Dosimetry, radiation protection. Nuclear measurement techniques.

Dr László Smeller Semmelweis University, Dept. Biophysics and Radiation Biology

Basic definitions

Reminder

- Nuclear radiation:
  - Produced in the transition of the nucleus
  - α (He^{2+}), β (e^-,e^+), γ (em.), … radiation
- Isotope (same atomic number, different mass number)
- Radioactive isotope (unstable, decays, emits radiation)
- Activity (Bq = decay/s)
- Exponential decay law

Interaction of the nuclear radiation with the matter

Reminder

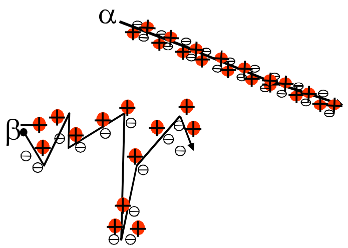
nuclear radiation — absorption
　　　　　　　　╲ detection

interaction ⇒ energy trasfer

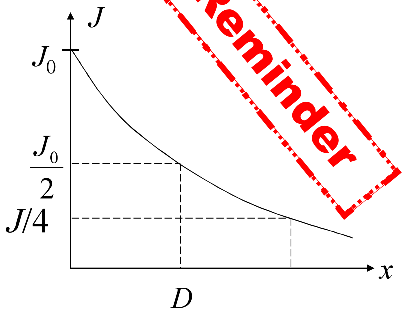
α, β	charged	➡	direct ionisation
γ, x-ray	uncharged	➡	indirect ionisation

Attenuation of nuclear radiations

charged	γ-ray



Ionisation ⇒ energy loss:
Runs out of the energy on a finite distance.
effective range



Reminder

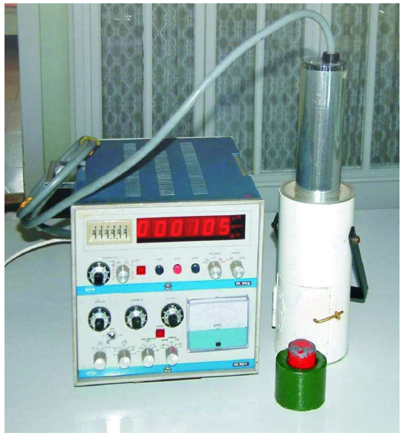
Exponential attenuation law
no effective range

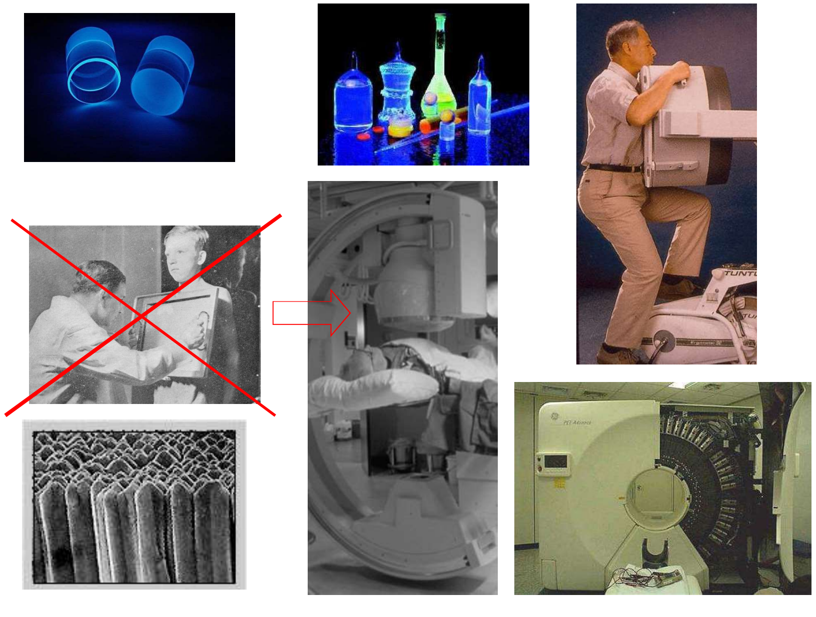
Detection of the ionizing radiation

scintillation based methods
gas-ionization detectors
thermoluminescent dosimeter
~~photographic methods (film)~~
semiconductor detectors

