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Radiation Protection of Nuclear Medicine Staff

Radiation protection of nuclear medicine staff

- Radiation Protection Basics
- Monitoring systems: workplace monitoring and individual monitoring
- Radiation Protection quantities
- Type of radiation detectors
- Nuclear medicine staff protection aspects
  - Whole body monitoring
  - Extremity monitoring
  - Eye lens monitoring
  - Contamination
  - Internal dosimetry

Concepts and aims

Primary aim:

"is to contribute to an appropriate level of protection for people and the environment against the detrimental effects of radiation exposure without limiting desirable actions"

Protect human health by

- Preventing deterministic effects
- Reducing the risks of stochastic effects

Cannot be achieved solely on basis of scientific knowledge:

- Scientific data are a prerequisite
- Social and economical aspects have to be considered

Concepts and aims

- The system deals a with number of sources, leading to exposure of individuals, groups, populations, in present and in future
- Above 100 mSv (“high” doses): proven effects
- Below 100 mSv:
  - LNT (linear no threshold) model is best practical approach to manage risks
  - Result: even at smallest doses, some risks must be assumed
  - Agrees with precautionary principle
- Leads to 3 fundamental principles:
  - Justification
  - Optimisation
  - Dose Limits

Types of exposure

- *Categories of exposure*
- Occupational:
  - Incurred as result of work
  - Employer and licensee have main responsibility for protection of workers
- Medical:
  - Diagnostic, interventional, therapeutic
  - Exposure is intentional and with direct benefit of the patient
- Public:
  - All exposures other than occupational and medical.
  - Including foetus and embryo of workers

Types of exposure

- Similarly: 3 types of exposed individuals
- Workers
  - ICRP recommends classification of areas (instead of workers, like EC BSS)
    - Controlled areas vs Supervised areas
  - No distinction between sexes
    - Pregnant worker: additional controls have to be considered
      - Extra dose to foetus should be <1 msv
      - Not necessary to avoid working with radiation, but working conditions should be reviewed
  - Includes exposure to cosmic radiation in commercial aircraft
    - Not including frequent flyers
- Members of public:
  - Use of representative person for the protection of a group
    - Representative of small group of highest exposed from public
    - Not including extreme habits
- Patients

Radiation protection system: principles

- JUSTIFICATION: any decision that alters the radiation exposure situation should do more good than harm
  - Introducing a new source
  - Reducing existing exposure
  - Reducing the risk of potential exposure

- Should achieve sufficient individual or societal benefit to offset the detriment
  - This detriment should be included in the decision making process
  - Not confined to radiation alone: should include all risks and benefits
  - Search for best alternatives

Radiation protection system: principles

- OPTIMISATION: to keep the likelihood of incurring exposures, the number of people exposed and the magnitude of individual doses as low as reasonably achievable, taking into account the current state of technical knowledge, and economic and societal factors
- ALARA: as low as reasonably achievable
  - Iterative process to find the optimised RP solution
    - Evaluation of exposure situation
    - Selection of constraint or reference level
    - Identification of protection options
    - Selection of best option
  - Constraints: provide a desired upper bound for the optimisation process
  - Applied in planning phase: compare to prospective doses
  - Taking into account technical and socio-economic factors
  - Optimisation is a frame of mind
  - ≠ minimising doses
  - Societal and ethical aspects: can include stakeholder involvement

Radiation protection system: principles

- DOSE LIMITS:
- Only in planned exposure situations
  - the sum of doses to an individual shall not exceed the dose limits laid down for occupational exposure or public exposure.
- Dose limits shall not apply to medical exposures
- Does not include the background radiation
- Apply to the sum of doses due to external exposures and committed doses from internal exposure due to intake of radionuclides

Dose Limits in Planned Exposure Situations:

- Prevention of deterministic effects
- Reduction of stochastic effects to level deemed acceptable

Type of limit	Occupational	Public
Annual effective dose	[redacted]	[redacted]
Annual equivalent dose to:		
Lens of the eye	[redacted]	[redacted]
Skin[c]	[redacted]	[redacted]
Hands and feet	[redacted]	—

- [redacted]

Objectives of monitoring

- Estimation of the radiation exposure of workers, to demonstrate compliance with legal requirements
- Demonstration of good working practices
- Determining the radiological conditions in the workplace to see if these are under adequate control
- Evaluation of operating procedures
- Provision of information that can be used to motivate workers to reduce their exposure.
- Provision of information for the evaluation of dose in the event of accidental exposure.
- To provide input for the medical records
- For epidemiological studies

Individual monitoring is:

- Individual measurements
  - using equipment worn by individual workers
  - of quantities of radioactive substances in or on their bodies, and the interpretation of such measurements

- In cases where individual measurements are not possible or inadequate the individual monitoring shall be based on:
  - an estimate based on individual measurements made on other exposed workers
  - workplace monitoring and the interpretation of such measurements
  - the basis of calculation methods approved by the competent authority

Design of individual monitoring:

- Individual measurements:
  - for external exposure, for internal exposure and for skin contamination
- Workplace monitoring:
  - for external radiation, for air contamination and for surface contamination
- The details of the programmes will be influenced by factors such as the type and energy of the radiation and the radionuclides involved
  - The equipment should be suitable for the types of radiation and the forms of radioactive material encountered in the workplace
  - The equipment should be calibrated to meet appropriate standards
  - The monitoring programme should be conform the quality assurance requirements
  - The records should be promptly compiled and correctly maintained
- All of these aspects should be reviewed regularly, at predetermined intervals

Requirements for workplace monitoring

- When individual measurements may not be feasible or practicable: reliance should be placed on workplace monitoring
  - Particularly in the assessment of internal exposure
- Where this is the case, the monitoring programme should provide detailed information on the worker's movements and on the temporal and spatial variations in air concentrations in the worker's immediate environment

Workplace monitoring systems / instruments

- Selection of monitoring equipment should be done in consultation with the RPO and/or qualified experts
- Monitoring equipment must be suitable to the task
  - All monitors have an energy threshold. This is determined by the type of detector, the monitor casing and other factors.
  - Only certain types of monitor can measure beta radiation
- Personal dosemeters are generally not suitable for workplace monitoring (measurement quantities different)

Workplace monitoring

- Workplace monitoring has a role in:

  - Prior work planning (optimization)
  - Estimating exposure retrospectively if individual dosimeters are lost or damaged
  - Clearly defining controlled or supervised radiation areas
  - Detecting changes in radiation levels
  - Confirming that radiation field measurements agree with design and expected radiation conditions
  - Assisting in designing and establishing protective measures
  - Providing data for ongoing review of the optimization of protection
  - Commissioning tests, following plant construction and modification
  - Confirming that design safeguards, such as shielding, are effective
  - Detecting abnormal conditions to allow an appropriate corrective response in a timely manner

Choice of monitoring system

- Selection of personal dosemeter based on conditions in the workplace
  - Type of radiation, energy and directional distribution
  - Range of expected doses and dose rates
  - Environmental conditions
  - With a prescribed overall accuracy
- Select or establish monitoring service that:
  - Is approved by the Regulatory Authority
  - Provides a reliable measurement of the appropriate quantities
  - Is responsible for the accuracy and reliability of the dose assessment
  - Can evaluate dosemeters within a short time if an overexposure is indicated

Assessment of occupational exposure

- Assessment of occupational exposure involves assessment of both the external and internal exposure components
- Total effective dose is the sum of the external and internal exposure components

The following equation is used for assessment of occupational exposure and demonstration of compliance with dose limits:

$$E_t = H_p(10) + \sum_j e(g)_{j,ing}\, I_{j,ing} + \sum_j e(g)_{j,inh}\, I_{j,inh}$$

- $H_p(10)$ is the personal dose equivalent
- $e(g)_{j,ing}$ is the dose coefficient for ingestion
- $I_{j,ing}$ is the intake from ingestion
- $e(g)_{j,inh}$ is the dose coefficient for inhalation
- $I_{j,inh}$ is the intake from inhalation

• Dose Limits in Planned Exposure Situations:

- Prevention of deterministic effects
- Reduction of stochastic effects to level deemed acceptable

Type of limit	Occupational	Public
Annual effective dose	20 mSv (avg. over 5 years[a])	1 mSv[b]
Annual equivalent dose to:		
Lens of the eye	20 mSv (avg. over 5 years[a])	15 mSv
Skin[c]	500 mSv	50 mSv
Hands and feet	500 mSv	—

- [a] Not exceeding 50 mSv in any single year; additional restrictions apply to occupational exposure of pregnant women
- [b] In special circumstances, a higher value of effective dose could be allowed in a single year, provided that the average
over 5 years does not exceed 1 mSv per year
- [c] Averaged over 1 cm^2 area of skin regardless of the area exposed

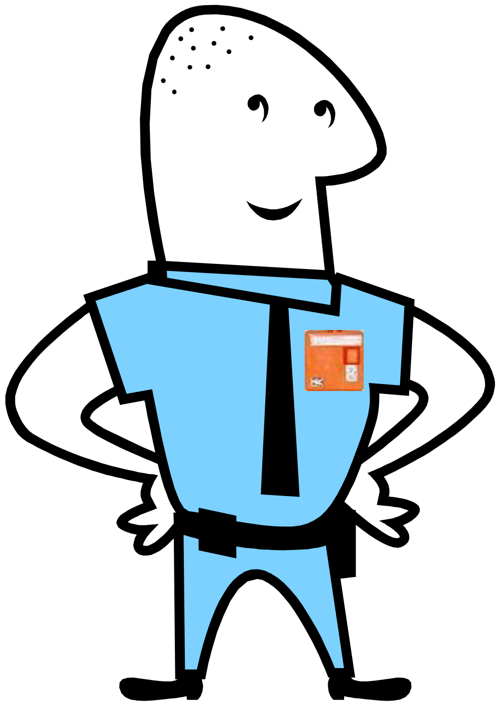
Monitoring period

- Depends on
  - Exposure situation – dose level
  - Characteristics of the dosimeters
  - Based on advise of qualified expert
- One month is generally recommended
- Three months may be acceptable for exposures that will generally lead to doses well below the relevant dose limit
- Between a week and a month may be appropriate where the rate of exposure is very non-uniform
- If daily monitoring is required, a direct reading dosemeter should be used

- Dosemeter placement

- The dosemeter should be placed in a position representative of the most highly exposed part of the surface of the torso
  - Normally on the front of the body

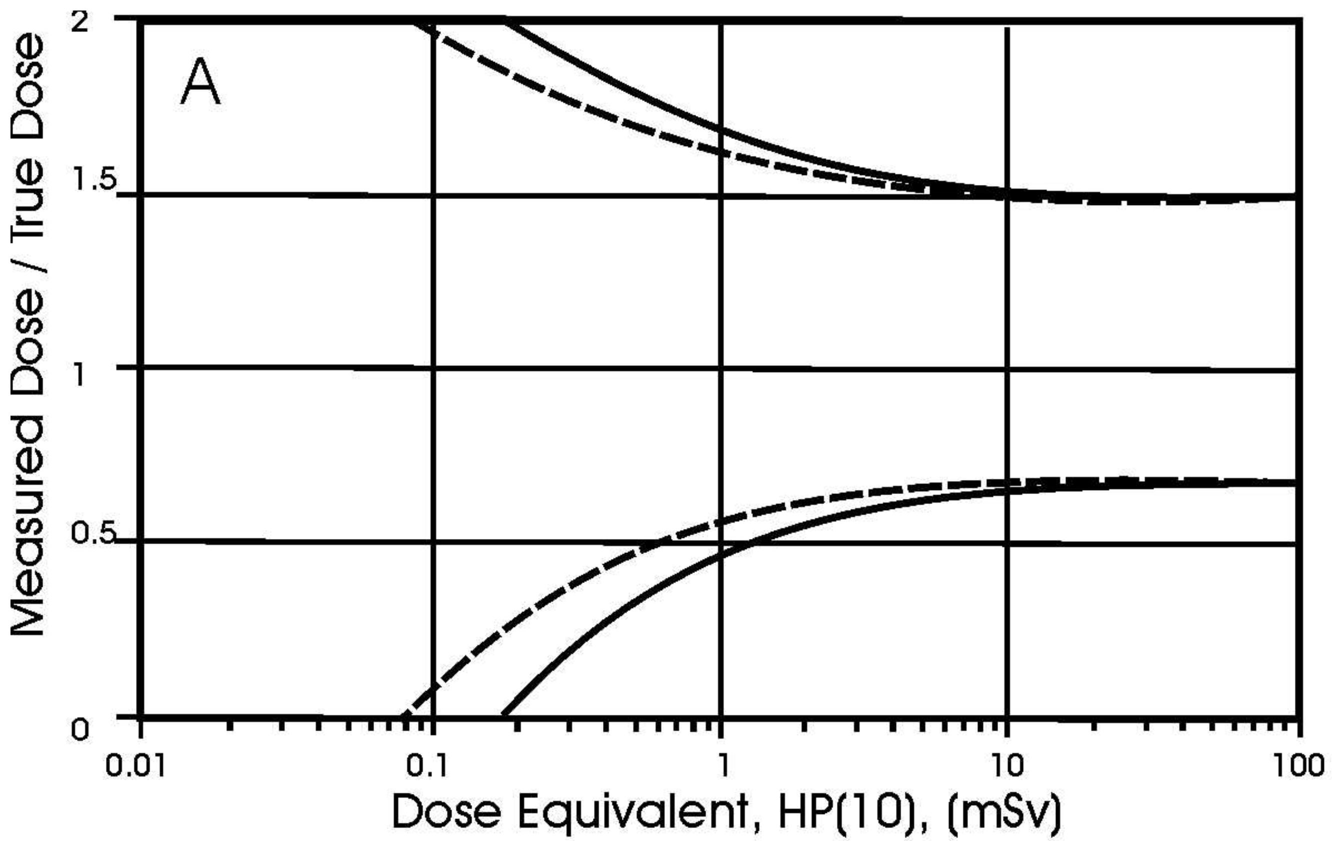
- If radiation comes primarily from the back, the dosemeter should be worn on the back



- Required accuracy according ICRP

- ICRP Publication No. 75: accuracy in making measurements with individual dosemeters in the workplace :
  - In good laboratory conditions: it is possible to achieve an accuracy of about 10% (k=2)
  - In the workplace: the uncertainties will be significantly greater
    - The energy spectrum and orientation of the radiation field are generally not well known
    - The overall uncertainty around the relevant dose limit may well be a factor of 1.5 in either direction for photons= +50% and -33%
    - May be substantially greater for neutrons of uncertain energy and for electrons
    - Greater uncertainties are also inevitable at low levels of effective dose for all qualities of radiation: factor 2

Required accuracy follows the trumpet curve



Minimal value of recording level

- The ICRP has also prescribed a minimum value for the recording level, i.e. the dose above which recording of the doses should be required. It is stated that:
  - "The Commission considers that the recording level for individual monitoring should be derived from the duration of the monitoring period and an annual effective dose of no lower than 1 mSv or an annual equivalent dose of about 10% of the relevant dose limit."
- For $H_p(10)$ and $H_p(3)$
  - For monthly exchange: 1 mSv/12 = 83 µSv
  - For three monthly exchange: 1 mSv/4 = 250 µSv
- For APD (daily)
  - 1 mSv/240 = 4.2 µSv
- For skin dose $H_p(0.07)$
  - For monthly exchange: 50 mSv/12 = 4.2 mSv

Accuracy and detection levels

- Minimal recorded level

- No dose report should contain values lower than detection limit
- Monthly reported dose of e.g. 15 µSv or 22.5 µSv are nonsense

- Three possibilities to report values below DL
  - Zero value
  - "<DL"
  - DL
- Reporting of values below DL can be dependent on national regulations

