(The bases of)

Radiation Protection

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To tell you in one hour all about radiation protection is a

Mission Impossible IV

- Radiobiological bases
- Prompt radiation produced by accelerator operation
- Residual radioactivity
- Radiation shielding
- Rules and regulations
- Operational radiation protection
- Monitor instrumentation
- Individual dosimetry
- Etc…

Objective of radiation protection

Whenever a particle (charged or neutral) or a photon of sufficient energy (E > Eth and E > Coulomb barrier) hits a nucleus, a nuclear reaction takes place. The reaction induces emission of particles and/or photons (prompt radiation) and generally leaves behind a residual nucleus which is radioactive, that is emits "delayed" radiation.

The use of proton and electron accelerators for particle physics, applied physics, industrial or medical uses, generates radiation and involves the potential exposure of people (workers and members of the public) to (prompt) radiation escaping from the shielding structures, to ("delayed") residual radioactivity in the accelerator, beam lines, targets, etc, and the release of radioactivity into the environment.

The aim of Radiation Protection is to prevent - by shielding, interlocks, procedures, etc - direct detrimental effects (death and tissue reactions), and to limit the probability of stochastic effects to levels deemed by society to be acceptable.

The topics covered in this lecture include:

1. Quantities and units
2. Effects of radiation
3. Determining the risks

The *activity* of a radioactive source is its rate of decay = number of disintegrations per second

The unit of activity is the Becquerel

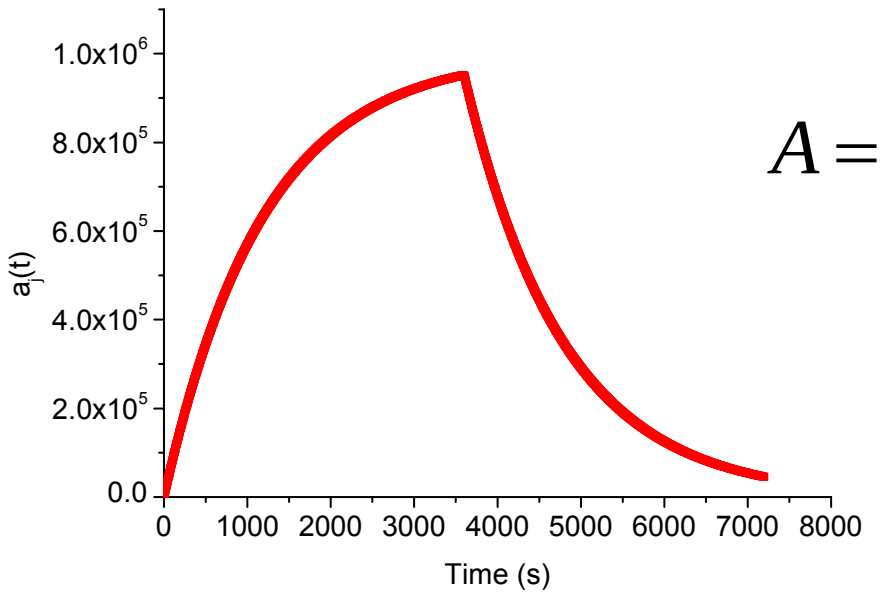
$1\ Bq = 1\ s^{-1}$

The *half-life* of a radionuclide is the time necessary for half of the nuclei present in the sample to decay

The *biological half-life* is the time required for the body to eliminate half of an administered dose of any substance by metabolic processes of elimination. It is approximately the same for both stable and radioactive isotopes of a particular element.

Rule-of-thumb (probably very obvious):

the shorter the half-life, the fastest the build-up, the fastest the decay



$$A = A_s(1 - e^{-t_{irr}/\tau})e^{-t_{dec}/\tau}$$

It takes about 5 half-lives to reach saturation of activity

- There are two types of health effects caused by radiation:
  - Tissue reactions (also called *non stochastic effects* or *deterministic effects*)
  - Stochastic effects
- The quantity in use for tissue reactions is the absorbed dose, D
- When particles other than photons and electrons (low-LET radiation) are involved, an RBE-weighted dose may be used.

- *Linear energy transfer (LET)*
  Mean energy lost by charged particles in electronic collisions per unit track length.

- *Low-LET radiation*
  X-rays and gamma rays or light charged particles such as electrons that produce sparse ionizing events far apart at a molecular scale (L < 10 keV/µm).

