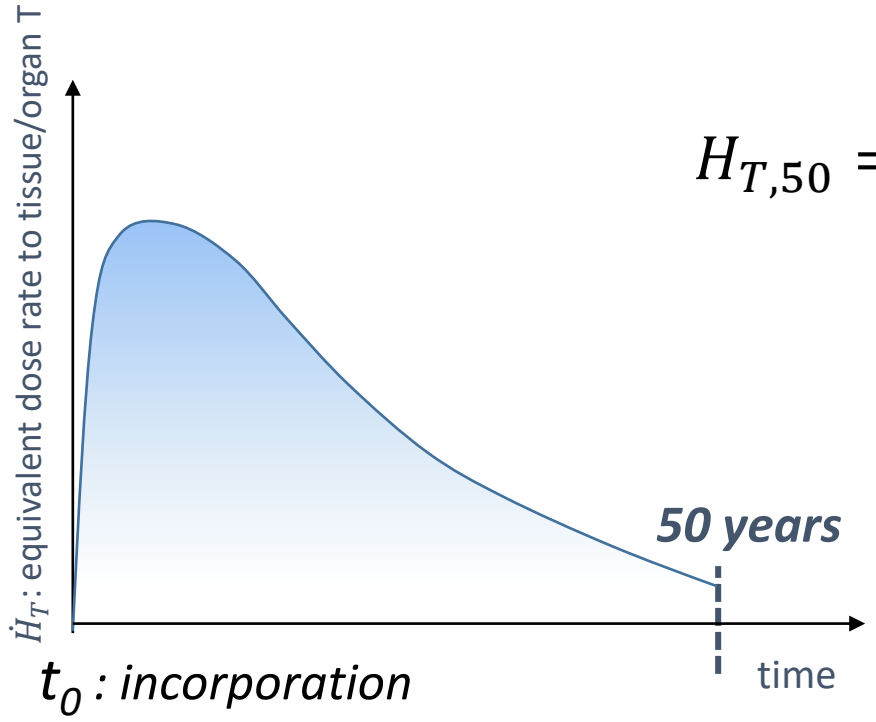


Injection



Absorption
(intact skin or wounds)

Effective dose received by the whole body during the 50 years that follow an intake.



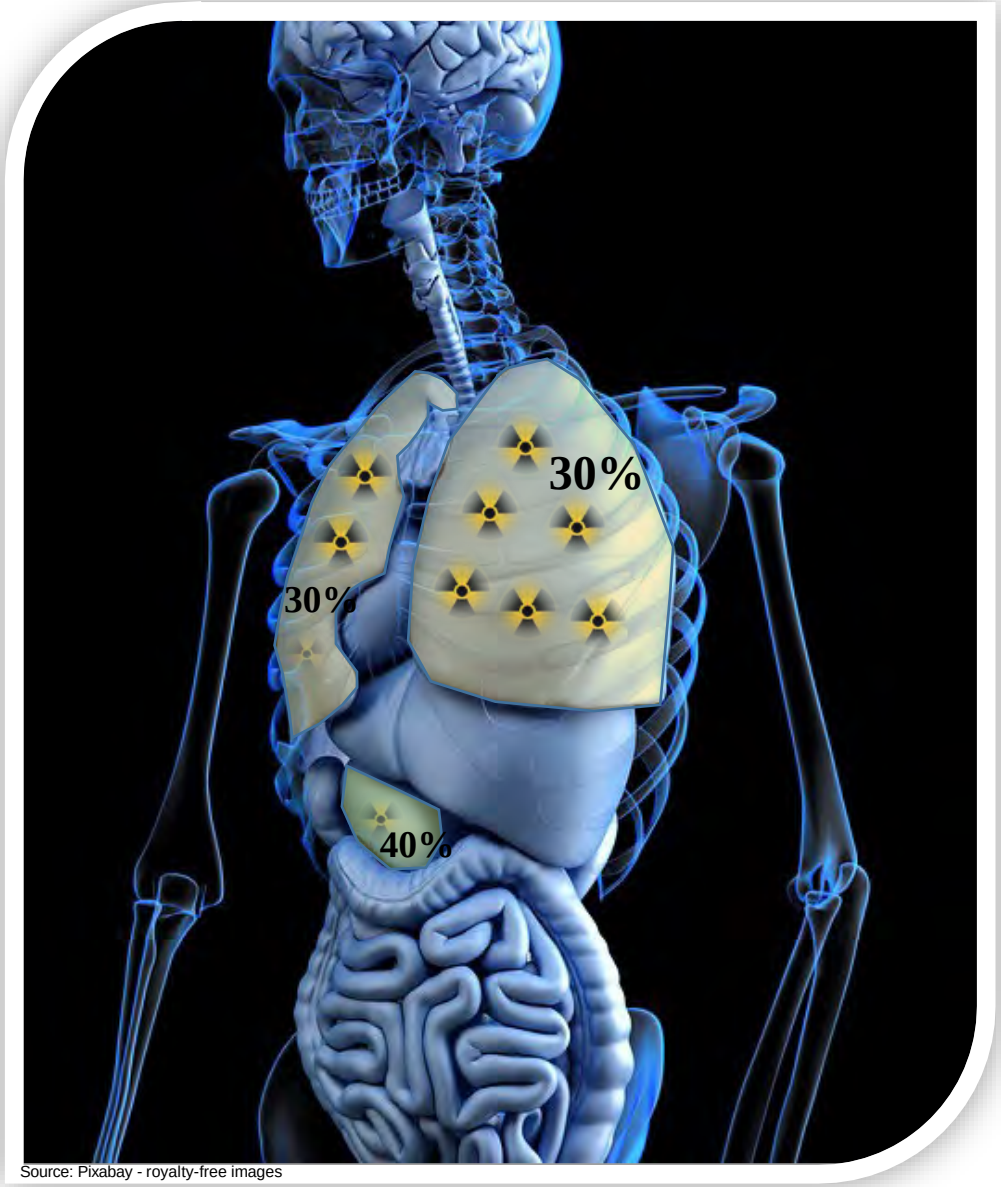
$$H_{T,50} = \int_{t_0}^{t_0+50\ years} \dot{H}_T(t)dt$$

$$\boldsymbol{E_{50}} = \sum_T w_T \cdot H_{T,50}$$

Not a directly measurable quantity → indirect estimation from *in vivo* and *in vitro* measurements.

Individual monitoring in case of internal irradiation

➔ How is the committed effective dose – E_{50} – calculated?



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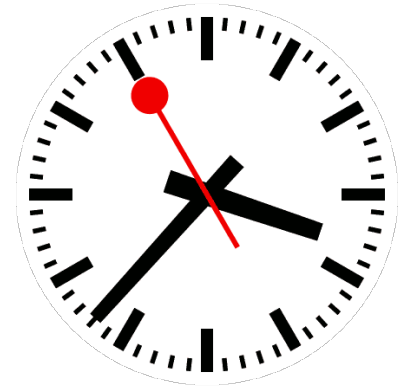
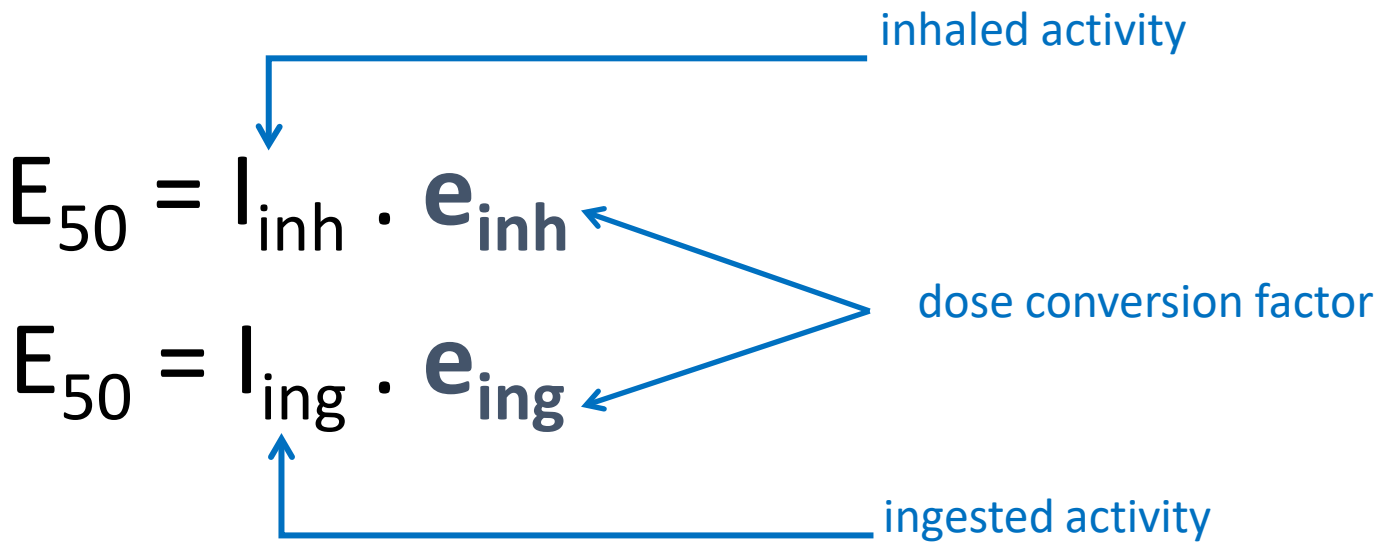


Determination of the committed effective dose



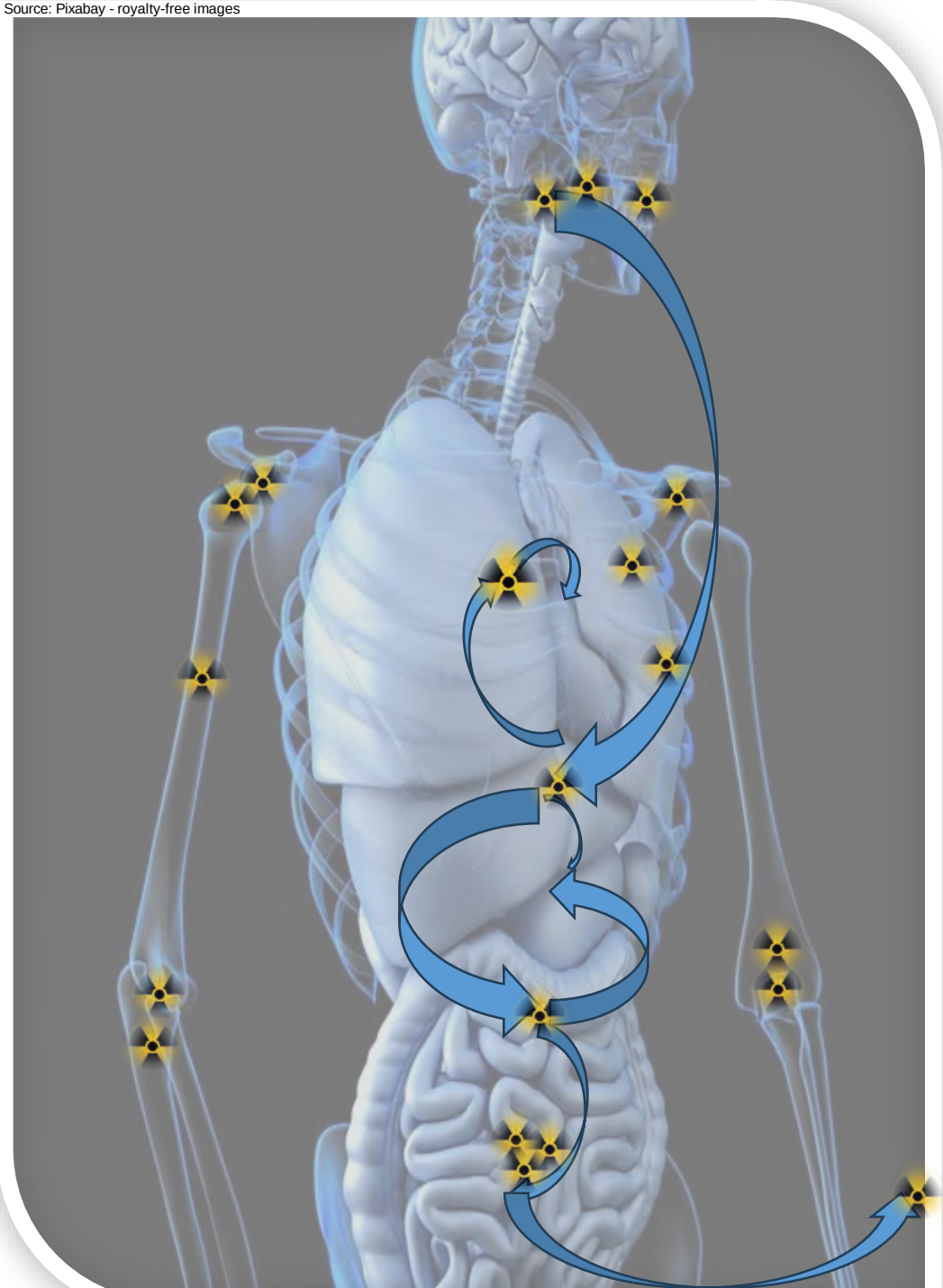
The conversion factors e_{inh} and e_{ing} take into account:

- Radionuclide and its radiation type and energy
- Mode of incorporation (inhalation or ingestion)
- Metabolism of the incorporated radionuclide

Radiological protection ordinance

			Assessment quantities					Clearance limit		Licensing limit	Guidance values		
Radionuclide	Half-life	Type of decay/ radiation	e_{inh} Sv/Bq	e_{ing} Sv/Bq	h_{10} (mSv/h)/ GBq at 1 m distance	$h_{0,07}$ (mSv/h)/ GBq at 10 cm distance	$h_{c,0,07}$ (mSv/h)/ (kBq/cm²)	LL Bq/g		LA Bq	CA Bq/m³	CS Bq/ cm²	Unstable daughter nuclide
1	2	3	4	5	6	7	8	9		10	11	12	13
Tc-97	2.6 E6 a	ec / ph	1.60E-10	8.30E-11	0.017	4	<0.1	1.E+01		3.00E+07	5.00E+04	1000	
Tc-97m	90.1 d	it / ph	2.70E-09	6.60E-10	0.014	30	0.7	1.E+02		2.00E+06	3.00E+03	10	→ Tc-97
Tc-98	4.2 E6 a	β^- / ph	6.10E-09	2.30E-09	0.215	2000	1.5	1.E-01		8.00E+05	1.00E+03	3	
Tc-99	2.111 E5 a	β^-	3.20E-09	7.80E-10	<0.001	1000	1.1	1.E+00		2.00E+06	3.00E+03	3	
Tc-99m	6.015 h	it, β^-/ ph	2.90E-11	2.20E-11	0.022	300	0.2	1.E+02	[1]	2.00E+08	3.00E+05	30	→ Tc-99
Tc-101	14.2 min	β^- / ph	2.10E-11	1.90E-11	0.055	1000	1.6	1.E+02	[1]	2.00E+08	4.00E+05	3	
Tc-104	18.3 min	β^- / ph	4.80E-11	8.10E-11	1.219	1000	1.8	1.E+01	[1]	1.00E+08	2.00E+05	3	
Ru-94	51.8 min	ec, β^+ / ph	7.40E-11	9.40E-11	0.100	20	0.1	1.E+02	[1]	7.00E+07	1.00E+05	100	→ Tc-94
Ru-97	2.9 d	ec / ph	1.60E-10	1.50E-10	0.055	100	0.1	1.E+01		3.00E+07	5.00E+04	100	→ Tc-97

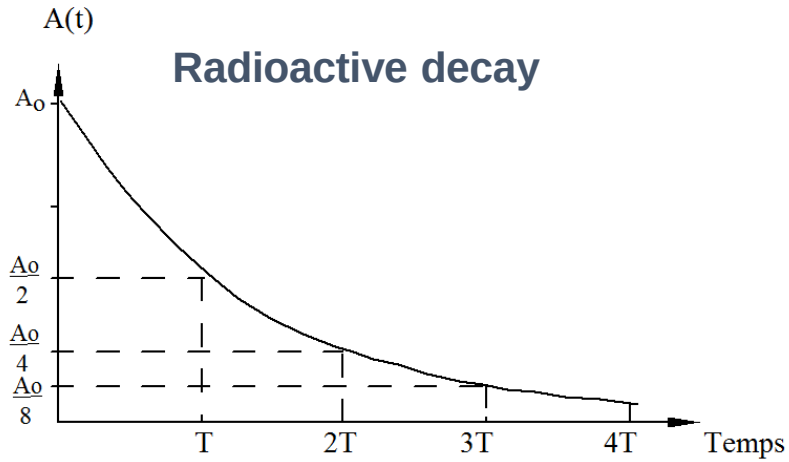
Source: Pixabay - royalty-free images



Intake, biodistribution, biokinetics and excretion pathways

Physics

Radioactive decay

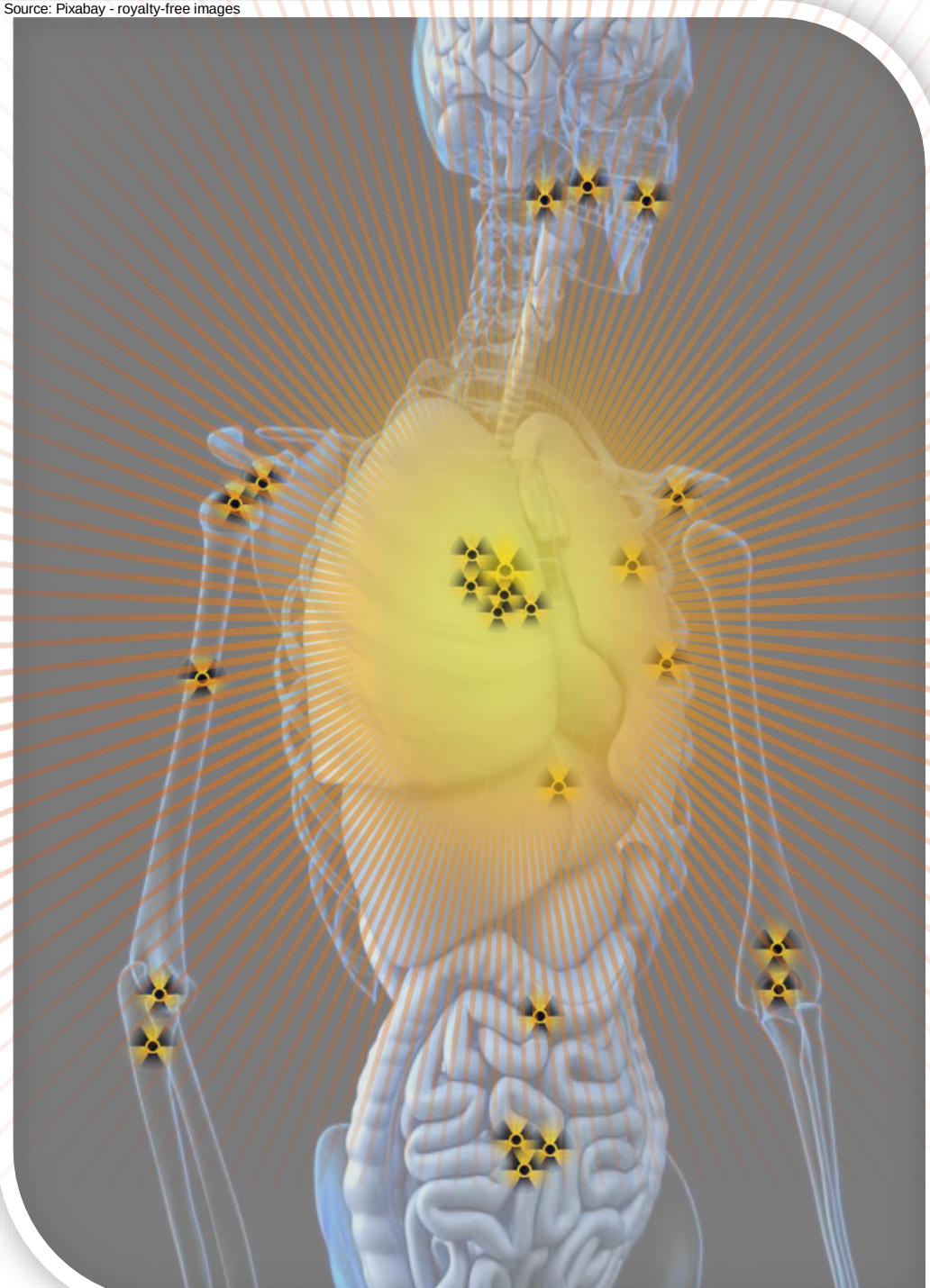


Biology

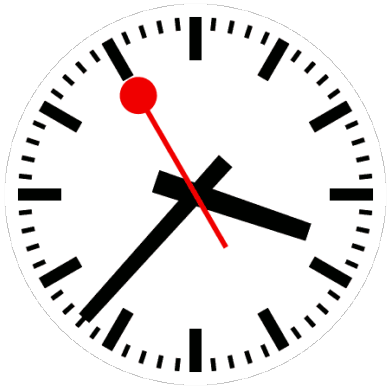
- Retention
- Transfer
- Excretion rates

Effective half-life

Source: Pixabay - royalty-free images



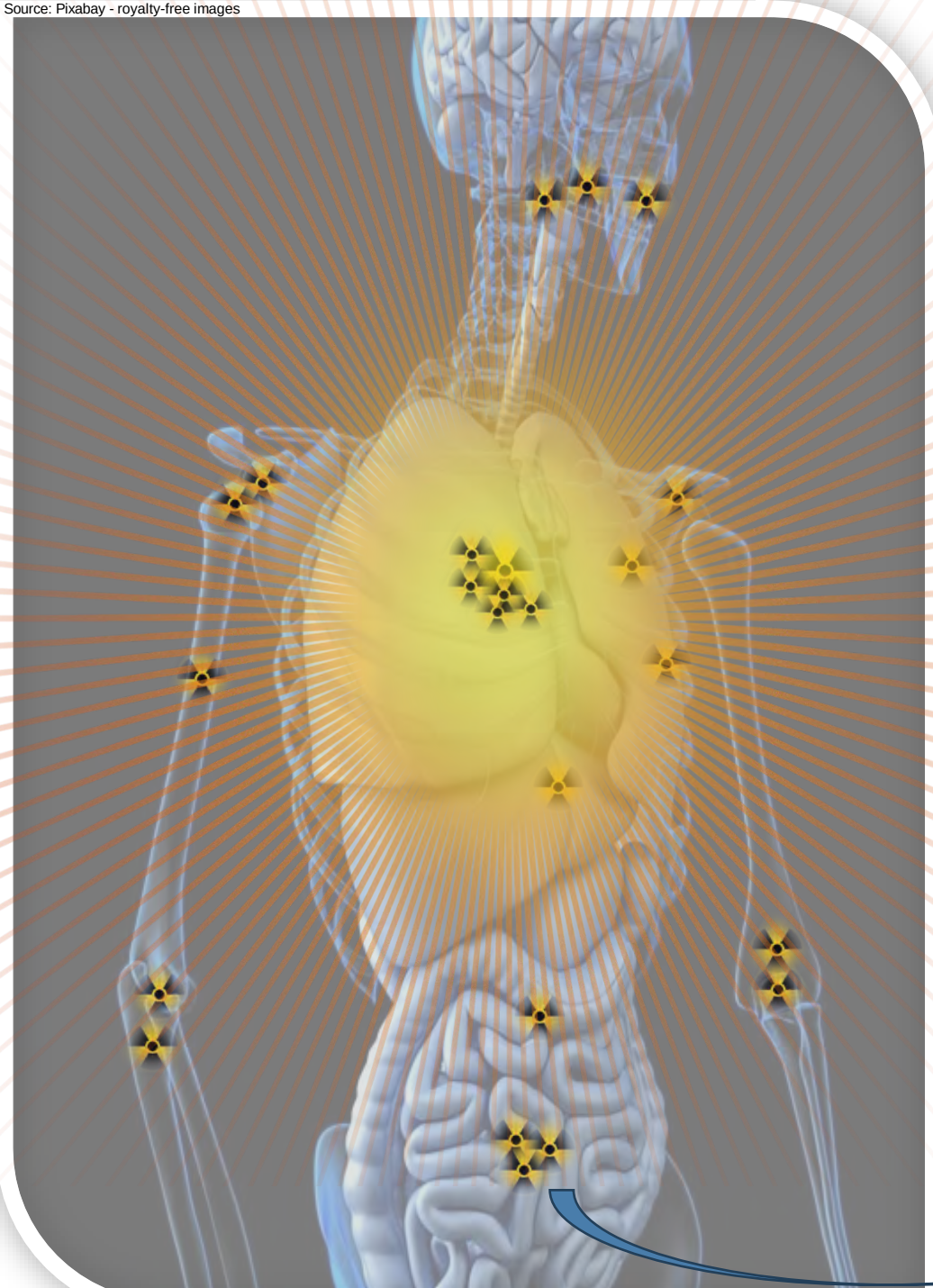
Measurements



How can we measure the intake activity?