- Background subtraction is needed

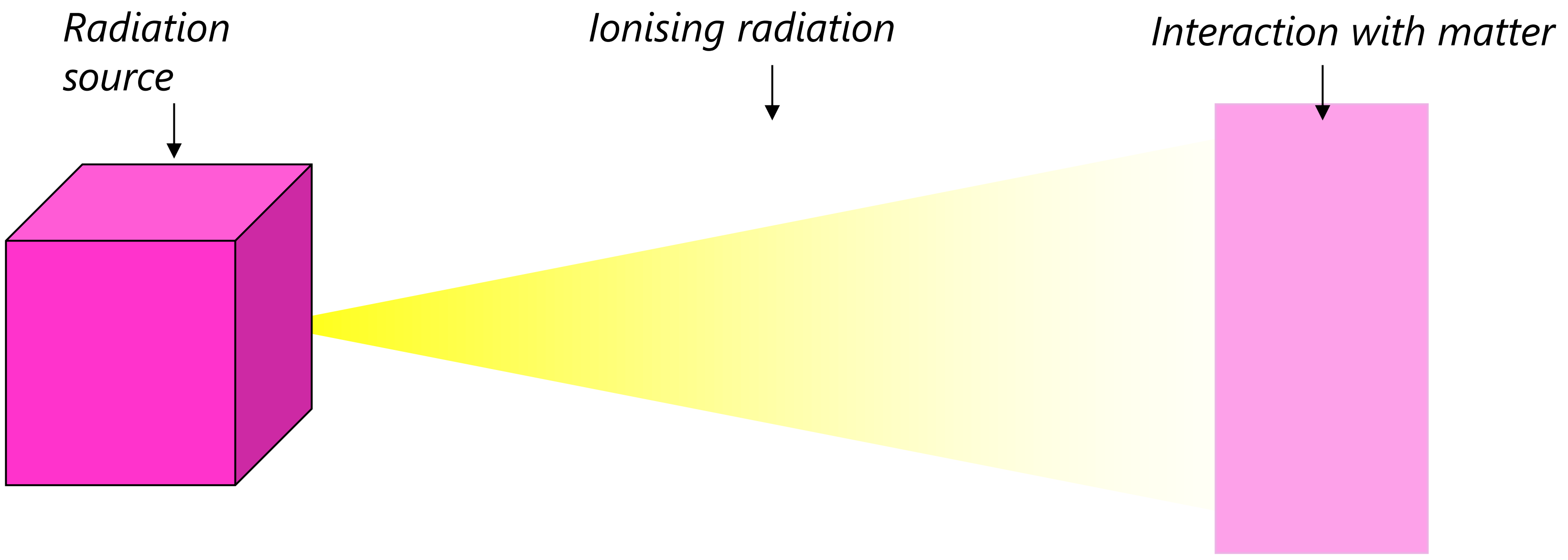
- The dose limits count for occupational exposures
- The personal dosemeter will include a contribution from the natural (radiation) background in addition to any dose from the worker’s occupational radiation field
- The zero dose indication and the natural background dose need to be subtracted
- The zero dose indication (background or blank indication) of a dosimetry system comprises the readout system background plus the detector intrinsic background
- Estimates of the associated uncertainties should be included in the overall uncertainty assessment

Background subtraction

- Background radiation is visible on your personal dosemeter

- Lifetime dose of the average Belgian
  - Man: 354 mSv, Woman: 382 mSv
- Monthly dose from natural radiation in Belgium (not including medical exposures) = 208 µSv/month
  - 119 µSv from Radon/Thoron
  - 23 µSv from internal (K-40)
  - 35 µSv terrestial
  - 31 µSv cosmic
  - 0,04 µSv/h on ground (3-5 µSv/h in airplane)
  - 4 µSv man-made
- From external radiation sources: around 70 µSv, or 2.3 µSv/day
- This 70 µSv is what your dosemeter sees every month, even if it is not used…

Quantities



Activity A
Half life $T_{1/2}$

kVp
mAs
filtration

Particle fluence
Energy fluence
Particle flux density
Energy flux density

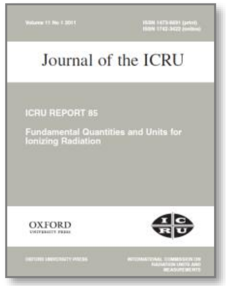
(Mass) stopping power
LET
Range

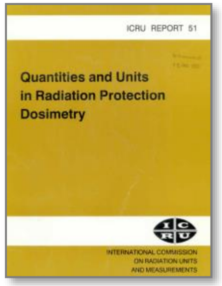
(Mass) attenuation coefficient
(Mass) absorption coefficient
Half Value Layer

Kerma
Absorbed dose

Quantities

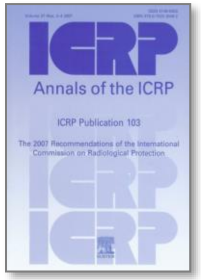
Dose quantities		
basic physical quantities	**operational quantities**	**protection quantities**
Fluence (m^{-2}) Kerma (Gy) Absorbed dose (Gy)	Dose equivalent (Sv) Ambient dose equivalent (Sv) Directional dose equivalent (Sv) Personal dose equivalent (Sv)	Equivalent dose for organs and tissues (Sv) Effective dose for the whole body (Sv)
Realised by **primary standards**	Measured with a calibrated **routine dosemeter**	Quantity for which **dose limits** are stated
Defined by ICRU		Defined by ICRP





ICRU reports

International Commission on Radiological Units and measurements



Annals of the ICRP

International Commission on Radiological Protection

- Primary physical quantities can not be used directly for dose limitation

- Different body tissues have different biological sensitivities to the same radiation type and dose
  - Tissue weighting factor, w_T

- The same absorbed dose levels of different radiations (i.e. photons and neutrons) do not have the same level of biological effect
  - Radiation weighting factor, w_R

THE EQUIVALENT DOSE H

H = radiation weighting factor w_R x absorbed dose D

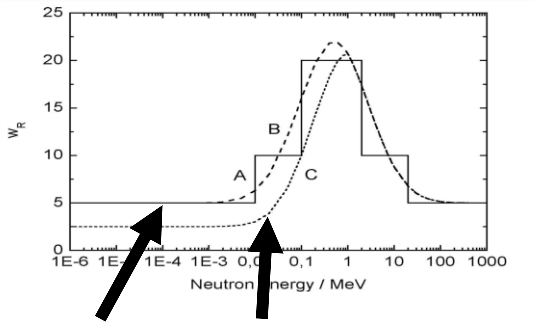
unit: Sievert (Sv)

- Radiation weighting factors: related to radiation outside the body
- Macroscopic quantity (per organ or type of tissue): the absorbed dose D is the average absorbed dose per organ or type of tissue

Protection quantities

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy (see Fig. 1 and Equation 4.3)

ICRP 103



ICRP 60
ICRP 103

THE EFFECTIVE DOSE

E = sum over all organs of the (tissue weighting factor x H_{organ})

unit: Sievert (Sv)

$E = \Sigma\, w_T\, \Sigma\, w_R\ \ D_{T,R}$

= a way to compare all possible exposures (different organs, partial/whole body radiation) on one risk scale

Tissue weighting factors w_T (cfr. risk estimates):

- do not take into account gender, age and weight of individual persons
- only for stochastic effects!
- reflects different radiosensitivity of organs or tissues T
- The SI unit is J/kg, special name for the unit of equivalent dose is sievert (Sv)

- Legacy unit of equivalent dose was rem, with 1 rem = 0.01 J kg–1 = 0.01 Sv

Protection quantities

Bone marrow Breast Colon Lung Stomach	0.12
Gonads (UNSCEAR 2001)	0.08
Bladder Liver Oesophagus Thyroid	0.04
Skin Bone surface Brain Kidney Salivary glands	0.01
Remainder	0.12

*Remainder tissues: Adrenals, extrathoracic (ET) region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (♂), small intestine, spleen, thymus, uterus/cervix (♀)

Protection quantities

Application	Occupational	Dose limit public
Effective dose	20 mSv per year, averaged over defined periods of 5 years	1 mSv in a year
Annual equivalent dose in: the lens of the eye the skin the hands and feet	20 mSv 500 mSv 500 mSv	15 mSv 50 mSv -

OPERATIONAL QUANTITIES

- Protection quantities, equivalent dose and effective dose, cannot be measured directly
- Other measurable quantities were introduced for the purpose of monitoring external radiation
- Operational quantities are designed to provide a failsafe (conservative) estimate of the limiting quantities: substantial underestimates are avoided
- Detectors for area and individual monitoring are calibrated in terms of operational quantities

Operational quantities

- Two types of operational quantities
  - Environmental monitoring: without phantom
  - Personal monitoring: to be used on phantom (backscatter + shielding)

[sievert=Sv]	Ambient dosemeters	Personal dosemeters
Effective dose	Ambient dose equivalent $H^*(10)$	Personal dose equivalent $H_p(10)$
Organ equivalent dose		
- **Eye lens**	Directional ambient dose equivalent $H'(3,\Omega)$	Personal dose equivalent $H_p(3)$
- **Skin, hands, feet**	Directional ambient dose equivalent $H'(0.07,\Omega)$	Personal dose equivalent $H_p(0.07)$

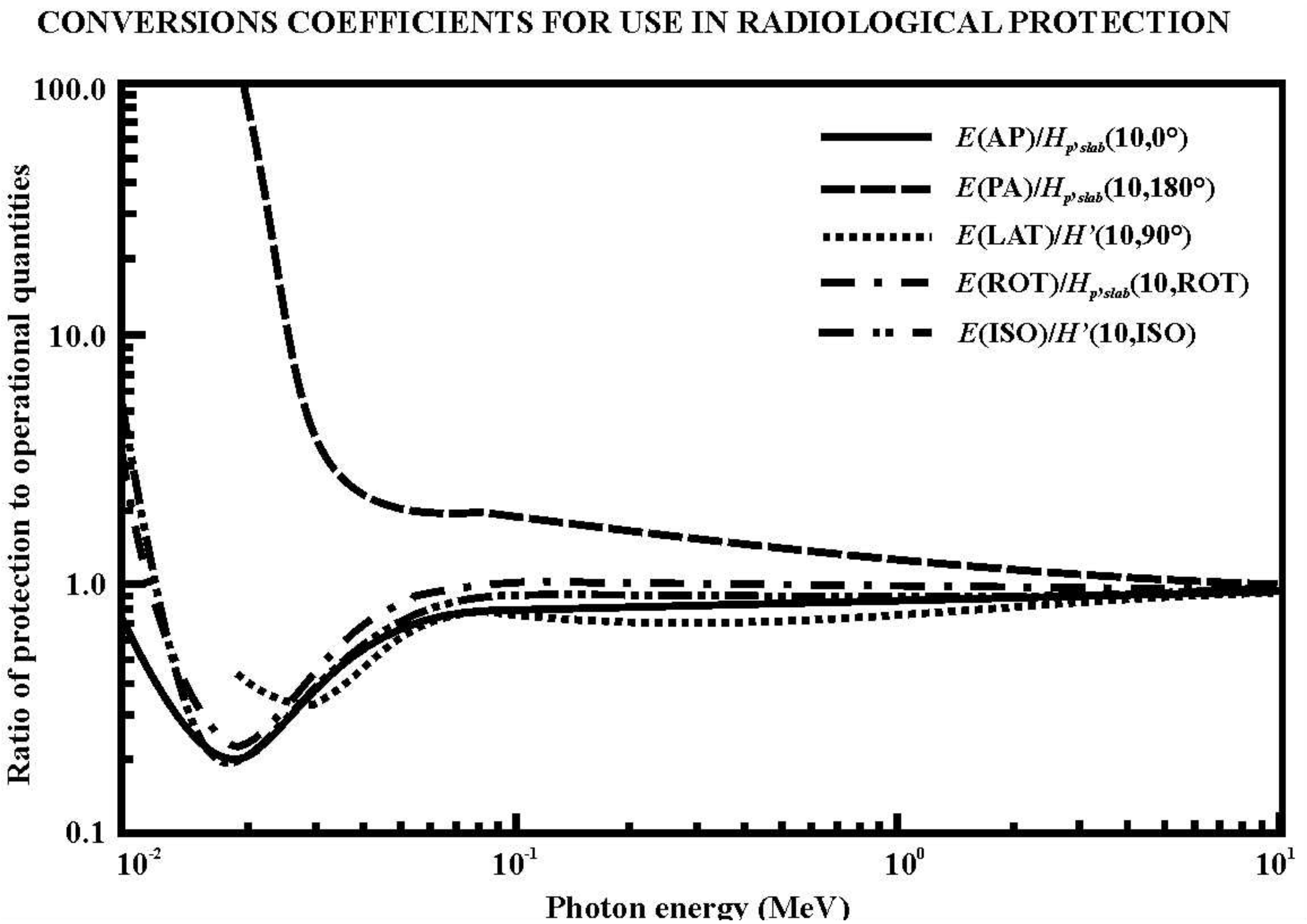
Operational quantities

- Ambient dose equivalent, $H^*(d)$, at a point in a radiation field is the dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth, d, on a radius opposing the direction of the aligned field: $H^*(d)$

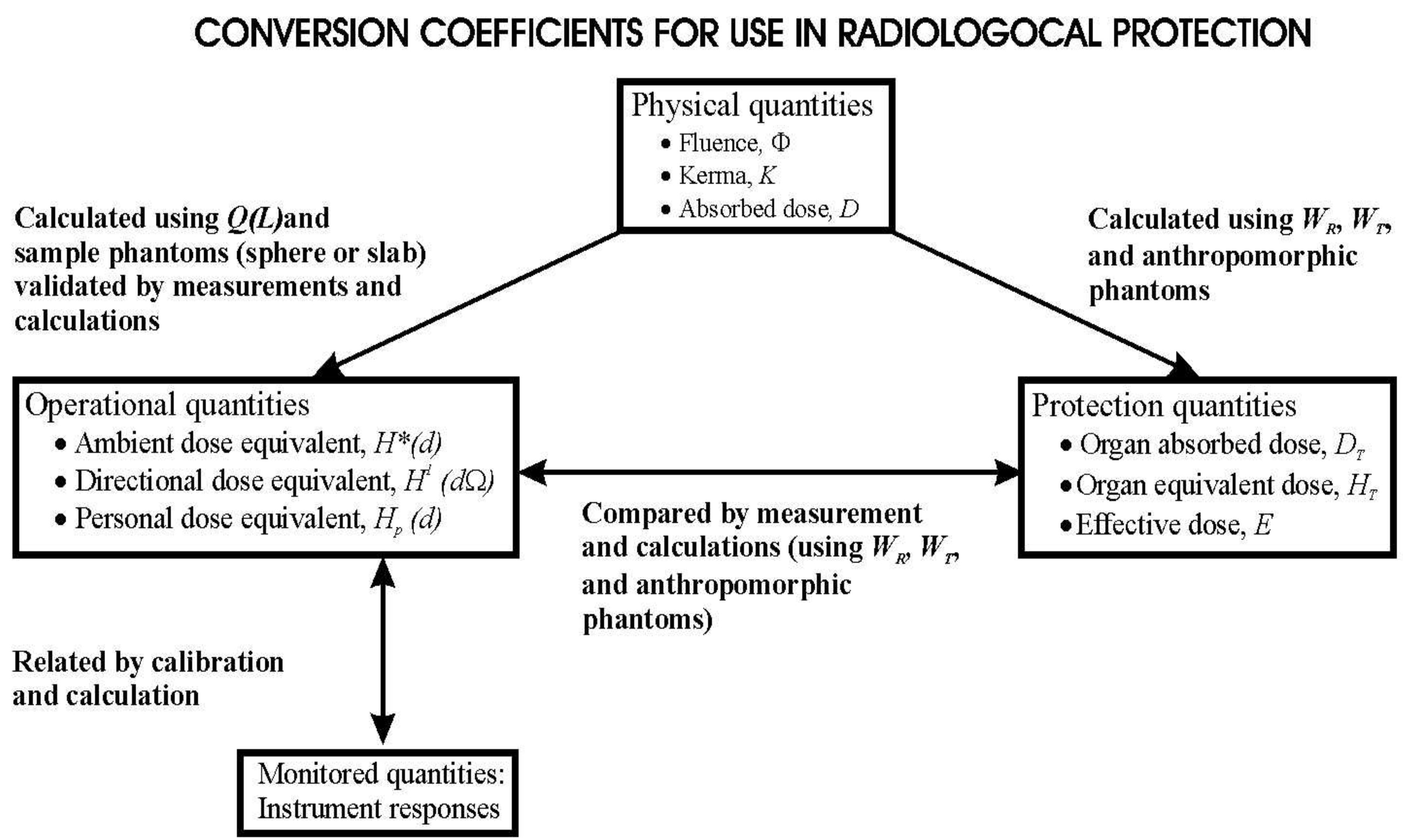
- Personal dose equivalent $H_p(d)$ at a point in a radiation field is the dose equivalent in soft tissue at an appropriate depth d, below a specified point on the body: $H_p(d)$