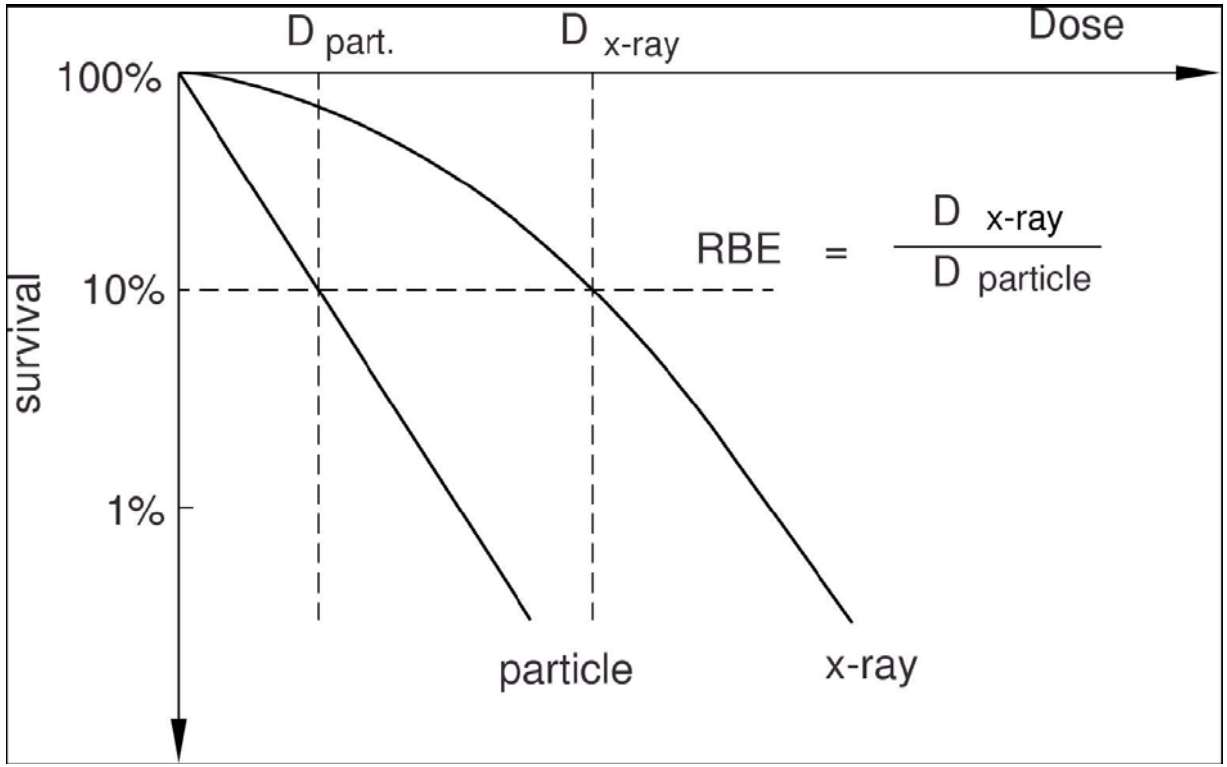
- *High-LET radiation*
  Neutrons, heavy charged particles that produce ionizing events densely spaced at a molecular scale (L > 10 keV/µm).

The *absorbed dose* in a point is defined as the ratio of the mean energy imparted by ionizing radiation to the matter in a volume element and the mass of the matter in this volume element:

$$D = \frac{d\bar{\varepsilon}}{dm}$$

The unit of absorbed dose is the Gray:

1 Gy = 1 J/kg



The RBE of a given radiation is the reciprocal of the ratio of the absorbed dose of that radiation to the absorbed dose of a reference radiation (usually x-rays) required to produce the same degree of biological effect

For purpose of radiation protection, a quantity that correlates better with the more important deleterious effects of exposure to radiation, more particularly with the delayed stochastic effects, is the *dose equivalent*

$$H = Q \cdot D$$

The unit of dose equivalent is the Sievert:

$$1\ Sv = 1\ J/kg$$

Q is a conventional factor called *Quality factor* applied to the absorbed dose at a point to take into account the biological effectiveness of the charged particles producing the absorbed dose.

- For a particular radiation, the value of Q was derived by extrapolating RBE values obtained at high dose levels down to the dose levels of relevance in radiation protection and then selecting a value of relevance to radiation hazards.