2 minutes by yourself
5 minutes in a group of 3

Source: Pixabay - royalty-free images



Measurements

In-vivo : direct measurements

gamma

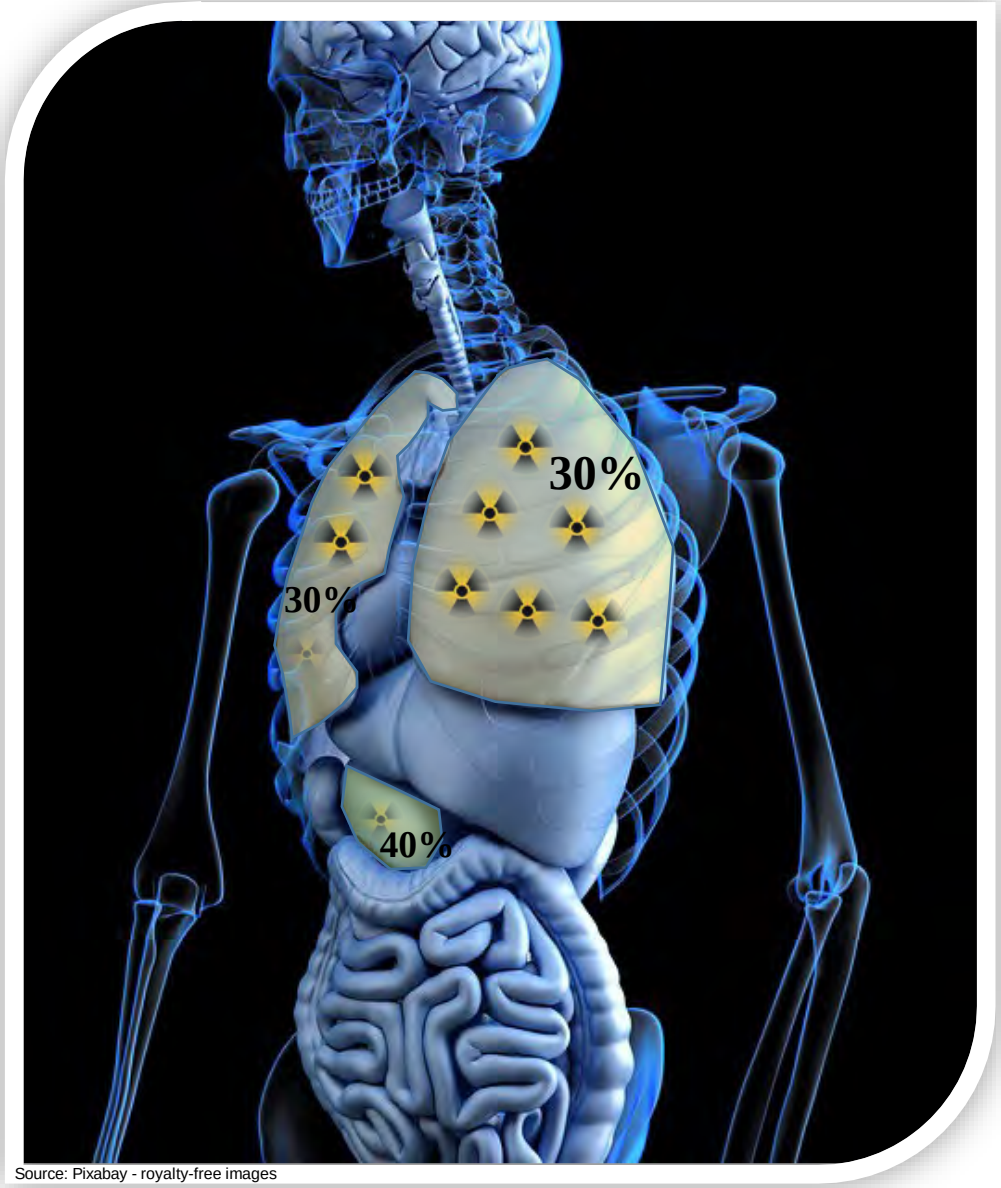
In-vitro : indirect measurements

urine and faeces / or nasal smear

alpha-
beta-
low-energy

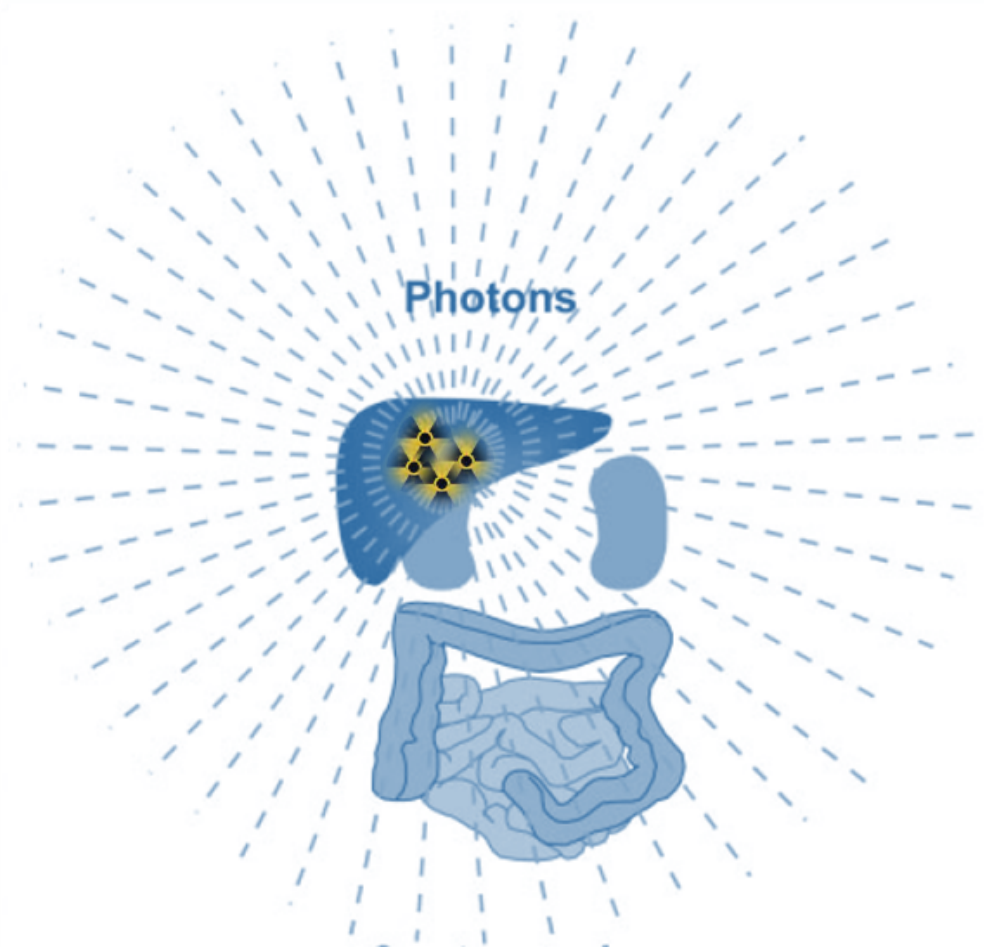
Individual monitoring in case of internal irradiation

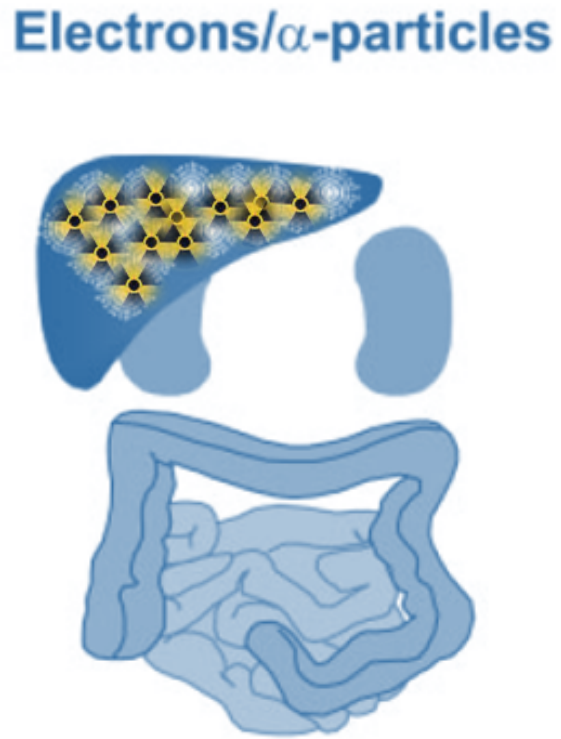
Organ exposure and dose calculation

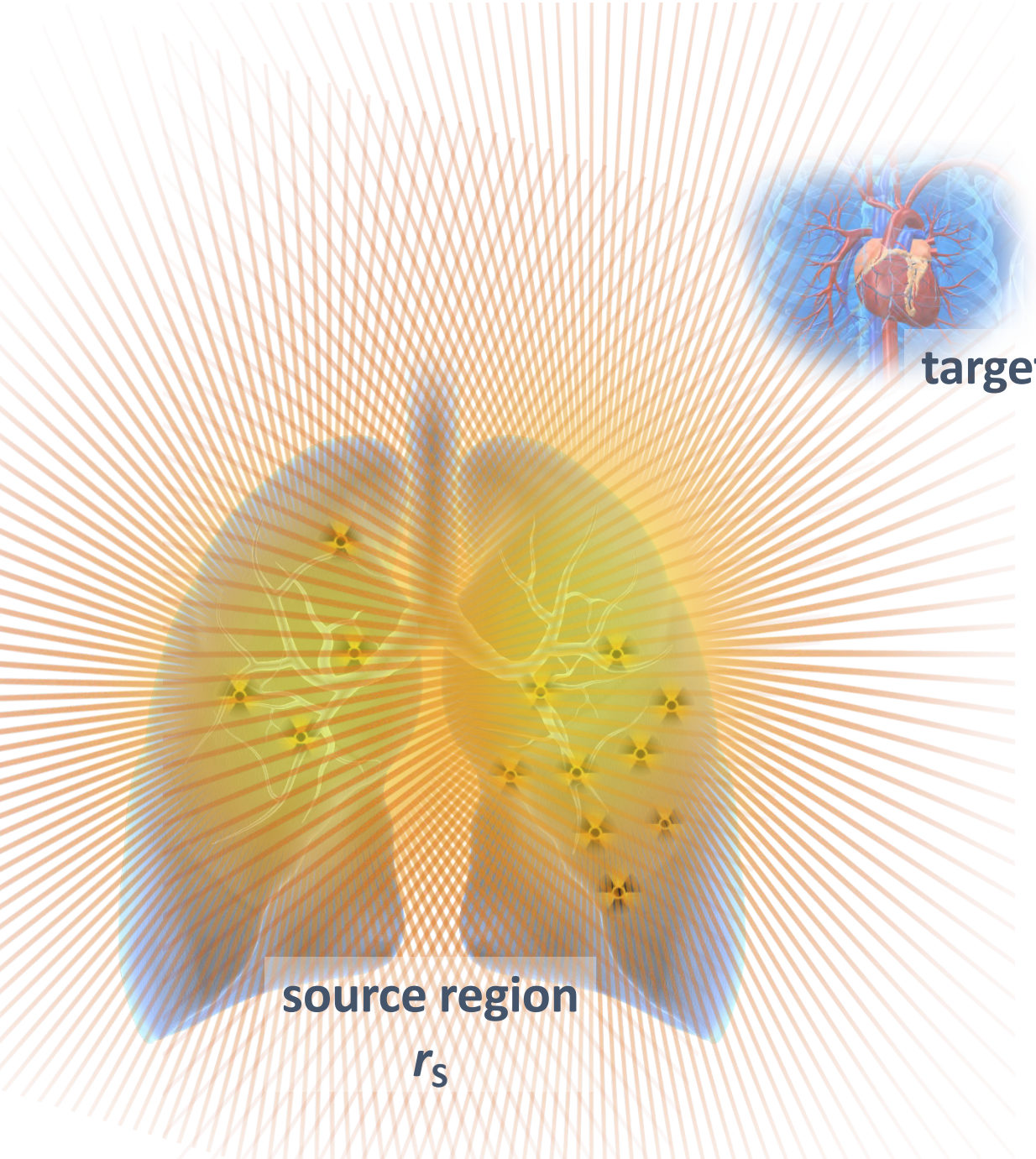


Source: Pixabay - royalty-free images

Irradiation of neighbouring organs / self irradiation







Number of **nuclear transformations** in source region r_S during time τ

$$\tilde{A}(r_s, \tau)$$

$$S_w(r_T \leftarrow r_S)$$

S-factor

conversion factor between $\tilde{A}$ in a compartment (region r_s) and the dose in a target organ (r_T)

Dose from **one source region** r_s to one **target region** r_T

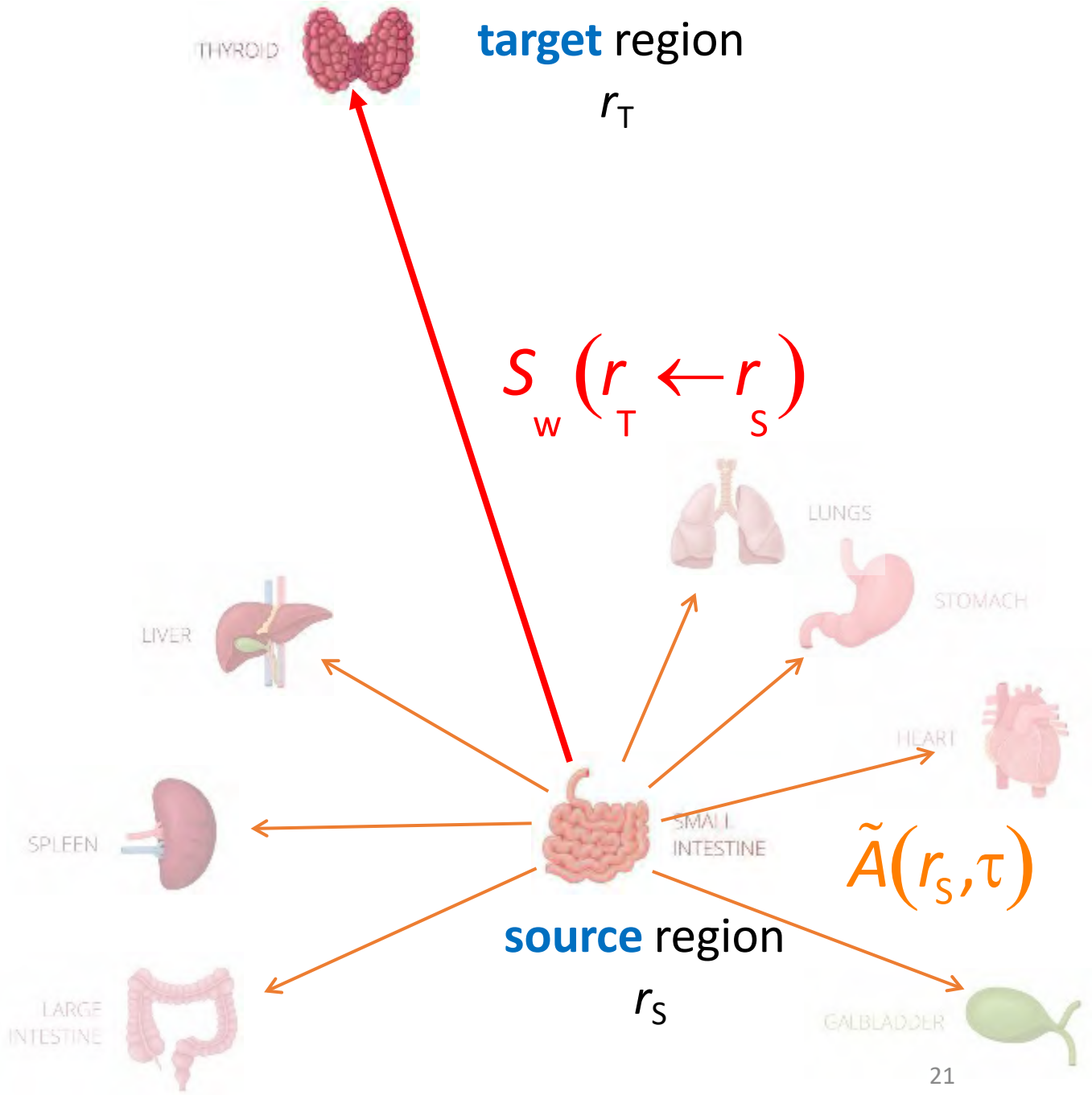
Physiology Biokinetic

Physics Radiophysics & geometry

$$H_{T\leftarrow S} = \tilde{A}(r_S,\tau)\, S_w(r_T \leftarrow r_S)$$

per unit of intake ***I***

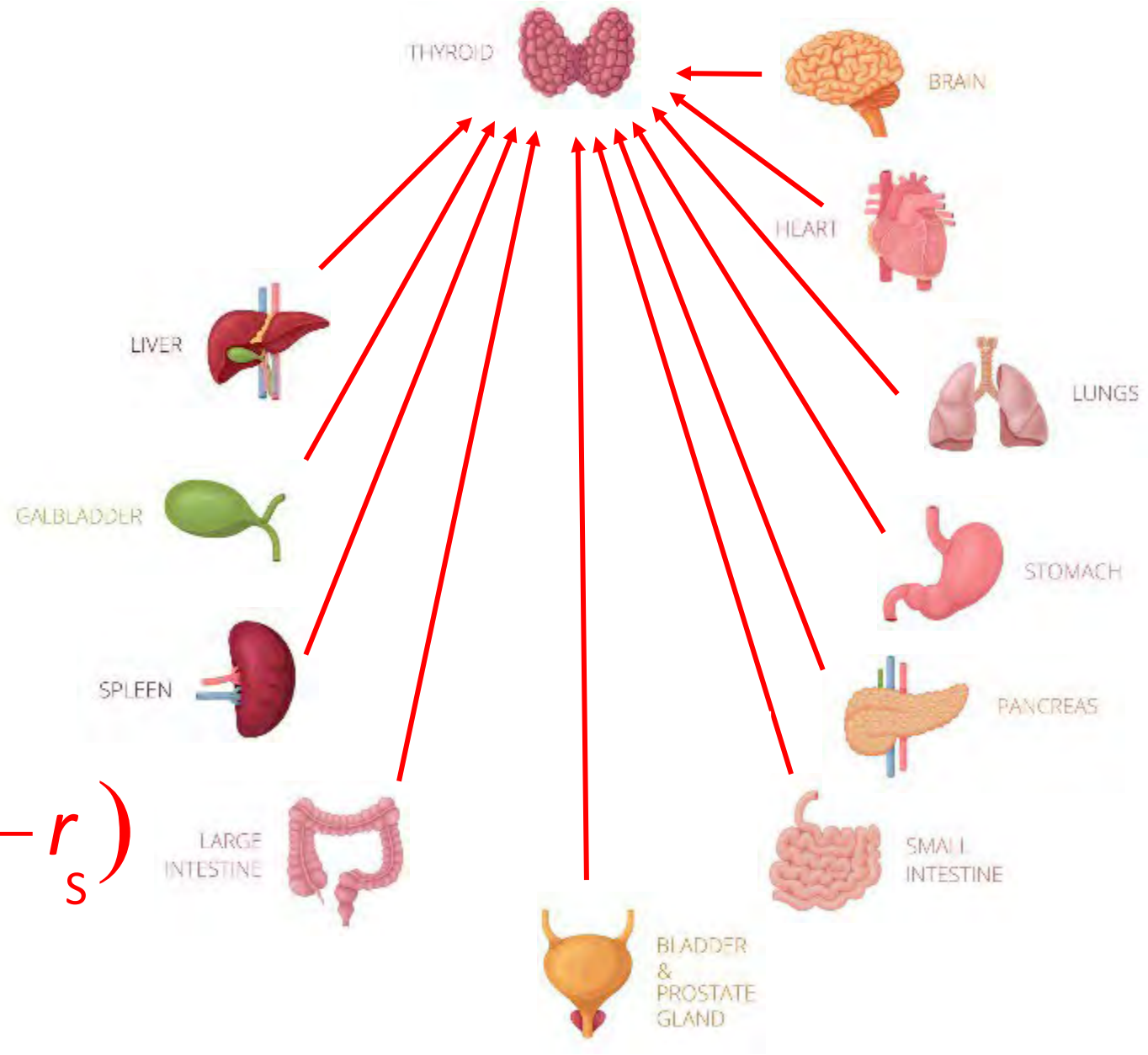
$$h_{T\leftarrow S} = \frac{\tilde{A}(r_S,\tau)}{I}\, S_w(r_T \leftarrow r_S)$$



https://www.gettyimages.ch/detail/illustration/human-anatomy-icons-male-body-lizenfreie-illustration/1174952367

