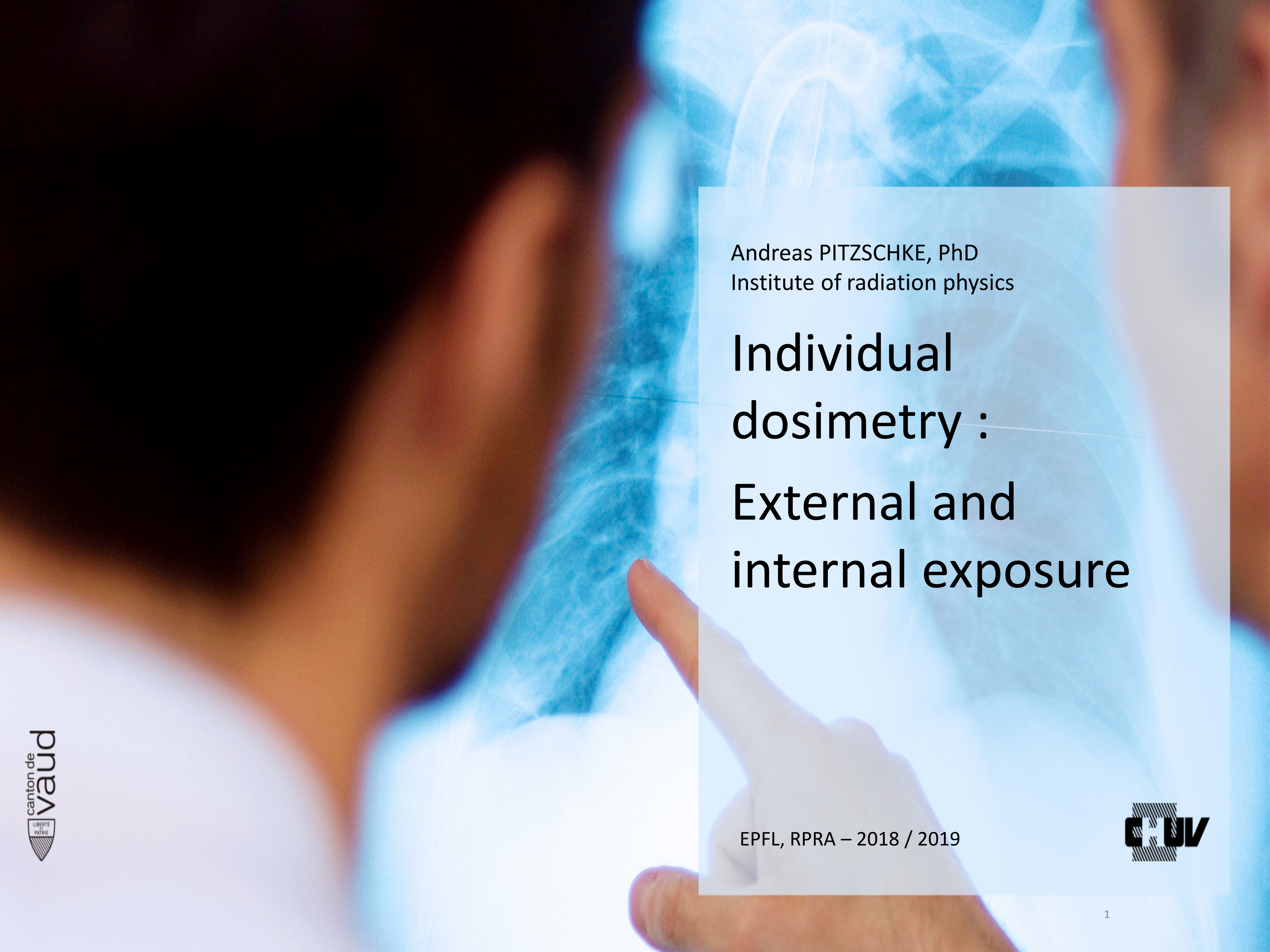

Andreas PITZSCHKE, PhD
Institute of radiation physics

Individual dosimetry : External and internal exposure

EPFL, RPRA – 2018 / 2019

Reminder

D	Absorbed dose
H	Equivalent dose
E	Effective dose
w_R	Radiation weighting factor
w_T	Organ/tissue weighting factor (expression of the associated radiological risk)

$$H = \sum_{R} W_R \, . \, D_R$$

$$E = \sum_{T} W_T \, . \, H_T$$

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Course goals

- Explain the methods of personal dosimetry.
- Calculate doses delivered in an intake situation
- Design dosimetric monitoring for a given situation

Outline

I. Role of personal monitoring in radiation protection

II. Personal monitoring of external exposure

   1. Monitored quantities
   2. Measurement techniques

III. Personal monitoring for external contamination

IV. Personal monitoring for internal contamination

   1. Models for incorporation and dose evaluation
   2. Dose evaluation linked to an intake

Outline

I. **Role of personal monitoring in radiation protection**

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Role of personal monitoring in radiation protection

Personal monitoring:

Used for determining an accumulated dose for an individual.

Radiological Protection Ordinance:

https://www.admin.ch/opc/en/classified-compilation/20163016/index.html

> **814.501**
>
> *English is not an official language of the Swiss Confederation. This translation is provided for information purposes only and has no legal force.*
>
> **Radiological Protection Ordinance**
> **(RPO)**
>
> of 26 April 2017 (Status as of 5 June 2018)
>
> ---
>
> *The Swiss Federal Council,*
>
> based on the Radiological Protection Act of 22 March 1991[1] (RPA)
> and on Article 83 of the Federal Act of 20 March 1981[2] on Accident Insurance,
>
> *ordains:*

Ensure that the individual dose remains below the limits

Role of personal monitoring in radiation protection

– Art. 56 Dose limits

[1] For occupationally exposed persons, the effective dose must not exceed the limit of 20 mSv per calendar year.

E

[2] For such persons, by way of exception and with the approval of the supervisory authority, the limit for the effective dose may be up to 50 mSv per calendar year, provided that the cumulative dose over five consecutive years, including the current year, is less than 100 mSv.

[3] For such persons, the equivalent dose must not exceed the following limits:

H_T

a. for the lens of the eye: 20 mSv per calendar year or a cumulative dose of 100 mSv over five consecutive calendar years, subject to a maximum dose of 50 mSv in a single calendar year;

b. for the skin, hands and feet: 500 mSv per calendar year.

[4] Occupationally exposed persons from abroad must, in Switzerland, only accumulate an effective dose of 20 mSv per calendar year, allowing for the dose already received in the current calendar year.