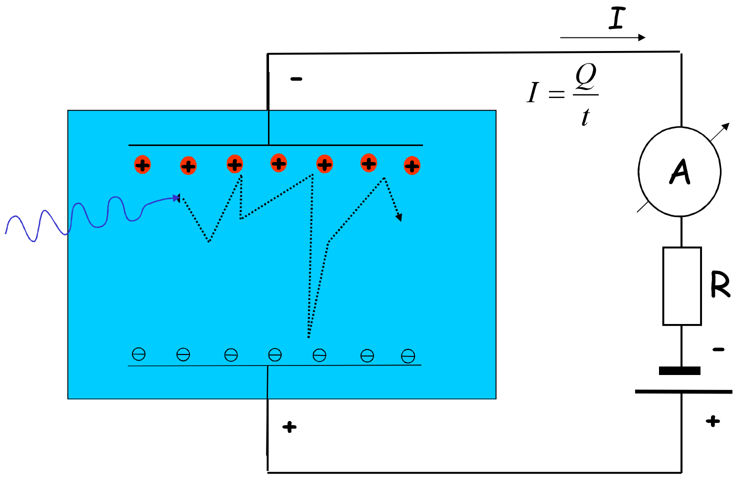
Scintillation counter

see practical exercises!



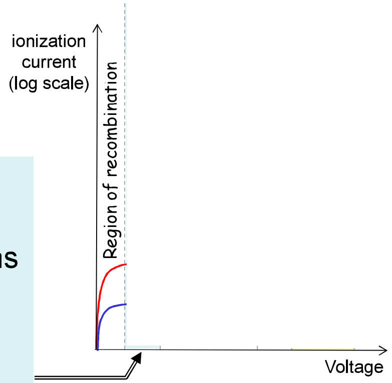


Gas-ionization detectors

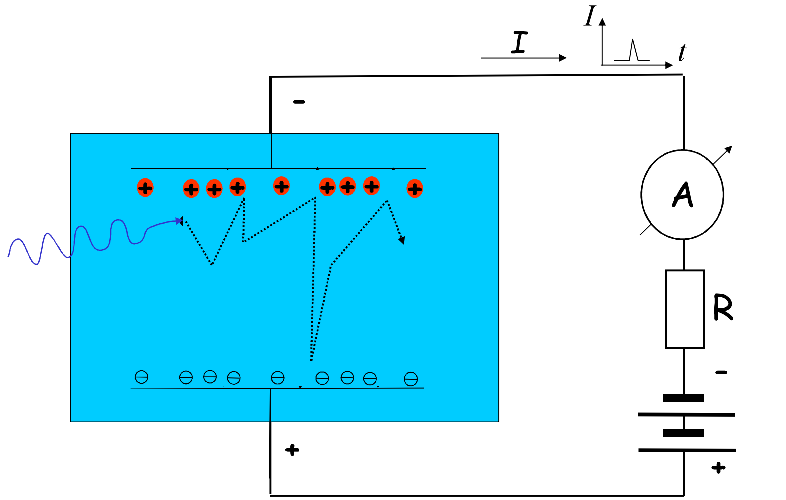


Gas-ionization detectors

Ionization chamber:
collects all the ions
Measures the
ionizing effect
of the radiation
see: dosimetry