- Unit: J/kg^{-1}, special name sievert (Sv)

Operational quantities



Quantities


CONVERSION COEFFICIENTS FOR USE IN RADIOLOGOCAL PROTECTION
Physical quantities
• Fluence, Φ
• Kerma, K
• Absorbed dose, D
Calculated using Q(L) and sample phantoms (sphere or slab) validated by measurements and calculations
Calculated using W_R, W_T, and anthropomorphic phantoms
Operational quantities
• Ambient dose equivalent, H*(d)
• Directional dose equivalent, H' (dΩ)
• Personal dose equivalent, H_p (d)
Protection quantities
• Organ absorbed dose, D_T
• Organ equivalent dose, H_T
• Effective dose, E
Compared by measurement and calculations (using W_R, W_T, and anthropomorphic phantoms)
Related by calibration and calculation
Monitored quantities: Instrument responses

Scheme of different detector types

Charge creation

Gas

- Ionization chamber
- Proportional counter
- Geiger Müller counter

Semiconductor

Light creation

Scintillator

Stimulated luminescence

- TL detectors
- OSL detectors
- RPL detectors

Others

Calorimeter

Film detector

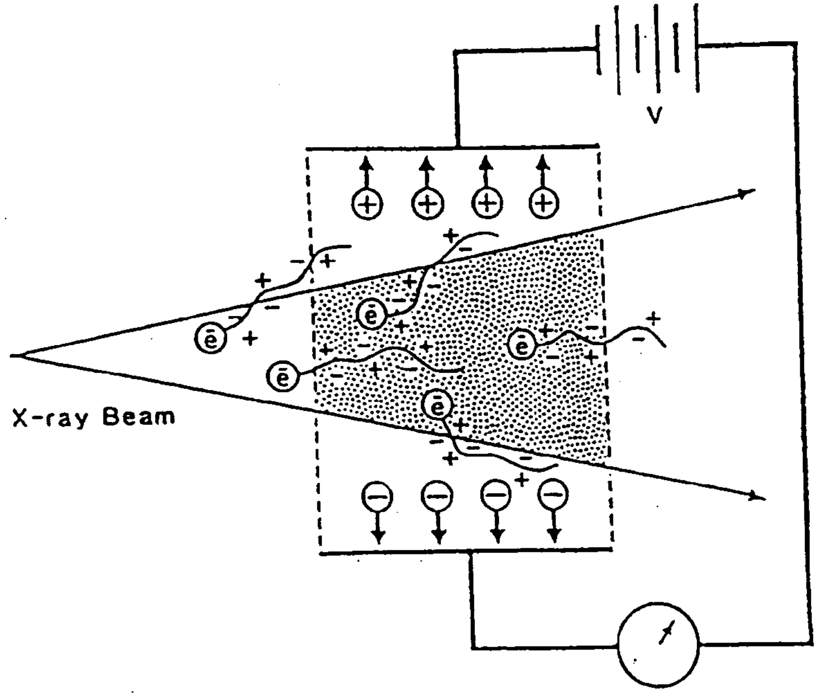
Bubble detector

Track etch detector

Activation detector

Charge creation: Gas counters

- Ionizing radiation causes ionization and excitation
- Creation of free pairs of positively and negatively charged particles
- Charge collection by applying electric field
- Measured current gives information on radiation field

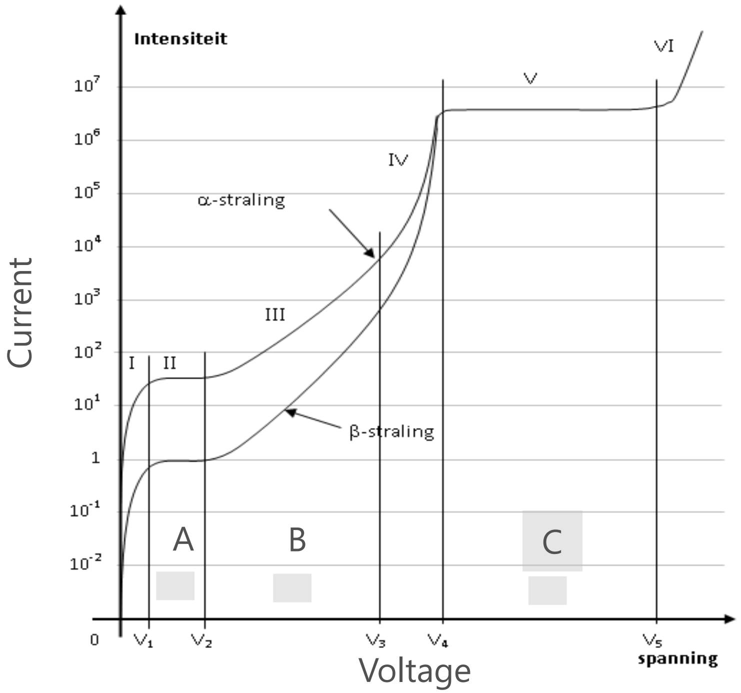


Different gas-filled detectors depending on the voltage

A Gas ionization chamber

B Proportional counter

C Geiger-Müller counter



Ionization chamber

- Low voltage around 200-300 V
- Weak electric current
- Good for measurement of very intense fields
- Single radiation particle current pulse cannot be detected
- Sensitive for atmospheric conditions (temperature, pressure)
- Usually cylindrical, filled with air and fixed to the instrument
- Very rapid response time
- Tend to be expensive, more as reference instrument

Some examples of ionization chambers

RAM ION

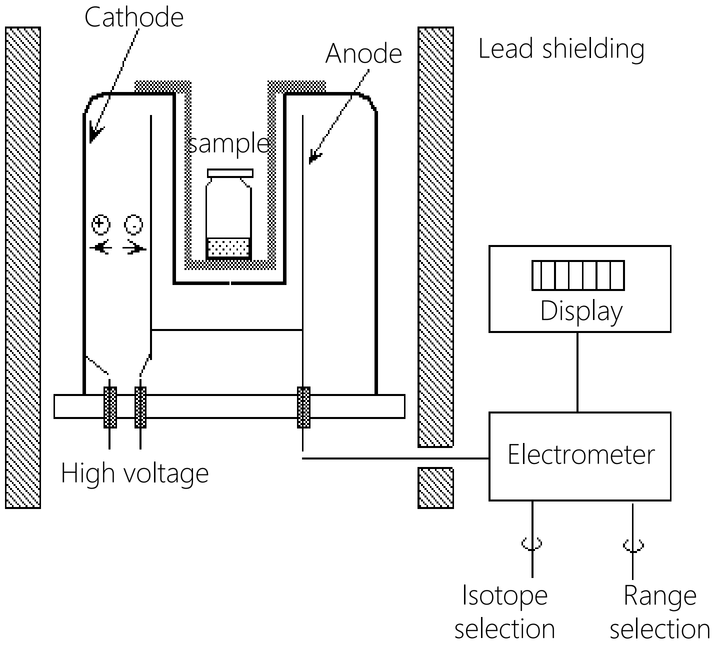
Dose Area Product (DAP) meter

Fluke 481

CT ionization chamber

Some examples of ionization chambers

Dose calibrator in nuclear medicine



Proportional counter

- Voltage high enough such that secondary electrons cause further ionization of the gas
- Inherent current amplification by avalanche effect
- Single radiation particle pulses can be detected
- Pulse height is proportional to the energy deposited by particle
- Alpha particles produce larger pulses than a beta particle or photon
- Discriminator can reject photons and betas
- Can be higly sensitive

Examples of proportional counters

Xenon gas proportional
(low level beta survey)

Alpha air proportional
(Alpha survey)

Large area gas proportional
(alpha – beta survey)

Portable contamination monitor

Geiger Muller counters

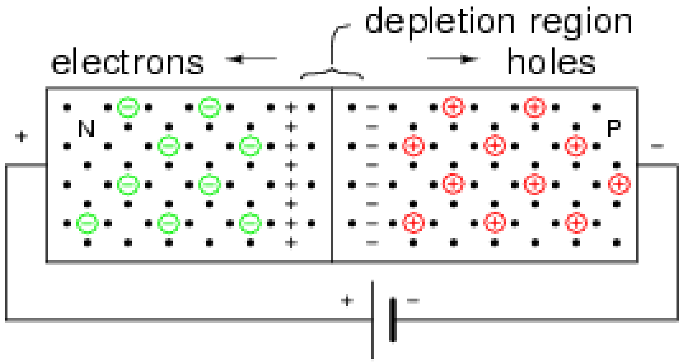
- Further increasing the voltage leads to increasing amount of secondary avalanches
- A single ionizing event in GM tube causes a "pulse" or "count"
- All pulses are the same size
- GM counters cannot distinguish between radiation types or energies
- Simple circuitry
- Can experience “dead time” at higher exposure rates
- Considerable variance in response to different photon energies

Measurement methods

Ambient monitor

Semiconductor detectors

- Semiconductor detectors: two layers of semiconductor material or diode: “n-type” and “p-type”
- Electrons from the n-type migrate across the junction between the two layers to fill the holes in the p-type, creating a depletion zone.
- Radiation interact with the atoms inside the depletion zone leading to the creation of electron-hole pairs
- Under the influence of an electric field, electrons and holes travel to the electrodes, where they result in a pulse that can be measured in an outer circuit
  - The number of pulses: intensity of the incident radiation
  - The pulse height: energy of the radiation

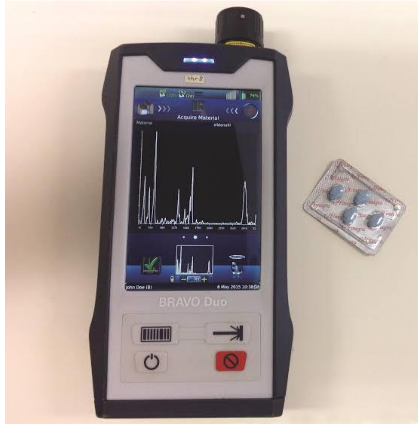


Semiconductor detectors

- The energy required to produce electron-hole-pairs is very low compared to a gas detector (~3 eV in comparison with ~30 eV)
- The small scale of the detector: quick collection of electron-hole pairs: quick response time
- Consequently the energy resolution is higher (spectroscopy)
- High density: charged particles give off their energy in relatively small dimensions
- Mostly Si-based. Other type of semiconductor detectors: diamond, Germanium, Cadmium telluride (CdTe), cadmium zinc telluride (CZT) detectors

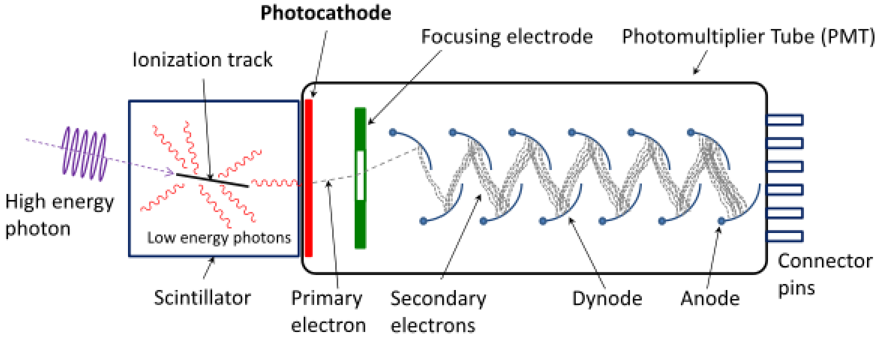
Examples of semiconductor detectors

Portable monitors and spectrometers




Scintillator detectors

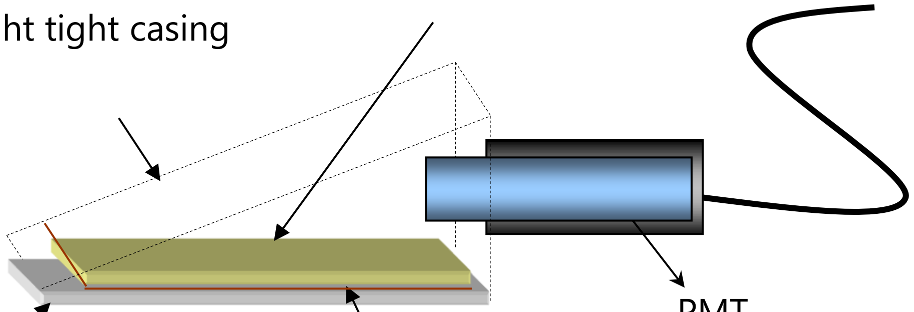
- Radiation interacts with the scintillator material: results in a distinct flash of light
- Connection of a scintillator material with a photomultiplier (PM) tube
- PM tube uses a photocathode in combination with a series of electrodes (dynodes) to convert each pulse of light into a current pulse (or CCD camera)
- Signal processed by electronics: amplification to generate a voltage pulse that can then be read and interpreted
- Number of pulses: indication of the strength of the radioactive source
- Pulse height proportional to energy deposited: spectroscopy possible
- Highly sensitive



Scintillator detectors

- Appropriate scintillator materials
  - Plastic scintillators
  - Liquid organic scintillators
  - Solid inorganic scintillators such as NaI(Tl) and CsI(Tl)
- Spectroscopy (even for gamma) with limited energy resolution
- Radiation detected depends on material:
  - Sodium iodide: photons
  - Anthracene or plastic: betas
  - Zinc sulfide: alphas
  - Cesium iodide (CsI): protons and alpha particles.
- The scintillator must be shielded from all ambient light
  - To achieve this a thin opaque foil, such as aluminized mylar, is often used

Examples of scintillator detectors



Dual scintillator for surface contamination monitor

Examples of scintillator detectors

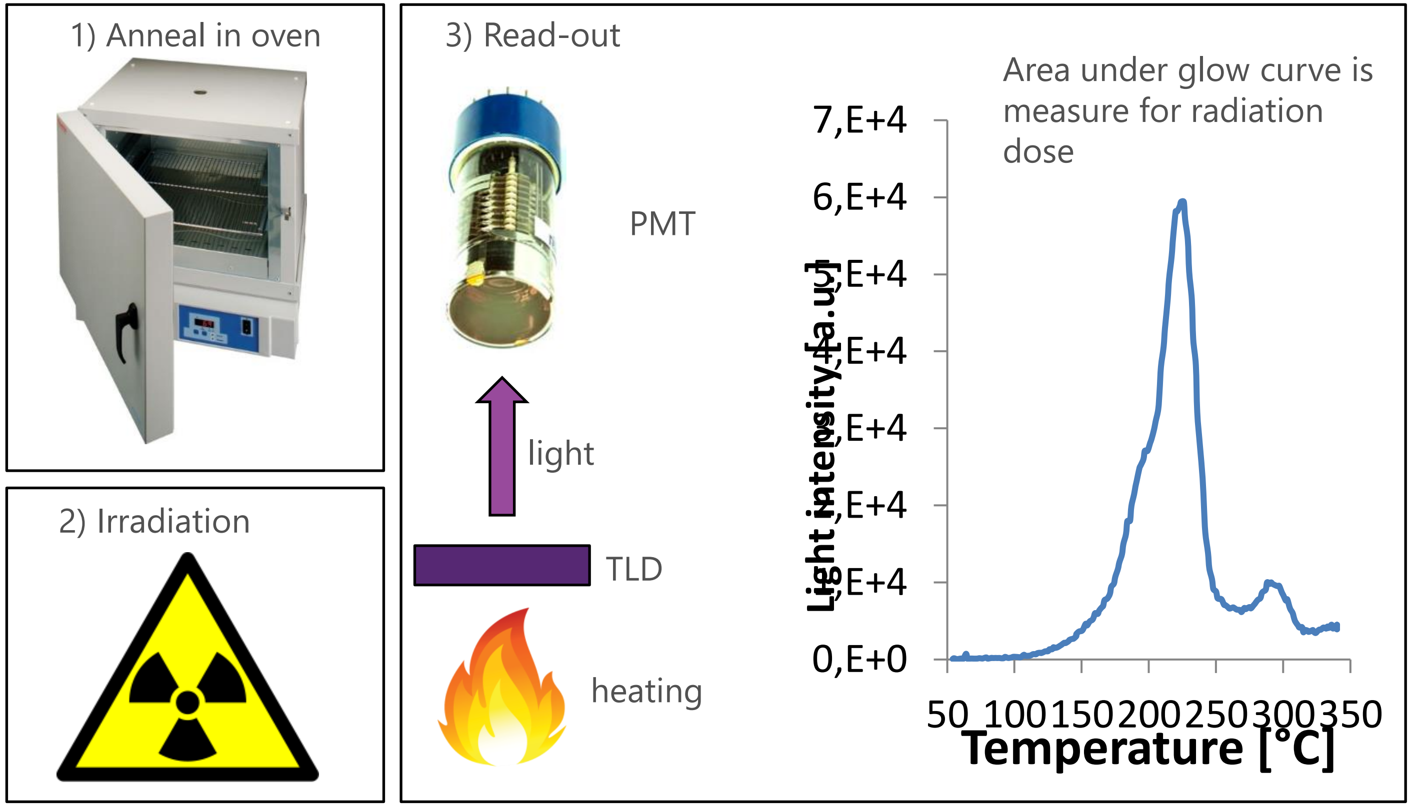
Portable monitors and spectrometers

Instruments for surface contamination monitoring

- Surface contamination
  - Activity per surface: Bq/m^2 (or cps)
  - Type of contamination: isotope
- Direct method:
  - Detecting contamination directly using instruments
  - For both fixed and loose contamination
- Indirect method:
  - Using of dry or wet wipes
  - Detecting contamination on wipes using instruments
  - Used to detect loose contamination and by calculation the total contamination
- Selection of monitor according the type and energy of the radiation
  - A full list of nuclides which could be encountered must be made
  - The calibration of the monitor also requires knowledge of type and energy of radiation
  - Conversion from cps to Bq/m^2: detection efficiency
- Mostly, a range of different contamination monitors is needed