- Although the dose equivalent seems to be a not measurable quantity, in radiation protection a quantity is considered as measurable if a method of measurement is available which directly yields the value of the quantity to be measured → properly designed instrumentation

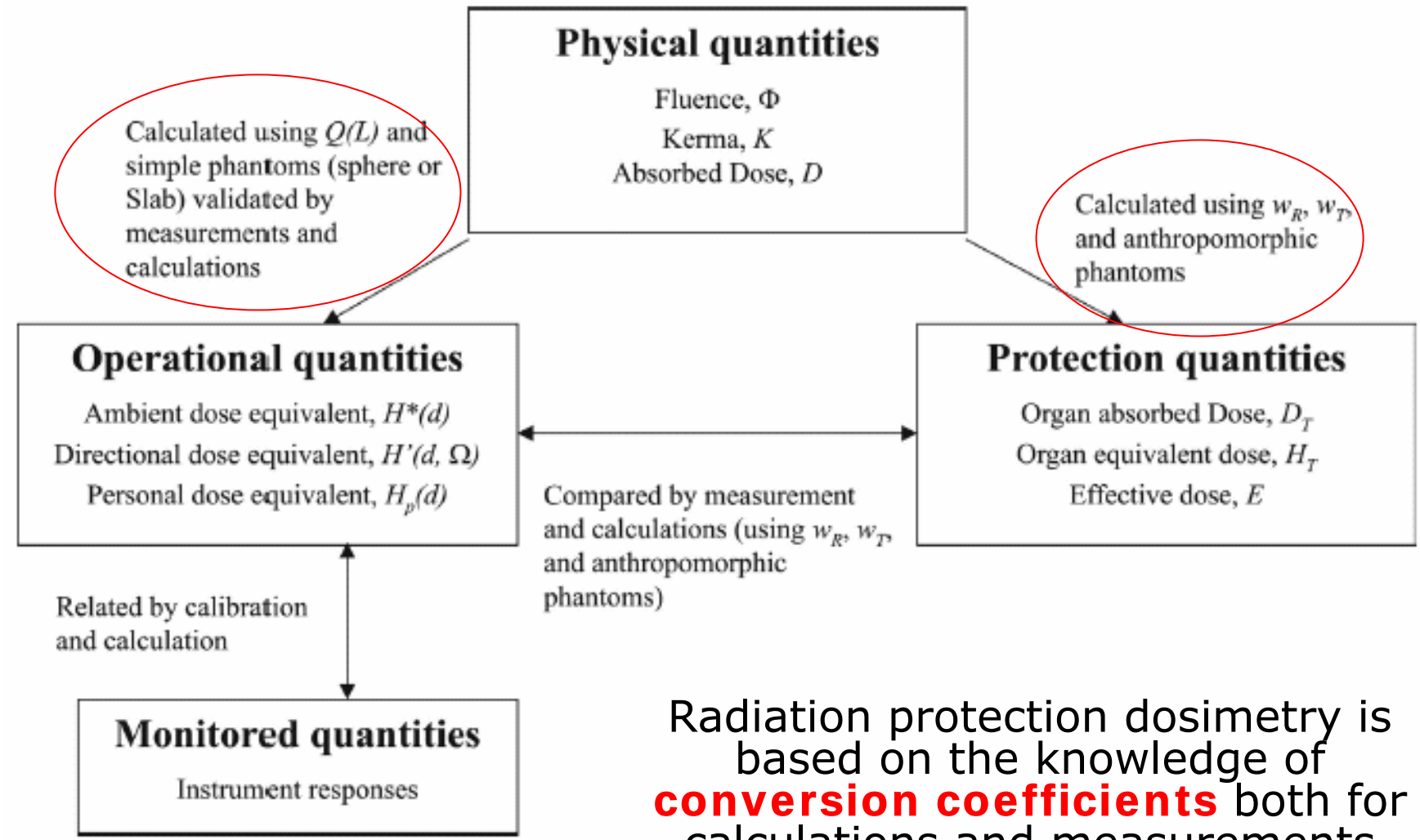
The Bq is a small unit so that activities are often measured in kBq, MBq, etc, however the **radiotoxicity** depends on the radionuclide: for example, 1 kBq of the α-emitter ^{241}Am if ingested will give you a dose of 27 mSv, higher than the annual limit for occupationally exposed workers

You need 4.2 Gray to raise the temperature of one litre of water by 10^{-3} °C, however a whole body dose of 1 Gy received in a short time will give you severe radiation sickness and a whole body dose of 4 Gy is very likely to be lethal

- ***Protection quantities*** defined for the human body by the **ICRP** and employed as reference parameters in the general recommendations.