Dose from **all source region** r_s
to one **target region** r_T

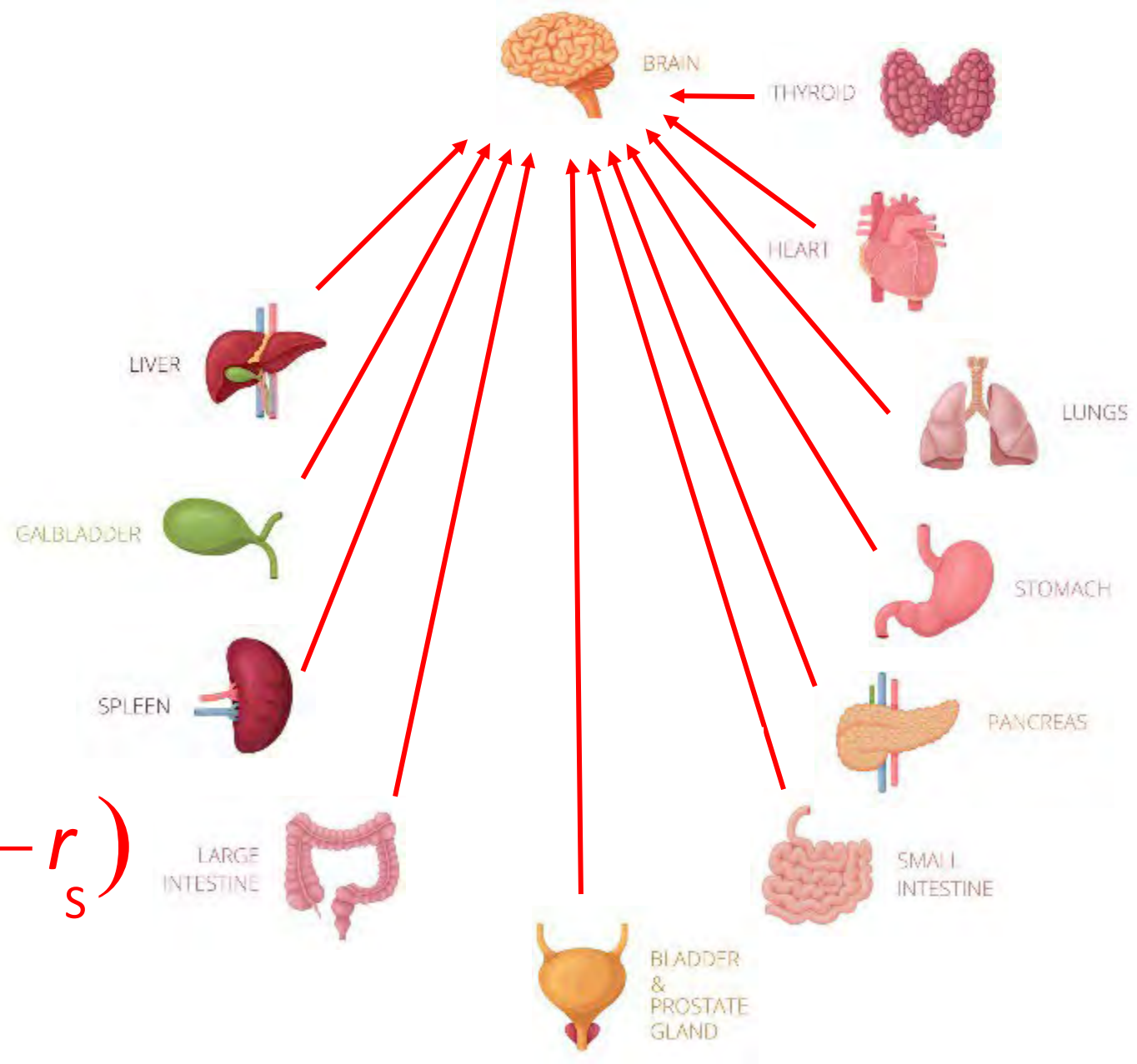
$$h_T = \sum_{r_S} \frac{\tilde{A}(r_S, \tau)}{I} s_w(r_T \leftarrow r_S)$$



https://www.gettyimages.ch/detail/illustration/human-anatomy-icons-male-body-lizenfreie-illustration/1174952367

Same goes for each and every organ

Dose from **all source region** r_S to one **target region** r_T



$$h_T = \sum_{r_S} \frac{\tilde{A}(r_S, \tau)}{I} s_w(r_T \leftarrow r_S)$$

https://www.gettyimages.ch/detail/illustration/human-anatomy-icons-male-body-lizenfreie-illustration/1174952367

Step 1

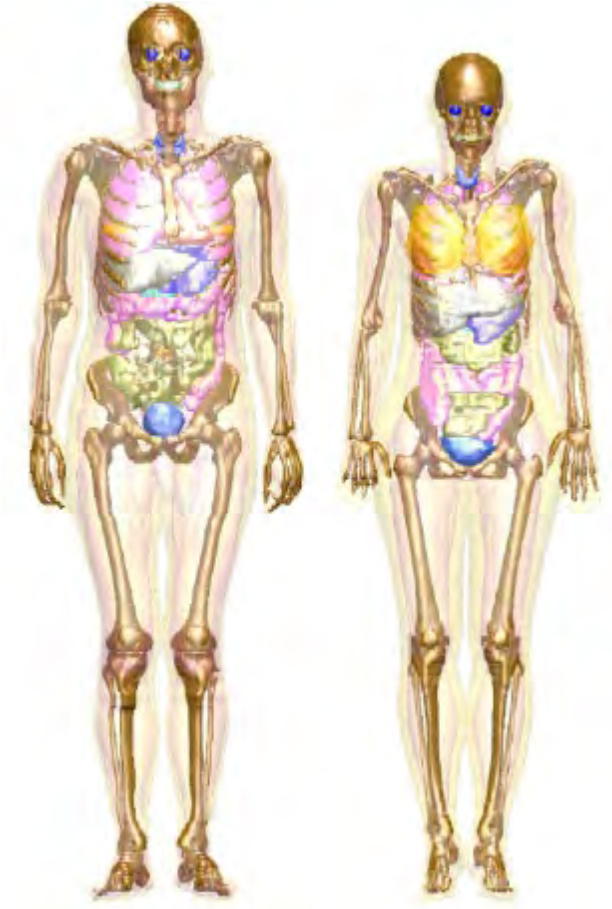
$S_w(r_t \leftarrow r_s)$ can be computed:

By Monte Carlo simulation transport codes:

- Individual tracking of emitted radiations
- Computed from each source region r_S *(within the phantom)*
- For a set of mono-energetic
  - photons
  - electrons
  - positrons
  - alpha-particles

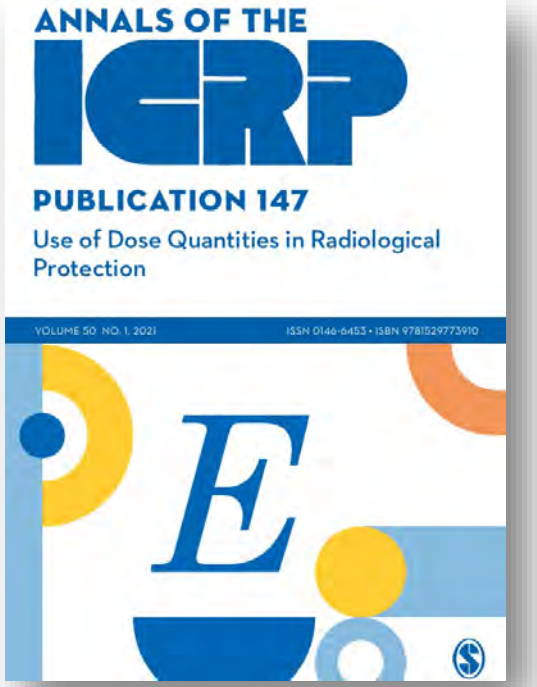
male ref phantom
176 cm and 73 kg

female ref phantom
163 cm and 60 kg



ICRP-110 voxel phantoms

Before moving to $\tilde{A}$



3.5. Committed dose

(45) Radionuclides incorporated into the human body irradiate organs and tissues over time periods determined by their physical half-life and their biological retention within the body. Radionuclides with long physical half-lives and long biological half-times may continue to deliver doses to body tissues over many years after intake. The need to control such exposures led to the definition of committed dose quantities (ICRP, 1991a, 2007a). The committed dose from an incorporated radionuclide is the total dose expected to be delivered within a specified time period. The committed equivalent dose, $H_T(\tau)$, in a tissue or organ T is defined by:

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T(t)\,dt$$

where τ is the integration time following the intake at time t_0. Committed effective dose, $E(\tau)$, is then given by:

$$E(\tau) = \sum_T w_T H_T(\tau) \qquad (3.4)$$

(46) The committed dose is assigned to the year in which the intake occurred. For workers and adult members of the public, the committed dose is integrated over the 50-year period following the intake. For infants and children, the dose is evaluated to 70 years of age.

(47) It has been argued that the use of committed dose introduces hidden conservatism into calculations of doses from annual intakes (Gonzalez et al., 2013). For some radionuclides with long half-lives and long biological retention times, only a small proportion of the committed dose is delivered in the year of intake. For ^{239}Pu, for example, effective dose in the first year after intake will be generally <10% of the total committed effective dose. For most radionuclides, however, this effect will be much less significant, and for many, including ^{131}I and ^{137}Cs, dose will be delivered entirely or very largely in the year of intake. For practical purposes, the use of committed dose ensures that longer-term exposures from intakes of radionuclides are taken into account.

Final step

e_{50} can be computed:

$$h_T = \sum_{r_S} \frac{\tilde{A}(r_S, \tau)}{I} S_w(r_T \leftarrow r_S)$$

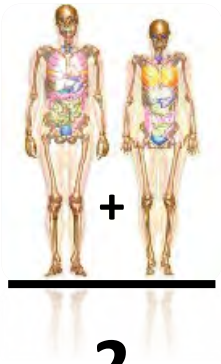
equivalent dose coefficients (h) in the **target region** r_T summed over *N* radionuclides *i*

$$h^M(r_T, \tau) = \sum_{i=1}^{N} \sum_{r_S=1}^{M} \frac{\tilde{A}_i(r_S, \tau)}{I} S_w^M(r_T \leftarrow r_S)$$

$$h^F(r_T, \tau) = \sum_{i=1}^{N} \sum_{r_S=1}^{M} \frac{\tilde{A}_i(r_S, \tau)}{I} S_w^F(r_T \leftarrow r_S)$$

committed effective dose coefficient **(e)**

(committed effective dose for 1 Bq intake)



2

$$e(\tau) = \sum_T w_T \left[\frac{h_T^M(\tau) + h_T^M(\tau)}{2} \right]$$

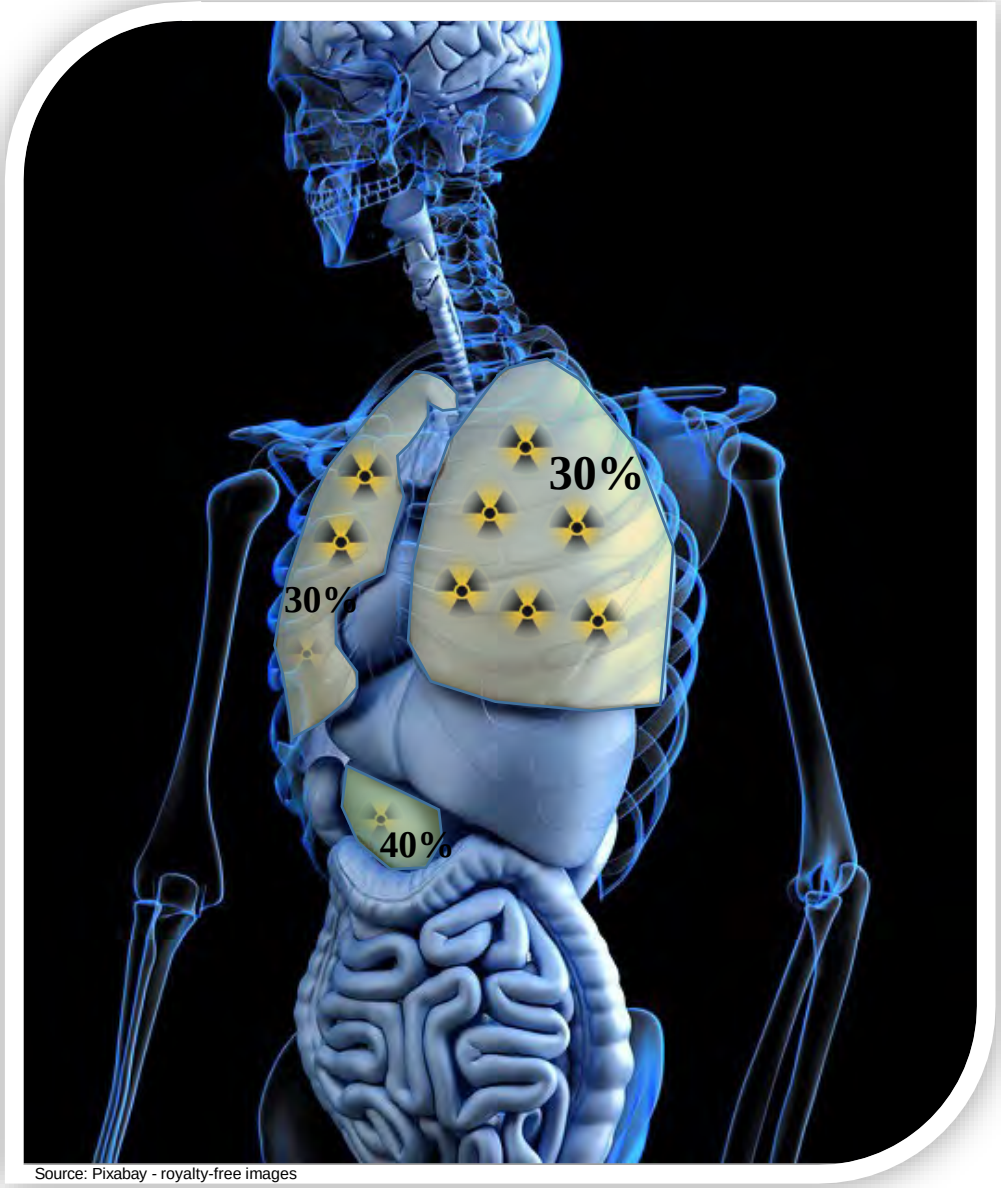
Tissue	w_T	$\sum w_T$
Active bone marrow, breast, colon, lung, stomach, remainder tissues*	0.12	0.72
Gonads	0.08	0.08
Urinary bladder, oesophagus, liver, thyroid	0.04	0.16
Bone endosteum, brain, salivary glands, skin	0.01	0.04

Back to Step 2

Individual monitoring in case of internal irradiation

How is the activity in each organ defined according to time?

which leads to $\tilde{A}$



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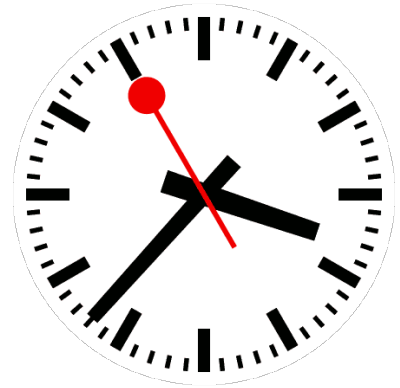
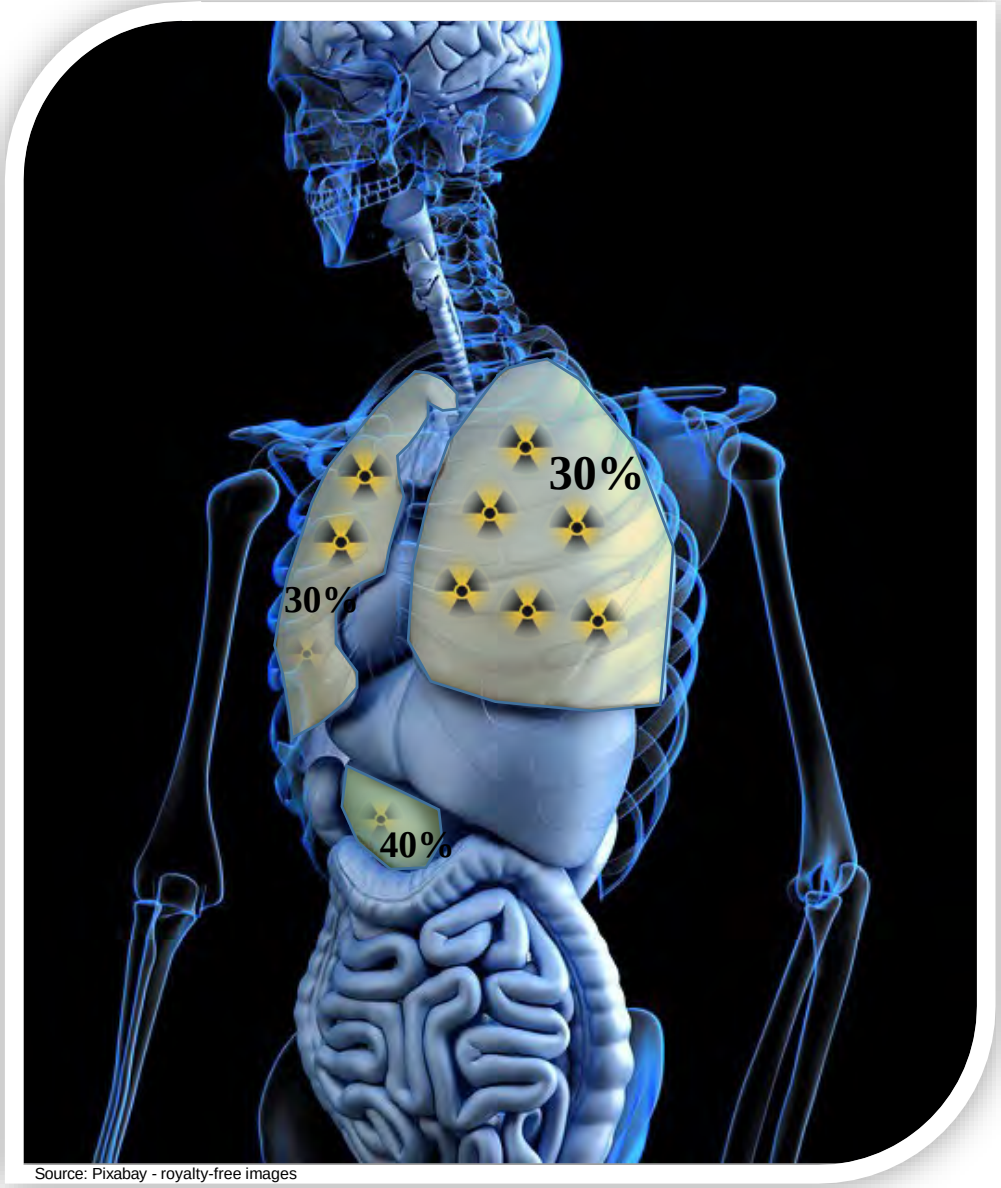


Individual monitoring in case of internal irradiation

Biokinetic and
Compartmental models



Source: Pixabay - royalty-free images

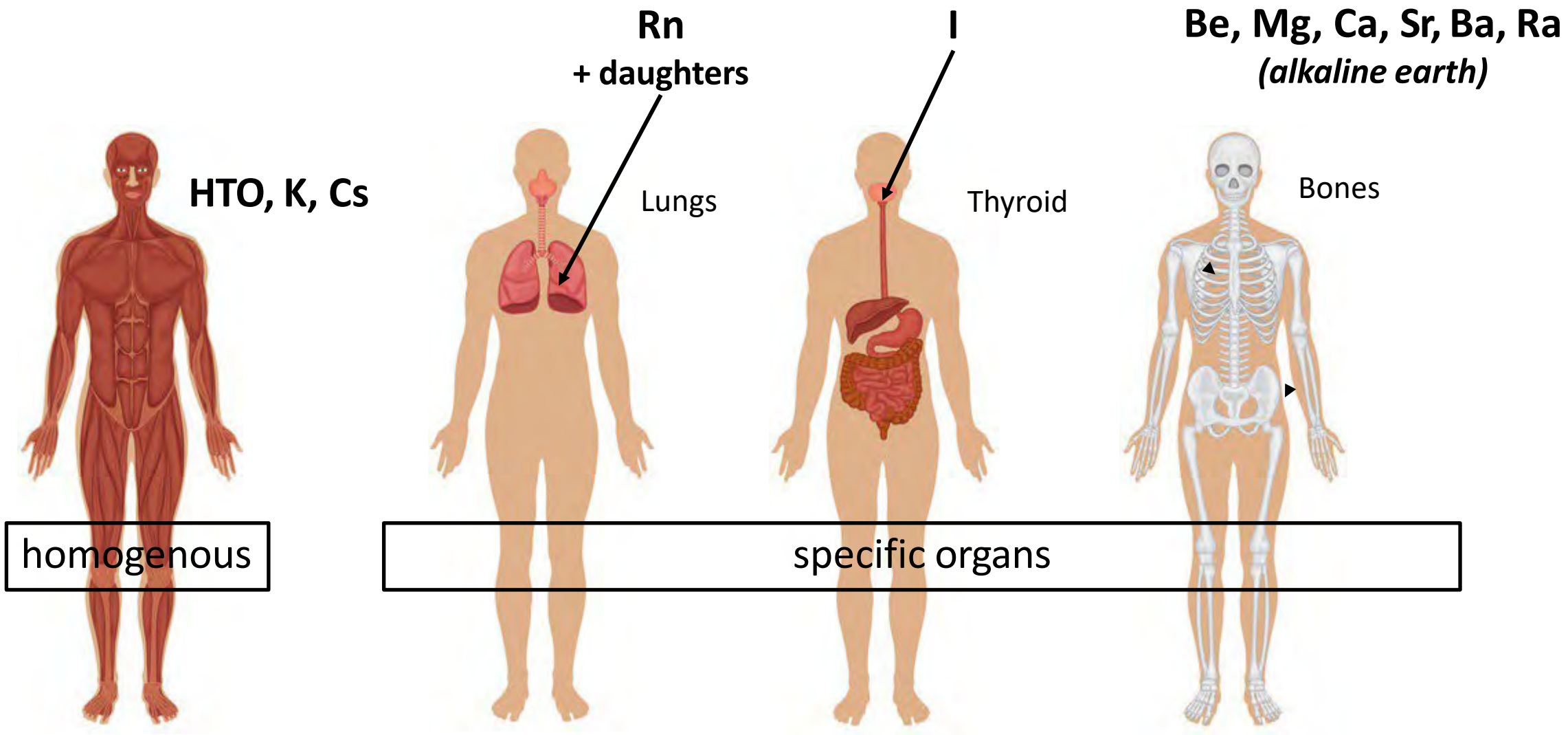
Individual monitoring in case of internal irradiation