Gas-ionization detectors



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Ionization chamber:
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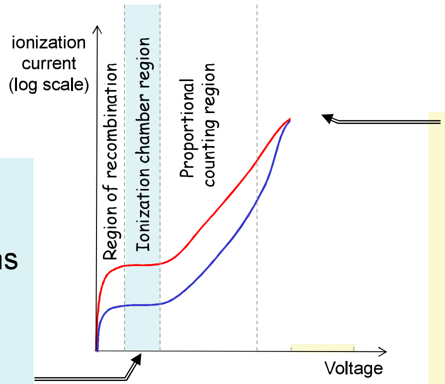
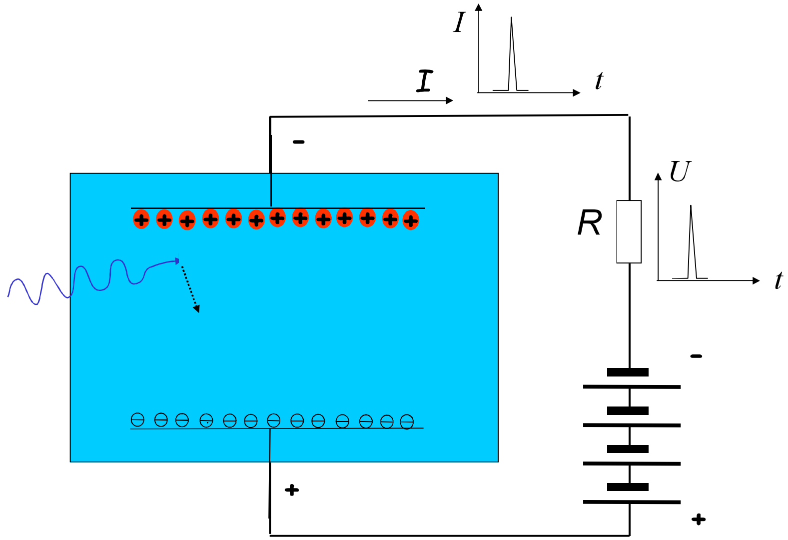
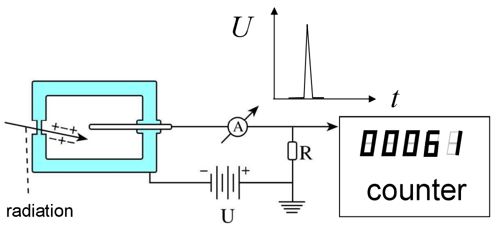


Geiger-Müller range:
avalanche-effect:
particle
⇓
voltage pulse

Geiger-Müller tube



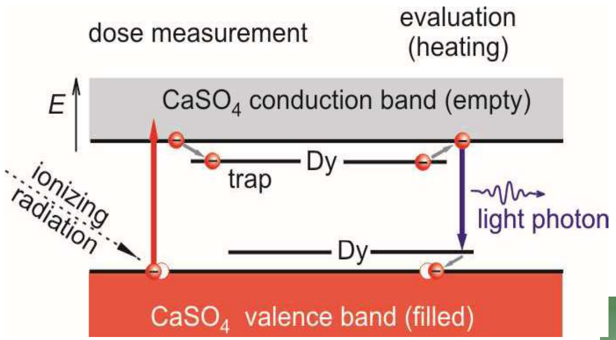
G-M tube



advantage: simple construction,
disadvantage: no energy selectivity,
low efficiency for γ-ray

usage: mainly in dosimetry

Thermoluminescent dosimeter (TLD)

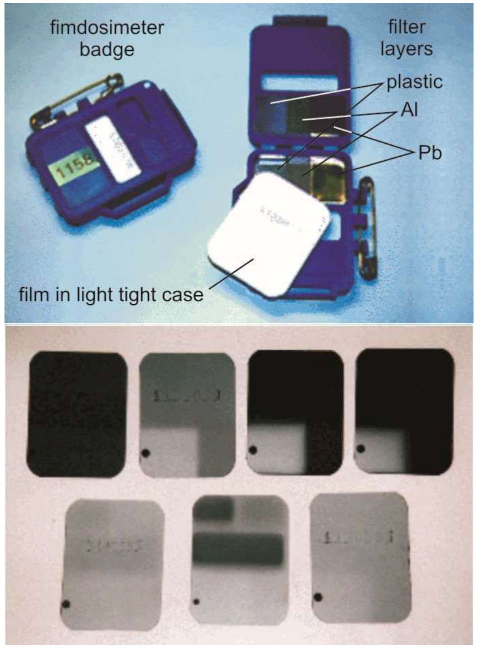


An american astronaut uses the TLD dosimeter „Pille" produced by KFKI Budapest (Photo: NASA ISS002E7814)