Types of personal dosemeters

Thermoluminescence dosimetry (TLD)

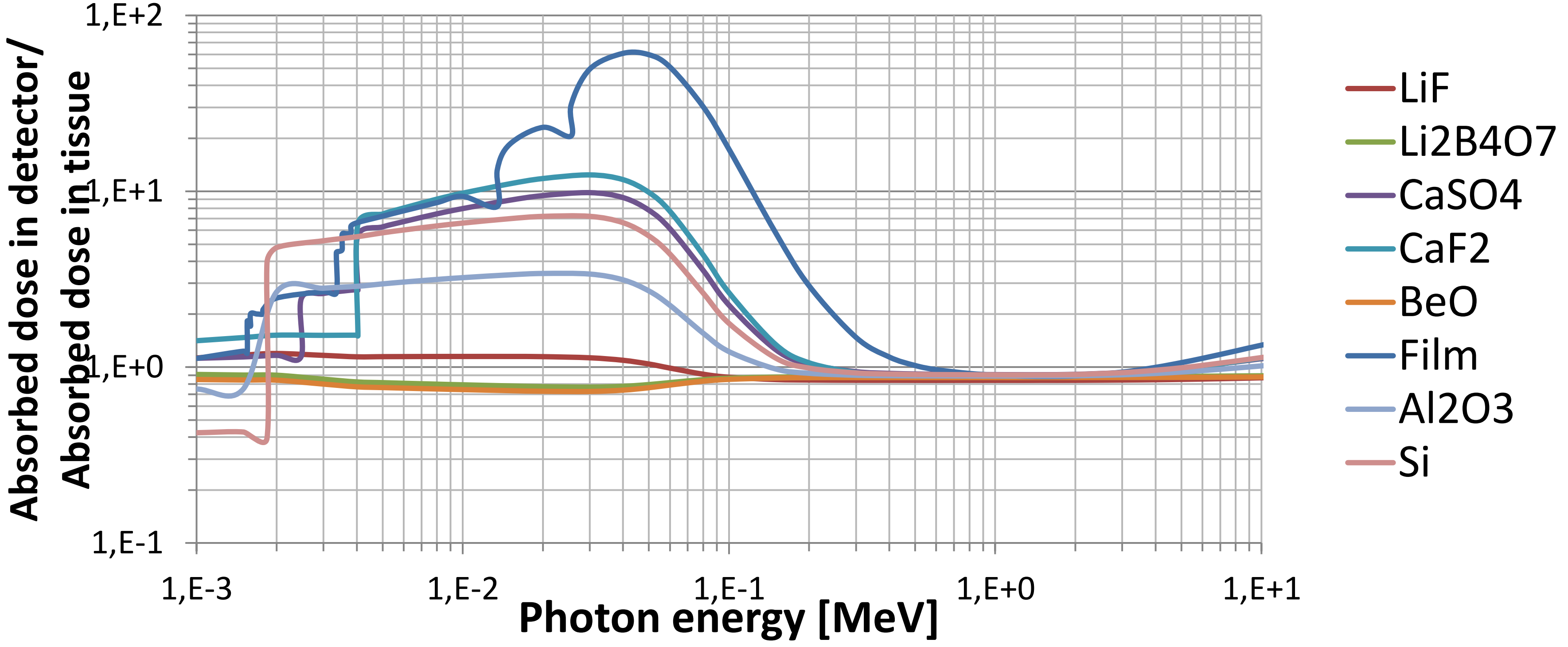


Thermoluminescence dosimetry (TLD)

- Easy process of read-out
- Some TL materials are nearly tissue-equivalent
- TL offers high sensitivity, accuracy, low detection limit and linearity over a wide dose range
- Many TL materials are commercially available as small solid detectors adaptable for automatic processing
- Particularly suited to eye lens and extremity dosimetry

- Examples: LiF: Mg,Ti; LiF: Mg,Cu,P; $Li_2B_4O_7$:Mn; $CaSO_4$: Dy; CaF_2:Tm; BeO
- Li-based TLD's most used because of their near tissue equivalence

Energy dependence of TLD materials



Thermoluminescence dosimetry (TLD)

- Pro’s and con’s
- Advantages
  - Very compact
  - Reusable
  - High sensitivity
  - Near tissue equivalence
- Disadvantages
  - Only one read out is possible
  - Reproducible and controlled heating is a challenge
  - Fading (depending on material and preheat)

- Often used in occupational dosimetry: different commercial systems available

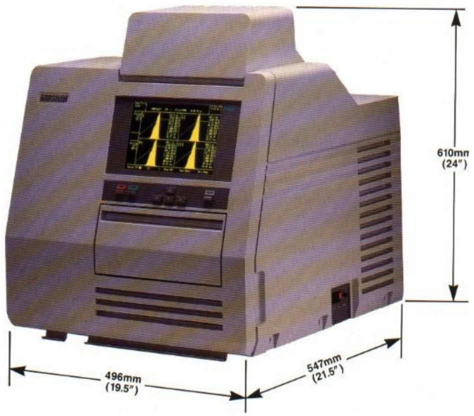
Thermoluminescence dosimetry (TLD)

- Also used for patient dosimetry

Measurements of organ doses with anthropomorphic phantoms

Commercial TLD systems

- Harshaw
- Different configurations in badge possible (2 or 4 elements)
- LiF:Mg,Ti detectors (also possible with LiF:Mg,Cu,P)
- Readers of different size and capacity



Commercial TLD systems

- Panasonic
- Badge consists of
    - 2 $CaSO_4$:Tm detectors
    - High sensitivity but not tissue equivalent
    - 2 $Li_2B_4O_7$:Cu detectors
    - Near tissue equivalent
- Branching algorithm to calculate $H_p(10)$

Commercial TLD systems

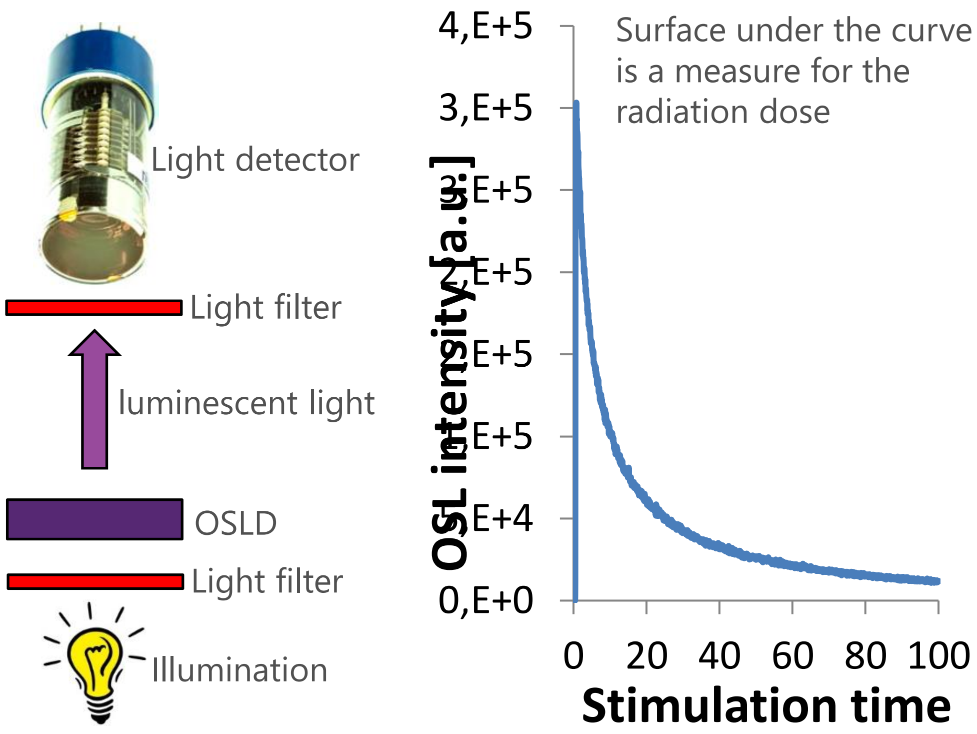
- Rados
- Badge consists of 2 or 4 elements
- LiF:Mg,Ti or LiF:Mg,Cu,P detectors
- Different filters possible

Optically Stimulated Luminescence dosimetry (OSLD)

1) reset OSLD by illumination

2) Irradiation OSLD

3) Read out OSLD



OSLD materials

- Examples:
  - Al_2O_3:C
    - Al2O3:C powder is mixed with a polyester binder and coated onto a roll of clear polystyrene film (Luxel)
    - Not tissue equivalent: multiple element dosemeter needed + algorithm
    - The wavelength of the stimulation beam is 532 nm
    - Blue luminescence has a peak wavelength of 420 nm
  - Halides: KCl, KBr, NaCl, RbI, CaF_2
  - Sulfates: $MgSO_4$, $CaSO_4$
  - Sulfides: MgS, SrS, CaS, BaS
  - Oxides: BeO
    - Near tissue equivalent, Toxic
    - The wavelength of the stimulation beam is around 450 nm
    - The wavelength of the emission is around 270 nm
- Only Al_2O_3:C and BeO have been developed into commercial systems

Optically Stimulated Luminescence dosimetry (OSLD)

- Pro’s and con’s
- Advantages
  - Very compact
  - Reusable
  - High sensitivity
  - Fast and controllable read out
  - Multiple read outs are possible
  - Near tissue equivalent (BeO)
- Disadvantages
  - Not tissue equivalent (Al2O3:C)
  - Need to be shielded from environmental light

- Increasingly used in occupational dosimetry

Commercial OSLD systems

- Landauer
- Badge consists of 4 elements of Al_2O_3:C behind different filters
- Algorithm to calculate $H_p(0.07)$ and $H_p(10)$
- Readers of different sizes and capacities

Commercial OSLD systems

- Dosimetrics
- Badge consists of BeO material
- Different badge layout and number of elements possible

Commercial OSLD systems

- Radpro: MyOSL
- Badge consists of BeO material

Commercial OSLD systems

- RADKOR: Pdose, WBDose
- Badge consists of BeO material

Radiophotoluminescence dosimetry (RPLD)

- Photoluminescence is based on formation of induced luminescent centers in silver doped phosphate glass
- Electrons can be excited to these luminescent centres by ionizing radiation
- Trapped electrons can be excited within the luminescent centers by UV light
- When exposed to UV light, fluorescent light of a larger wave length is emitted with intensity linearly related to absorbed dose
- Centers are not destroyed by normal read-out and are stable
- Because of the high Z value of the glass materials, energy compensation filters are required
- Annealing (heating) is needed to reuse detector

Radiophotoluminescence dosimetry (RPLD)

- Pro’s and con’s
- Advantages
  - Compact
  - Reusable
  - Fast and controllable read out
  - Multiple read outs are possible, no signal loss
  - No need to shield from environmental light
- Disadvantages
  - Not tissue equivalent
  - High temperature anneal needed for reuse

Commercial RPLD systems

- Chiyoda
- Badge consists of phosphate glass material
- Different elements behind different filters with an algorithm

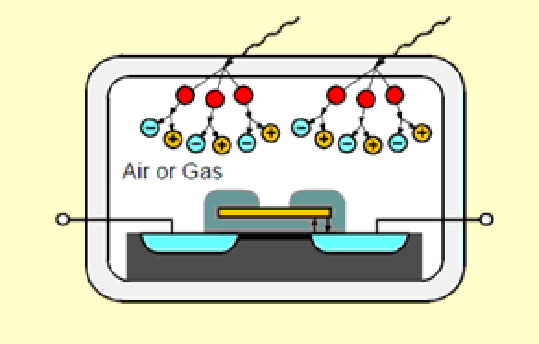
Glass Badge for wide energy range

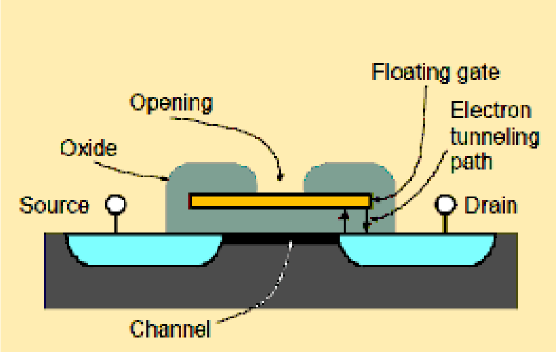
Glass Badge for neutrons over wide range

Glass Ring

Direct Ion Storage (DIS), semiconductor

- Principle of operation
- Radiation creates charges in small ionisation chamber above the detector
- Charges are collected on floating gate of Mosfet
- Measurement of voltage gives indication of dose
- Measurement is non destructive





- Direct Ion Storage: Instadose

- No more monthly exchange:
  - Dosemeter can stay with wearer
  - Exchange when dosemeter is full (100 mSv)
  - Exchange when recalibration is needed
- Read out is automatic
- Read-out frequency can be programmed
- Extra read outs are possible by push on button
- Dose measurements stored in dosemeter, even without transfer possibilities
- Change of wearer is possible at any time
- Background still needs to be subtracted
- Detection limit can be higher than other techniques

Advantages of APDs

- Immediate read-out possible
    - More feedback to worker
    - Better use and care for dosemeters by workers
    - Will in general help in decreasing doses
- Alarm function possible
- Instant or direct reading
- Data transfer to and from computer network
- They measure $H_p(10)$ at least as good than passive dosemeters
- Lower detection limit

Limitations of APDs

- Dosemeter cost
- Mass and size of dosemeter
- Battery type and life span
- Possibly poor low energy photon energy dependence
- Poor beta radiation response
- Sensitivity to electromagnetic fields (older models)
- Possibly saturation at high dose rates

For what purpose are they used?