Role of personal monitoring in radiation protection

Theory	Practice
Protection quantities: E, Effective dose $H_{T,}$ Equivalent dose to the organ	Operational quantities
Not measurable	**Measurable**

Role of personal monitoring in radiation protection

External exposure

	Personal dosimetry
Effective dose monitoring (E)	Personal deep dose : **$H_p(10)$ ⇔ H_p**
Skin dose or hands dose monitoring (H_T)	Personal surface dose : **$H_p(0.07)$ ⇔ H_s** Dose equivalent to the extremities : **H_{Ext}**

Internal exposure

	Personal dosimetry
Effective dose monitoring (E)	Committed effective dose : **E_{50}**

E_{50} = Sum of effective doses received over the 50 years which follow an intake

Role of personal monitoring in radiation protection

Total effective dose :

$E = E_{external} + E_{internal}$

Total equivalent dose to the skin :

H_{skin}

As a first approximation :

$E_{external} = H_p(10)$

$E_{internal} = E_{50}$

As a first approximation :

$H_{skin} = H_p(0.07)$

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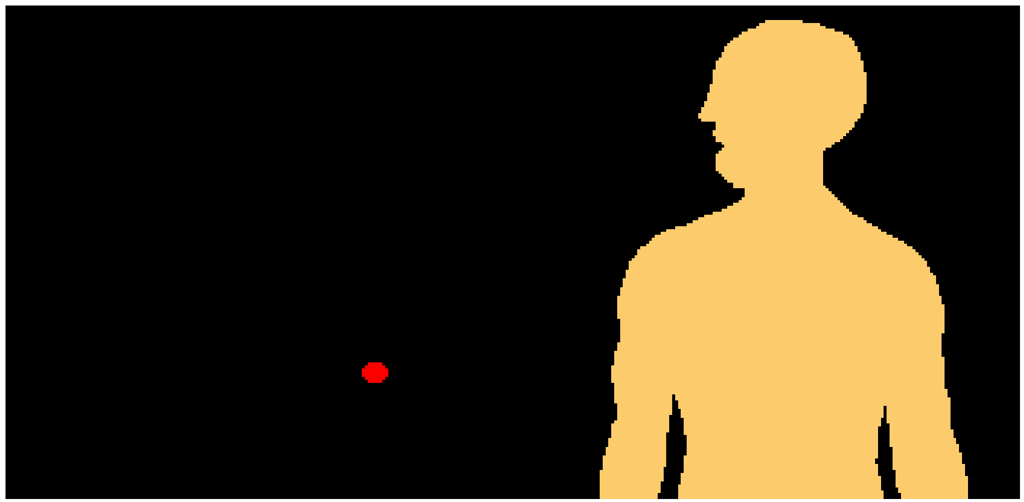
Personal monitoring of external exposure



Personal monitoring of external exposure

Monitored quantities:

- Personal deep dose, **$H_p(10)$ ou H_p**

  Dose equivalent at 10 mm depth in soft tissue (at the thorax)

- Personal surface dose, **$H_p(0.07)$ ou H_s**

  Dose equivalent at 0.07 mm depth in soft tissue (at the thorax)

- Dose equivalent to the extremities, **H_{ext}**

  Dose equivalent at 0.07 mm depth in soft tissue (hands, feet)

Personal monitoring of external exposure

Measurement techniques:

Passive individual / badge dosemeter

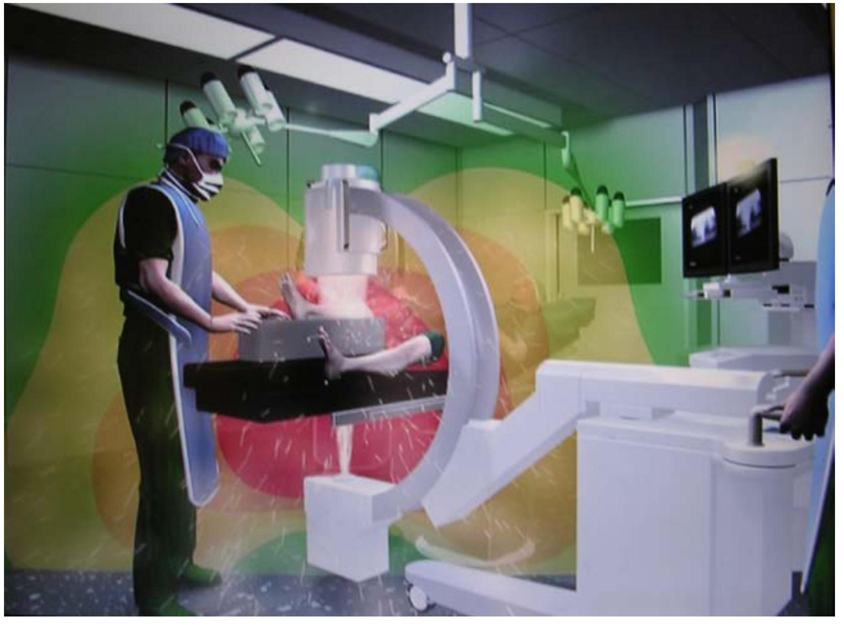
- **$H_p(10)$** and **$H_p(0.07)$**
- β, γ and X-ray radiation
- Monthly measurement (immediate reading of the dosemeter is possible)

Personal monitoring of external exposure

Measurement techniques:

Passive individual / badge dosemeter

In the medical field



- 1 dosimètre : Worn under the apron

OR

- 2 dosimètres : Worn over and under the apron

$$H_p = H_{p.under} + a \cdot H_{p.over}$$

$$H_s = H_{s.under} + H_{s.over}$$

- With :
  - a = 0.1 if the apron does not protect the thyroid gland
  - a= 0.05 if the apron protects the thyroid gland

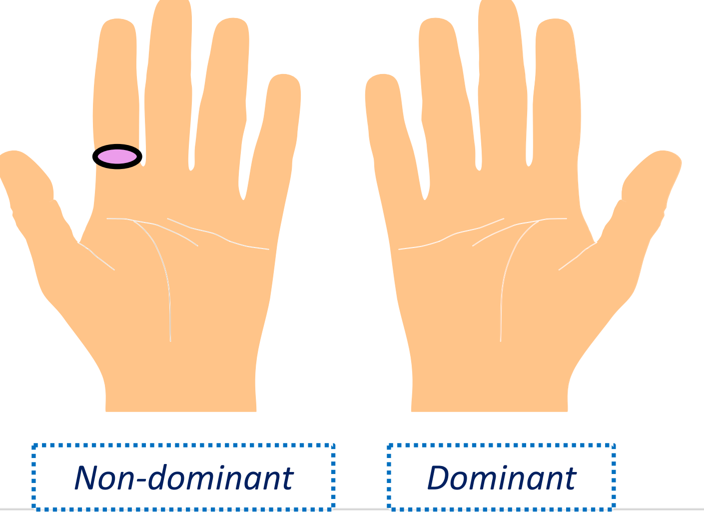
Personal monitoring of external exposure

Measurement techniques:

Ring dosemeter (passive)

- **$H_p(0.07)$**
- When dose equivalent to the extremities may exceed 25 mSv/year
- Must be worn at the location where the highest dose is expected