Personal dosimeters

Photochemical detection

obsolete

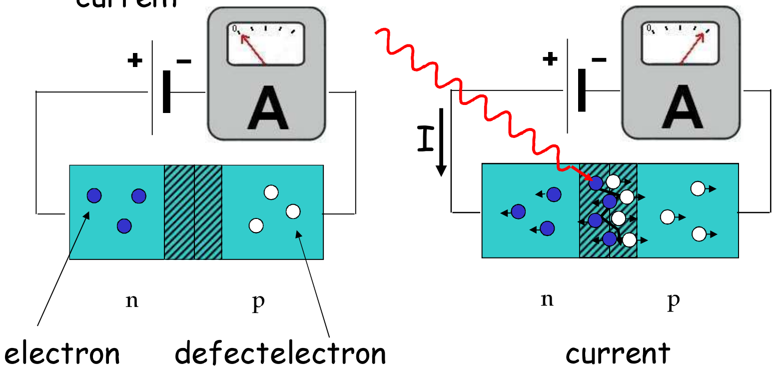


Semiconductor detector

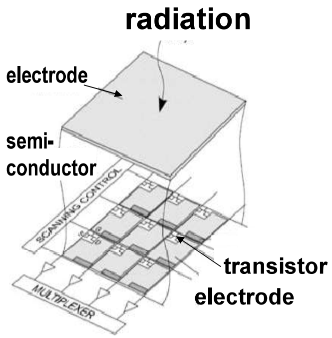
Principle:

Semiconductor diode connected reverse biased

The radiation induces free charges and consequently current



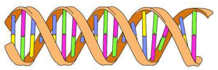
Semiconductor detectors in the diagnostics



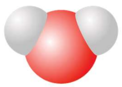
Semiconductor based dosimeters

Biological effect of the ionizing radiation

The mechanism of the radiation damage



direct
⇕
indirect



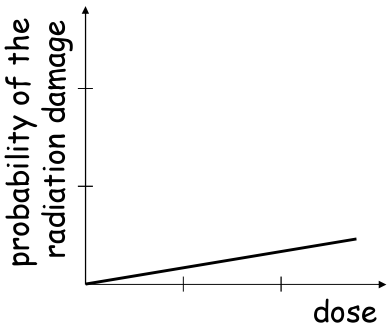
Physical phase:
10^{-17} - 10^{-12} s ionisation

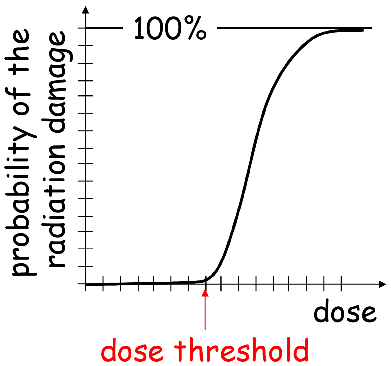
Chemical (biochemical) phase:
10^{-10} -1s: free radical reactions

Biological phase:
hours: alteration in the tissues
days-years: stomach-bowel damage of the haematogenesis
somatic damage

Mechanism of radiation damage

Stochastic | Deterministic





Stochastic

already at low dose level
small number of targets
no dose threshold
severity is **in**dependent of the dose

⇩

personnel at workplaces using ionisation radiation,

patients of X-ray and nuclear imaging investigations

Deterministic

High dose (>threshold)
many targets should be hit
only above the threshold
severity increases with the increasing dose