Biokinetic – example with drugs – similar concept for radioactive substances

https://www.youtube.com/watch?v=E1a-MIbAGdU

Distribution of the radionuclides within the body

Uptake and retention of radioactive substances in organs = radioactivity being absorbed or accumulating in specific tissues or organs



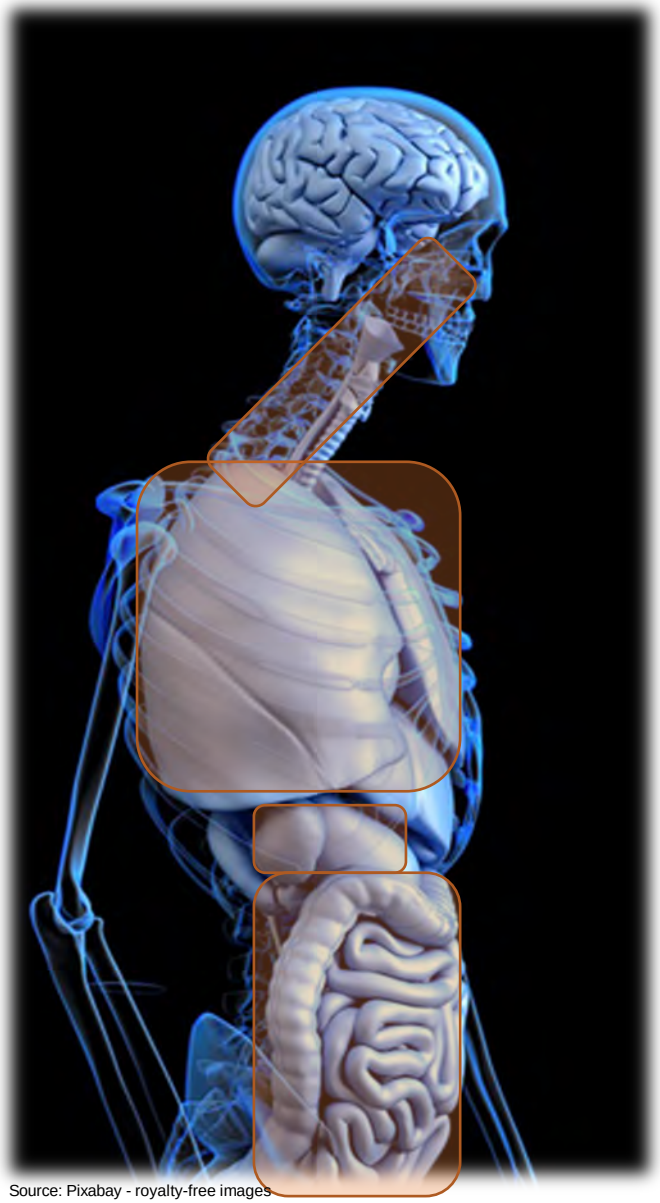
https://www.vectorstock.com/royalty-free-vector/human-body-systems-vector-909054

Compartmental models

International Commission for Radiological Protection (ICRP)

The distribution of a radioactive substance within the body is modelled by a group of organs and/or tissues (referred as **compartments**):

- The body is modelled as a group of compartments.
- The exchange of a radioactive substance within the different compartments is described by a transfer rate.



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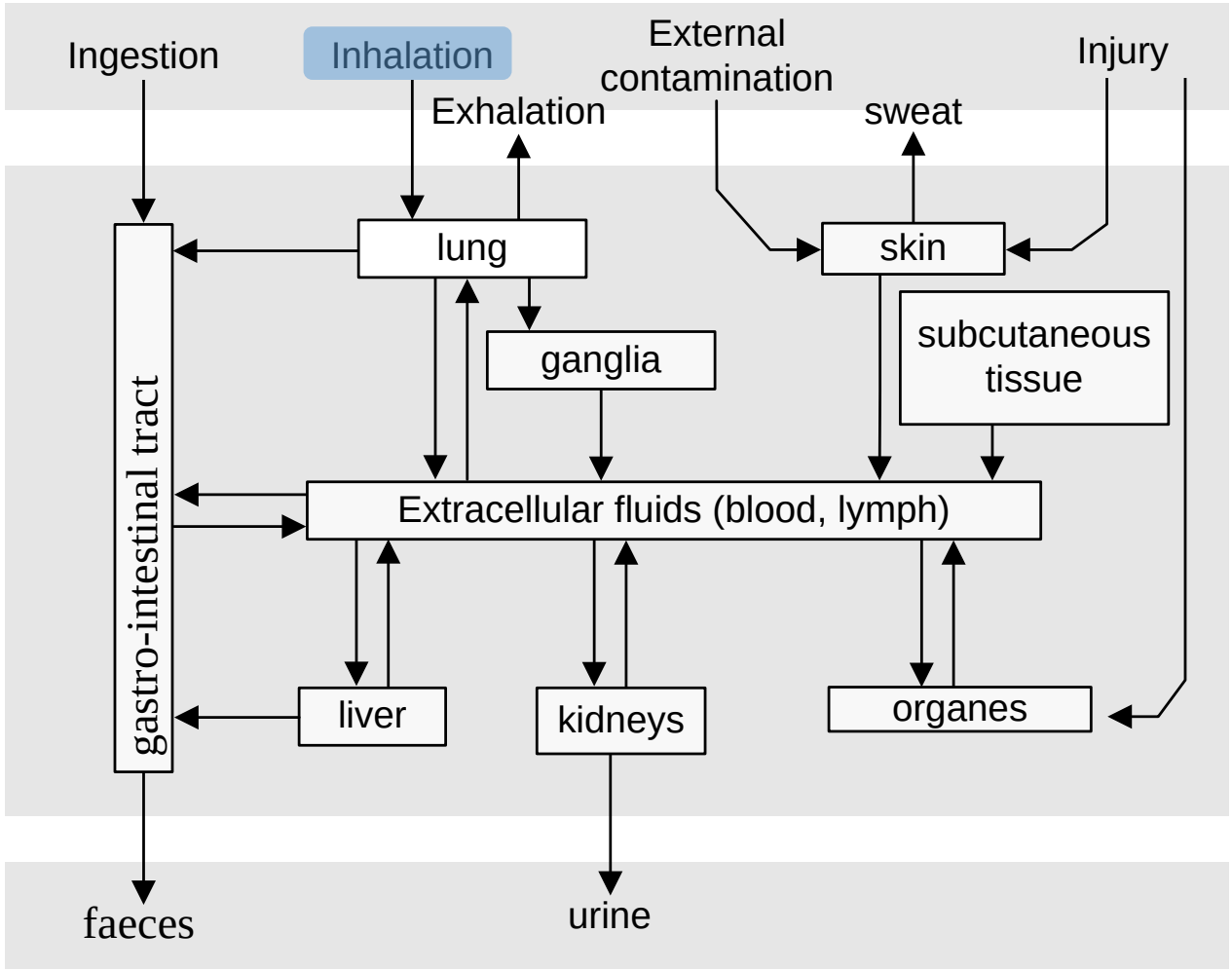
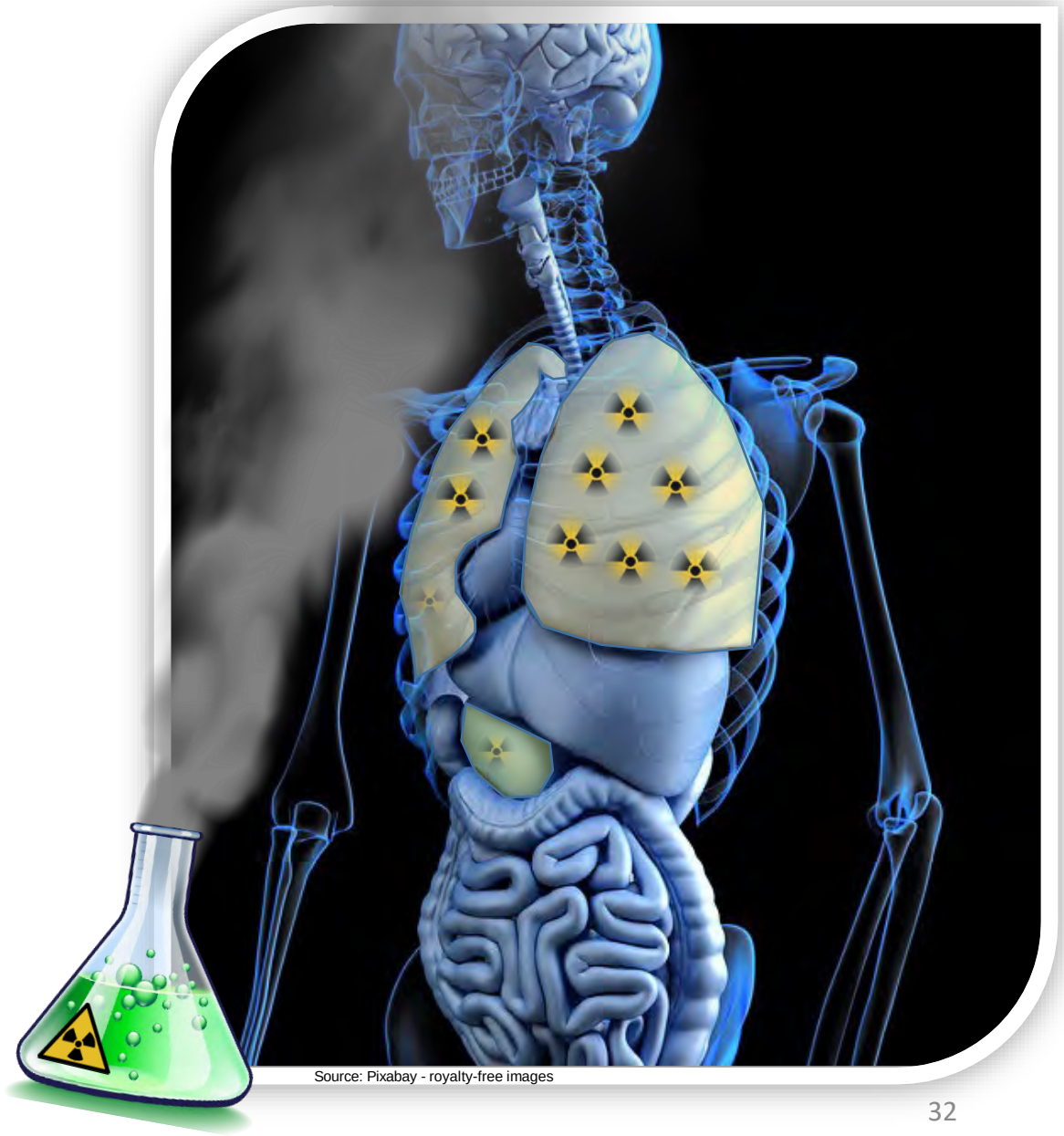
Compartmental models

Principal metabolic pathways for radionuclides in the body



Special models were developed by the ICRP for the respiratory system, the gastro-intestinal tract, bone retention …



Source: Pixabay - royalty-free images

Compartmental models

ICRP 100: Human Alimentary Tract Model for Radiological Protection

5. DESCRIPTION OF THE MODEL

5.1. Overview

(138) The structure of the HATM is shown in Fig. 5.1. The model depicts the following processes:

- entry of a radionuclide into the oral cavity by ingestion, or into the oesophagus after mechanical clearance from the respiratory tract; sequential transfer through the contents of the oral cavity, oesophagus, stomach, small intestine, and segments of the colon, followed by emptying in faeces;
- radionuclide deposition and retention on or between the teeth and return to the oral cavity; deposition and retention in the oral mucosa or walls of the stomach and intestines;

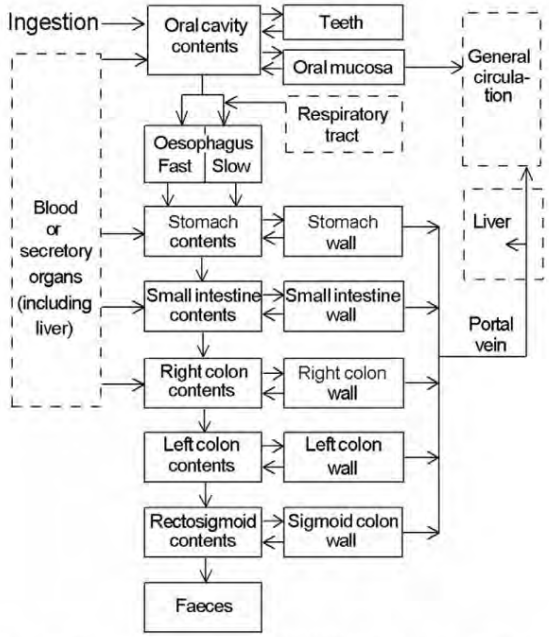


Fig. 5.1. Structure of the human alimentary tract model (HATM). The dashed boxes are included to show connections between the HATM and the human respiratory tract model or systemic biokinetic models.

ICRP 130 Human Respiratory Tract Model

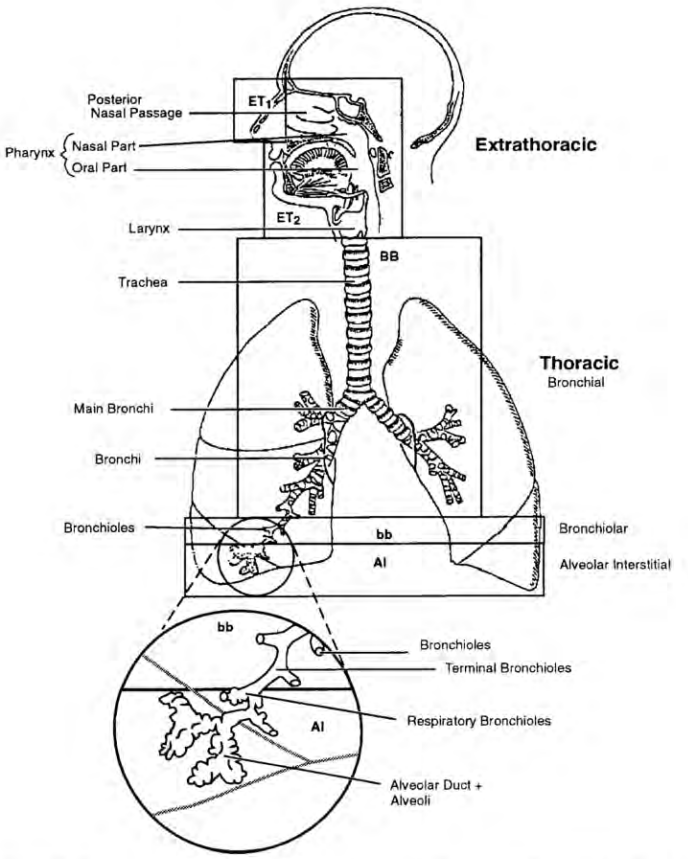
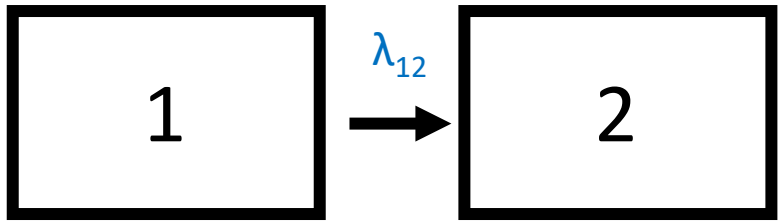


Fig. 3.2. Respiratory tract regions defined in the Human Respiratory Tract Model. Note that the oral part of the pharynx is no longer part of ET_2.
ET_1: extrathoracic region including the anterior nasal passage; ET_2: extrathoracic region including posterior nasal passage, pharynx and larynx; BB: bronchial region; bb: bronchiolar region; AI: alveolar interstitial region. Taken from ICRP (1994a).

Compartmental models



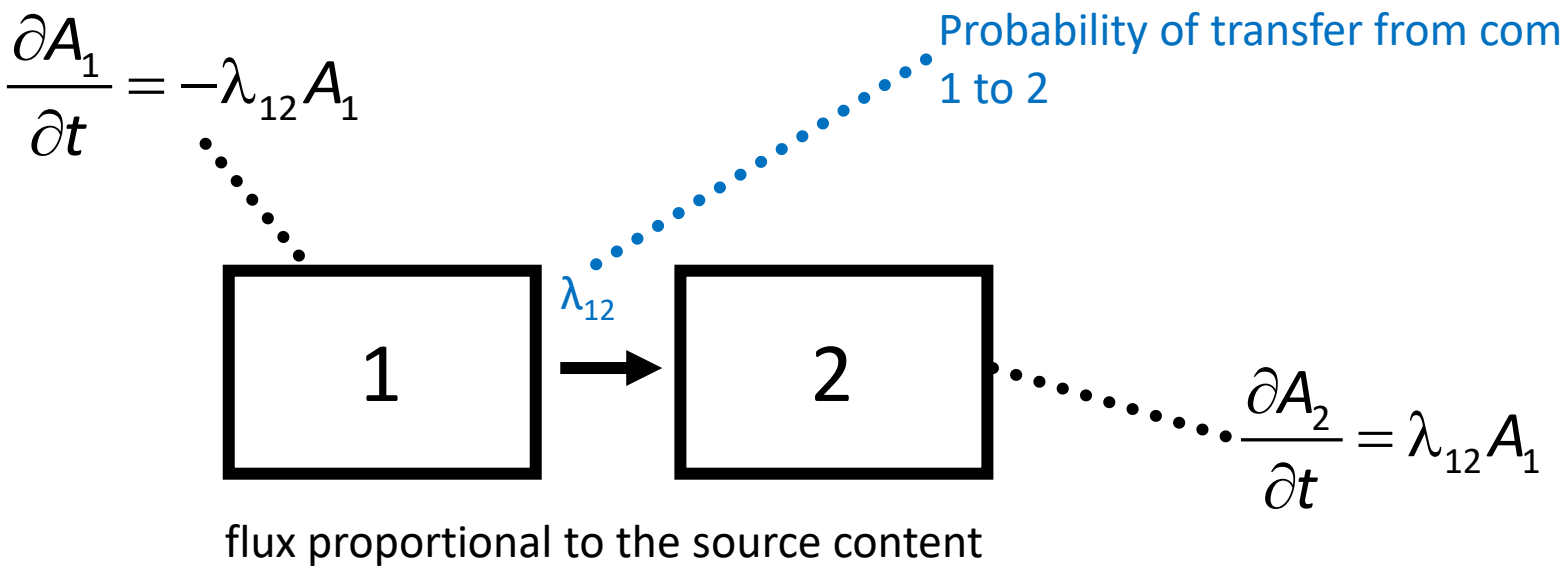
The compartments are considered as **instantaneously homogenous**.

Continuous transfer between the compartments.

Transfer **proportional** to A in the source

λ **fractional transfer rate :**probability of transfer from one compartment to another per unit of time.