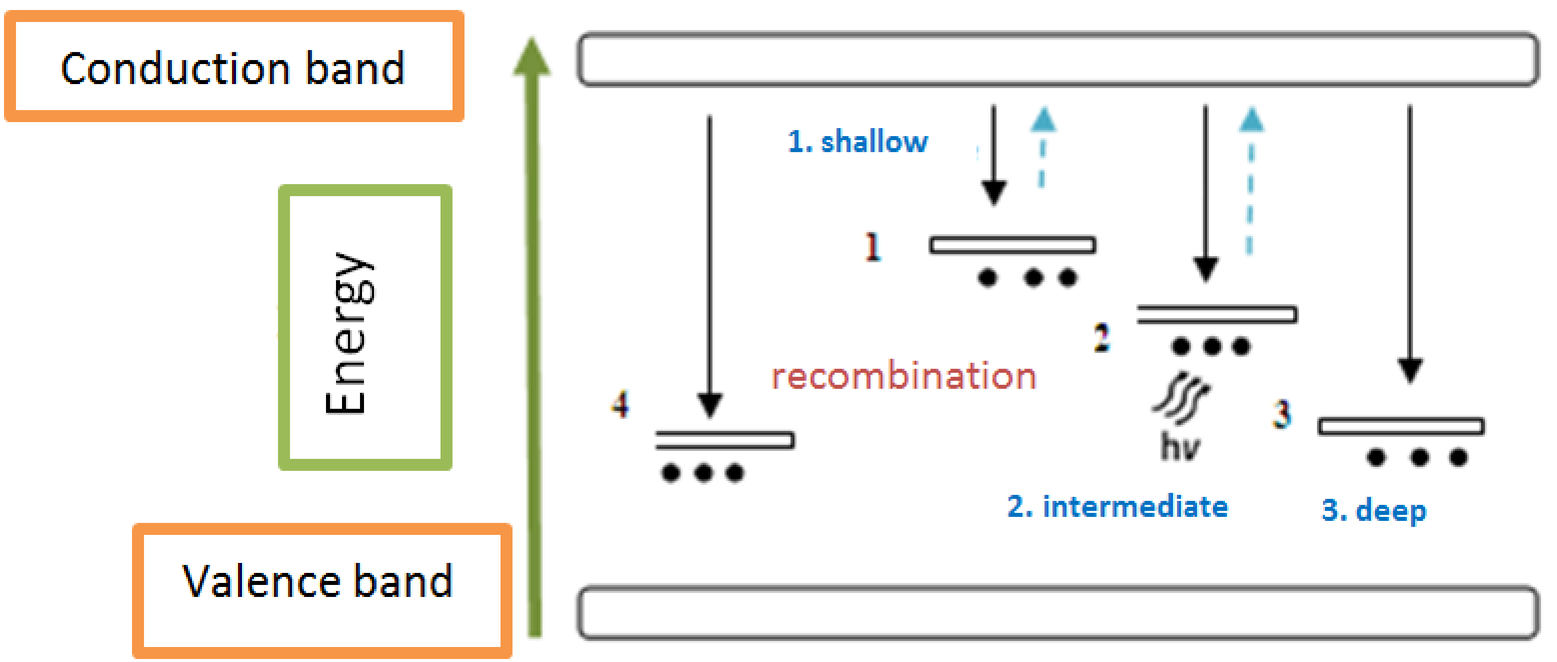
Recommended position



Personal monitoring of external exposure

Measurement techniques:

Working principle of passive dosemeters



Personal monitoring of external exposure

Measurement techniques:

Active individual dosemeter

- **Hp(10) (Hp(0.07), neutrons ...)**
- Direct-read instrument
- Configurable thresholds
- Configurable alarms
- Currently, electronic dosimeters are used only in high dose rate situations

Personal monitoring of external exposure

Measurement techniques:

Active individual dosemeter

+	-
High precision (semiconductor)	Absence of national or international standards
Low detection limit (applicable for low dose exposures)	Lack of dosimeter for extremities
Visual and audible alarms, dose and dose rate function	Difficulty in measuring surface dose
Direct reading (active radiation protection, training, less work for individual monitoring service)	High price
Easy transfer of dosimetric informations to a data base (facilitates and speeds up data processing)	Underestimation of dose at high dose rates and in pulsed fields (issue in medicine and accident situations)
Good acceptability by users (more confidence in dose value)	Reticence of monitoring bodies toward new dosimeters (dosemeter and doses can be manipulated)

Personal monitoring of external exposure

Regulation in Switzerland:

Directive L-06-01

Type de nuclide	Dosimétrie du corps entier		Dosimétrie des extrémités	
	Activité en travail	*Activité annuelle manipulée*	*Activité en travail*	*Activité annuelle manipulée*
Général :				
Emetteurs γ	> 1 LA			> 200 LA
Emetteurs β avec E_β^{max} < 1 MeV	-		-	
Emetteurs β avec E_β^{max} > 1 MeV	> 100 LA (secteur de travail B)	> 200 LA	> 100 LA (secteur de travail B)	> 200 LA
en particulier :				
H-3/C-14/ S-35/P-33	-		-	
P-32	> 100 LA (secteur de travail B)	> 200 LA	> 100 LA (secteur de travail B)	> 200 LA
Cr-51/Tc-99m	> 1 LA			> 200 LA
I-123	> 1 LA			> 200 LA
I-125	> 100 LA (secteur de travail B)	> 200 LA	> 100 LA (secteur de travail B)	> 200 LA
I-131	> 1 LA			> 200 LA

Personal monitoring of external exposure

If $H_p(10) < E_{threshold}$	As a first approximation : $H_p(10) = E_{external} = E$
If $H_p(10) > E_{threshold}$	**Investigations are required**