⇩

accidents

Radiotherapy

Dose concepts

Absorbed dose:

$$D = \frac{\Delta E}{\Delta m}$$

The energy absorbed from the radiation by the mass Δm

unit J/kg = Gy

Luis Harold Gray

➡ absorbed energy by unit mass of absorbing medium

can be used for all types of radiations

Absorbed dose :

$$D = \frac{\Delta E}{\Delta m} \quad [Gy]$$

How to measure:

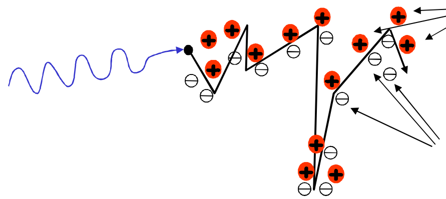
- hard to measure directly (unmeasurably small temperature change ΔT = 0,006°C/4 Gy)
- indirect detection methods:
  - ionisation chamber
  - semiconductor detector
  - thermoluminescent detector
  - ...

Exposure:

$$X = \frac{\Delta Q}{\Delta m}$$

the positive charge produced in the air of mass Δm

unit: C/kg

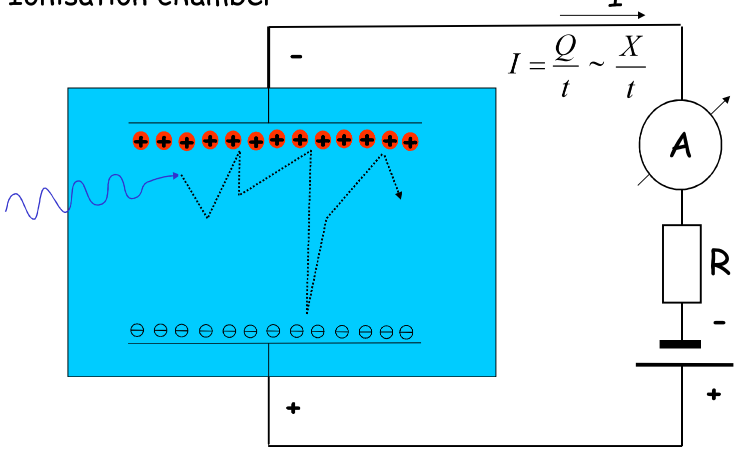


Olny for $\gamma-$ and x-ray in air!

How to measure the exposure:

$$X = \frac{\Delta Q}{\Delta m}$$

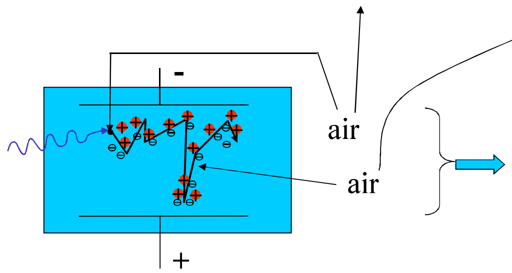
Ionisation chamber



Exposure:

$$X = \frac{\Delta Q}{\Delta m}$$

The location of the detection and of the ionization



Characterises the dose in air

How to convert it to absorbed dose?
Exposure was measured in air
how to convert it to the dose in the tissue?

Exposure:

$$X = \frac{\Delta Q}{\Delta m}$$

Conversion to absorbed dose:

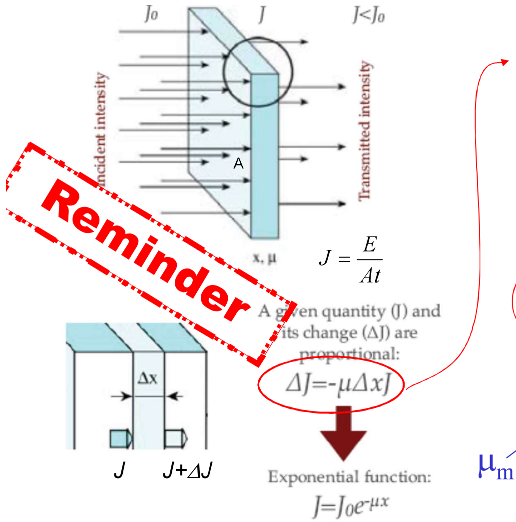
To produce 1 pair of ions one needs 34 eV energy in air*