- ***Operational quantities*** defined by the **ICRU** and employed for demonstrate, by means of measurements, compliance with the system of protection.

Physical, protection and operational quantities



Radiation protection dosimetry is based on the knowledge of **conversion coefficients** both for calculations and measurements

Mean absorbed dose in an organ or tissue:

$$D_T = \frac{1}{m_T} \int_{m_T} D dm$$

Equivalent dose in an organ or tissue:

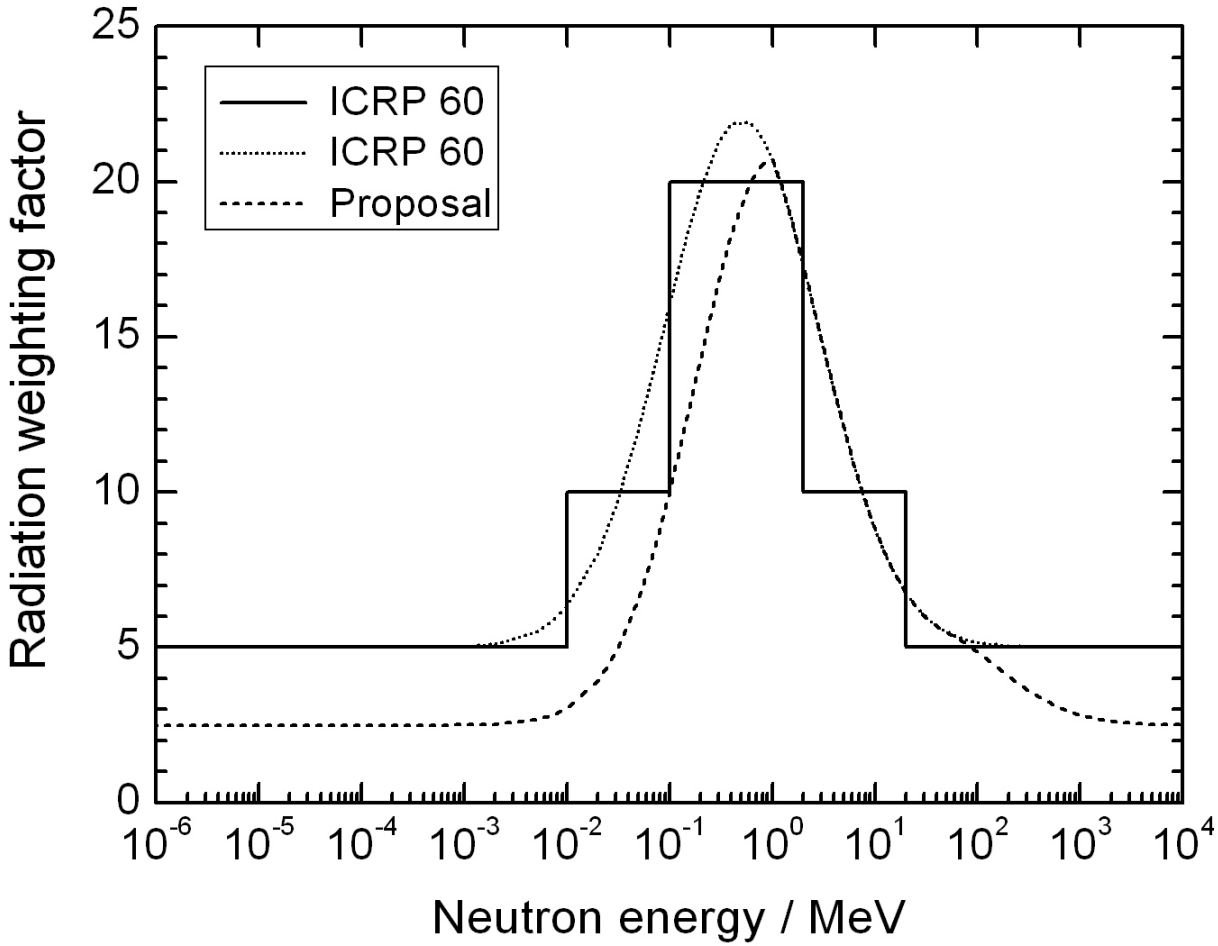
$$H_T = w_R D_{T,R}$$

- $D_{T,R}$ is the absorbed dose averaged over the organ or tissue T due to radiation R
- w_R is the radiation weighting factor for radiation R