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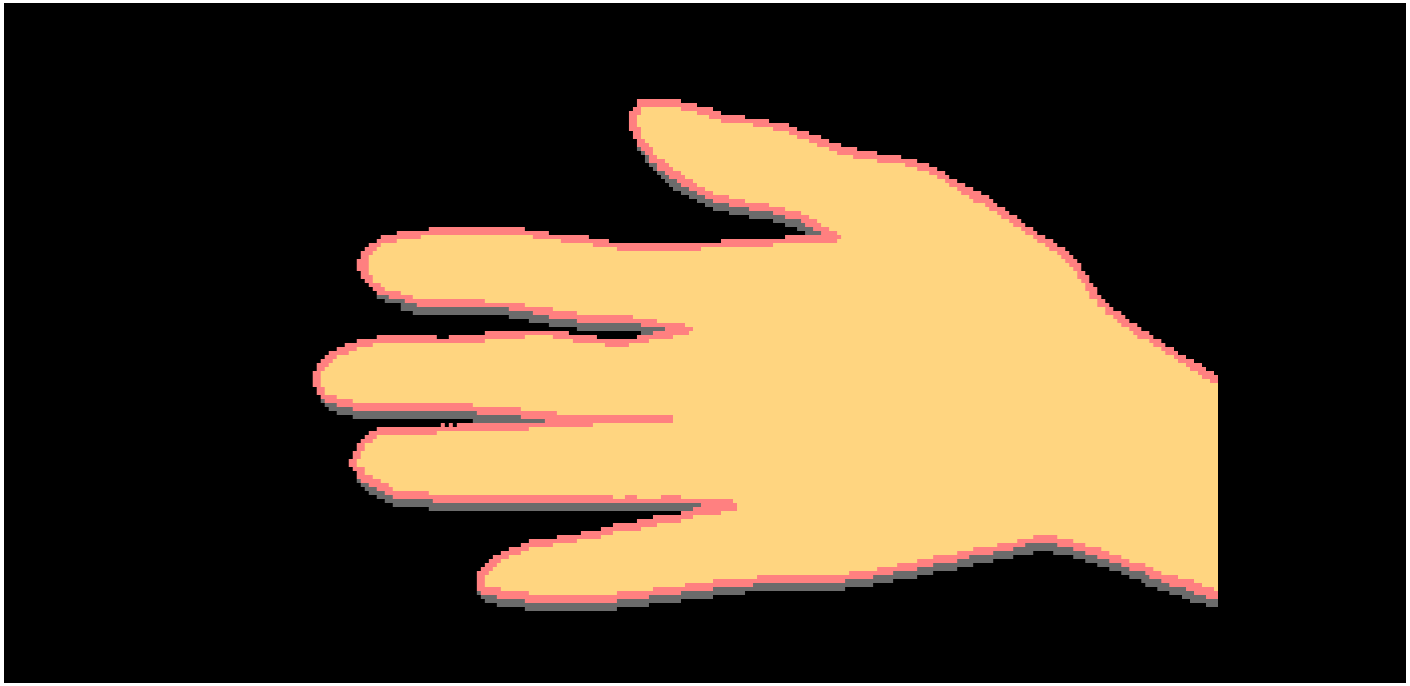
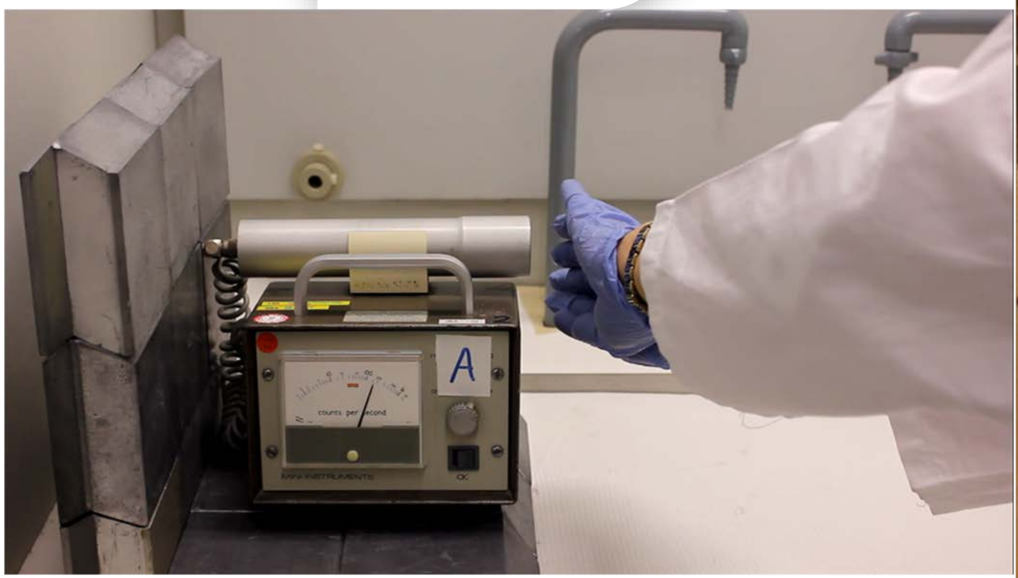
Personal monitoring for external contamination



Personal monitoring for external contamination

Contamination monitor



Personal monitoring for external contamination

If the measurement is positive:

- Indication of contamination
- Measured values not (directly) usable for dose or dose rate calculation

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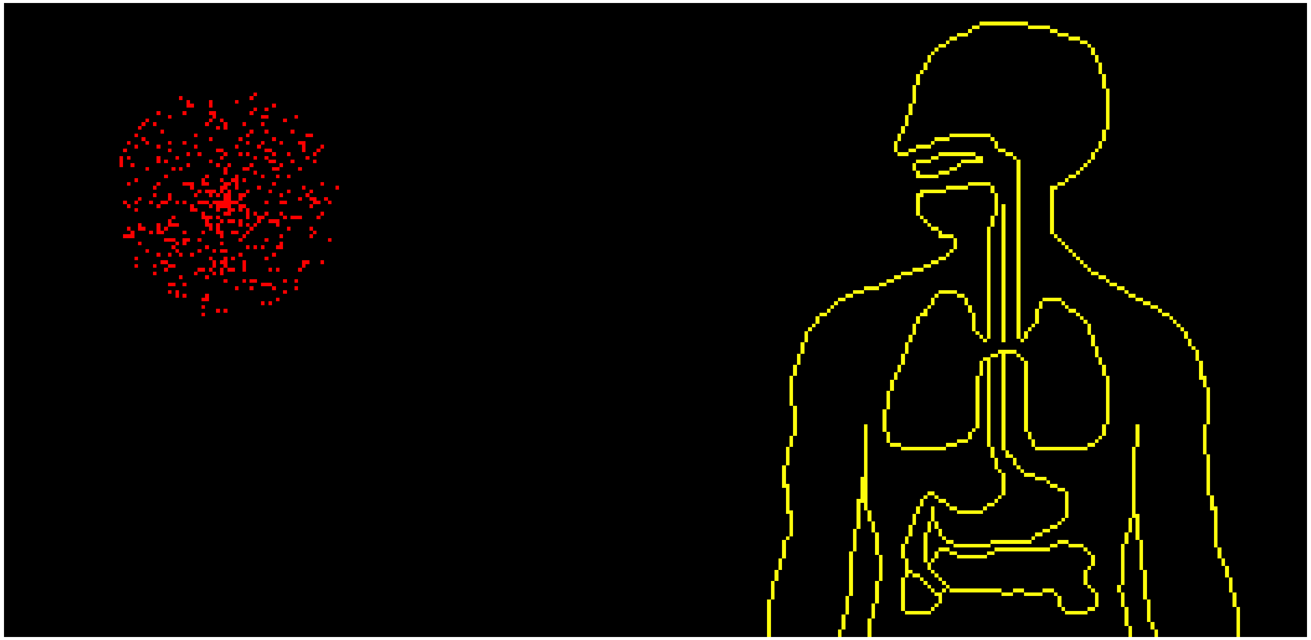
Personal monitoring for internal contamination