34 eV= 34 · 1.6 ·10^{-19} J → 1.6 ·10^{-19} C
34 J → 1 C

$$1\frac{\text{C}}{\text{kg}} \Rightarrow 34\frac{\text{J}}{\text{kg}} = 34\,\text{Gy}_{\text{air}}$$

* In case of electrons. For protons and α particles ≈35 eV

Conversion of absorbed dose measured in air to absorbed dose expected in tissue



$$\Delta J = -\mu \Delta x J$$

$$J = \frac{E}{At}$$

$$\Delta E = |\Delta J| At$$

$$D = \frac{\Delta E}{\Delta m} = \frac{|\Delta J| At}{\rho A \Delta x} =$$

$$= \frac{\mu \Delta x J t}{\rho \Delta x} = \mu_m J t$$

μ_m

$$D \sim \mu_m$$

Conversion of absorbed dose measured in air to absorbed dose expected in tissue

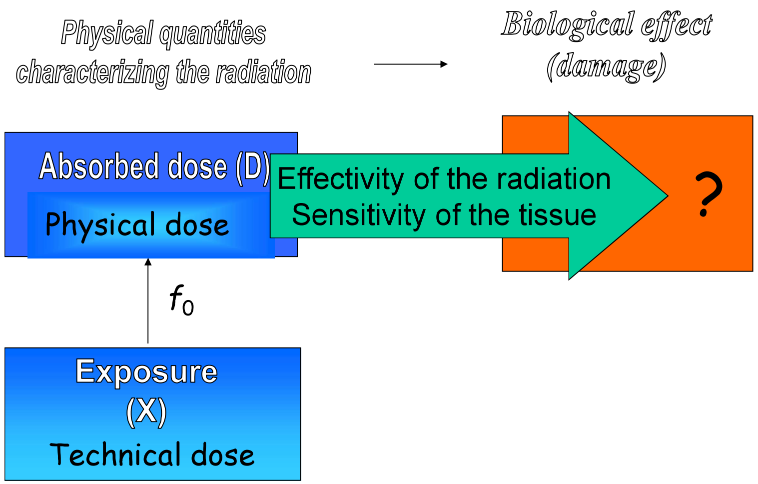
$$\frac{D_{tissue}}{D_{air}} = \frac{\mu_{m,tissue}}{\mu_{m,air}} \Rightarrow D_{tissue} = \frac{\mu_{m,tissue}}{\mu_{m,air}} D_{air}$$

$$D_{tissue} = \frac{\mu_{m,tissue}}{\mu_{m,air}} f_0 X$$

$$f_0 = 34 \frac{J}{C}$$

If E_{photon}<0,6 MeV, for soft tissue: $\frac{\mu_{m,tissue}}{\mu_{m,air}} \approx 1.1$

Dose concepts so far:



Biological damage in…

→ **Radiotherapy** (Deterministic effect)

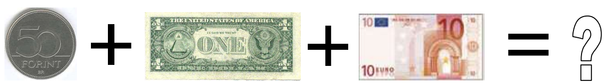
typically
- single type of radiation is used
- single type of tissue is irradiated

Absorbed dose → proportional → Biological effect

→ **Radiation protection** (Stochastic effect)

typically
- several types of radiations are absorbed
- several different tissues are irradiated

Absorbed dose → weighted summation → Biological effect



Equivalent dose

Absorbed dose → weighted summation → Biological effect

Weighting factors for: effectivity of the radiation ←
tissue sensitivity

Equivalent dose: $H_T = \sum_R w_R D_{T,R}$ [Sv]

Weighted sum of the absorbed doses from the different radiations (R) in a given tissue (T).
w_R: radiation weighting factor