Compartmental models



$$A_1(t) = A_{1,0} e^{-\lambda_{12} t}$$

***Generalization** to **N** compartments*

*N*x1 vector containing the activities in each compartment

*N*x*N* matrix containing the fractional transfer rate coefficients

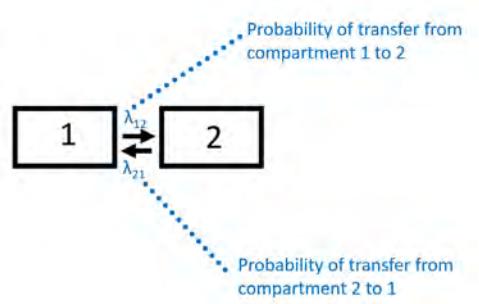
$$\frac{\partial \mathbf{A}}{\partial t} = \mathbf{\Lambda A} \quad \text{solution} \quad \mathbf{A}(t) = \mathbf{A}_0 e^{\mathbf{\Lambda} t}$$

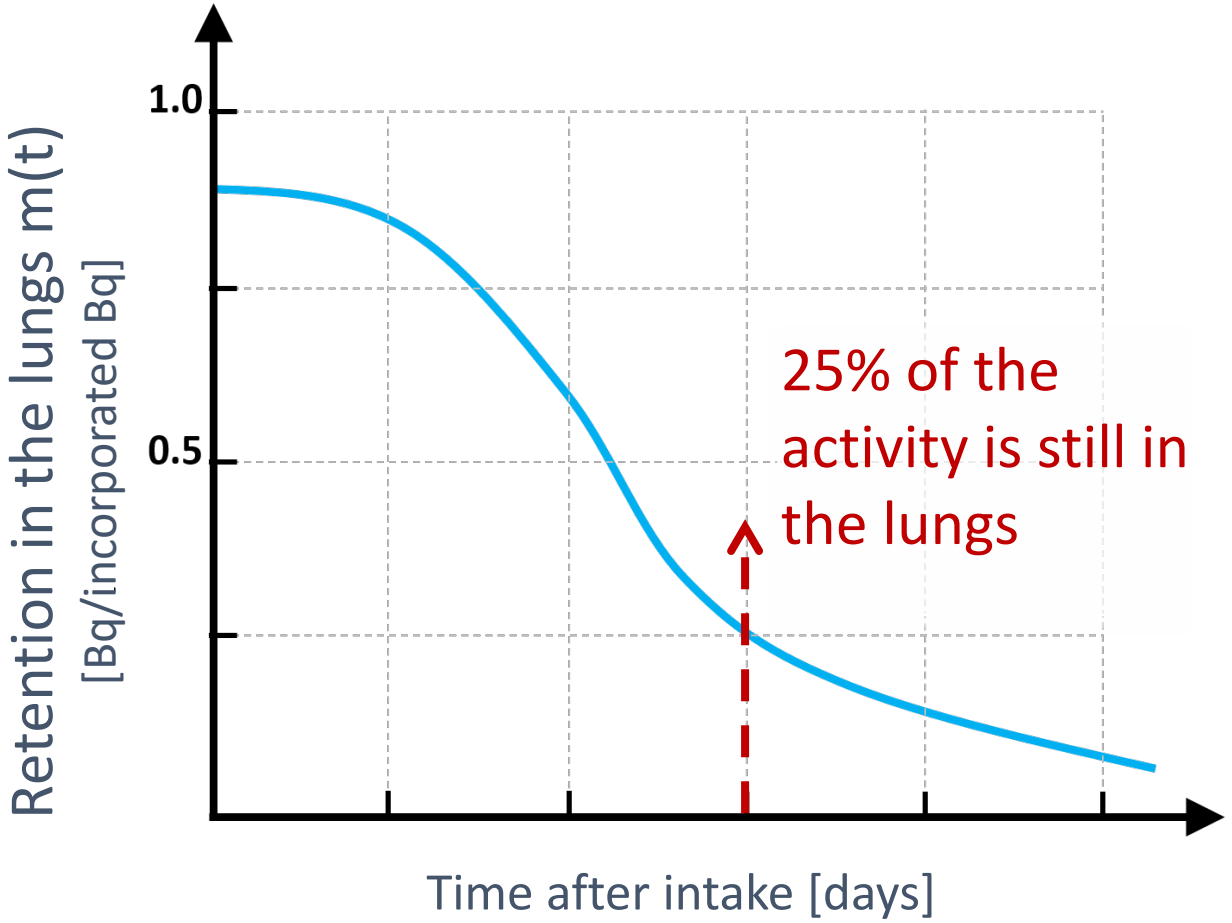
Compartmental models

By solving the first order differential equations describing the models we obtain the retention functions m(t).

They provide the fraction of initially-incorporated activity that is present in a given compartment according to time.

the overall process gets slightly more complicated as a fraction of the activity may be transfer both ways, on different time scales.



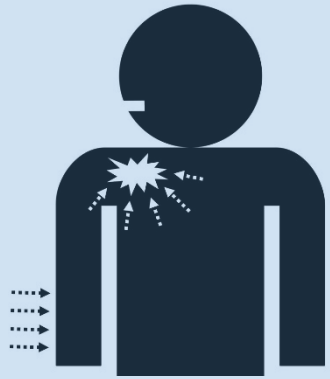


Compartmental models

Generic models – not specific a radionuclide

HRTM
Human Respiratory Tract Model

HATM
Human Alimentary Tract Model



skin + wound

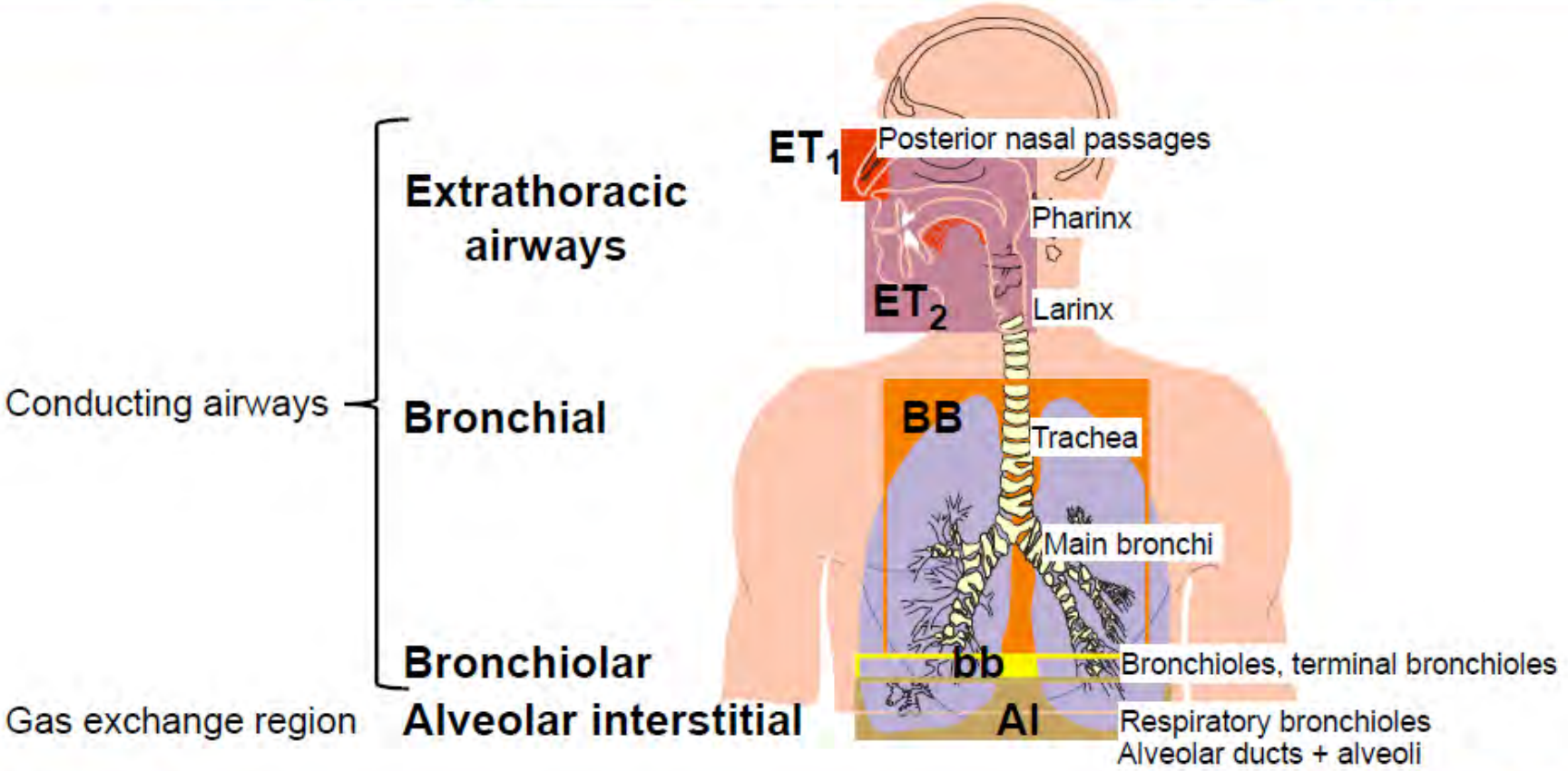
element-specific systemic models

Dedicated model – specific a given radionuclide

HRTM

Human Respiratory Tract Model

Anatomy: respiratory tract regions ET, BB, bb, AI

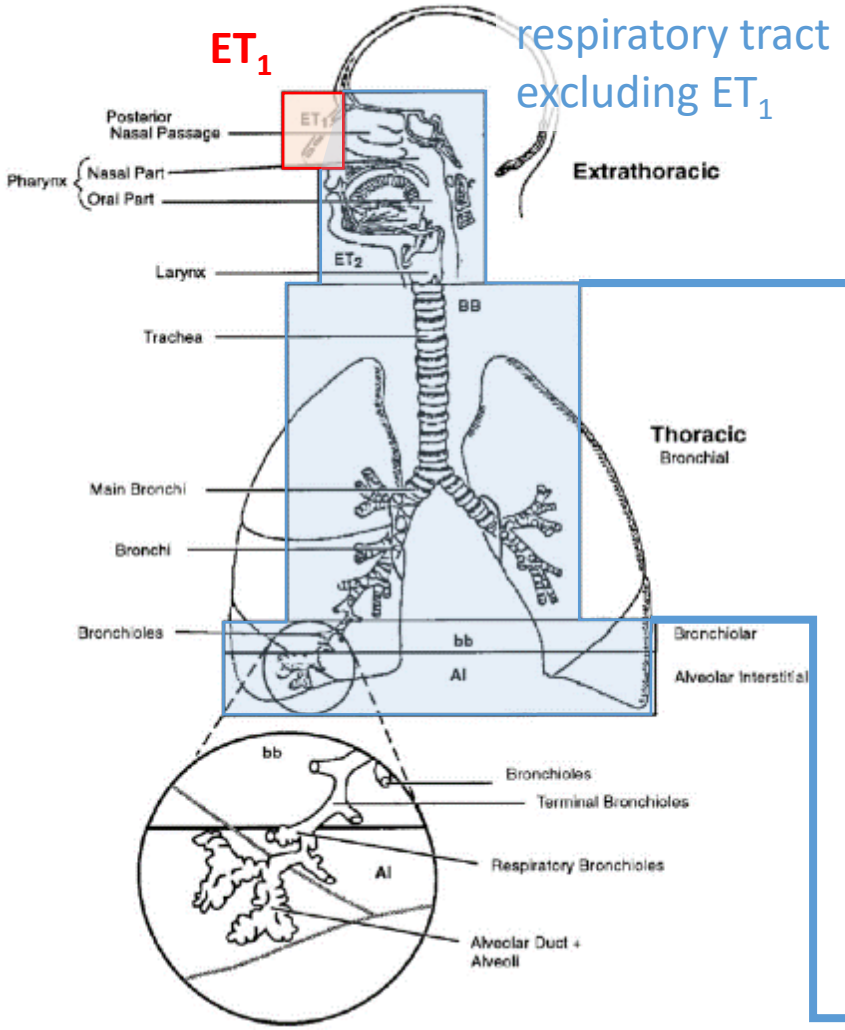


HRTM

Human Respiratory Tract Model

ICRP-130

Fig. 3.2. Respiratory tract regions defined in the Human Respiratory Tract Model. Note that the oral part of the pharynx is no longer part of ET_2.
ET_1: extrathoracic region including the anterior nasal passage; ET_2: extrathoracic region including posterior nasal passage, pharynx and larynx; BB: bronchial region; bb: bronchiolar region; AI: alveolar interstitial region. Taken from ICRP (1994a).



respiratory tract excluding ET_1

HATM

lymph nodes

blood general circulation

element-specific systemic models

HRTM
Human Respiratory Tract Model

ICRP-130

3.2.2. Clearance: particle transport

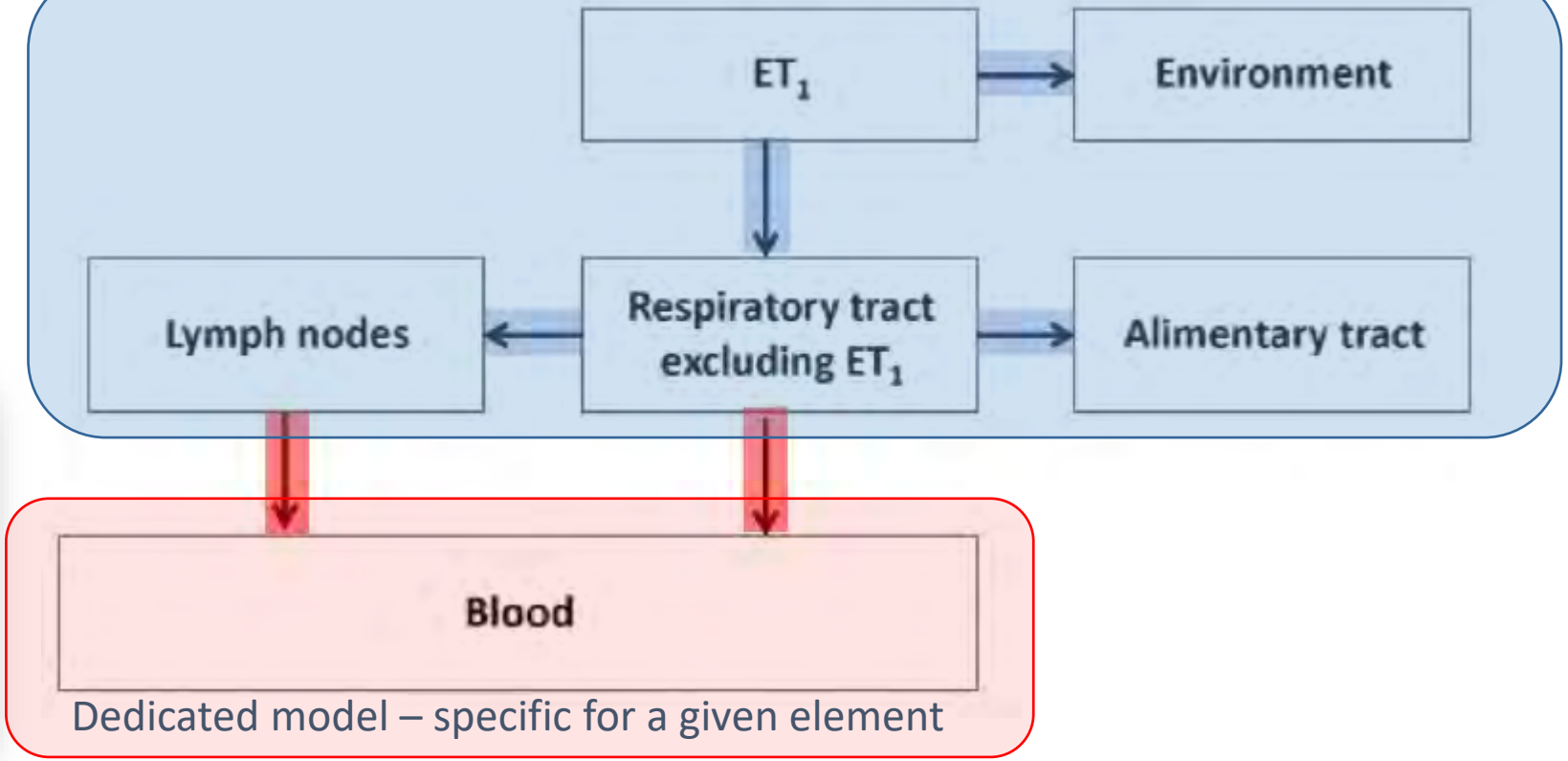
(94) The model describes several routes of clearance from the respiratory tract (Fig. 3.3). Some material deposited in ET_1 is removed by extrinsic means such as nose blowing. In other regions, clearance is competitive between the movement of particles towards the alimentary tract and lymph nodes (particle transport), and the absorption into blood of material from the particles in the respiratory tract. Removal rates due to particle transport and absorption into blood are taken to be independent of each other. It is further assumed that all clearance rates are independent of age and sex.

(95) As in the original HRTM, it is assumed that particle transport rates are the same for all materials. A generic compartment model is therefore provided to describe particle transport of all materials. The revised particle transport model adopted here is shown in Fig. 3.4 (the original model is shown in Annex A, with details of the background to the revisions made, and the choice of parameter values in the revised model). Reference values of rate constants were derived, as far as

Particle clearance from the HRTM by:

- Particle (radioactive substances) **transport**
- **Absorption** into blood

Generic models – not specific for an element



HRTM
Human Respiratory Tract Model

Particle clearance from the HRTM by:

- Particle **transport**

  → transfer rates between compartments

- **Absorption** into blood

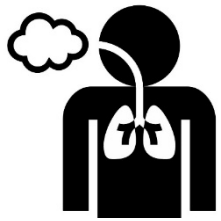
  → chemical form defines absorption parameters values (F: fast, M: moderate, S: slow)

Intake of Radioactive Substances: ICRP Human Respiratory Tract Model (HRTM), the F, M, and S absorption types

Key Concept:

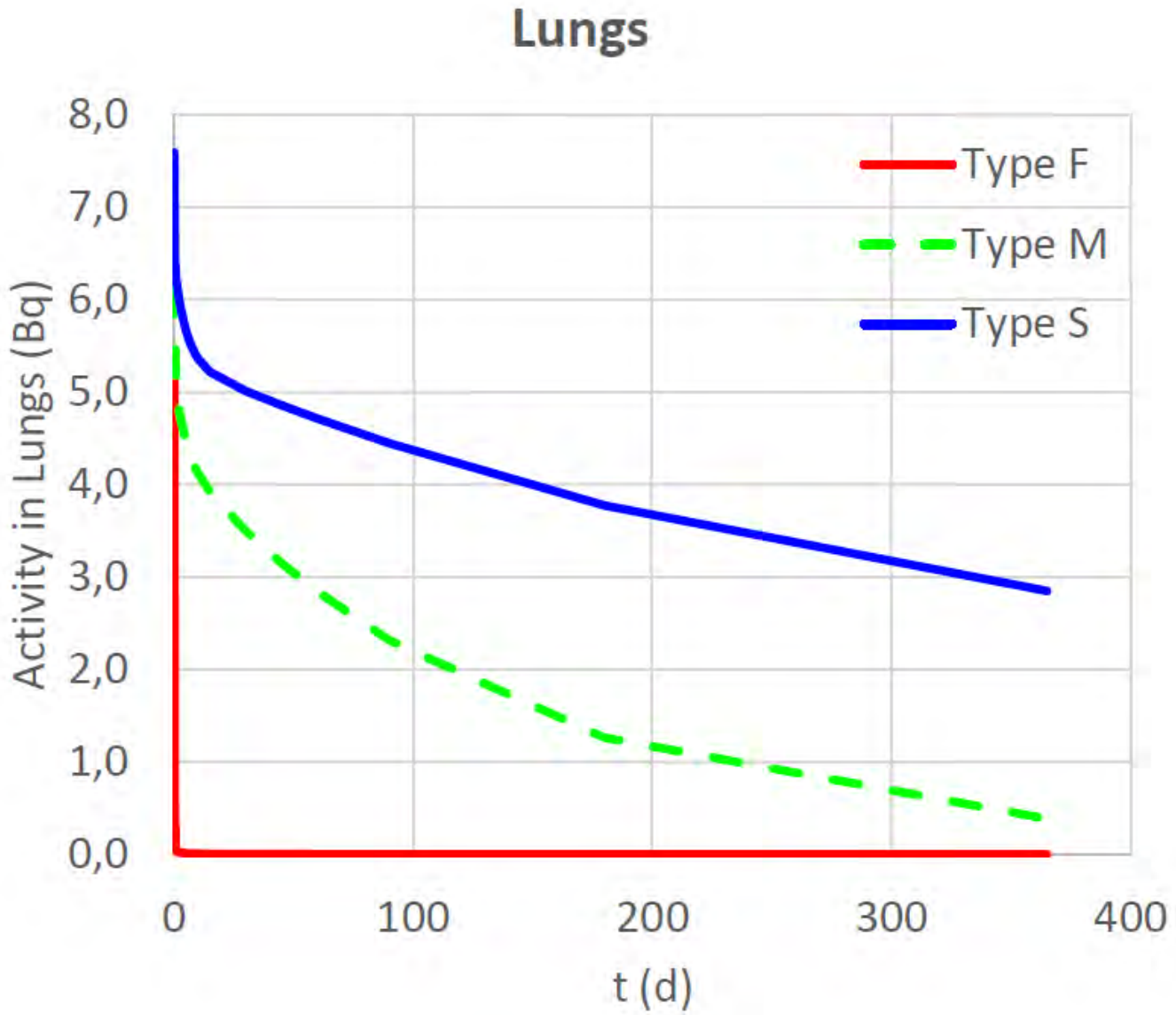
- **F, M, S** describe how fast inhaled radionuclides move from the lungs to the blood and organs.
- Faster absorption → higher systemic dose, lower lung retention.
- Slower absorption → lower systemic dose, higher lung retention → long-term localized effects.