- Supplementary dosemeters of the direct reading type
  - For controlling individual exposure on a day to day basis
  - During a particular task
  - Can be useful for optimisation
- Can be recommended for specific purposes
  - Short term radiation control of workers’ exposures, or during a particular task
  - For situations where the radiation field could increase unexpectedly and significantly (say, by a factor of ten)
  - For operations of short duration in high radiation fields
- Maintains alertness to possible accidental exposures
- Useful for education and training
- Sometimes used for visitors and outside workers, pregnant staff
- Mostly passive for legal dose of record, while APD is used as ALARA or alarm dosemeter
- Possibly also for record keeping purposes (the dosemeter of record)

Active personal dosemeters

- Many types of active personal dosemeters are commercially available (>50)
    - Some on Geiger-Müller detection methods
    - Most with semiconductor detection methods (diodes)
- GM devices mainly for photons >30 keV
- GM devices not suited for pulsed fields
- Diode based APDs can have several diodes for simultaneous measurement of $H_p(10)$ and $H_p(0.07)$ for photons and betas
- Large variation in specifications and quality

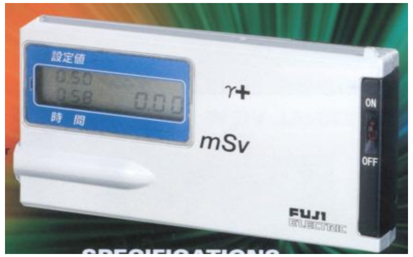
Some selected types of APDs

Raysafe i3

Rados RAD60

Polimaster PM1721

Mirion DMC3000



Fuji Dosemeter

ThermoFischer TruDose

Tracerco PED+

Monitoring of extremity doses

- $H_p(10)$ is considered an estimate of effective dose E
- Dose limit for stochastic effects is 20 mSv/year for E
- If $H_p(10)$ is below dose limit, no risk for deterministic or tissue effects
    - Except for localised and non-homogeneous exposures, like skin on the extremities
- Extremity dosemeters sometimes needed to assess doses to skin, hands/ forearms, feet/ankles…

Quantities: how to measure extremity doses

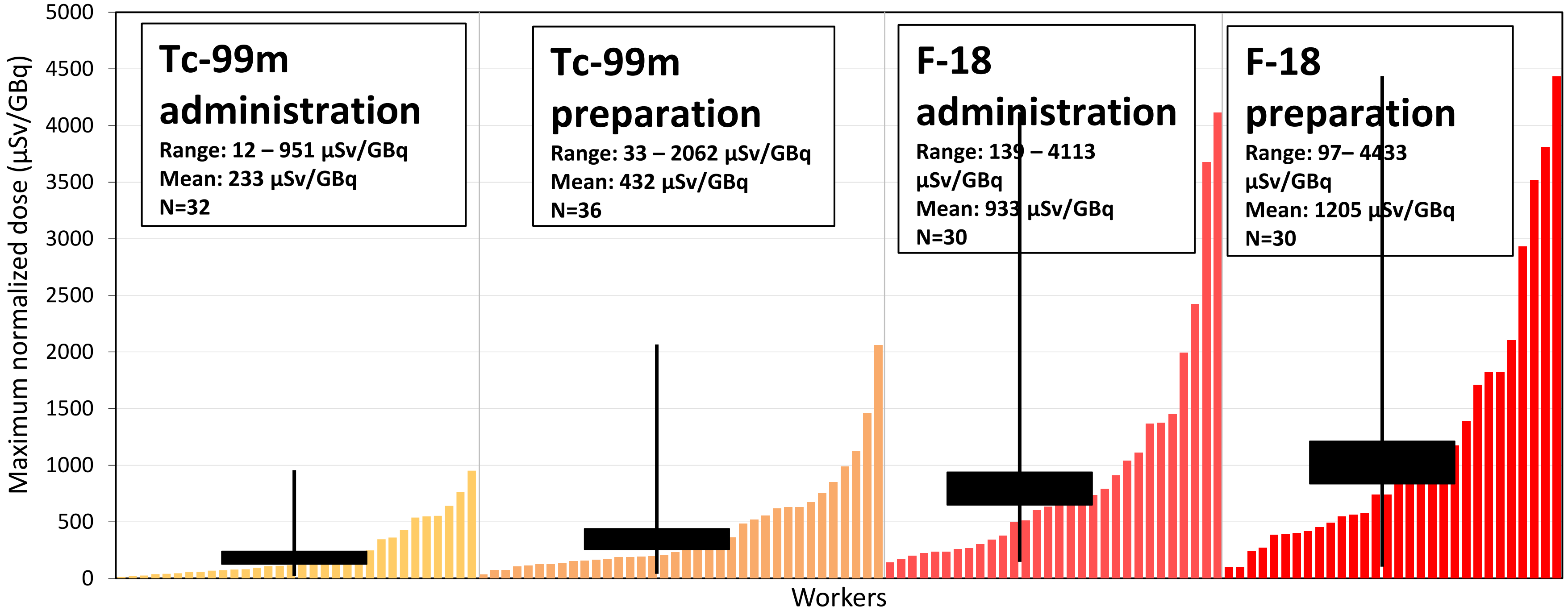
- Skin and extremity monitoring:
  - Measurement of $H_p(0,07)$, the equivalent dose to the skin
- The ICRP recommended dose limits :
  - An equivalent dose limit to the extremities (hands and feet) or the skin of 500 mSv in a year
  - The equivalent dose limits for the skin apply to the average dose over 1 cm^2 of the most highly irradiated area of the skin

- In practice, an estimate of equivalent dose to the skin is a conservative estimate of equivalent dose to the extremities

Extremity dosimetry

- The equivalent dose limits for the skin apply to the average dose over 1 cm^2 of the most highly irradiated area of the skin
  - Most highly irradiated area is not known in advance….
  - Very dependent of situation, person, isotopes, procedure,…

- ORAMED data: Very large range of maximum finger doses among the same procedure…



When monitoring?

- In situations with nonhomogeneous exposure conditions for which the whole-body monitoring does not provide an adequate estimate of the dose to the skin or the extremities
  - Exposures can be significant when weakly penetrating radiation such as low energy photons or beta radiation is present
  - Workplaces where extremities are particularly close to the radiation emitter or radiation beam
    - E.g. nuclear medicine, and dismantling applications
- The following monitoring levels are recommended:
  - 3/10th of the limit, as recommended in European BSS
  - For dose levels expected to be lower than the recommended monitoring levels, a survey, demonstrating that the levels are not exceeded, should be sufficient.

Assessment of dose levels prior to monitoring

- Prior to routine monitoring, it is important to assess the dose levels in a workplace field situation in order to decide which method and period of routine monitoring is necessary
- The doses obtained should be extrapolated to annual doses and compared with the monitoring levels
- The assessment should be repeated when the working conditions or workload change significantly, or if the effect of such changes cannot be estimated with confidence

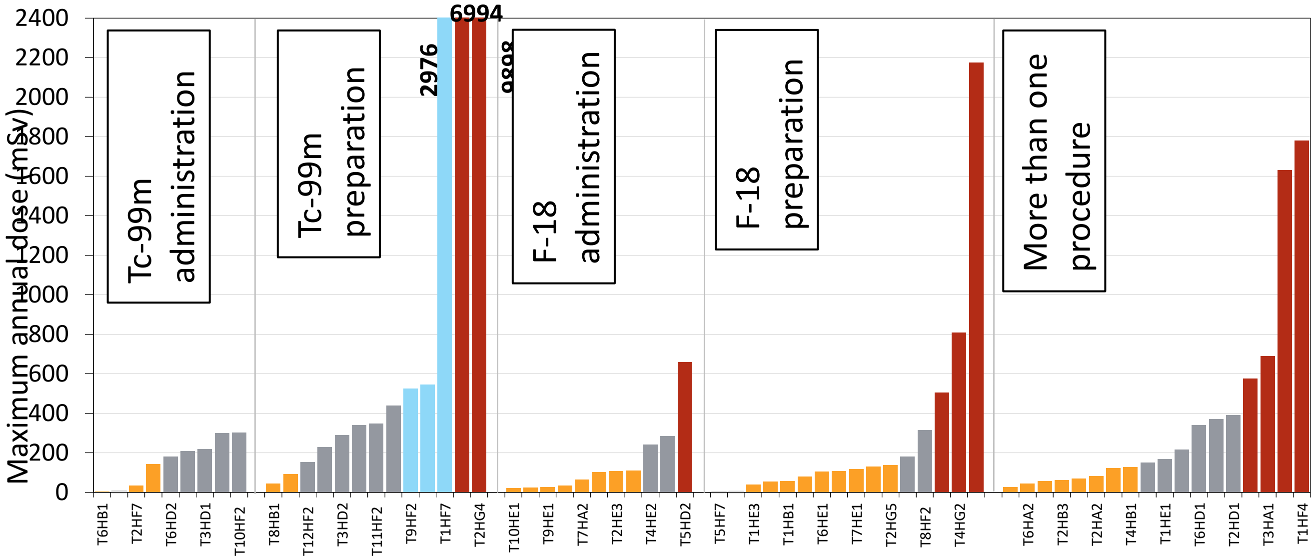
Indications from literature

- Martin and Whitby: with good practices it is possible to stay within the limits

Group	Range of annual doses [mSv]
Interventional radiologists (hands)	10-200
Interventional radiologists (legs)	10-200
Interventional radiologists (legs, with shield)	1-15
Cardiologists (hands)	5-100
Cardiologists (legs)	5-100
Cardiologists (legs, with shield)	0.5-10
Radiopharmacy staff	10-200
Nuclear medicine staff	5-40

Indications from literature

- ORAMED project: Annual dose estimation for nuclear medicine workers
- Real risk of surpassing the dose limits



D < 150 mSv → 49%

150 mSv < D < 500 mSv

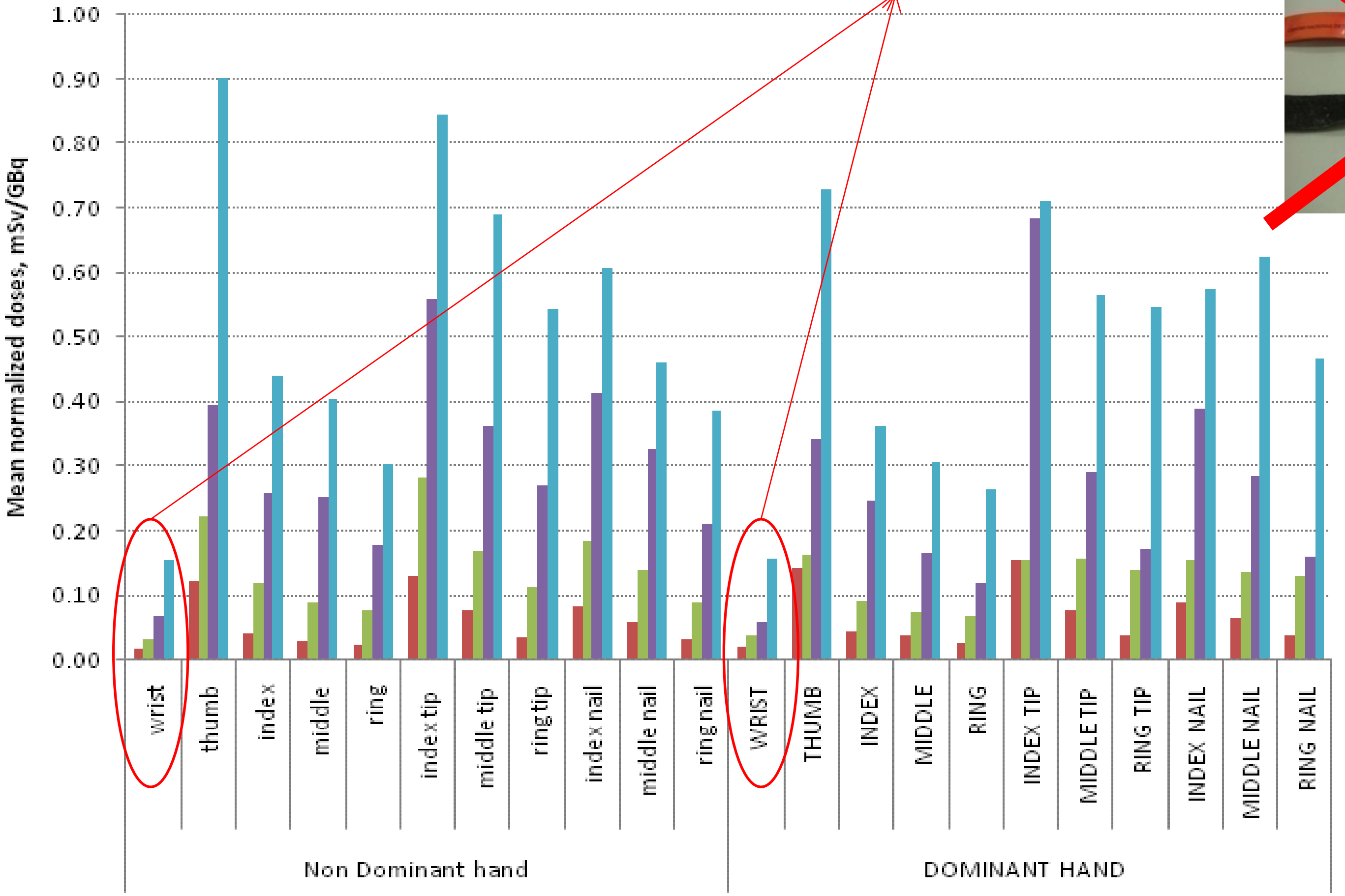
D > 500 mSv → 19%

Locations to monitor

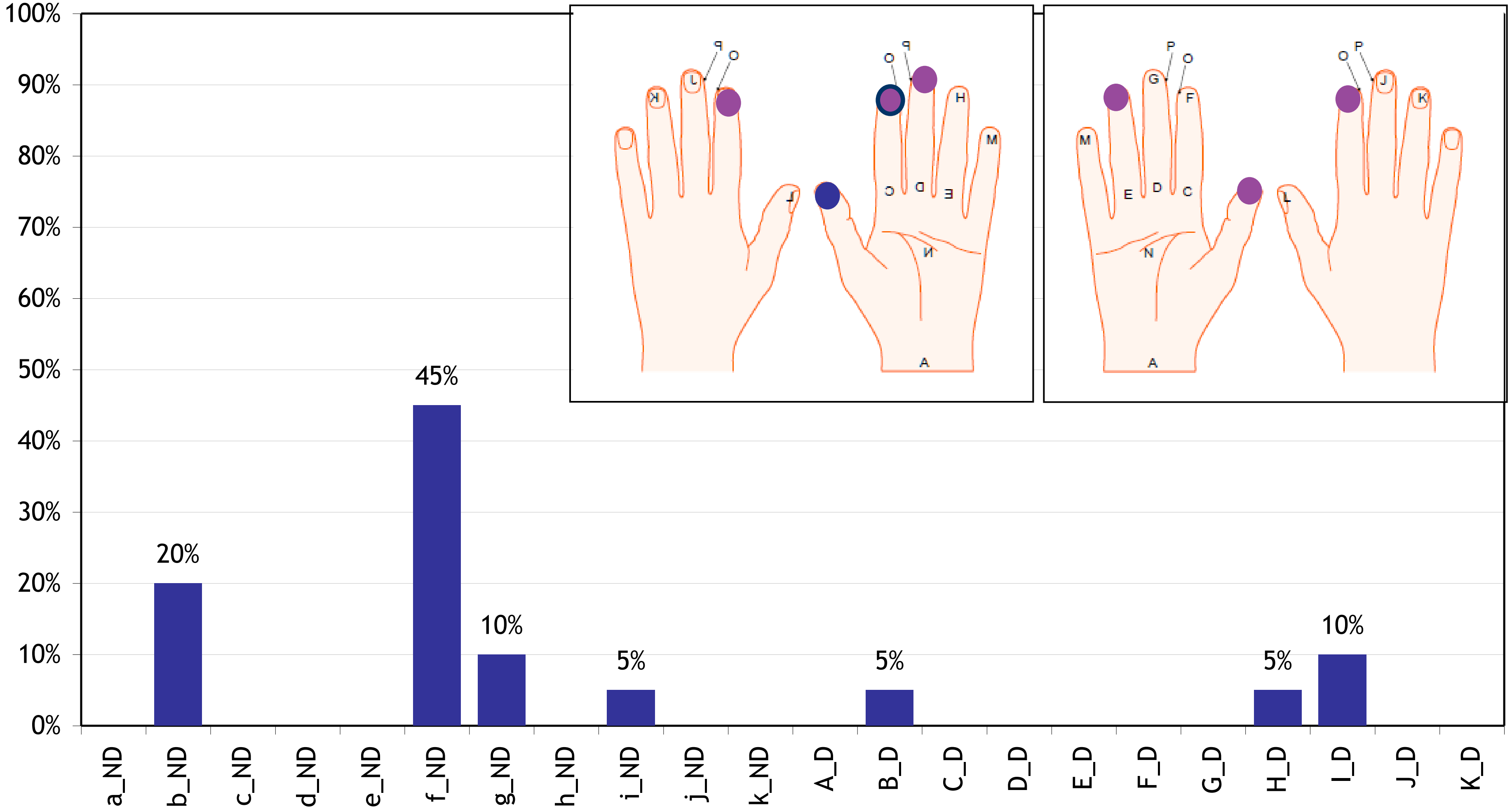
- For direct or close handling of radioactive sources, finger-stall dosemeters on the fingertip, or ring dosemeters should be used on the finger which is frequently the most exposed
- The dosemeter should be oriented towards the radiation source
- For nuclear industry fields, interventional radiology, or other similar radiation fields, either a ring dosemeter or a wrist dosemeter worn at the most exposed hand shall be used
- The dosemeter shall be worn under protective clothing, especially inside gloves, if such clothing is worn

Extremity dosimetry

Wrist or ring dosemeter?