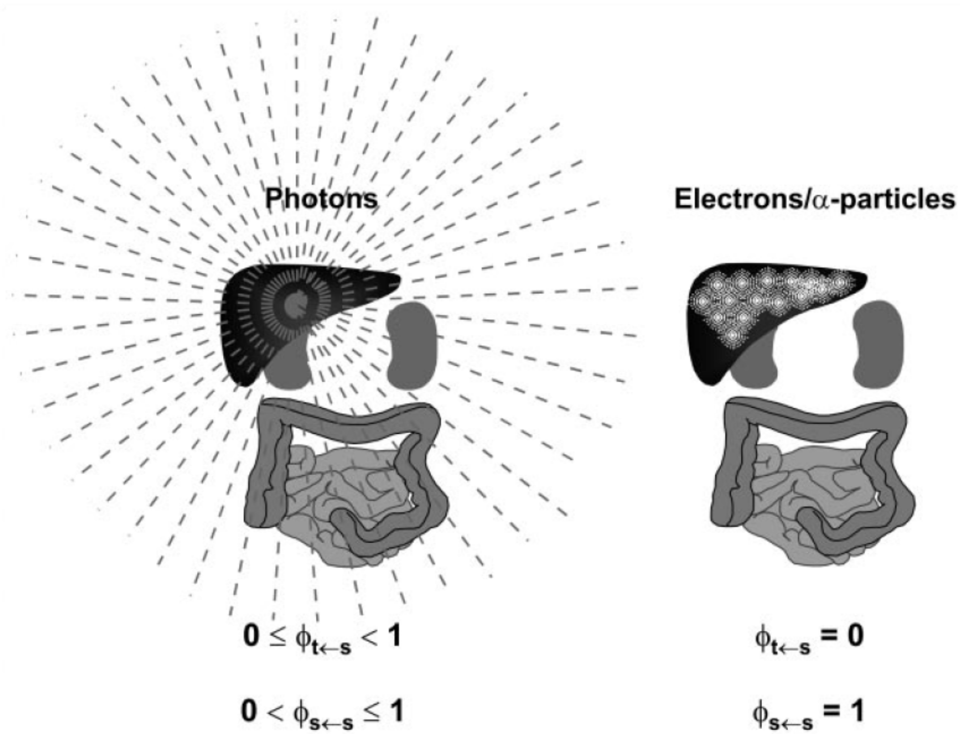
Personal monitoring for internal contamination

Internal exposure

	Personal dosimetry
Effective dose monitoring (E)	Committed effective dose E_{50}

E_{50} = Sum of effective doses received over the 50 years which follow an intake

Personal monitoring for internal contamination



Irradiation of organs:

γ: Irradiation of the specific organ and all other organs

α et β: Irradiation of the specific organ

Personal monitoring for internal contamination

Calculating the dose to an organ

	Definition	Unit
s	Source organ	-
t	Target organ	-
i	Type of radiation	-
$S(s \rightarrow t)_i$	Specific effective energy : Dose in the target organ *t*, produced by type *i* radiation , when decay occurs in the source organ *s*	$Sv.Bq^{-1}.s^{-1}$
U_s	Number of decays which occur in the source organ *s* per unit of activity incorporated during a period of 50 years	s
h_T	Dose-activity factor linked to the decay in organ *s*	$Sv.Bq^{-1}$

$$h_T = U_s . \sum_i S(s \rightarrow t)_i = U_s . S(s \rightarrow t)$$

Personal monitoring for internal contamination

Calculating the dose to an organ

$$h_T = U_s . \sum_i S(s \rightarrow t)_i = U_s . S(s \rightarrow t)$$

This formula takes only one source organ into account.

The contribution of all source organs must then be summed up:

$$h_T = \sum_s U_s . S(s \rightarrow t)$$

This formula takes only one target organ into account.

To take into account all the target organs, w_T is used:

$$e = \sum_T w_T h_T = \sum_T w_T \sum_s U_s . S(s \rightarrow t)$$

$Sv.Bq^{-1}$

Personal monitoring for internal contamination

Calculating the dose to an organ

$$e = \sum_T w_T \, h_T = \sum_T w_T \sum_s U_s \, . \, S(s \rightarrow t)$$

And so for an inhalation situation:

Sv.Bq-1 →

$$e_{inh} = \sum_T w_T \sum_s U_{s,inh} \, . \, S(s \rightarrow t)$$

The dose can be deduced knowing **e** and the **incorporated activity I (Bq)**.

For an inhalation situation, the committed effective dose is :

Sv →

$$E_{50_{inh}} = I_{inh} \, . \, e_{inh}$$

Personal monitoring for internal contamination

Calculating the dose to an organ

$$E_{50_{inh}} = I_{inh} \cdot e_{inh}$$

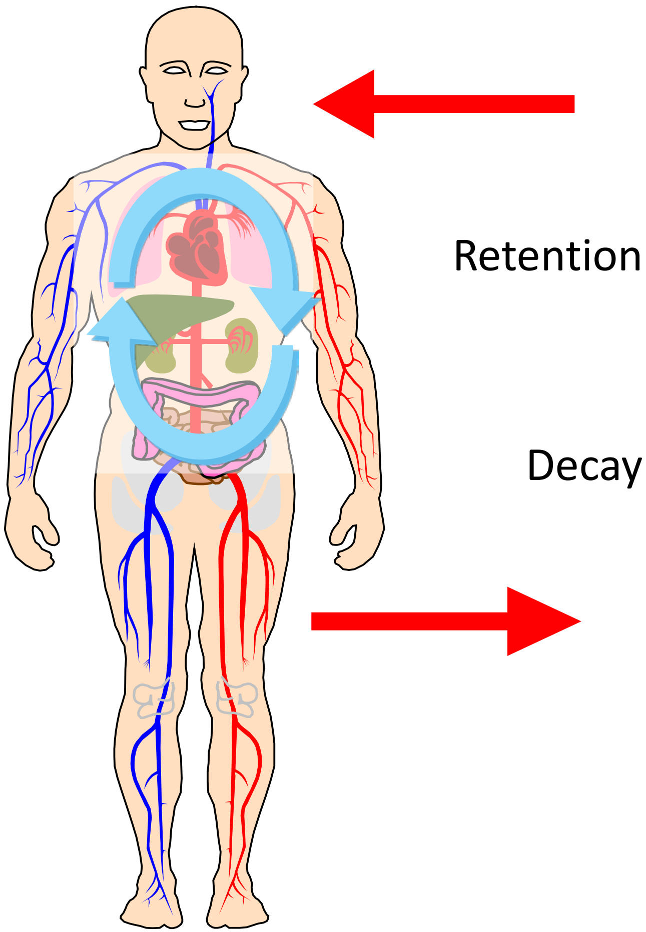
$$E_{50_{inh}} = I_{inh} \cdot \sum_{T} W_T \sum_{S} U_{S_{inh}} \, S(s \rightarrow t) = I_{inh} \cdot e_{inh}$$

In an intake situation, the committed effective dose depends on many factors:

- The quantity of incorporated radionuclide;
- The type and energy of the emitted radiation;
- The (effective) half-life of the radionuclide;
- The intake mode (inhalation, ingestion, contamination from a wound),
- The metabolism of the incorporated substance.