Parameter	F (Fast)	M (Moderate)	S (Slow)
Absorption Rate	Rapid	Intermediate	Slow
Retention in Lungs	Low	Moderate	High
Biological Half-life in Lungs	Minutes to days	Days-Months	Months to years
Typical Materials	Soluble salts (e.g., CsCl)	Mixed compounds	Insoluble oxides (e.g., PuO_2)
Main Health Concern	Quick systemic uptake	Both systemic and lung dose	Long-term lung dose



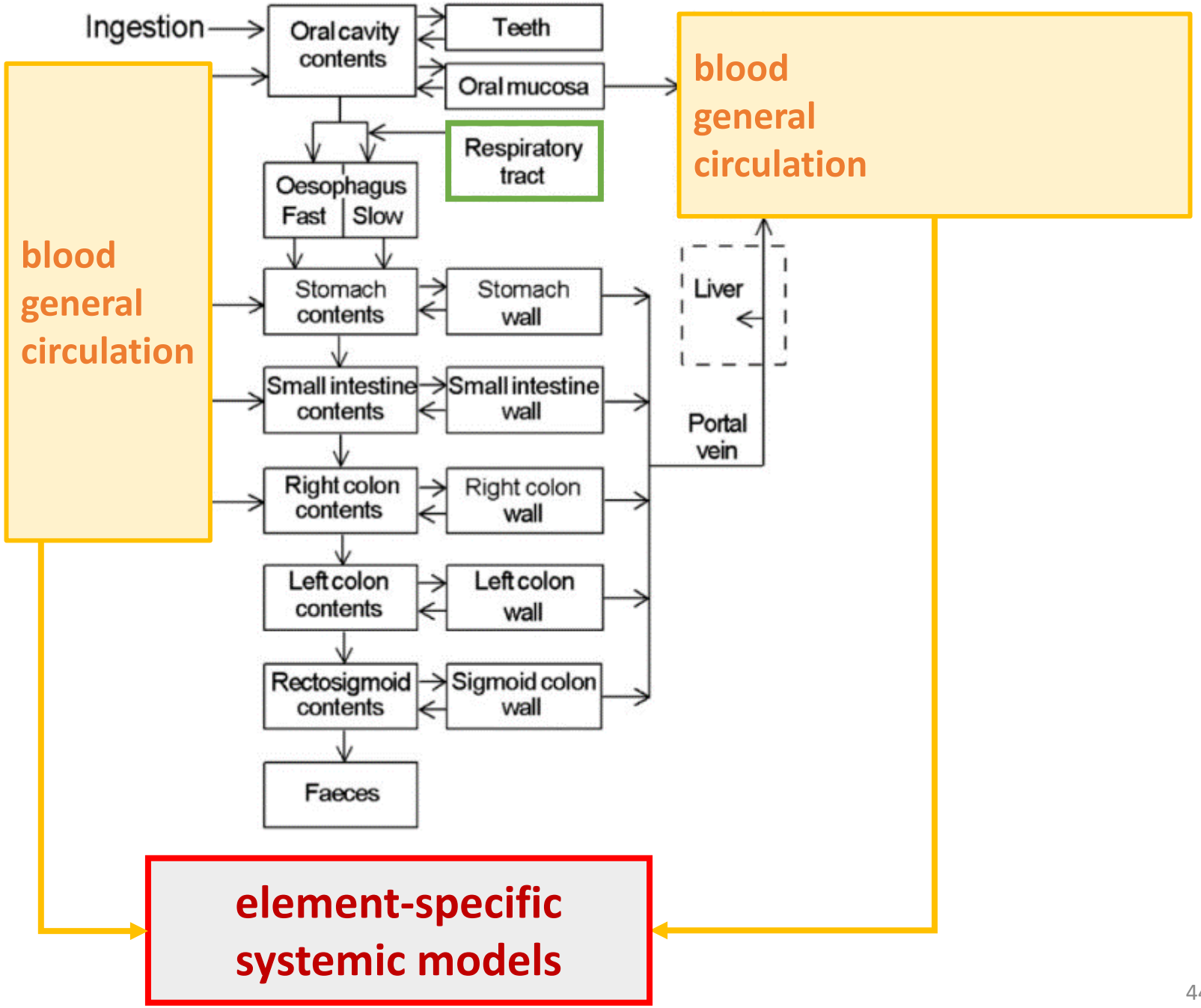
HRTM
Human Respiratory Tract Model

Inhalation of 100 Bq of U-235



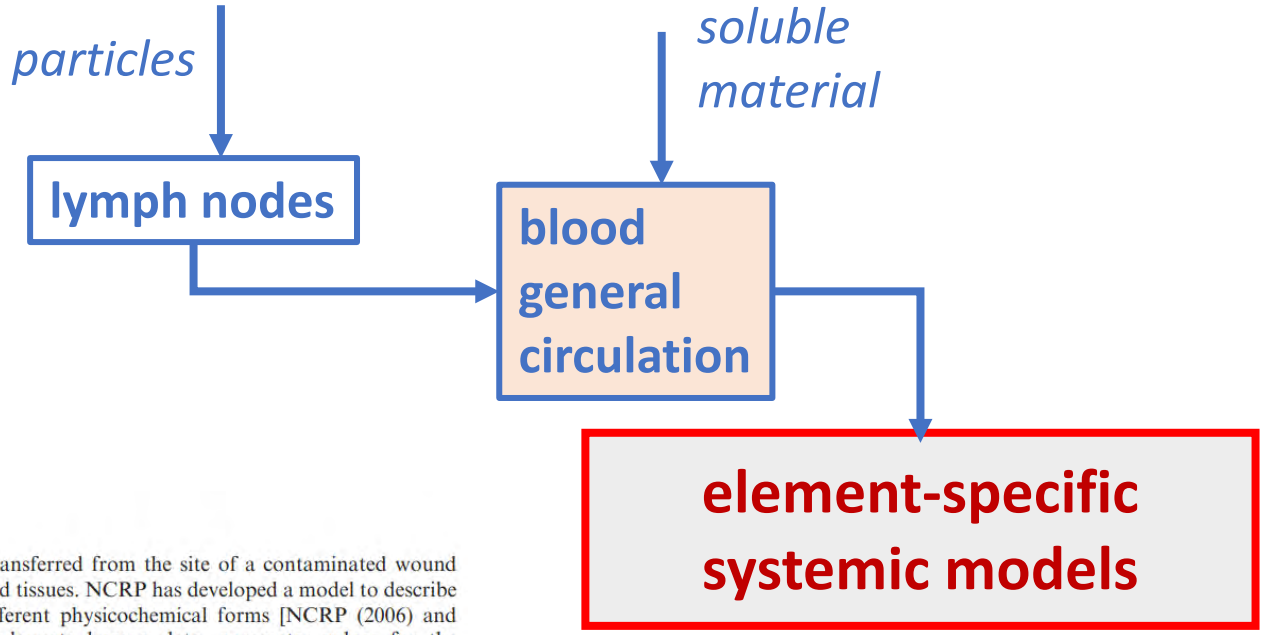
HATM

Human Alimentary Tract Model



wound is considered on a case-by-case basis (5 compartments):

1. soluble material
2. colloidal and intermediate-state material
3. particles
4. aggregates, and bound state
5. trapped particles and aggregates fragments



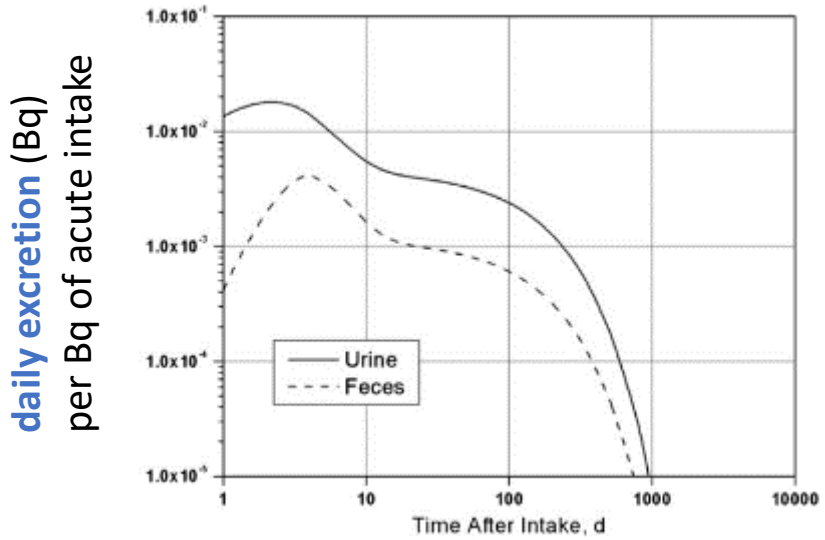
ICRP-130

3.4.2. Wounds

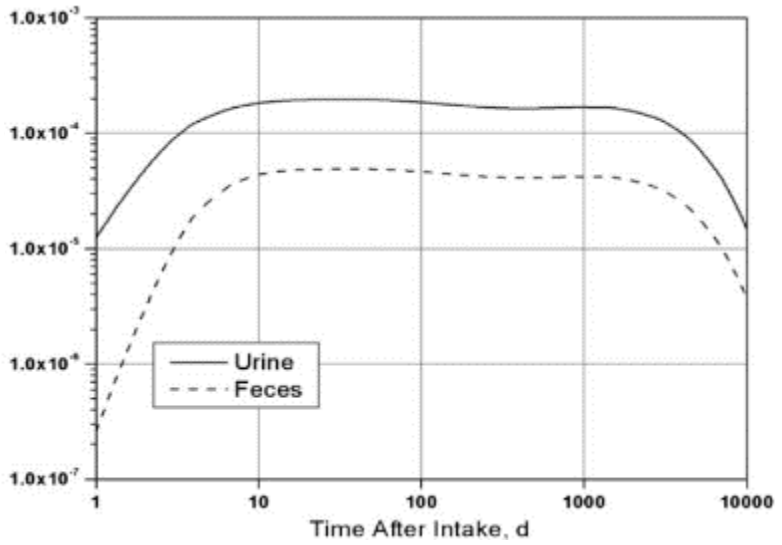
(161) Radionuclides may be transferred from the site of a contaminated wound into blood and to other organs and tissues. NCRP has developed a model to describe this transfer for materials in different physicochemical forms [NCRP (2006) and Fig. 3.7]. Due to the lack of adequate human data, parameter values for the model were based on experimental animal data. When coupled with an element-specific systemic biokinetic model, the model can be used to calculate committed equivalent doses to organs and tissues, and committed effective doses following transfer of the radionuclide to the blood and systemic circulation, as well as to predict urinary and faecal excretion.

examples

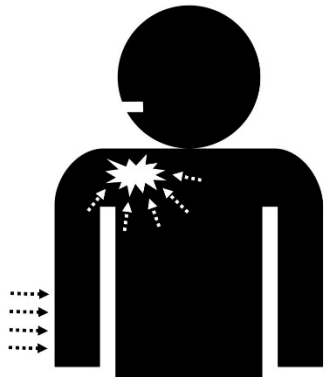
wounds with **soluble ^{137}Cs**



wounds with **particle ^{137}Cs**



ICRP-130



skin + wound

element-specific systemic models

element-specific systemic models

ICRP Publication 137

5.2. Routes of intake

5.2.1. Inhalation

(183) Detailed information on the behaviour of inhaled gases and vapours of iodine is available from studies in human volunteers. Hence, although information is also available from animal experiments, it is not reviewed here. Some information on absorption from the respiratory tract is available on inhaled particulate forms of iodine, as iodide from animal experiments, and associated with irradiated fuel fragments from human exposures.

(184) Absorption parameter values and types, and associated f_A values for gas and vapour forms of iodine are given in Table 5.2, and for particulate forms in Table 5.3. Exposures to both gas/vapour forms and particulate forms of iodine are common, and it is therefore recommended in the OIR series that 50% particulate and 50% gas/vapour should be assumed in the absence of information (ICRP, 2002a).

Example of **iodine**

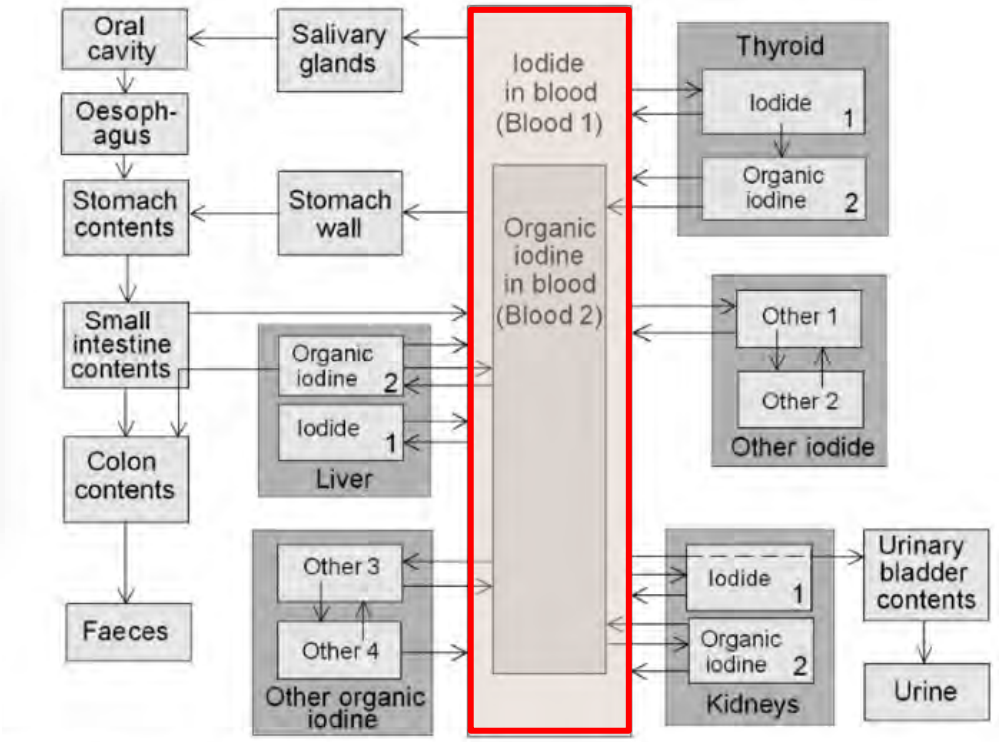


Fig. 5.2. Structure of the biokinetic model for systemic iodine used in this publication.

Pathway	Transfer coefficient (d^{-1})
Blood 1 to Thyroid 1	7.26*
Blood 1 to urinary bladder contents	11.84
Blood 1 to salivary gland	5.16
Blood 1 to stomach wall	8.60
Blood 1 to Other 1†	600
Blood 1 to Kidneys 1	25
Blood 1 to Liver 1	15
Salivary gland to oral cavity	50
Stomach wall to stomach contents	50
Thyroid 1 to Thyroid 2	95
Thyroid 1 to Blood 1	36
Thyroid 2 to Blood 2‡	0.0077
Thyroid 2 to Blood 1	0§
Other 1 to Blood 1	330
Other 1 to Other 2†	35
Other 2 to Other 1	56
Kidneys 1 to Blood 1	100
Liver 1 to Blood 1	100
Blood 2 to Other 3†	15
Other 3 to Blood 2	21
Other 3 to Other 4	1.2
Other 4† to Other 3	0.62
Other 4 to Blood 1	0.14
Blood 2 to Kidneys 2	3.6
Kidneys 2 to Blood 2	21
Kidneys 2 to Blood 1	0.14
Blood 2 to Liver 2	21
Liver 2 to Blood 2	21
Liver 2 to Blood 1	0.14
Liver 2 to right colon contents	0.08

element-specific systemic models

Example of **Nickel**

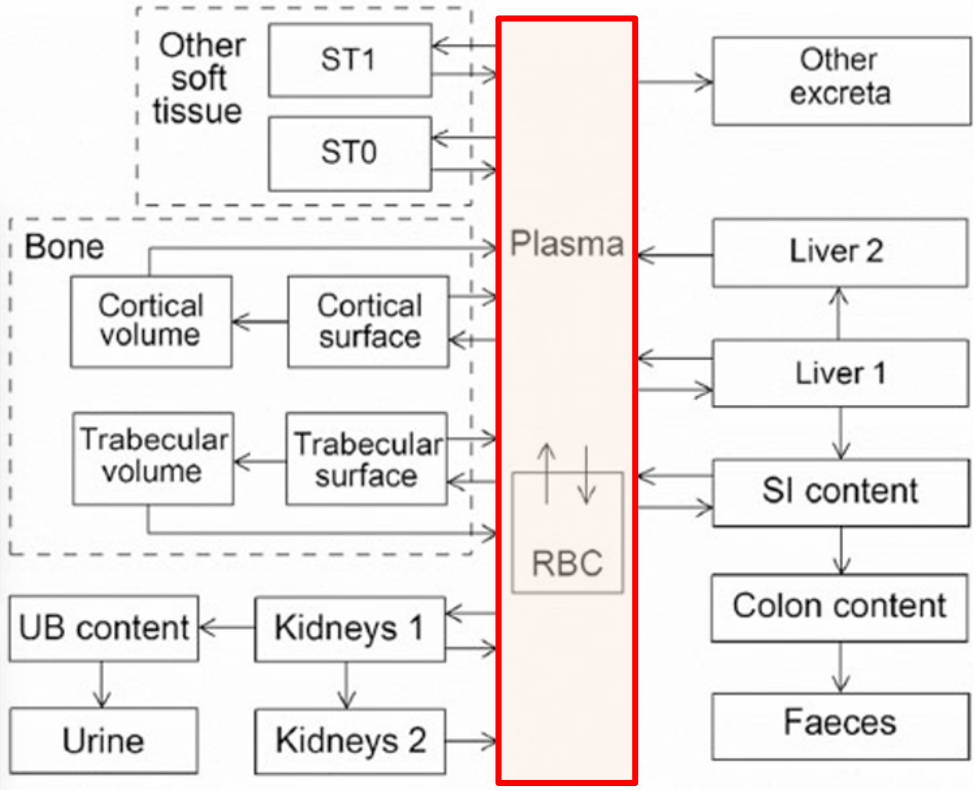


Table 15.4. Transfer coefficients in the biokinetic model for systemic nickel.

From	To	Transfer coefficient (d^{-1})
Plasma	Kidneys 1	12.7
Plasma	Small intestine content	0.18
Plasma	Liver 1	0.45
Plasma	Cortical bone surface	0.675
Plasma	Trabecular bone surface	0.675
Plasma	ST0	7.2
Plasma	ST1	1.2
Plasma	RBC	0.075
Plasma	Other excreta	0.34
RBC	Plasma	0.231
Kidneys 1	Plasma	35
Kidneys 1	Urinary bladder content	15
Kidneys 1	Kidneys 2	0.0013
Kidneys 2	Plasma	0.00173
Liver 1	Plasma	1.9
Liver 1	Liver 2	0.29
Liver 1	Small intestine content	1.46
Liver 2	Plasma	0.00173
ST0	Plasma	1.9
ST1	Plasma	0.00173
Cortical bone surface	Plasma	1.9
Cortical bone surface	Cortical bone volume	0.0192
Trabecular bone surface	Plasma	1.9
Trabecular bone surface	Trabecular bone volume	0.0192
Cortical bone volume	Plasma	0.0000821
Trabecular bone volume	Plasma	0.000493

RBC, red blood cells. ST, soft tissue. ST0 and ST1 are compartments of other soft tissues representing two phases of biological removal to blood.

15.2. Routes of intake

15.2.1. Inhalation

(228) Little information was found on the behaviour of inhaled nickel in man: National Research Council (1975) reports post-mortem measurements of nickel concentrations averaging 0.1, 0.6, and 70 μg g^{-1} lung (dry mass), respectively, in groups of normal subjects, ore miners, and 'victims of nickel carbonyl poisoning' who had also been chronically exposed to dust with a high nickel content. However, although they show some accumulation following occupational exposure, the deposits were not related to specific exposures, and the retention time in the lungs cannot be estimated. Inhalation of nickel radioisotopes is not generally of major concern, but because of the recognised chemical toxicity of nickel, numerous studies have been conducted on its behaviour following deposition in the respiratory tract (National Research Council, 1975; Sivulka, 2005; Goodman et al., 2011). Information is available from experimental studies of nickel compounds including the carbonyl, chloride, sulphate, sulphides, and oxide – mostly in rats, with a few studies in dogs or monkeys.

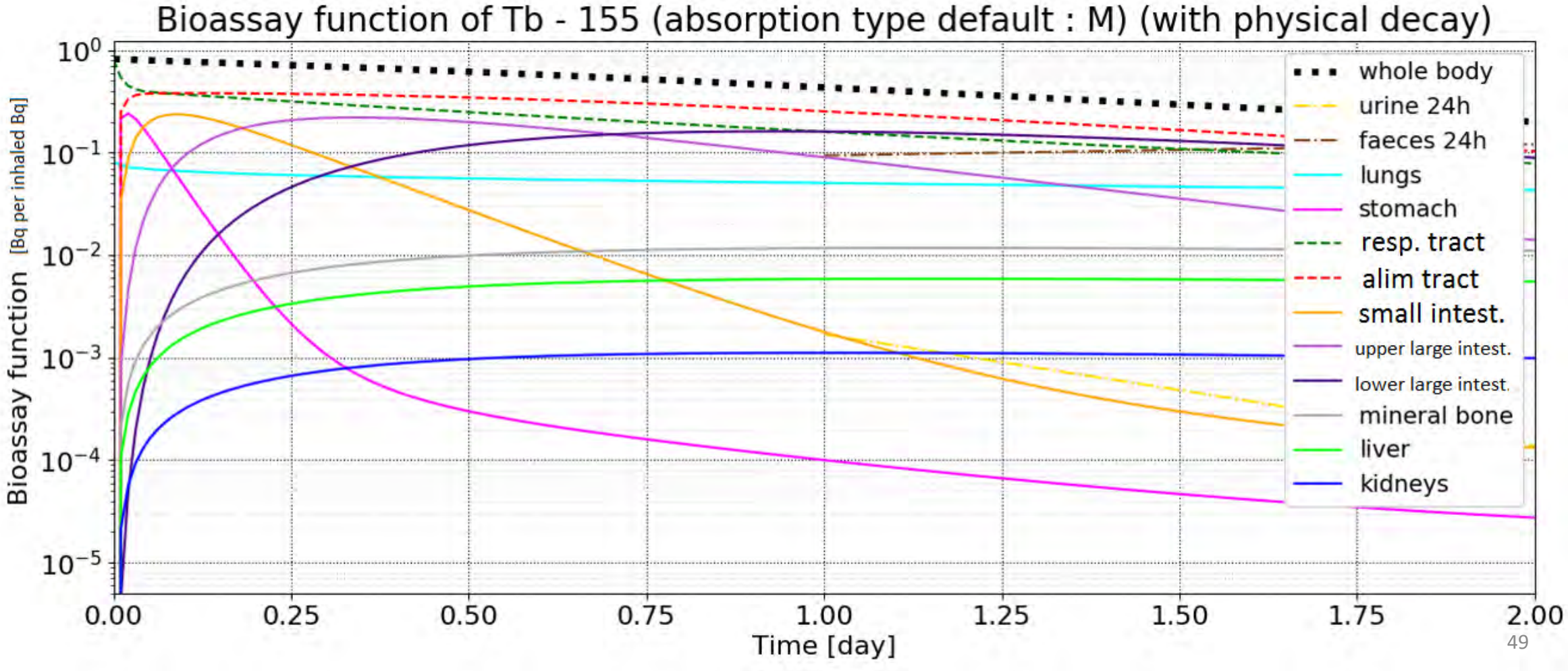
15.2.2. Ingestion

(274) Nickel absorption studies were reviewed in *Publications 30* and *67* (ICRP, 1981, 1993), by the International Agency for Research on Cancer (IARC, 1990), by the United Nations International Programme on Chemical Safety (1991), by the Nickel Producers Environmental Research Association (NiPERA, 1996), by Toxicology Excellence for Risk Assessment for the Metal Finishing Association of Southern California, the United States Environmental Protection Agency and Health Canada (TERA, 1999), by the United States Agency for Toxic Substances and Disease Registry (ATDSR, 2005a), and by the Danish Environmental Protection Agency (2008).

(275) Ingested nickel is transported through the membrane of the intestinal epithelium into the interstitial areas proximal to capillaries, although the specific mechanism is not exactly known. Specific transport processes may control the manner by which nickel is absorbed from the lumen and transported into the interstitial space. The absorption and secretion of nickel by the jejunum of rats occurs by transmembrane diffusion (Foulkes and McMullen, 1986). Refvik and Andreassen (1995) investigated the surface binding and uptake of Ni^{2+} in human kidney epithelial cells and found that calcium ionophore potentiated nickel uptake into cells, suggesting that nickel may be transported via Ca^{2+} channels. The third mechanism of nickel uptake is the phagocytosis of particulate nickel or nickel compounds (Heck and Costa, 1982; Kuehn et al., 1982).