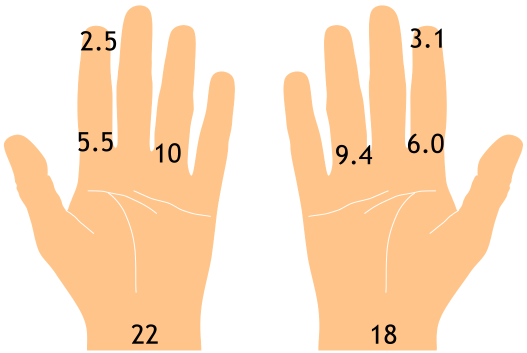


Maximum can be on different locations of the hand

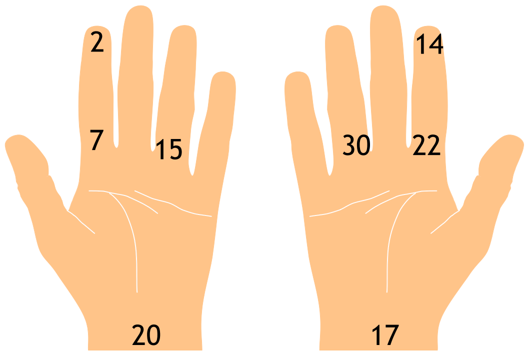


Application of correction factor

- Common extremity monitoring positions, such as the base of the fingers or the wrist, often underestimate the maximum dose
- To estimate the maximum skin dose from a routine dosemeter, a correction factor shall be established and employed
- ORAMED: multiplying the reading of the dosemeter worn in the base of the index of the non dominant hand by 6
- Other studies: Ranges from 1.4 to 7.0 for different manipulations and operators
- ICRP Publication 106 recommends placing the routine dosemeter on the base of the middle finger with the detector positioned on the palm side. In this case, a correction factor of 3 should be applied

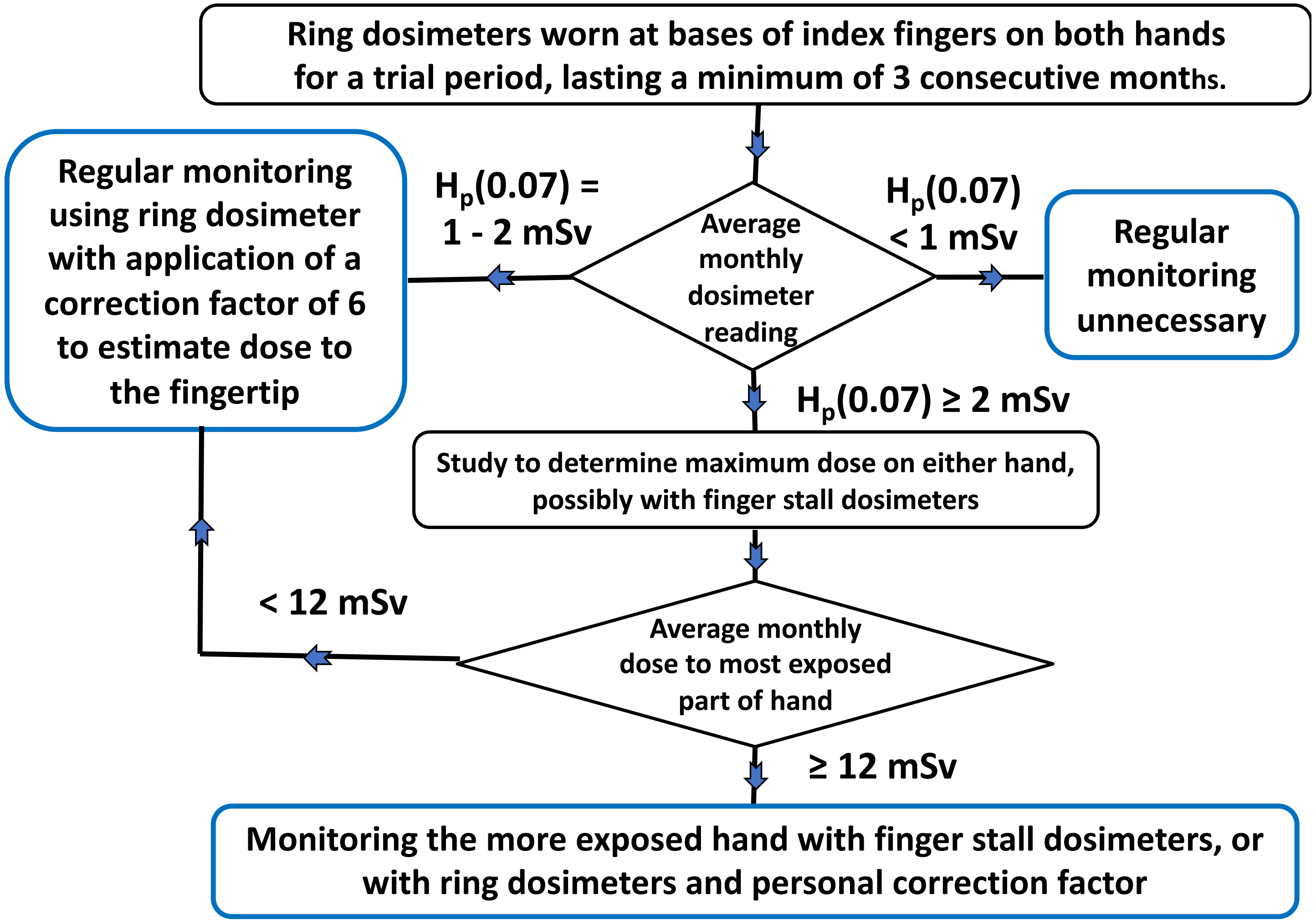


Diagnostics



Therapy

ICRP guidance on when to use extremity dosimetry



Types of extremity dosemeters

- Only one element is mostly possible in ring dosemeter
- Limited to tissue equivalent detectors, not possible to use algorithm
- A simple, one element TLD may be sufficient
- Also OSL materials possible
- The detector should be thin
- Filtered by a tissue equivalent material so that the dose at a nominal depth of 7 mg/cm^2 can be assessed
- Measurement in the range 5 to 10 mg/cm^2 would suffice
- Two types of passive dosimeter:
  - Rings: worn at the thumb, index, middle or ring finger
  - Finger-stalls: with the detector located at the fingertip
  - Wrist dosimeters are not recommended

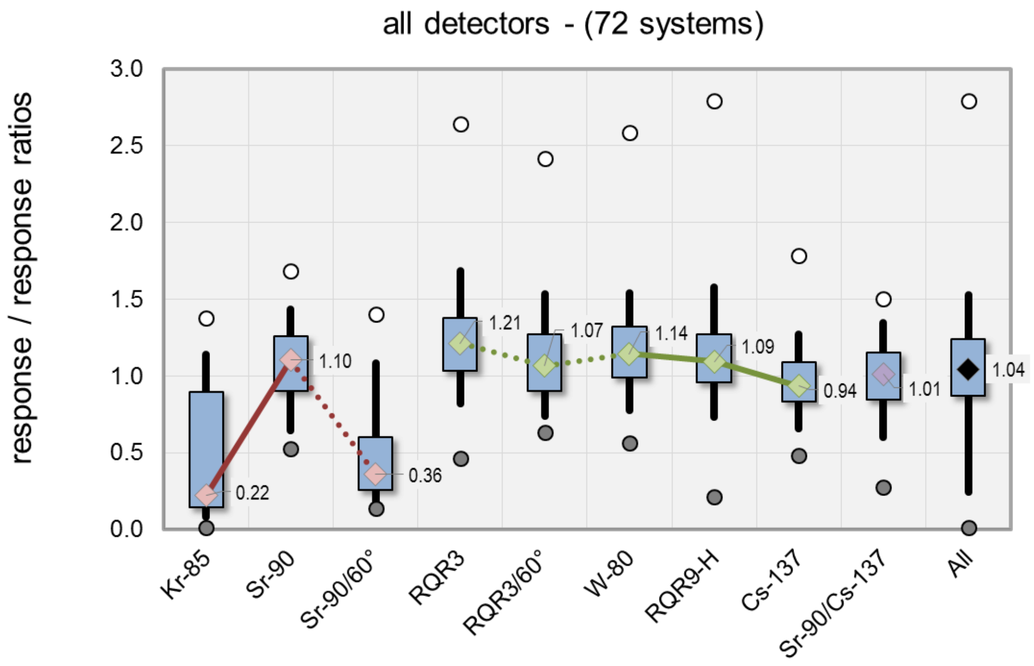




Performance of extremity dosemeters

- EURADOS intercomparisons

detector type	systems	% of all	% of type
TLD	**69**	**96%**	
LiF:Mg,Ti	36	50%	52%
LiF:Mg,Cu,P	29	40%	42%
Li2B4O7:Cu	3	4%	4%
LiF:Mg,Ti/LiF:Mg,Cu,P	1	1%	1%
Other	**3**	**4%**	
AlO	2	3%	67%
LiF T-100	1	1%	33%
All	**72**	**100%**	



How to measure eye lens doses

- Dose limit: 20 mSv/year
  - for $H_{T,\ eyelens}$: equivalent dose at the eye lens

- Not directly measurable
  - Need for operational quantity: $H_p(3)$
  - $H_p(3)$: Equivalent dose at 3 mm depth

- Operational quantity > limiting quantity

When to measure eye lens doses

- The following monitoring levels are recommended:
  - 3/10th of the limit, as recommended in European BSS
  - For the lens of the eye: if there is a reasonable probability to receive a dose in a single year greater than 15 mSv or in consecutive years greater than 6 mSv per year.
  - For dose levels expected to be lower than the recommended monitoring levels, a survey, demonstrating that the levels are not exceeded, should be sufficient.
- Prior to routine monitoring, it is important to assess the dose levels in a workplace field situation in order to decide which method and period of routine monitoring that is necessary

Literature data

- Very few data available, large individual variability, largely dependent on workload and procedural technique

- Kopec et al (Radiat. Meas. 46, 2011)
  - Ratio Hp(10)/Hp(3):
  - Scintigraphy : 1,1 ± 0,2
  - PET : 0,9 ± 0,5

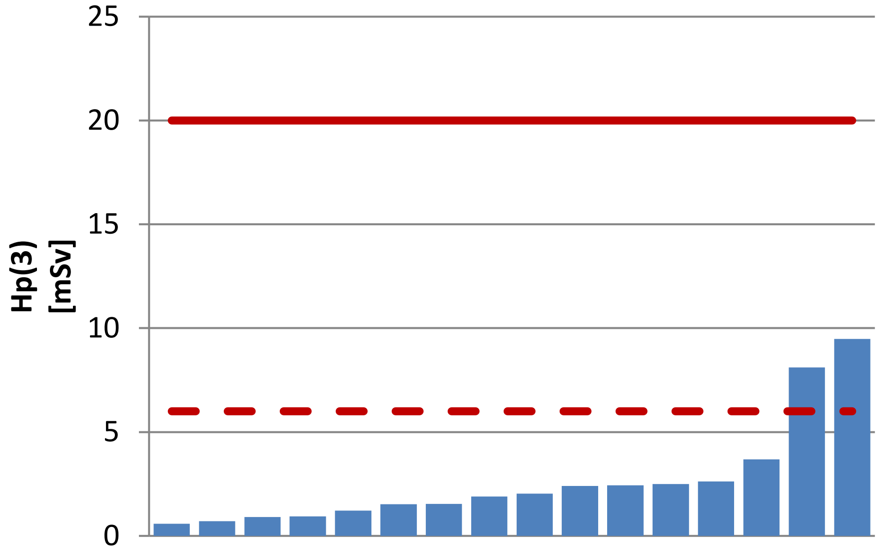
- Summers et al (Nucl. Med. Commun. 33(5), 2012)
  - Typical yearly workload: (Tc-99m and I-131):
  - around 4,5 mSv

- Leide-Svegborn (Radiat. Prot. Dosim. 149, 2012)
  - Typical yearly workload: (Tc-99m and I-131):
  - around 8 mSv

Eye lens dosimetry

Belgian study

- Dose measurements
  - Eye lens dose (MCP TLD, Hp(3))
  - Extrapolated to annual workload
- Procedures:
  - Preparation and administration
  - Radionuclides: Mostly Tc-99m and F-18
    - Also Ga-68, I-123, I-131,...
- All yearly doses below 20 mSv
  - But 6 mSv (3/10th of the limit) can be exceeded

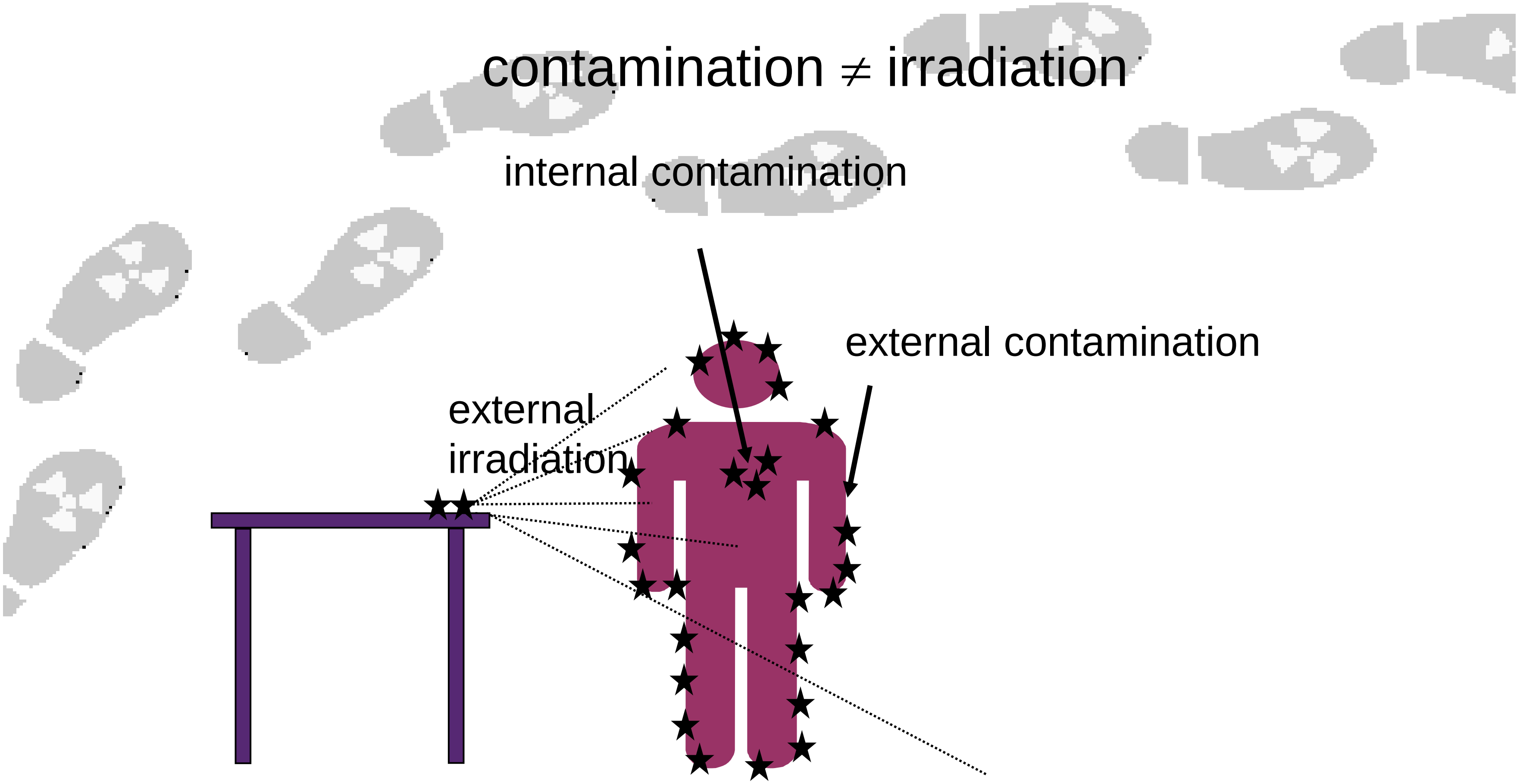


- Routine monitoring?
  - Use of correlation between chest – eye lens dose (chest dosimeter)