E.g.:

$$H_{skin} = w_\alpha D_{skin,\alpha} + w_\beta D_{skin,\beta} + w_\gamma D_{skin,\gamma}$$

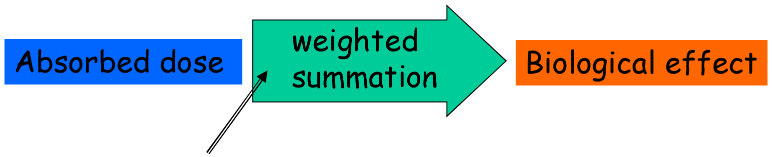
The w_R radiation weighting factors

How many times greater is the effectivity (considering stochastic effects) of the given radiation compared to the x-ray or γ-radiation.

Radiation and energy range		Radiation weighting factor
Photons, at every energy		1 ← by definition
Electrons, muons, at every energy		1
Neutrons, if the energy is	<10 keV	5
	10 keV–100 keV	10
	100 keV–2 MeV	20
	2 MeV–20 MeV	10
	>20 MeV	5
Protons, if the energy is	> 2 MeV	~~5~~ 2
α-particles, nuclear fission products, heavy nuclei		20

Continous function for neutrons

Effective dose:



Weighting factors for: effectivity of the radiation
tissue sensitivity

Effective dose: $E = \sum_T w_T H_T$ [Sv]

Weighted sum of the equivalent doses of the irradiated tissues (T)

$$\sum_T w_T = 1$$

$w_T H_T$ gives the contribution of the H_T dose to the damage of the whole body.
In case of homogenous irradiation $E=H_T$

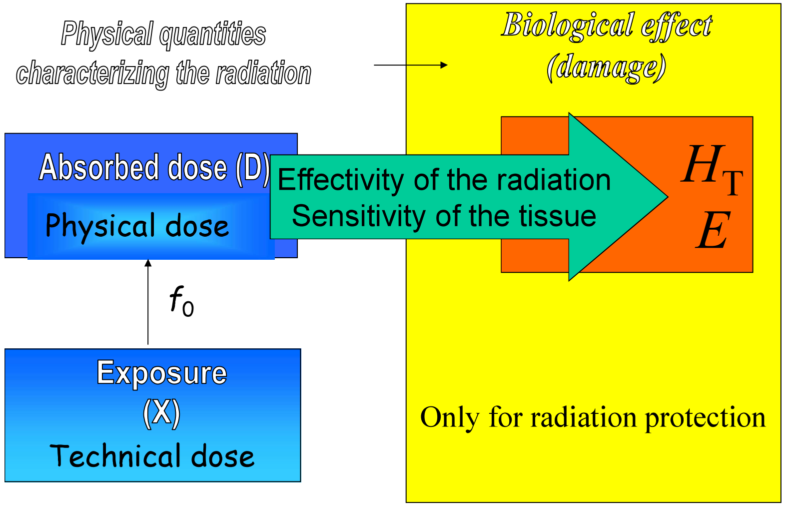
The w_T weighting factor

represents the relative contribution of that organ or tissue to the total damage in case of stochastic effects resulting from uniform irradiation of the whole body

Tissue	w_T	Tissue	w_T
Red bone marrow	0,12	Oesophagus	0,04
Large intestine	0,12	Liver	0,04
Lungs	0,12	Thyroid gland	0,04
Stomach	0,12	Surface of the bones	0,01
Breast	0,12	Brain	0,01
Other tissues*	0,12	Salivary glands	0,01
Gonads	0,08	Skin	0,01
Bladder	0,04		

*Other tissues: adrenal glands, upper respiratory tracts, gall-bladder, heart, kidney, lymp nodes, muscle, mucus membrane ,pancreas, prostate, small intestine,spleen, thymus, uterus.