$\tilde{A}(r_s, \tau)$ can be computed:

- By mathematically solving biokinetic models:
- By drawing time activity curves starting from measurement data



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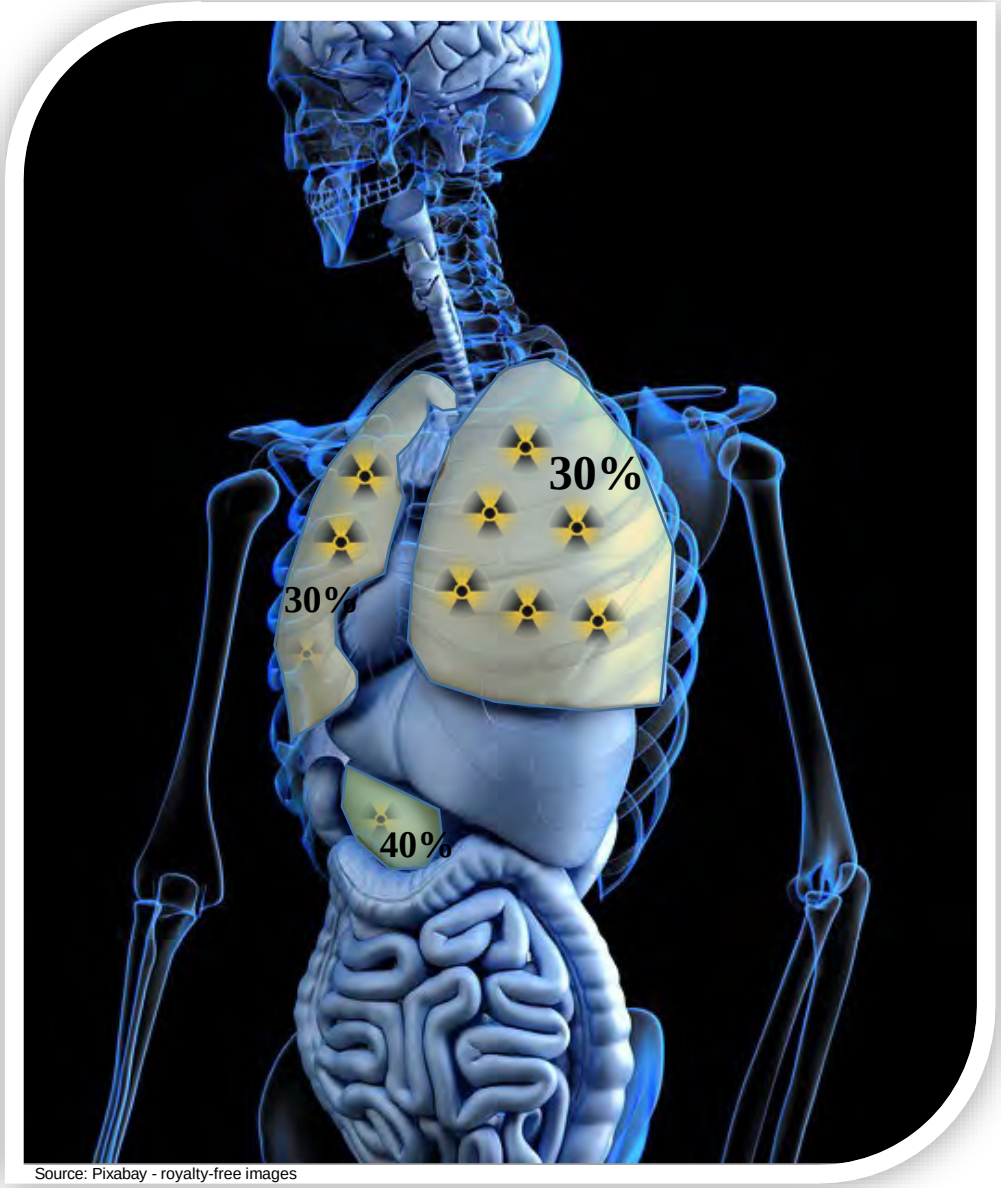
Individual monitoring in case of internal irradiation

Internal dosimetry – Switzerland



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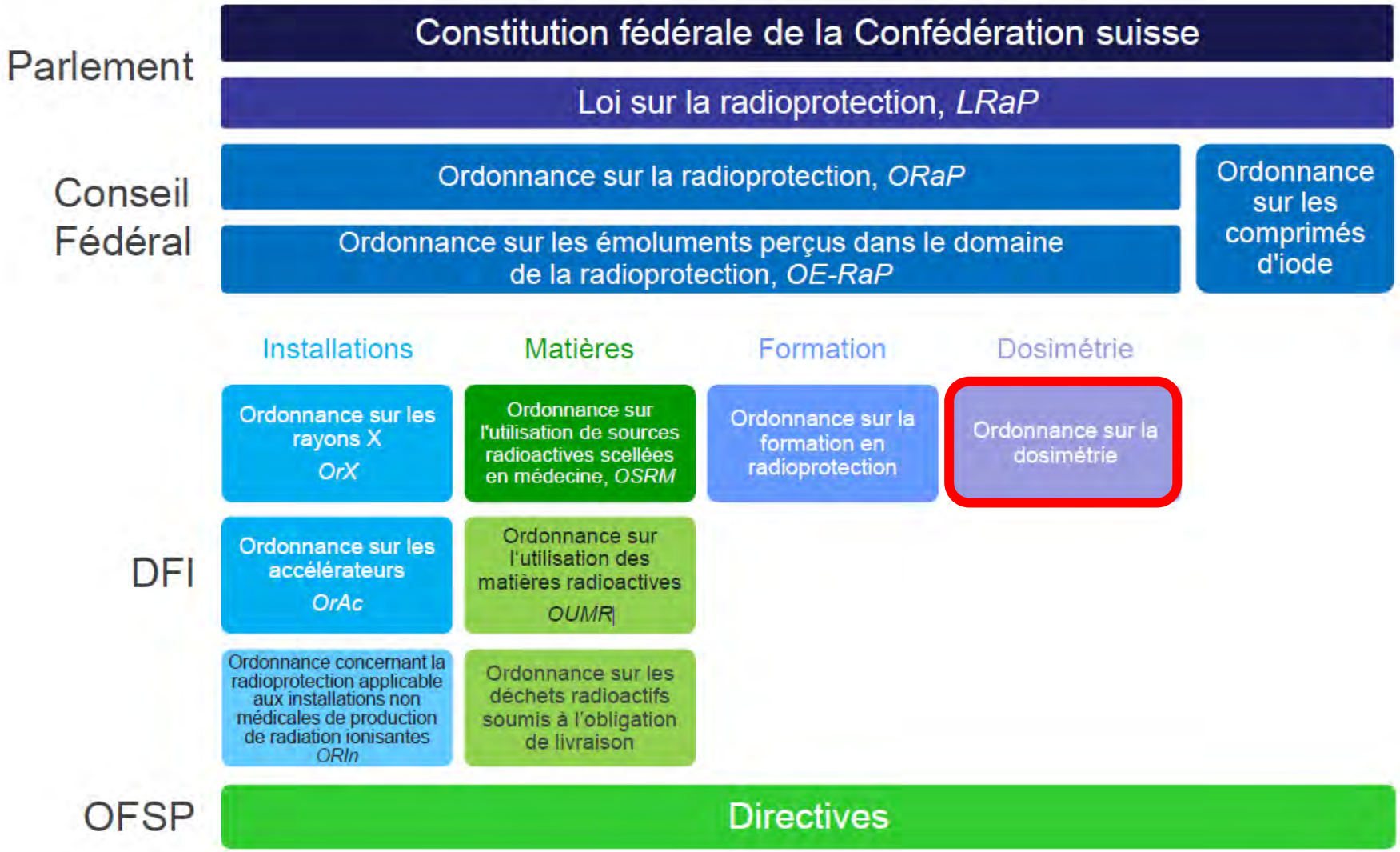
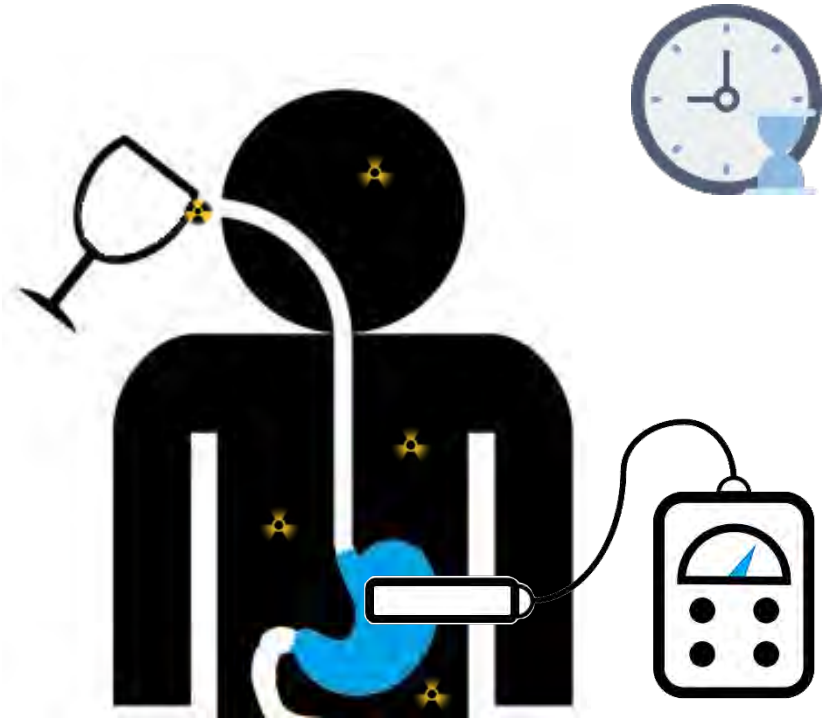
Swiss legislation framework



Determination of the effective dose

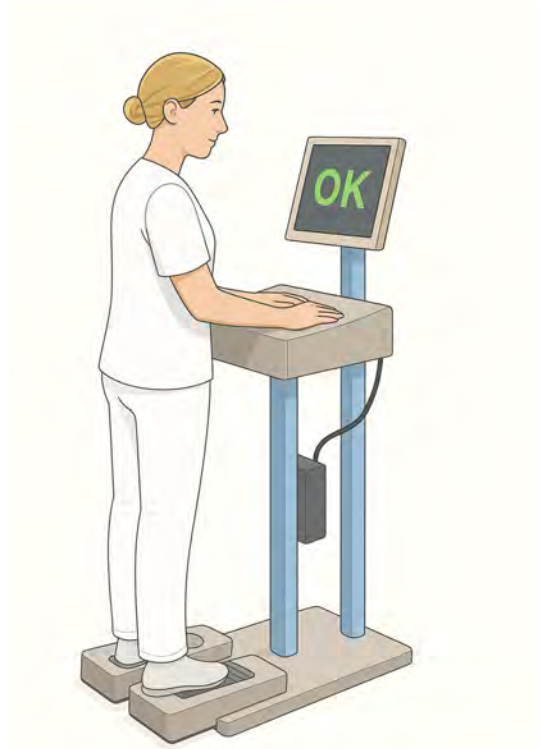


$$E_{50} = I \cdot e_{50} = \frac{M(t)}{m(t)} \cdot e_{50}$$

- E_{50} : committed effective dose (Sv)
- I : incorporated activity (Bq)
- e_{50} : dose per unit intake (Sv/Bq)
- $M(t)$: measured activity (Bq)
- $m(t)$: retention function (Bq per intaken Bq)

Determination of the effective dose

Screening measurement



Source: AI generated from a photo taken by IRA

Below given threshold?

YES

No other measurement required

NO

Incorporation measurement

(in-vivo or in-vitro)

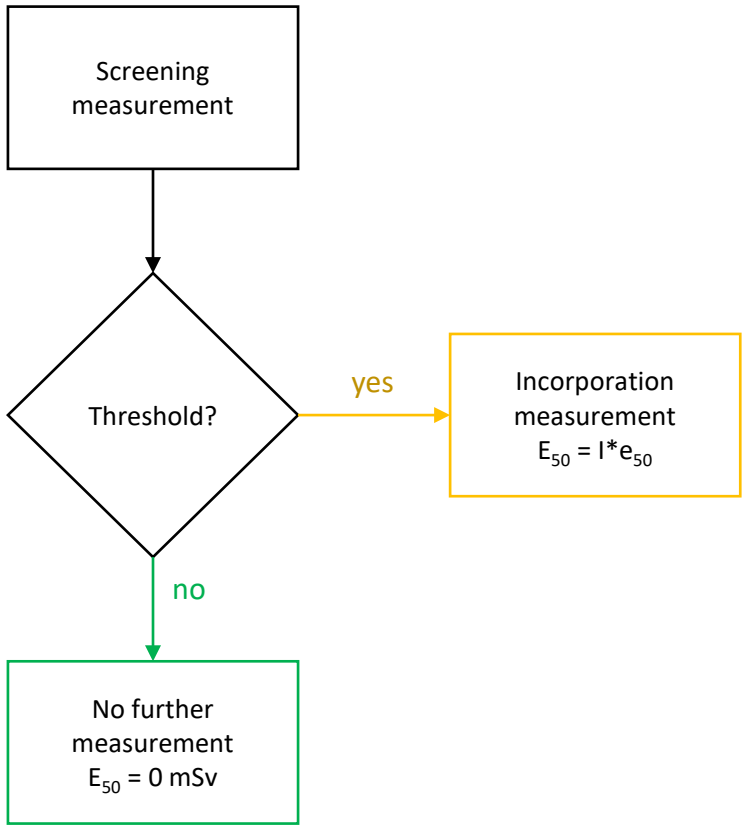
Source: AI generated from a photo taken by IRA

or

EN: *screening measurement* **FR**: *mesure de tri* **DE**: *Triagemessung* **IT**: *misurazione di sondaggio*

Determination of the effective dose

Measurement	Characteristics
Screening/triage	▪ Simple, rapid, cheap, frequent ▪ **Conducted by the worker** ▪ Qualitative measurement: yes/no ▪ No determination of E_{50}
Incorporation	▪ Only if screening measurement was positive ▪ **Conducted by an approved dosimetry service** ▪ Quantitative measurement: M(t) ▪ Determination of E_{50}



Determination of the effective dose

Source: AI generated from a photo taken by IRA

Screening measurement *in vivo:*

1. Simple
2. Rapid
3. Performed by workers themselves
4. With conventional RP instruments.

Triage monitoring, periodic measurements (not associated to a known event).

Screening intervals → not over-/under-estimate the dose by more than a factor of 3.

Screening threshold→ ideally detect incorporations leading to $E_{50} > 1$ mSv/year.

Swiss ordinance on dosimetry

26. I-125

26.1 Métabolisme

L'iode inhalé (classe d'absorption type F) est exhalé à 50 %. L'autre moitié atteint rapidement la circulation sanguine (taux de résorption $f_1 = 1$). De là environ 30 % est résorbé en 1 jour dans la glande thyroïde et 70 % est éliminé par voie urinaire. La période biologique dans la glande thyroïde est de 80 jours et la période physique est de 60 jours.

26.2 Méthodes de mesure

Mesure de tri

Mesure directe de l'activité fixée dans la glande thyroïde avec un moniteur de contamination.

Seuil de mesure: 1300 Bq

Mesure d'incorporation

Mesure à l'aide d'un moniteur thyroïdien de l'activité de I-125 M en Bq.

26.3 Intervalles de surveillance T et laps de temps t entre l'événement et la 1re mesure

T_{tri}:	30 jours	T_{mesure}:	90 jours	$t_{événement}$:	6–12 h

26. I-125

26.1 Stoffwechsel

Inhaliertes Jod (Absorptionsklasse Typ F) wird zu 50 % wieder ausgeatmet. Die andere Hälfte gelangt rasch ins Blut (Resorptionsanteil $f_1 = 1$). Davon werden 30 % im Verlauf eines Tages in die Schilddrüse eingebaut, 70 % werden über den Urin ausgeschieden. Die biologische Halbwertszeit in der Schilddrüse beträgt 80 Tage und die physikalische Halbwertszeit 60 Tage.

26.2 Messmethoden

Triagemessung

Direkte Messung der Schilddrüse mit einem Kontaminationsmonitor.

Messschwelle: 1300 Bq

Inkorporationsmessung

Messung der I-125-Aktivität M in Bq mit einem Schilddrüsenmonitor.

26.3 Überwachungsintervalle T und Zeitpunkt t der ersten Messung nach Ereignis

T_{Triage}:	30 Tage	$T_{Messung}$:	90 Tage	$t_{Ereignis}$:	6–12 h

https://www.fedlex.admin.ch/eli/cc/2017/504/fr

Swiss ordinance on dosimetry

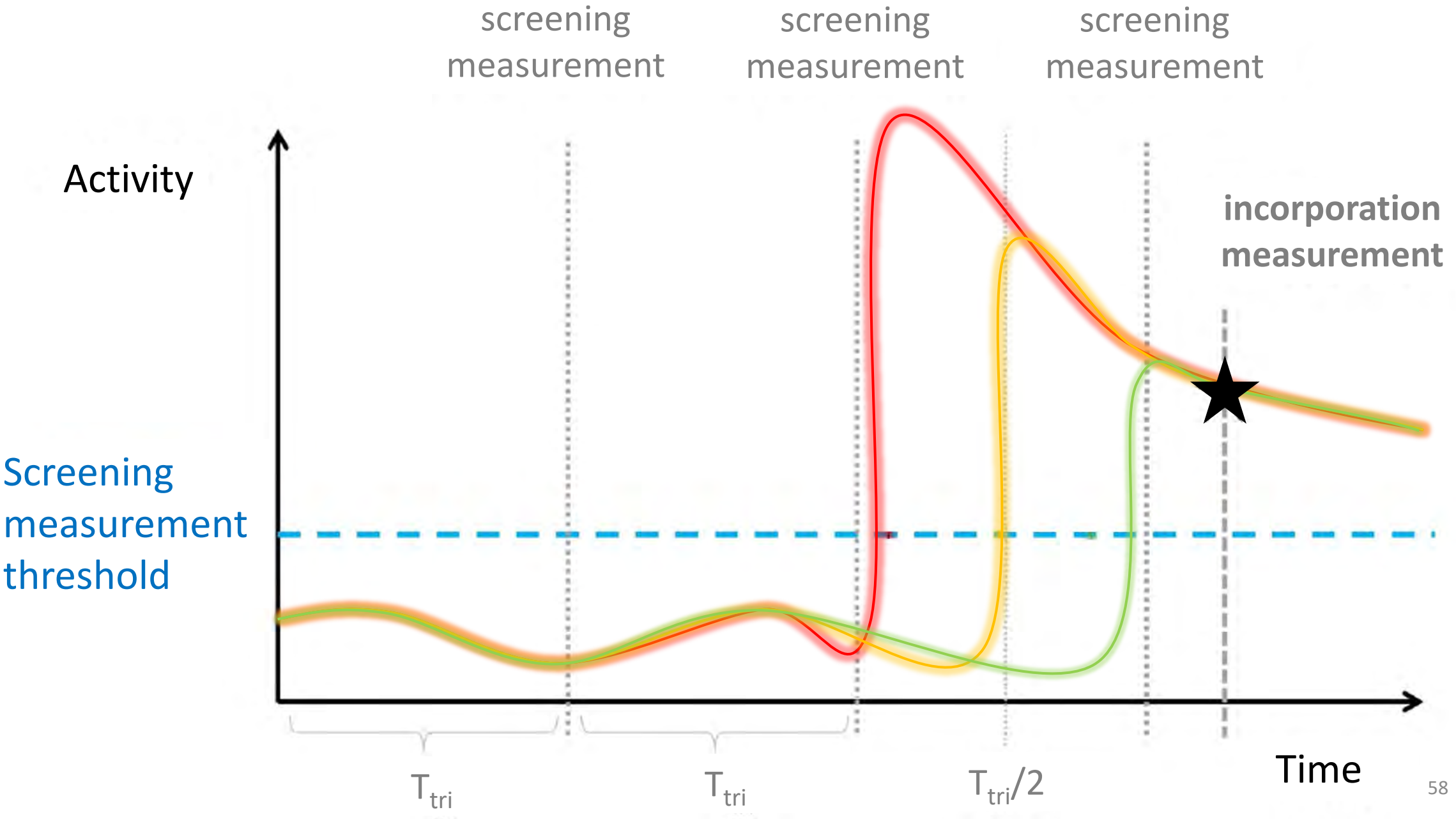
26.3 Intervalles de surveillance T et laps de temps t entre l'événement et la 1re mesure

T_{tri}:	30 jours	T_{mesure}:	90 jours	$t_{événement}$:	6–12 h

26.3 Überwachungsintervalle T und Zeitpunkt t der ersten Messung nach Ereignis

T_{Triage}:	30 Tage	$T_{Messung}$:	90 Tage	$t_{Ereignis}$:	6–12 h

- Screening measurement to be realized at the **interval defined by the ordinance** on dosimetry
- Interval duration depends on **effective half-life** of the radionuclide and **detection thresholds**
- In practice: one supposes that the incorporation took place in the **middle of the interval (T/2)** between two screening measurements
- Over/under estimation of committed effective dose by a factor of max. 3


screening measurement
screening measurement
screening measurement
Activity
incorporation measurement
Screening measurement threshold
Time
T_{tri}
T_{tri}
$T_{tri}/2$

Determination of the committed effective dose E_{50}

1. Initially incorporated activity:

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

2. Committed effective dose:

$$E_{50} = I \cdot e_{inh} = \frac{M(t)}{m(t)} \cdot e_{inh} = \underbrace{M(t)}_{meas.} \cdot \underbrace{\frac{e_{inh}}{m(t)}}_{ODosim}$$

3. For routine surveillance, where incorporation is assumed to be happened in the middle of measuring interval T:

$$E_{50} = M(t) \cdot \frac{e_{inh}}{m(T/2)}$$

Determination of the committed effective dose E_{50}

26. I-125

26.1 Métabolisme

L'iode inhalé (classe d'absorption type F) est exhalé à 50 %. L'autre moitié atteint rapidement la circulation sanguine (taux de résorption $f_1 = 1$). De là environ 30 % est résorbé en 1 jour dans la glande thyroïde et 70 % est éliminé par voie urinaire. La période biologique dans la glande thyroïde est de 80 jours et la période physique est de 60 jours.