Eye lens dosimetry

- Dosemeters designed specifically for $H_p(3)$ are available
    - Measurement of $H_p(0.07)$ or sometimes $H_p(10)$ may provide estimate
- A simple, one element tissue equivalent detector will be sufficient
    - Filtered by a tissue equivalent material so that the dose at a nominal depth of 300 mg/cm^2 can be assessed
    - Should be responsive to backscatter
    - Multiple element detectors very difficult to implement in eye lens dosemeters
    - In practice limited to tissue equivalent detectors
- Radiation doses to the eyes have been found to be similar to whole-body doses
    - A whole-body dosimeter worn on the chest should give a measure of probable eye dose levels
    - If these are high (approaching 6 mSv per year), independent measurements of eye doses should confirm the levels of the eye lens doses

contamination ≠ irradiation



Skin dose monitoring under contamination

- Immediate and rapid decontamination measures are of higher priority than an exact evaluation of skin activity and dose
- There is a proportional relationship between instrumentation count rate and skin dose rate for contamination averaged over a small area (1 cm^2 or less)
  - Evaluations where the dose is low can be done without knowing the individual radionuclide activities, as the uncertainties will be big anyhow
  - For higher doses, though, it is important to determine the radionuclide activities so that a more accurate estimation of the skin dose can be made
- When contamination is on protective clothing (e.g. gloves), it contributes to the skin dose
  - Its contribution to the skin dose should be quantified, **taking into account attenuation** through the protective clothing

Estimation of the dose to the skin from contamination

- A skin contamination in the working environment is unlikely to be recorded by a personal dosemeter but can be detected by the routine use of contamination monitors.
- To evaluate the contribution of the contamination to the skin dose an on-site investigation shall be performed to localize and identify the contamination and then quantify its activity.
- Characteristics (size and position) and activity values for radionuclides on the skin as well as the duration of the contamination are necessary for the dose assessment.
- The dose rates per unit of activity over 1 cm^2 can be calculated by several methods: a calculation with the deterministic code like VARSKIN and a Monte Carlo simulation code of radiation transport

Estimation of the dose to the skin from contamination

- The contamination on protective clothing (e.g. gloves) irradiates the skin and contributes to the skin dose. Its contribution to the skin dose should be quantified.
- After quantification, if its value is higher than the dosemeter reading, it shall be registered as the skin dose value
- When the contamination is homogenous across the protective clothing or located directly at the dosemeter position, the dosemeter reading already takes into account the contribution.
- If an individual dosemeter is contaminated, the dosemeter reading is larger than the true dose to the respective individual.
- If the time the dosemeter has been contaminated, the activity and position of the contamination is known, this excessive reading of the dosemeter can be determined.

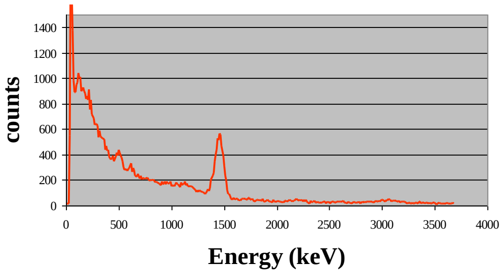
- Assessment of internal exposure:

- Risk of internal exposure: area monitoring
  - Determine activity concentration in air or intake of activity into the body
    - To be used as an indication of whether there is the potential for a significant individual exposure
  - The particular radioactive materials and exposure pathways of the relevant workplace should be taken into account
  - If the level is exceeded:
    - Additional direct measurements of the individual's internal exposure may be necessary

- This may also be desirable if there is any doubt if the assessed exposure for the specific workplace conditions is sufficiently accurate
- Or if contaminations have taken place

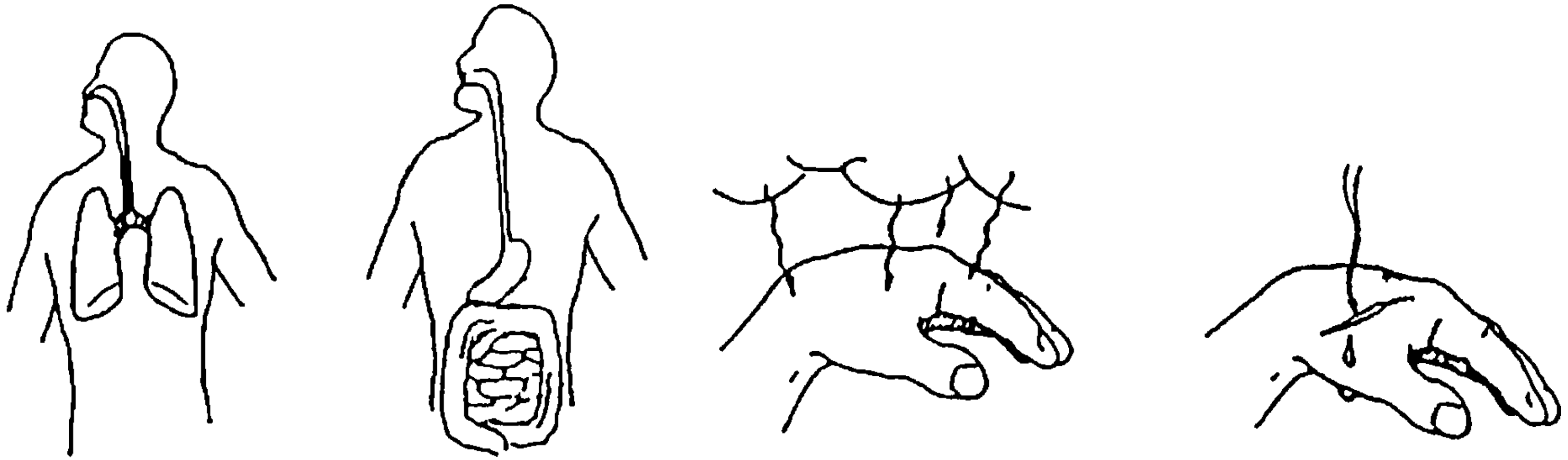
Internal dose monitoring

- An individual monitoring program for internal contamination should be decided based on risk assessment
  - E.g. Safety Standards Series, RS-G-1.2: Assessment of occupational exposure due to intakes of radionuclides
    - If the decision factor is positive, a technique of **whole-body counting** should be implemented to quantify the internal contamination (in Bq)
    - Once the activity (and the timing) is known, **an estimate of dose** can be obtained



Pathways

- inhalation
- ingestion
- penetration through the skin (absorption, injuries)



Direct measurement : the use of detectors placed external to the body to detect ionizing radiation emitted by radioactive material contained in the body

Indirect measurement : the analysis of excreta, or other biological materials, or physical samples (e.g. air filters) to estimate the body content of radioactive material

- Air sampling
- In-vivo measurements
  - For gamma emitters: whole-body counting, thyroid measurements
- Excreta measurements: in excreta: urine, faeces, nose blows
- Other biological samples

The choice of measurement technique will be determined by several factors:

- The radiation emitted by the radionuclide;
- The biokinetic behavior of the contaminant (chemical form);
- The degree to which the contaminant is retained within the body, taking account of both biological clearance and radioactive decay;
- The required frequency of measurements;
- The sensitivity, availability and convenience of appropriate measurement equipment

In-vivo measurements

Three types

- whole body monitor
- organ monitor
- wound monitors

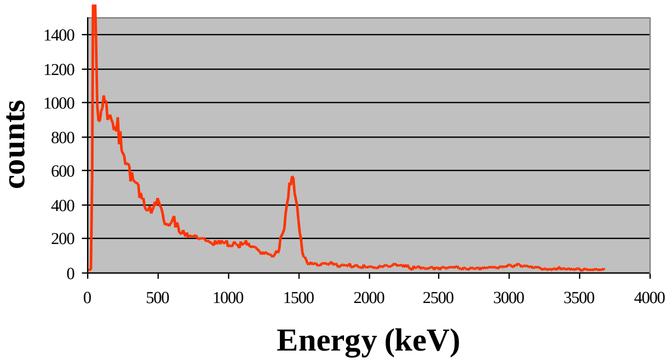
Main characteristics of detectors

- Resolution - ability to distinguish photons with different energies
- Efficiency - ability to detect low levels of activity
- Scintillation detectors, solid state detectors, gas filled detectors: all have specific characteristics for specific radiation energies

Shielding and sensitivity

- Well shielded counting camera
- Small room with thick walls made of low-background steel (~20 cm) and perhaps lined with a thin layer of lead (~1 cm).
- Ventilation issues can affect sensitivity
- Always signal of K-40 and cosmic background

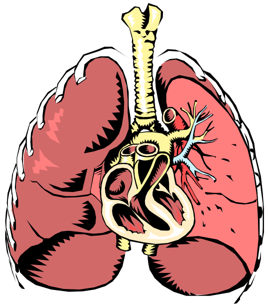
- Example sensitivity for Cs-137: DL 20 - 50 Bq.



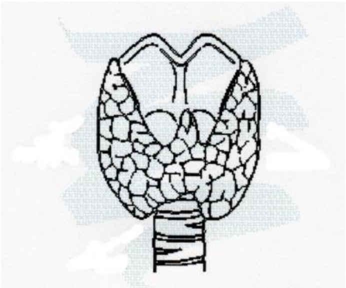
Individual organ measurement

Organ measurements may be required in situations where a radionuclide is known to concentrate in one particular organ

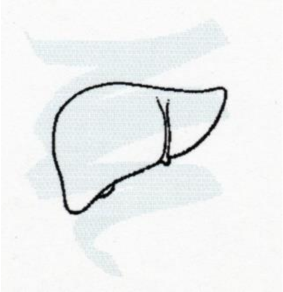
Lungs



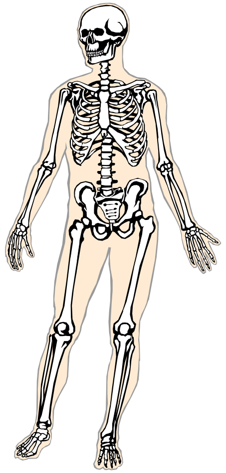
Thyroid



Liver



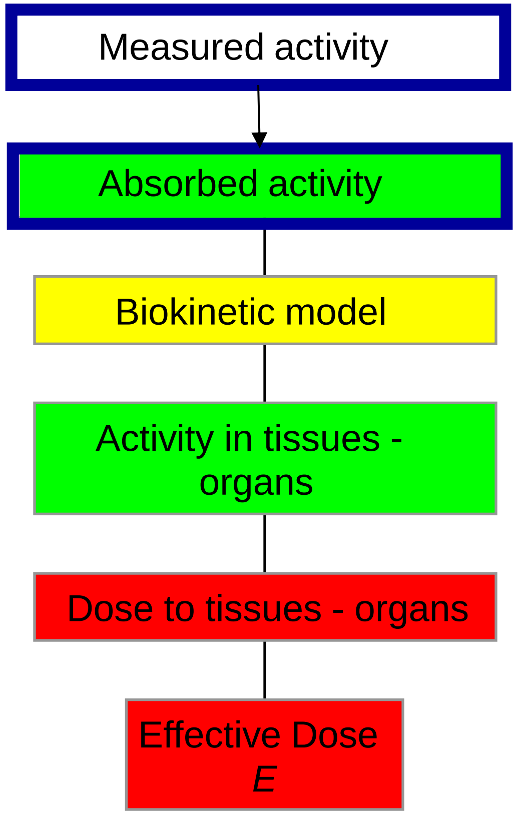
Skeleton



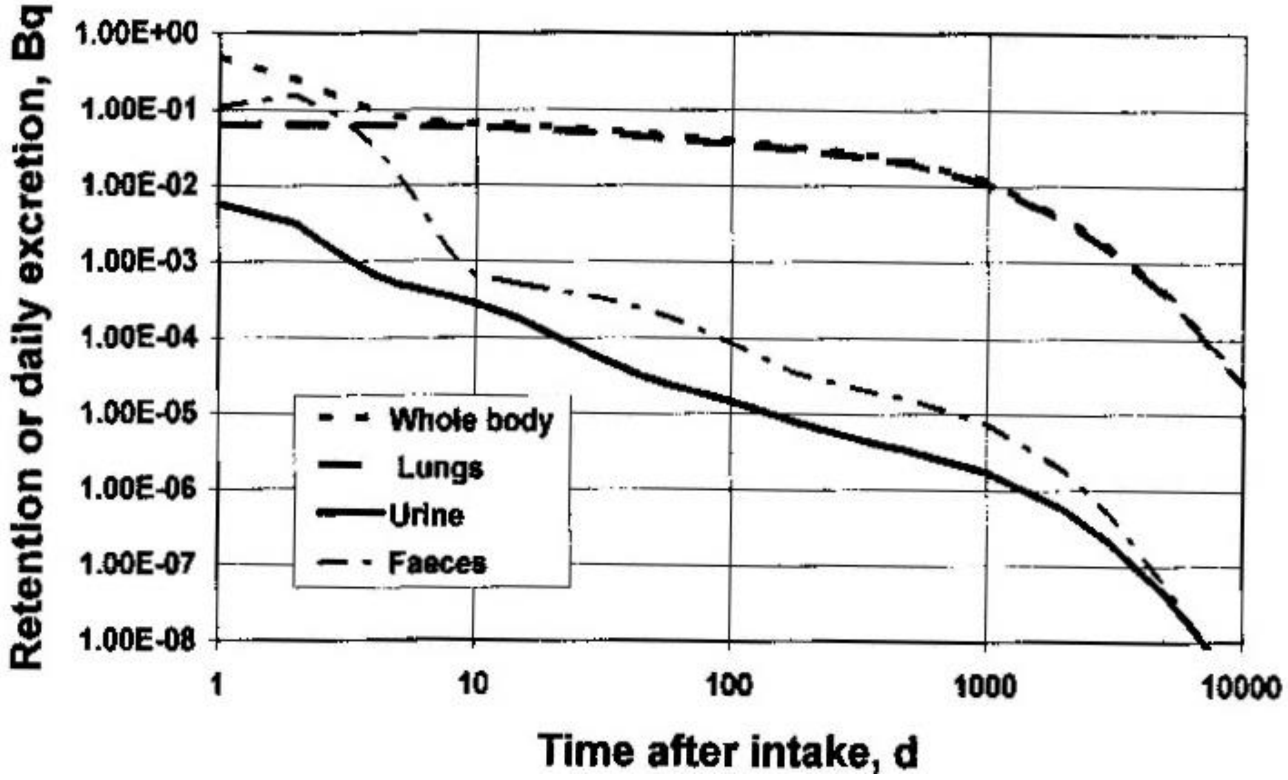
Lung monitoring

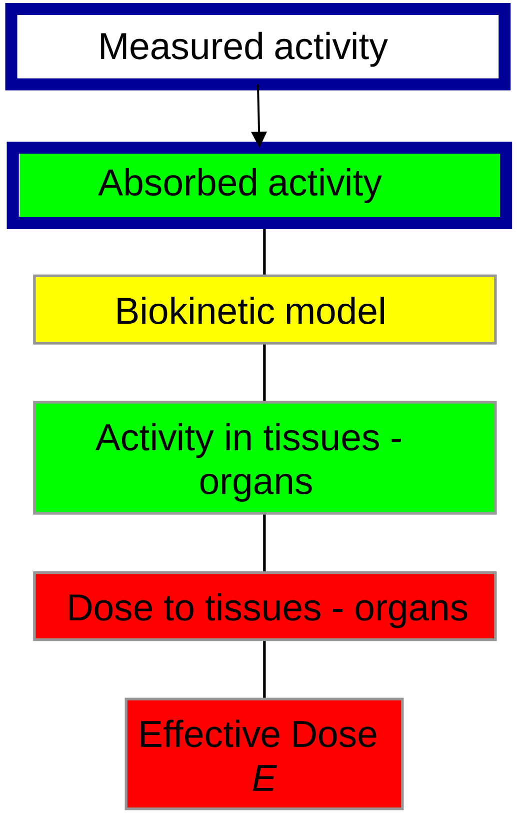
Internal dosimetry

- Measured activity:
  - direct:
    - For gamma emitters: whole-body counting, thyroid measurements
  - indirect: in excreta: urine, faeces, (blood)
- Estimate of the absorbed activity