Personal monitoring for internal contamination

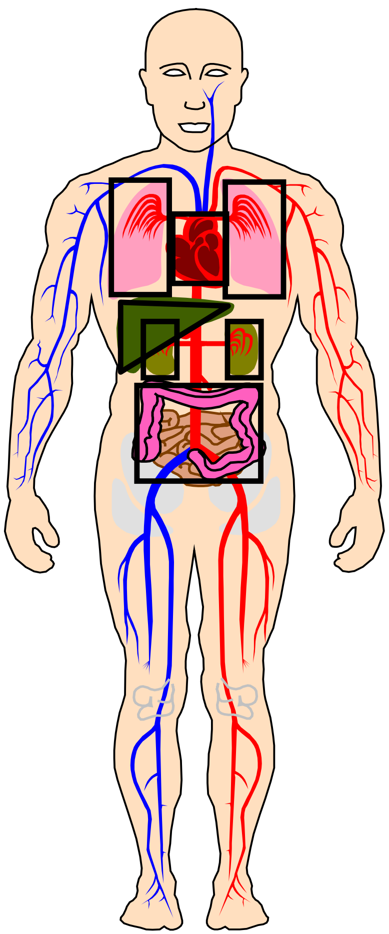
Compartmental model



To estimate the number of decays in each organ, it is mandatory to know the **where and when** (localisation of the contaminant at all time)

Personal monitoring for internal contamination

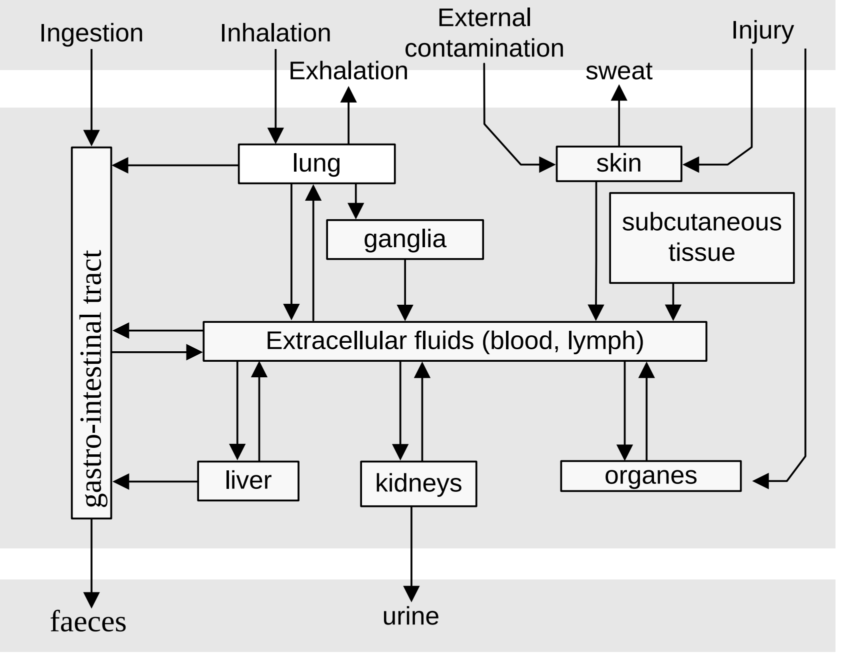
Compartmental model



- System divided into sub-systems (compartments).
- Continuous transfer of substances between the sub-systems.
- Flux from one compartment to another.

Personal monitoring for internal contamination

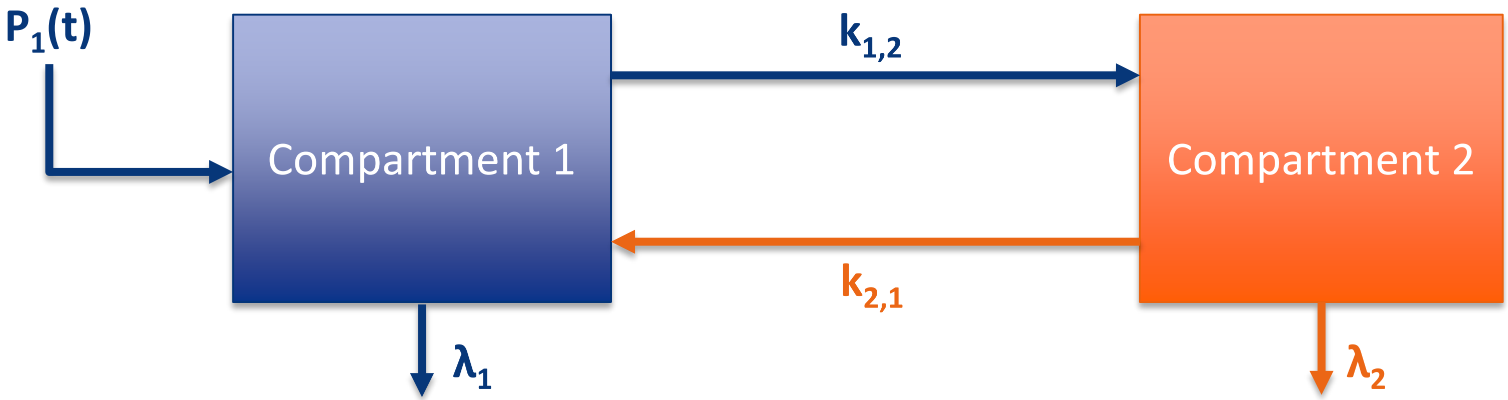
Compartmental model



Special models developed by the ICRP

Personal monitoring for internal contamination

Compartmental model



$$dN_1(t) = P_1(t)dt - \lambda_1 N_1(t)dt + k_{2,1}N_2(t)dt - k_{1,2}N_1(t)dt$$
$$dN_2(t) = P_2(t)dt - \lambda_2 N_2(t)dt + k_{1,2}N_1(t)dt - k_{2,1}N_2(t)dt$$

- Linear system of ODE: $\dot{\mathbf{N}}(t) + \Lambda\mathbf{N}(t) - \mathbf{P}(t) = 0$

- Retention function m(t): $r(t) = \dfrac{N_i(t)}{N_1(0)} = \dfrac{A_i(t)}{A_1(0)}$

$$m(t) = r(t)\cdot e^{-\lambda t} = r(t)\cdot e^{-\frac{\ln(2)}{T_{1/2}}t}$$

Personal monitoring for internal contamination

Dose determination for internal exposure

	Personal dosimetry
Effective dose monitoring (E)	Committed effective dose E_{50}

$$E_{50_{inh}} = I_{inh} \cdot \sum_{T} W_T \sum_{S} U_{S_{inh}} \; S(s \rightarrow t) = I_{inh} \cdot e_{inh}$$

$$E_{50_{ing}} = I_{ing} \cdot \sum_{T} W_T \sum_{S} U_{S_{ing}} \; S(s \rightarrow t) = I_{ing} \cdot e_{ing}$$