26.2 Méthodes de mesure

Mesure de tri

Mesure directe de l'activité fixée dans la glande thyroïde avec un moniteur de contamination.

Seuil de mesure: 1300 Bq

Mesure d'incorporation

Mesure à l'aide d'un moniteur thyroïdien de l'activité de I-125 M en Bq.

26.3 Intervalles de surveillance T et laps de temps t entre l'événement et la 1re mesure

T_{tri}:	30 jours	T_{mesure}:	90 jours	$t_{événement}$:	6–12 h

26.4 Interprétation sans tenir compte d'une incorporation antérieure

$E_{50} = M \cdot \{e_{inh}/m(t)\}$

E_{50}: Dose engagée durant 50 ans en Sv
M: Valeur de mesure en Bq
e_{inh}: Facteur de dose en Sv/Bq
m(t): Fraction de rétention
t: Laps de temps entre la mesure et l'incorporation en jours.
Lorsque le moment de l'incorporation est inconnu, on pose t = T/2

Intervalle de surveillance T = 90 jours

t [jour]	$e_{inh}/m(t)$ [Sv/Bq]
1	$0{,}56\times10^{-7}$
2	$0{,}52\times10^{-7}$
3	$0{,}52\times10^{-7}$
4	$0{,}56\times10^{-7}$
5	$0{,}56\times10^{-7}$
6	$0{,}56\times10^{-7}$
7	$0{,}56\times10^{-7}$
15	$0{,}66\times10^{-7}$
30	$0{,}90\times10^{-7}$
45	$1{,}2\times10^{-7}$
60	$1{,}6\times10^{-7}$
90	$2{,}6\times10^{-7}$
135	$6{,}1\times10^{-7}$

26. I-125

26.1 Stoffwechsel

Inhaliertes Jod (Absorptionsklasse Typ F) wird zu 50 % wieder ausgeatmet. Die andere Hälfte gelangt rasch ins Blut (Resorptionsanteil $f_1 = 1$). Davon werden 30 % im Verlauf eines Tages in die Schilddrüse eingebaut, 70 % werden über den Urin ausgeschieden. Die biologische Halbwertszeit in der Schilddrüse beträgt 80 Tage und die physikalische Halbwertszeit 60 Tage.

26.2 Messmethoden

Triagemessung

Direkte Messung der Schilddrüse mit einem Kontaminationsmonitor.

Messschwelle: 1300 Bq

Inkorporationsmessung

Messung der I-125-Aktivität M in Bq mit einem Schilddrüsenmonitor.

26.3 Überwachungsintervalle T und Zeitpunkt t der ersten Messung nach Ereignis

T_{Triage}:	30 Tage	$T_{Messung}$:	90 Tage	$t_{Ereignis}$:	6–12 h

26.4 Interpretation ohne Berücksichtigung einer früheren Inkorporation

$E_{50} = M \cdot \{e_{inh}/m(t)\}$

E_{50}: 50-Jahre-Folgedosis in Sv
M: Messwert in Bq
e_{inh}: Dosisfaktor in Sv/Bq
m(t): Retentionsanteil
t: Tage zwischen Messung und Inkorporation.
Bei unbekanntem Inkorporationszeitpunkt ist t = T/2

Überwachungsintervall T = 90 Tage

t [Tage]	$e_{inh}/m(t)$ [Sv/Bq]
1	$0{,}56\times10^{-7}$
2	$0{,}52\times10^{-7}$
3	$0{,}52\times10^{-7}$
4	$0{,}56\times10^{-7}$
5	$0{,}56\times10^{-7}$
6	$0{,}56\times10^{-7}$
7	$0{,}56\times10^{-7}$
15	$0{,}66\times10^{-7}$
30	$0{,}90\times10^{-7}$
45	$1{,}2\times10^{-7}$
60	$1{,}6\times10^{-7}$
90	$2{,}6\times10^{-7}$
135	$6{,}1\times10^{-7}$

Determination of the committed effective dose E_{50}

ordonnance sur la dosimétrie individuelle

γ emitter

17. I-131

1. Métabolisme

L'iode inhalé (classe d'absorption type F) est exhalé à 50 %. L'autre moitié atteint rapidement la circulation sanguine (taux de résorption $f_1 = 1$). De là environ 30 % est résorbé en 1 jour dans la glande thyroïde et 70 % est éliminé par voie urinaire. La période biologique dans la glande thyroïde est de 80 jours. La durée de séjour de l'iode-131 dans la thyroïde est ainsi déterminée par sa période physique de 8 jours.

2. Méthodes de mesure

Mesure de tri

Mesure directe de l'activité fixée dans la glande thyroïde avec un moniteur de contamination.

Seuil de mesure: 2000 Bq

Mesure d'incorporation

Mesure à l'aide d'un moniteur thyroïdien de l'activité de I-131 M en Bq.

3. Intervalles de surveillance T et laps de temps entre l'événement et la 1re mesure

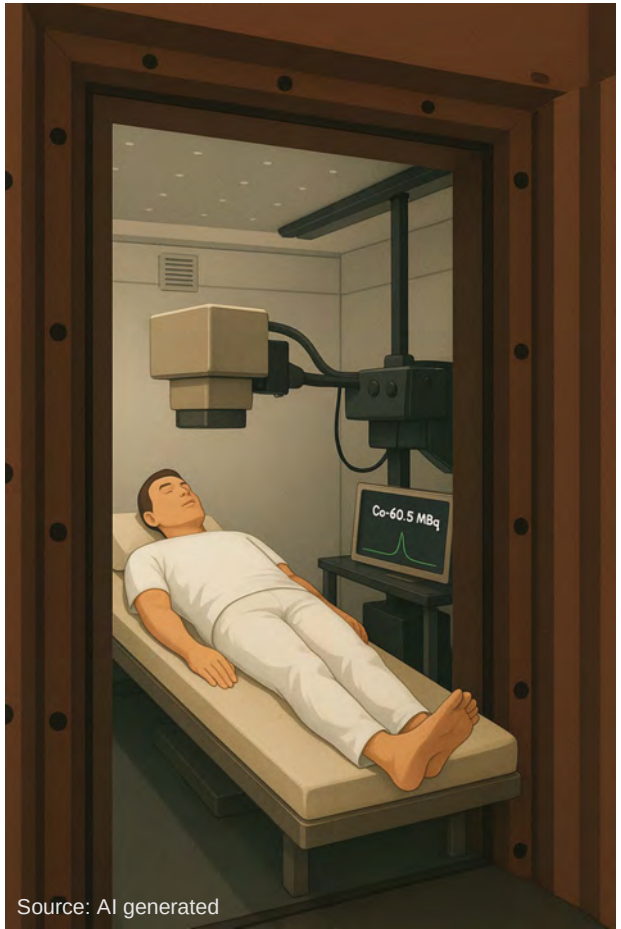
T_{tri}:	7 jours	T_{mesure}:	30 jours	$t_{événement}$:	6 – 12 h

Source: AI generated from a photo taken by IRA

Incorporation measurement

The measurement with the whole-body counter indicate an activity of 5 MBq of Cobalt-60.

Estimate the committed effective dose by assuming that the intake occurred three months earlier.



Source: AI generated

14. Co-60

1. Métabolisme

Le cobalt inhalé (classe d'absorption type S) est éliminé à 90 % en quelques heures à quelques jours via le nez, le tube digestif (taux de résorption f_1 = 0,05) et l'urine. Seulement 10 % séjourne plus longtemps dans le corps, principalement dans les poumons. Dans le cas du cobalt-60, la durée de séjour de cette fraction est déterminée principalement, à cause de la longue période physique, par les mécanismes de clearance pulmonaire.

2. Méthodes de mesure

Mesure de tri

Mesure directe du rayonnement gamma à l'aide d'un instrument de mesure de l'activité thoracique.

Seuil de mesure: 1200 Bq

Mesure d'incorporation

Mesure à l'aide d'un anthropogammamètre de l'activité en Co-60 M en Bq.

3. Intervalles de surveillance T et laps de temps t entre l'événement et la 1re mesure

T_{tri}:	180 jours	T_{mesure}:	180 jours	$t_{événement}$:	immédiatement

4. Interprétation sans tenir compte d'une incorporation antérieure

$E_{50} = M \cdot \{e_{inh}/m(t)\}$

E_{50}: Dose engagée durant 50 ans en Sv
M: Valeur de mesure en Bq
e_{inh}: Facteur de dose en Sv/Bq
m(t): Fraction de rétention
t: Laps de temps entre la mesure et l'incorporation en jours. Lorsque le moment de l'incorporation est inconnu, on pose t = T/2

Intervalle de surveillance T = 180 jours

t [jour]	$e_{inh}/m(t)$ [Sv/Bq]
1	$0{,}35\times10^{-7}$
2	$0{,}68\times10^{-7}$
3	$1{,}2\times10^{-7}$
4	$1{,}7\times10^{-7}$
5	$2{,}1\times10^{-7}$
6	$2{,}3\times10^{-7}$
7	$2{,}5\times10^{-7}$
15	$2{,}8\times10^{-7}$
30	$3{,}1\times10^{-7}$
60	$3{,}8\times10^{-7}$
90	$4{,}3\times10^{-7}$
180	$5{,}3\times10^{-7}$
270	$6{,}1\times10^{-7}$

5. Correction pour une incorporation antérieure

Intervalle de surveillance T = 180 jours: $E_{50} = M \cdot 4{,}3 \cdot 10^{-7} - E^{g}_{50} \cdot 0{,}70$

The measurement with the whole-body counter indicate an activity of 5 MBq of Cobalt-60.

Estimate the committed effective dose by assuming that the intake occurred three months earlier.

$$E_{50} = M \cdot \{e_{inh}/m(t)\}$$

$$e_{inh}/m(t) = 4.3 \times 10^{-7}$$

E_{50} = 2.15 Sv

Is that a high dose?
What effects can you expect?

14. Co-60

1. Métabolisme

Le cobalt inhalé (classe d'absorption type S) est éliminé à 90 % en quelques heures à quelques jours via le nez, le tube digestif (taux de résorption f_1 = 0,05) et l'urine. Seulement 10 % séjourne plus longtemps dans le corps, principalement dans les poumons. Dans le cas du cobalt-60, la durée de séjour de cette fraction est déterminée principalement, à cause de la longue période physique, par les mécanismes de clearance pulmonaire.

2. Méthodes de mesure

Mesure de tri

Mesure directe du rayonnement gamma à l'aide d'un instrument de mesure de l'activité thoracique.

Seuil de mesure: 1200 Bq

Mesure d'incorporation

Mesure à l'aide d'un anthropogammamètre de l'activité en Co-60 M en Bq.

3. Intervalles de surveillance T et laps de temps t entre l'événement et la 1re mesure

T_{tri}:	180 jours	T_{mesure}:	180 jours	$t_{événement}$:	immédiatement

4. Interprétation sans tenir compte d'une incorporation antérieure

$E_{50} = M \cdot \{e_{inh}/m(t)\}$

E_{50}: Dose engagée durant 50 ans en Sv
M: Valeur de mesure en Bq
e_{inh}: Facteur de dose en Sv/Bq
m(t): Fraction de rétention
t: Laps de temps entre la mesure et l'incorporation en jours. Lorsque le moment de l'incorporation est inconnu, on pose t = T/2

Intervalle de surveillance T = 180 jours

t [jour]	$e_{inh}/m(t)$ [Sv/Bq]
1	$0{,}35\times10^{-7}$
2	$0{,}68\times10^{-7}$
3	$1{,}2\times10^{-7}$
4	$1{,}7\times10^{-7}$
5	$2{,}1\times10^{-7}$
6	$2{,}3\times10^{-7}$
7	$2{,}5\times10^{-7}$
15	$2{,}8\times10^{-7}$
30	$3{,}1\times10^{-7}$
60	$3{,}8\times10^{-7}$
90	$4{,}3\times10^{-7}$
180	$5{,}3\times10^{-7}$
270	$6{,}1\times10^{-7}$

5. Correction pour une incorporation antérieure

Intervalle de surveillance T = 180 jours: $E_{50} = M \cdot 4{,}3 \cdot 10^{-7} - E_{50}^{a} \cdot 0{,}70$

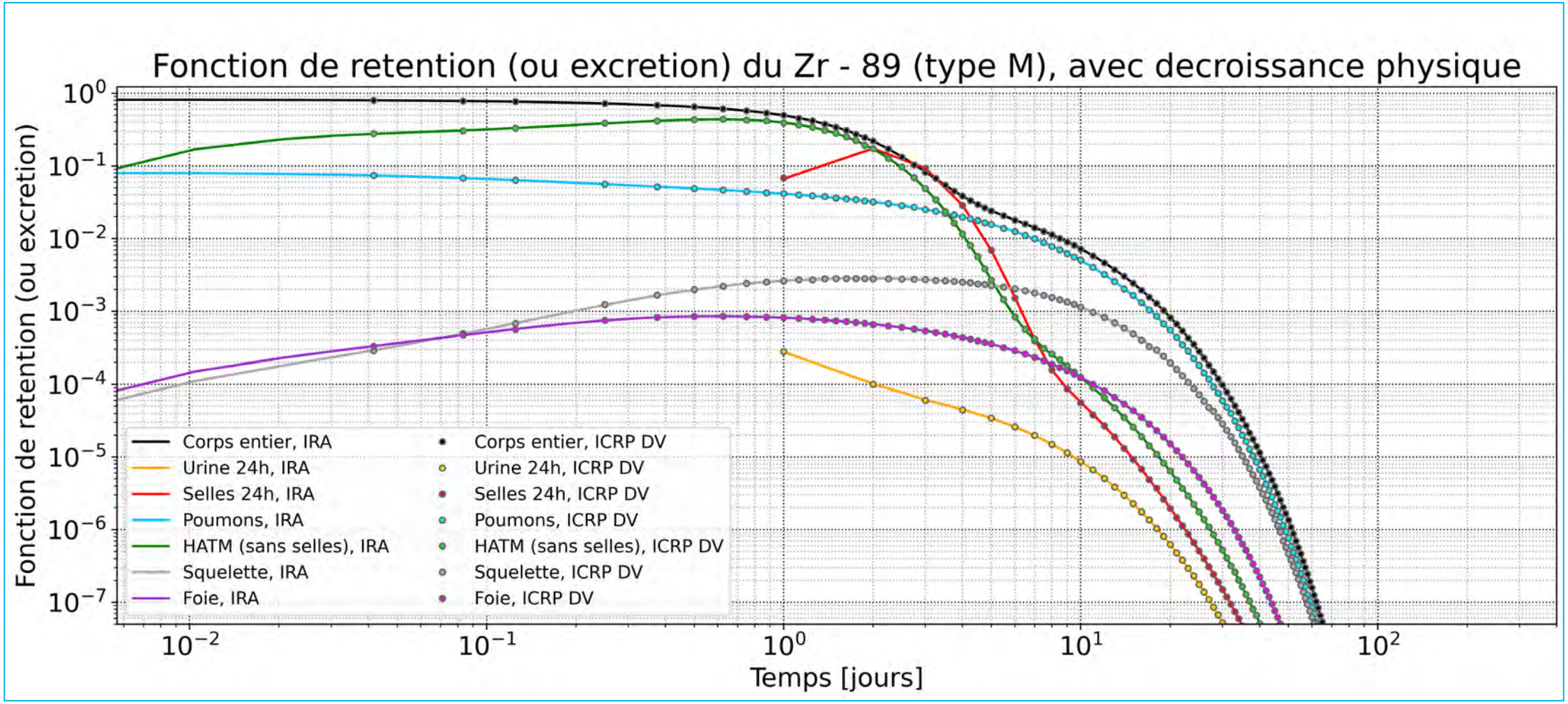
You are responsible for a lab that is labelling Zr-89 for nuclear medicine applications (visualize tumors by detecting the radiations emitted from the patient body).
The labelling process involves evaporation, the main risk of incorporation is given by accidental inhalation of the radionuclide (volatile).

A worker suspects an incorporation took place 1 week ago.

Currently, no indication is given in the Swiss Dosimetry Ordinance to monitor this radionuclide.

How would you proceed?

- in vivo?
- in vitro?
- how would you perform the measurement?



Nucléide	Période	Mode de désintégration / rayonnement	Grandeurs d'appréciation					Limite de libération		Limite d'autorisation	Valeurs directrices		
			e_{inh} Sv/Bq	e_{ing} Sv/Bq	h_{10} (mSv/h)/ GBq à 1 m de distance	$h_{0,07}$ (mSv/h)/ GBq à 10 cm de distance	$h_{c,0,07}$ (mSv/h)/ (kBq/cm²)	LL Bq/g		LA Bq	CA Bq/m³	CS Bq/cm²	Nucléide de filiation instable
1	2	3	4	5	6	7	8	9		10	11	12	13
Zr-88	83.4 d	ec / ph	4.10E-09	3.30E-10	0.076	50	0.1	1.E+00		1.00E+06	2.00E+03	100	→ Y-88 [6]
Zr-89	78.41 h	ec, β^+ / ph	7.50E-10	7.90E-10	0.182	400	0.5	1.E+01	[1]	7.00E+06	1.00E+04	10	
Zr-93	1.53 E6 a	β^-	2.90E-08	2.80E-10	<0.001	<1	<0.1	1.E+01		2.00E+05	3.00E+02	1000	→ Nb-93m

You are responsible for a lab that is labelling Zr-89 for nuclear medicine applications (visualize tumors by detecting the radiations emitted from the patient body).
The labelling process involves evaporation, the main risk of incorporation is given by accidental inhalation of the radionuclide (volatile).

A worker suspects an incorporation took place 1 week ago.

Currently, no indication is given in the Swiss Dosimetry Ordinance to monitor this radionuclide.

How would you proceed?

- in vivo
- Measurement at the level of the lungs → 50 kBq are measured today
- Roughly 1% of the activity remains
- Initially intake activity = 5 MBq
- $E_{50} = I_{inh} \cdot e_{inh} = 3.75\ mSv$

Is that a high dose?
What effects can you expect?

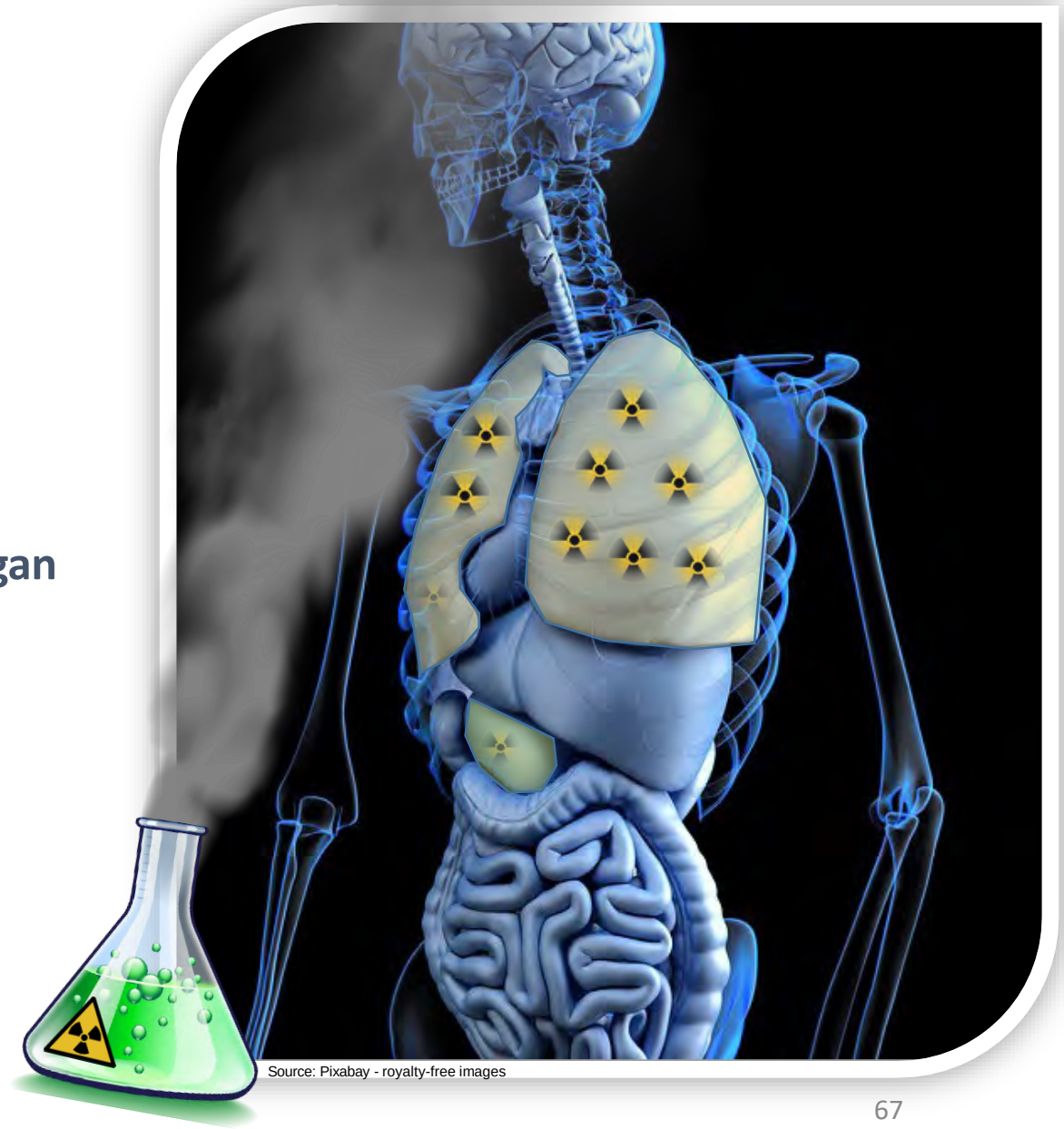
Objectives

Describe how the **incorporation** of a radioactive substance delivers a **dose** to a person

Explain how the **effective dose** delivered by a **radionuclide intake** can be estimated; in particular describe:

- what is a **compartmental model**
- how it is possible to **compute the dose** to a **tissue/organ**

Compute the **effective dose** received by a person when the **intake is known**



Source: Pixabay - royalty-free images