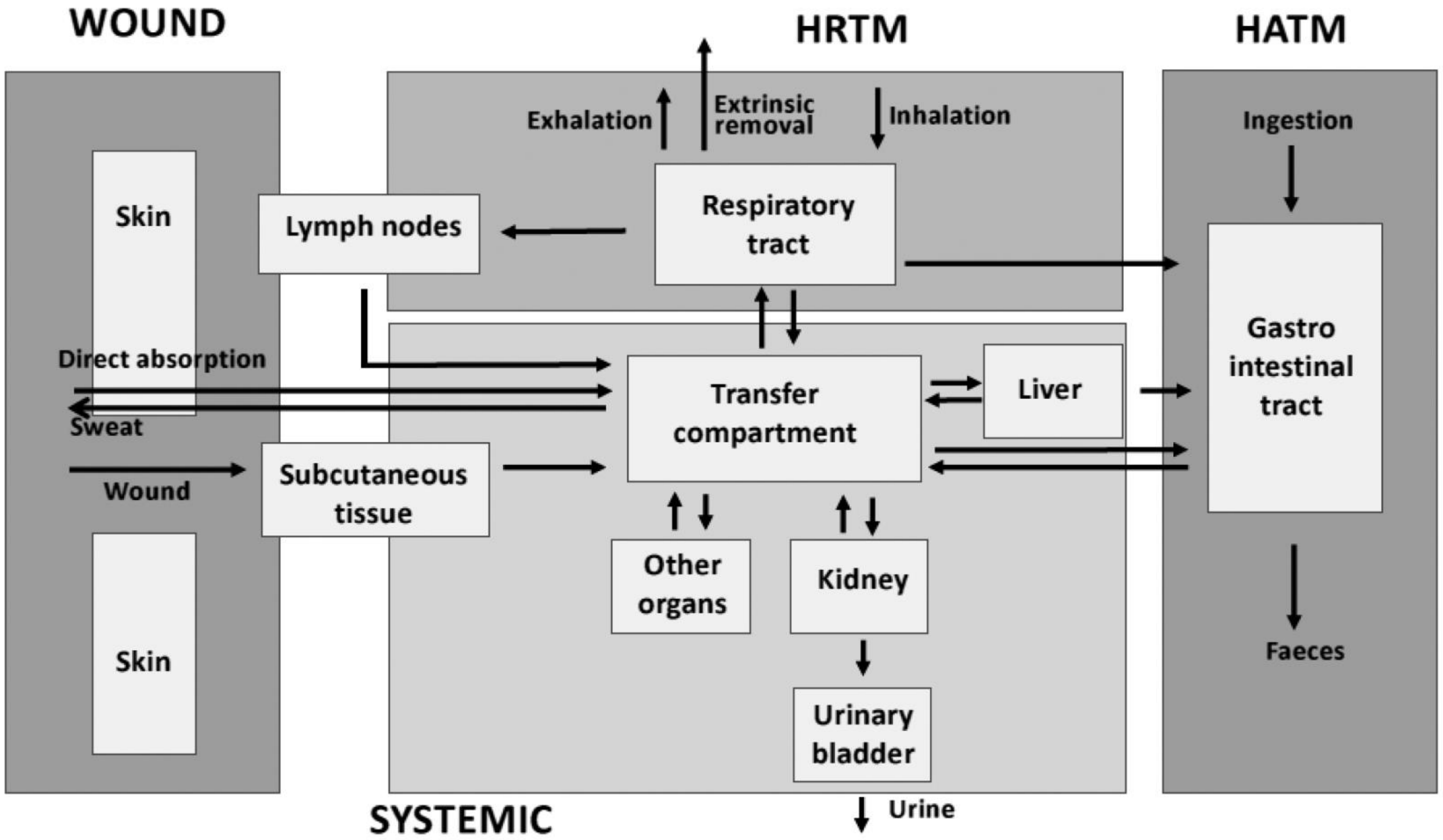
Co-60: Activity retained/excreted along time after intake per unit activity intake

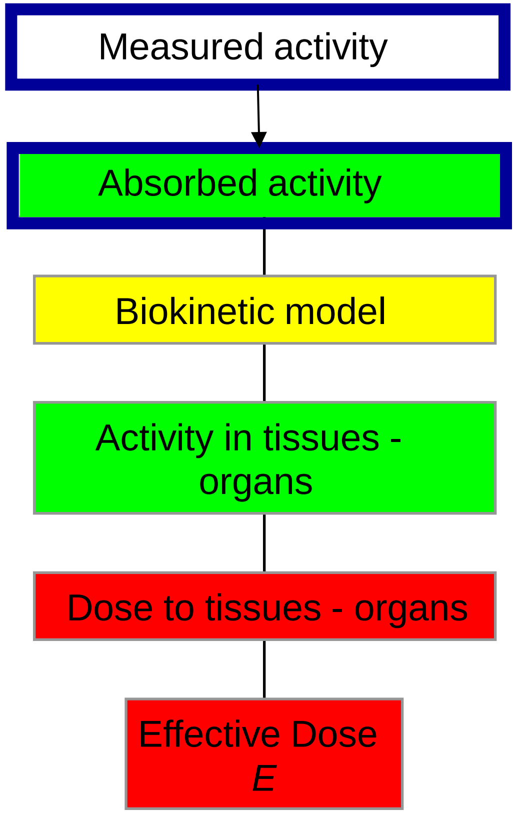




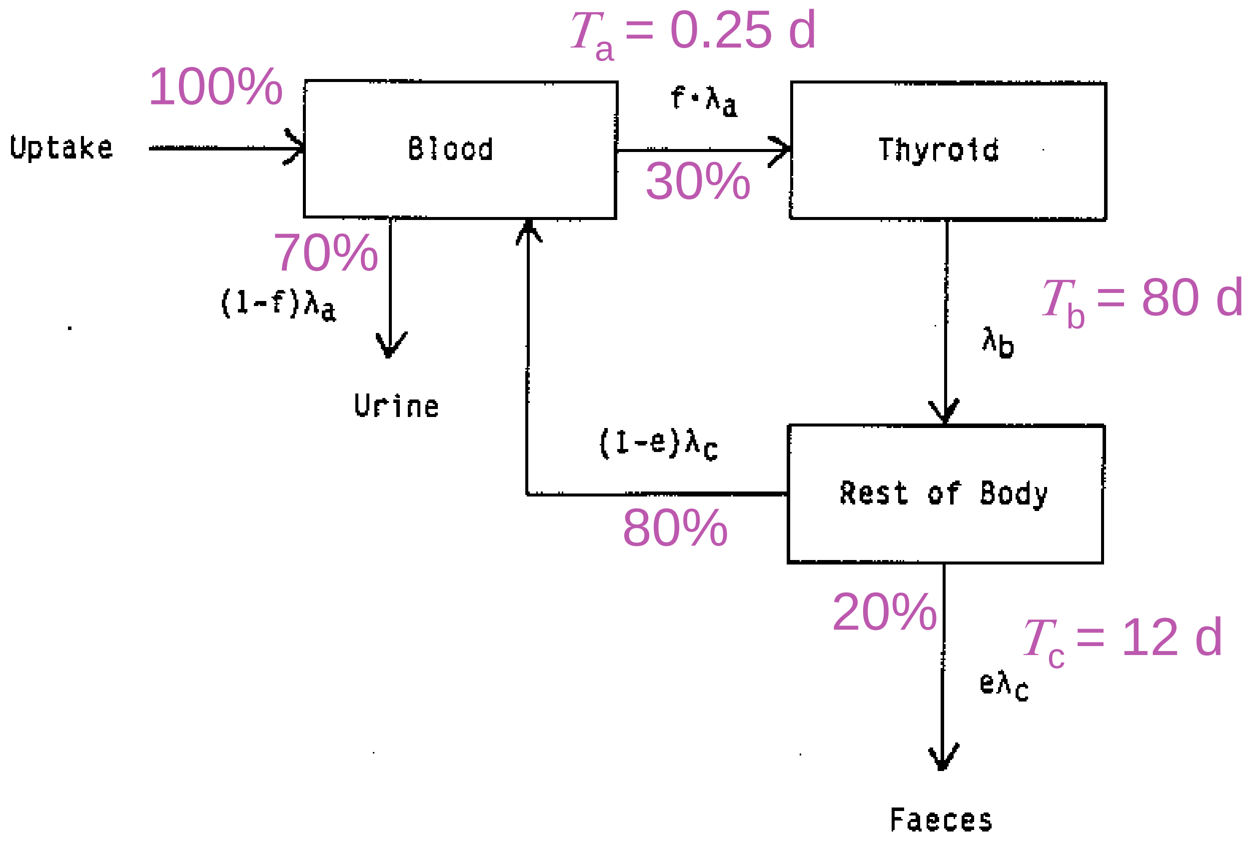
In routine monitoring it is always assumed that the intake has occurred in the middle point of monitoring interval

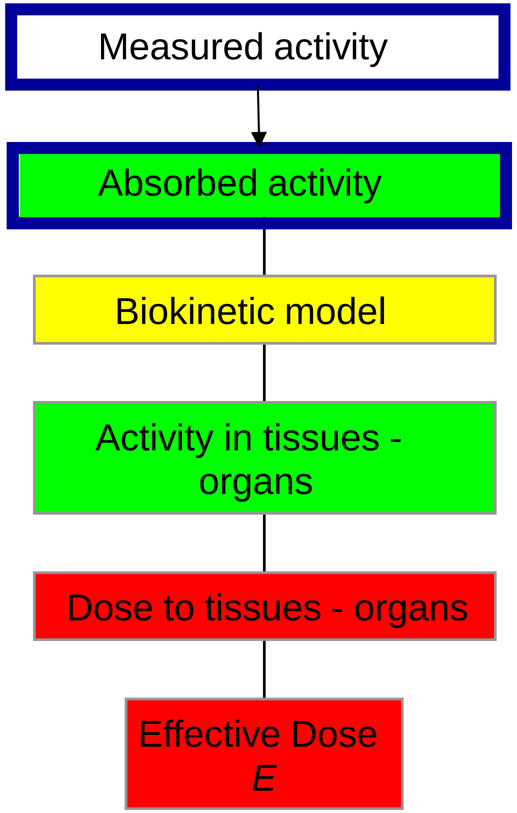
General biokinetic models





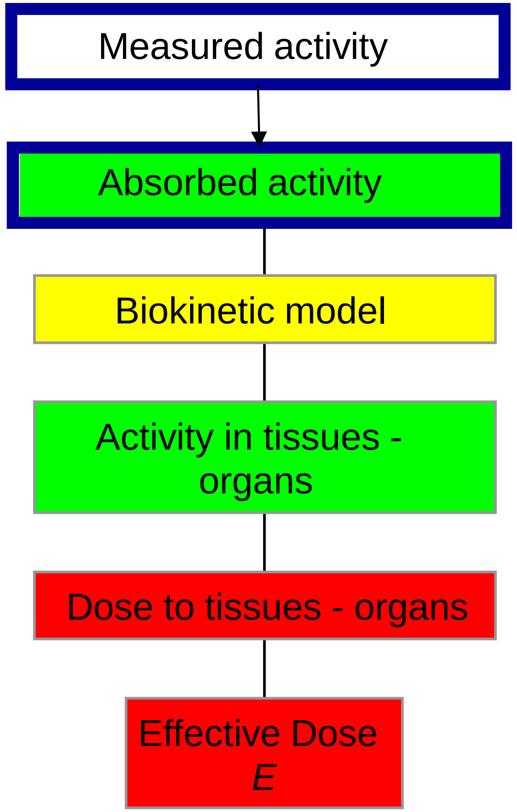
Assessment of internal dose from monitoring measurements: example of a biokinetic model for iodine



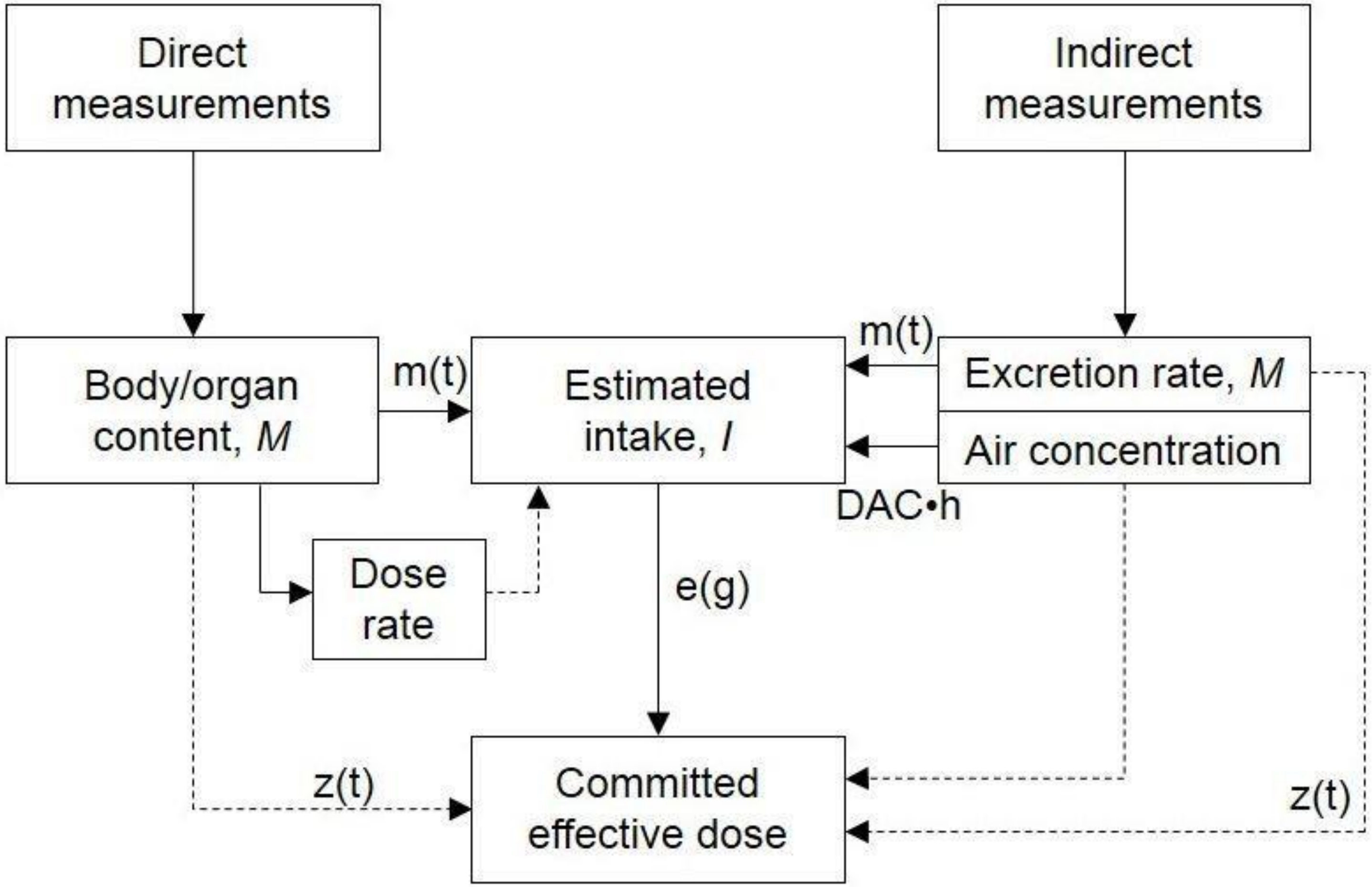


Interpretation of measurements and dose assessment

- Committed Effective dose E(50):
  - Effective dose integrated over 50 years to come
    - Including dose in future from desintegrations of incorporated nuclides
  - Considered as dose in year of intake



Assessment of internal dose from monitoring measurements



Dose coefficient

Committed effective dose arising from unit activity

Values depend on intake pathway, chemical form and particle size