Personal monitoring for internal contamination

Inhaled activity

$$E_{50} = I_{inh} \cdot e_{inh}$$

$$E_{50} = I_{ing} \cdot e_{ing}$$

Dose factors

Ingested activity

Radiological Protection Ordinance:
https://www.admin.ch/opc/en/classified-compilation/20163016/201806050000/814.501.pdf

			Assessment quantities					Clearance limit	Licensing limit
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/cm^2)	**LL** Bq/g	**LA** Bq
1	2	3	4	5	6	7	8	9	10
H-3, OBT	12.32 a	β⁻	4.10 E-11	4.20 E-11	<0.001	<1	<0.1	1.E+02	1.00 E+08
H-3, HTO		β⁻	1.80 E-11	1.80 E-11	<0.001	<1	<0.1	1.E+02	3.00 E+08
H-3, gaz [7]		β⁻	1.80 E-15		<0.001	<1	<0.1		3.00 E+12
Be-7	53.22 d	ec / ph	4.60 E-11	2.80 E-11	0.008	<1	0.1	1.E+01	1.00 E+08

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Personal monitoring for internal contamination

Goal of personal dosimetry:

Measure I to determine E_{50}

Measurement techniques for internal contamination

Type of radiation	Method	
Penetrating (γ, β^+)	In-vivo	Measuring the radiation emitted by the body / organ
Weakly penetrating (α, β^-)	In-vitro	Measuring the contamination in body waste (urine, feces)

Personal monitoring for internal contamination

Measuring procedure

Measurement	Characteristics
Screening/sorting measurement	• *Qualitative measurement (yes/no)* • *Done by the operator himself* • *Simple, quick, cheap*
Incorporation measurement	• *Only when the sorting measurement threshold has been exceed* • *<u>Quantitative measurement by an approved dosimetry service</u>* • E_{50} *calculated*

Personal monitoring for internal contamination

Ordinance on personal dosimetry

https://www.admin.ch/opc/fr/classified-compilation/20163018/index.html

Ordonnance sur la dosimétrie **814.501.43**

26. I-125

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.

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.

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

Personal monitoring for internal contamination

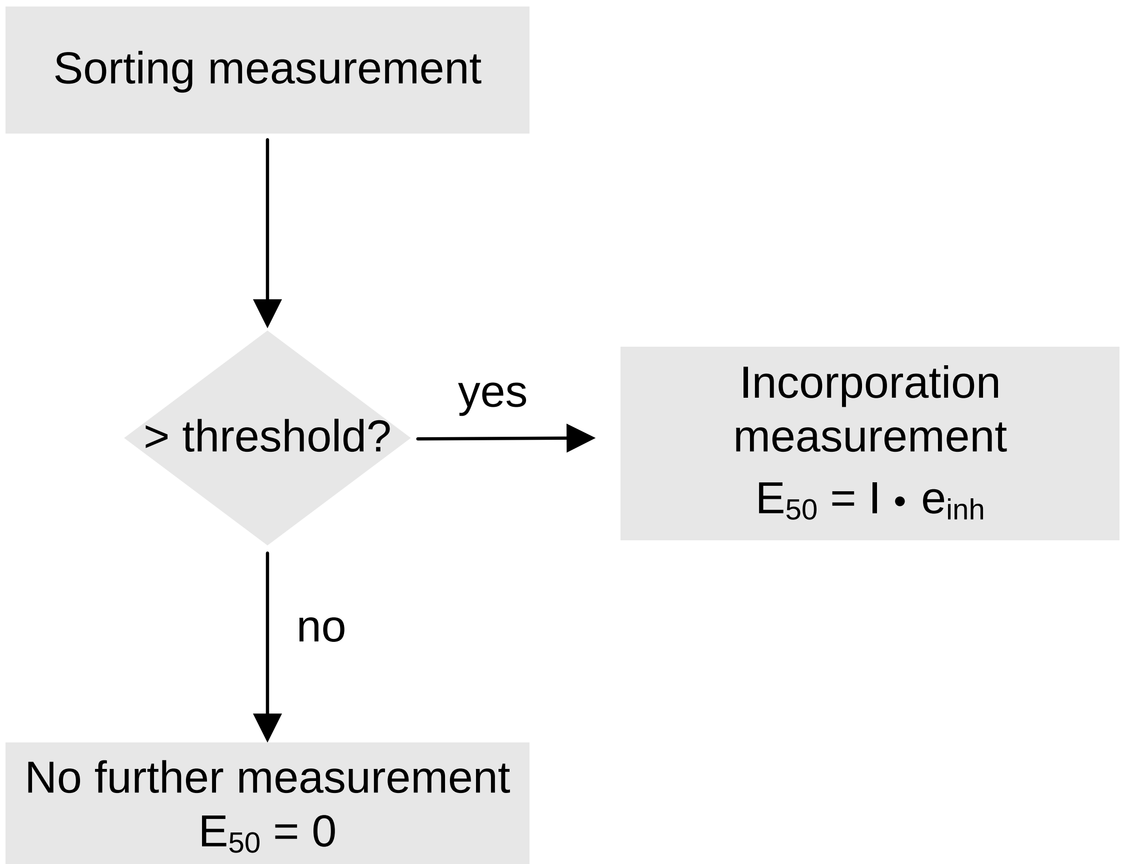
Measurement intervals

Measurement intervals are **defined** in the Ordinance on dosimetry.