Summary of dose concepts



Radiation protection

For personnel:

Justification

Rule out the deterministic effect

Reduction of the stochastic effect on a rationally acceptable level:

ALARA principle

Dose limits

Patients:

Justification

Cost-benefit principle

Measurement and documentation of patient dose values

Calculation of absorbed dose from γ radiation of an isotope

In case of point radiator:

$$D = \frac{K_\gamma \Lambda t}{r^2}$$

K_γ: dose constant $\left[\frac{\mu Gy \cdot m^2}{h \cdot GBq}\right]$

Λ: Activity [Bq]

r: distance from the isotope [m]

t: time [s,h]

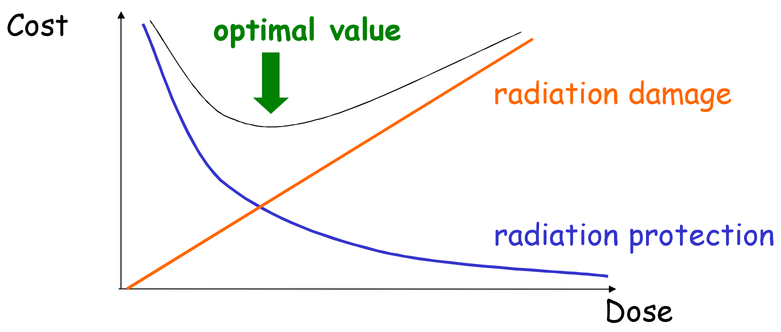
E.g K_γ=80 $\frac{\mu Gy \cdot m^2}{h \cdot GBq}$ for ^{137}Cs

1GBq ^{137}Cs gives 80 μGy/h in 1 m distance

↑ 800 x backgroud radiation level

ALARA principle

- As Low As Reasonably Achievable



Dose limits

(≠ allowed dose!)

For personnel at radiation workplace

- whole body: 20 mSv/year

(c.a.10μSv/working hour)*

- eye lens: 20 mSv/year
- skin: 500 mSv/year
- limb: 500 mSv/year

*compare.: background dose rate: ≈ 0,1 μSv/h

Threshold doses for deterministic effects

bone-marrow:	
Reduction of blood production	0,5 Gy
Testis:	
temporary sterility	0,15 Gy
permanent sterility	3,5-6 Gy
Eye lens	
obscurity	0,5-2 Gy
Cataracta	5 Gy
Skin:	
temporary erythema	2 Gy
erythema	6 Gy
temporary epilation	3 Gy

For whole-body irradiation: median lethal dose (LD_{50}) : 4 Gy
lethal dose 6 Gy

A few characteristic dose values

Background raditaion: 2,4 mSv/year
half of it from Rn.

Medical investigations (patient dose)
conventional x-ray image: 0,2-1 mSv
CT scan: 2-8 mSv

Treatment:
Intervention radiology
doctor: hand: 100 mSv/2 month
eye: 30 msv/2 month
knee: 20 mSv/2 month
gonad (under the lead apparel): 0,5 mSv/2 month

Patient: up to 1 Gy!!

Radiotherapy: tipically 45-60 Gy (2 Gy fractions.)

Dose limits and risks

Dose limit ≠ allowed dose
= dose with acceptable level of risk

Stochastic effects cannot be avoided even below the dose limit!

But! everything is dangerous!

life is dangerous!

risk ↔ benefit

Some of the above presented values are taken from:

Damjanovich et al.: Medical Biophysics
Köteles György: Sugáregészségtan (Medicina)
Fehér István, DemeSándor: Sugárvédelem (ELTE Eötvös kiadó)
Turák O., Osvay M.: A személyzet dózisa az intervenciós radiológia területén. OSSKI www.sugarvedelem.hu/sugarvedelem/docs/kulonsz/.../szemelyzet.pdf
Pellet Sándor, Giczi Ferenc, Gáspárdy Géza, Temesi Alfréda: Az intervenciós radiológia sugár-egészségügyi vonatkozásai. Magyar Radiológia 81 (2007) 32–39.