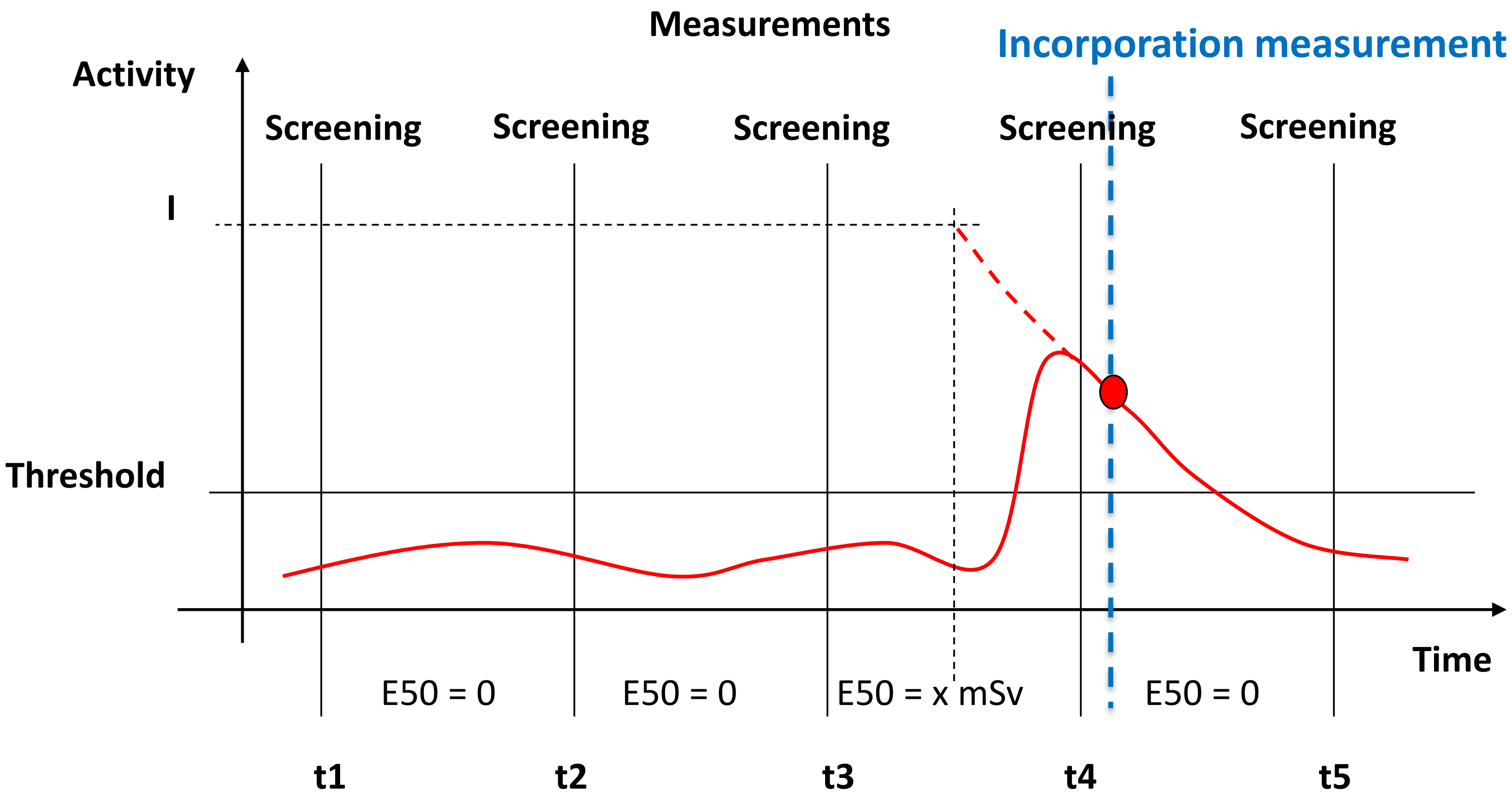
Measurement intervals will depend on the effective **half-life** of the radioelement and a **limit of a detectable quantity** (dose rate or activity) guaranteeing the required dose limit.

If the time of the intake is unknown, we consider that it occurred in the interval **between 2 screening measurements**.

Personal monitoring for internal contamination



Personal monitoring for internal contamination

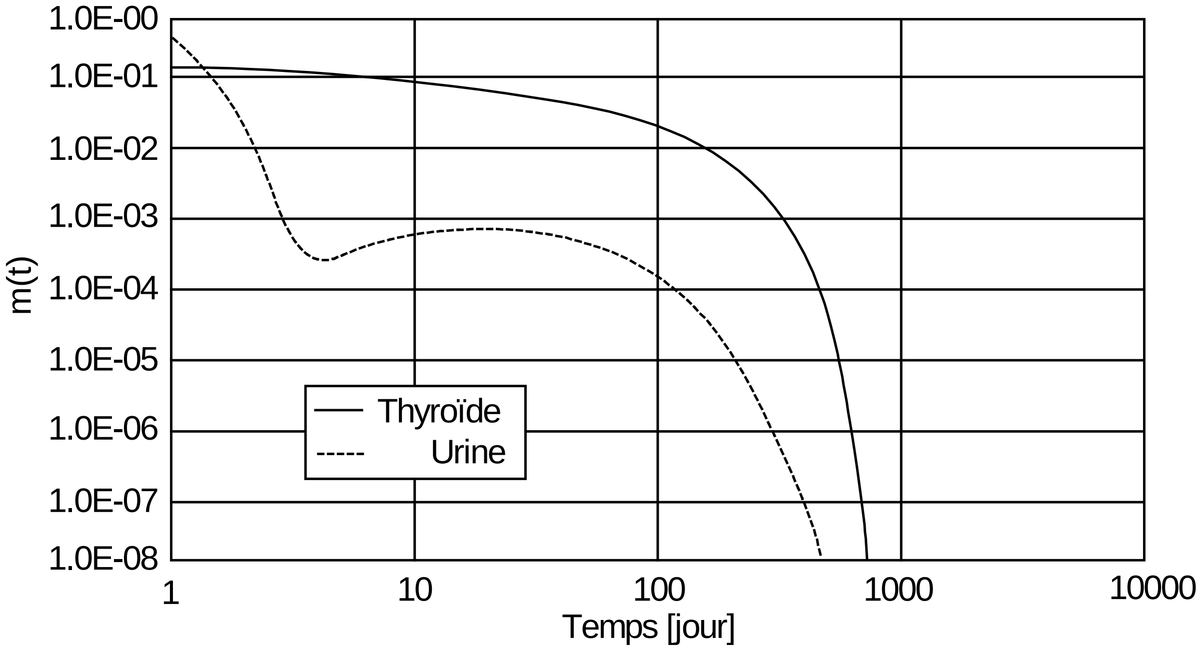


Personal monitoring for internal contamination

Calculating committed effective dose E_{50}

- **M(t):** activity in the organ or waste sample at time *t*
- **m(t):** fraction of the incorporated activity (*I*) located in the organ or waste sample at time *t* → tabulated values in the literature

Retention of Iodine-125 in the thyroid after inhalation



Personal monitoring for internal contamination

Calculating committed effective dose E_{50}

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

$$E_{50} = I \,.\, e_{inh} = \frac{M(t)}{m(t)} \,.\, e_{inh}$$

$$E_{50} = M(t) . \frac{e_{inh}}{m(t)}$$

For **routine monitoring**, when we consider that the intake occurred in the middle of interval T:

$$E_{50} = M(t) . \frac{e_{inh}}{m\left(\frac{T}{2}\right)}$$

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Personal monitoring for internal contamination

Ordinance on dosimetry

26. I-125

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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.

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

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	$0{,}56 \times 10^{-7}$
2	$0{,}52 \times 10^{-7}$
3	$0{,}52 \times 10^{-7}$
4	$0{,}56 \times 10^{-7}$
5	$0{,}56 \times 10^{-7}$
6	$0{,}56 \times 10^{-7}$
7	$0{,}56 \times 10^{-7}$
15	$0{,}66 \times 10^{-7}$
30	$0{,}90 \times 10^{-7}$
45	$1{,}2 \times 10^{-7}$
60	$1{,}6 \times 10^{-7}$
90	$2{,}6 \times 10^{-7}$
135	$6{,}1 \times 10^{-7}$

5. Interprétation en cas d'incorporation antérieure

Intervalle de surveillance T = 90 jours: $E_{50} = M \cdot 1{,}2 \cdot 10^{-7} - E_{50}^{a} \cdot 0{,}20$

Personal monitoring of internal exposure

If $E_{50} < E_{threshold}$	As a first approximation : $E_{50} = E_{internal} = E$
If $E_{50} > E_{threshold}$	**Investigations are required**