Radiation weighting factors (ICRP 1990)

Type and energy of radiation R	**Radiation weighting factor, w_R**
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons:	
<10 keV	5
10 to 100 keV	10
> 0.1 to 2 MeV	20
> 2 to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, E > 2 MeV ICRP 2007 (protons and charged pions)	5 (2)
Alpha particles, fission fragments, heavy nuclei	20

Radiation weighting factors (ICRP 2007)



Values for neutrons replaced by a continuous function in ICRP 2007

In order to take into account the not uniform irradiation of the human body and the different susceptibility to radiation of different organs and tissues, the ICRP defined the concept of Effective dose:

$$E = \sum_T w_T H_T$$

- H_T is the equivalent dose in tissue or organ T
- w_T is the weighting factor for tissue T

- In most countries, the legal limits are
  - for workers: 20 mSv/year (over a 12 month period)
  - for members of the public: 1 mSv/year

Tissue weighting factors (ICRP 2007)

Bone-marrow, Colon, Lung, Breast, Stomach, Remainder Tissues	0.12
Gonads	0.08
Bladder, Esophagus, Liver, Thyroid	0.04
Bone surface, Brain, Salivary glands, Skin	0.01

Upcoming new definition of Effective Dose

(2007 Recommendations of the ICRP)

$$E = \sum_T w_T \left[\frac{H_T^M + H_T^F}{2} \right]$$

The sum includes also the terms of the gonads (ovaries and testes), the male and the female breast and the male and female remainder

- Operational quantities are aimed at providing an estimate or upper limit for the value of the protection quantities related to an exposure:

$$\frac{H_{prot}}{H_{oper}} \leq 1$$

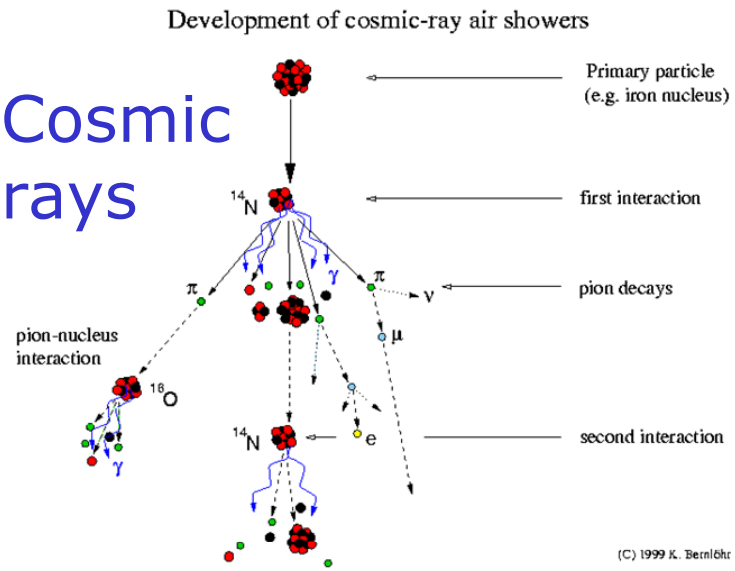
- For external exposure:
  - Operational quantities for area monitoring
    - →Ambient dose equivalent, H*(10), expressed in Sv, measured by monitoring instrumentation properly designed and calibrated
  - Operational quantities for individual monitoring
    - →Personal dose equivalent, $H_p(d)$, also expressed in Sv, measured by a dosimeter worn on the body

Exposures

- from natural radiation: (may vary by a factor of 3 in average)
  - altitude and cosmic radiation
  - terrestrial radiations (monazite, volcanic regions, etc.)
  - internal β and γ deposited radionuclides
- from medical irradiations
  - diagnostic medicine (dental x rays, radiography, CT)
  - diagnostic radiopharmaceutical (imaging techniques)

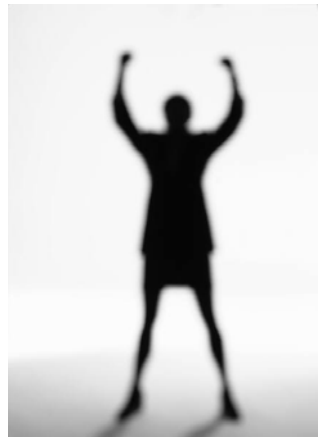
Natural sources of radiation

Cosmic rays



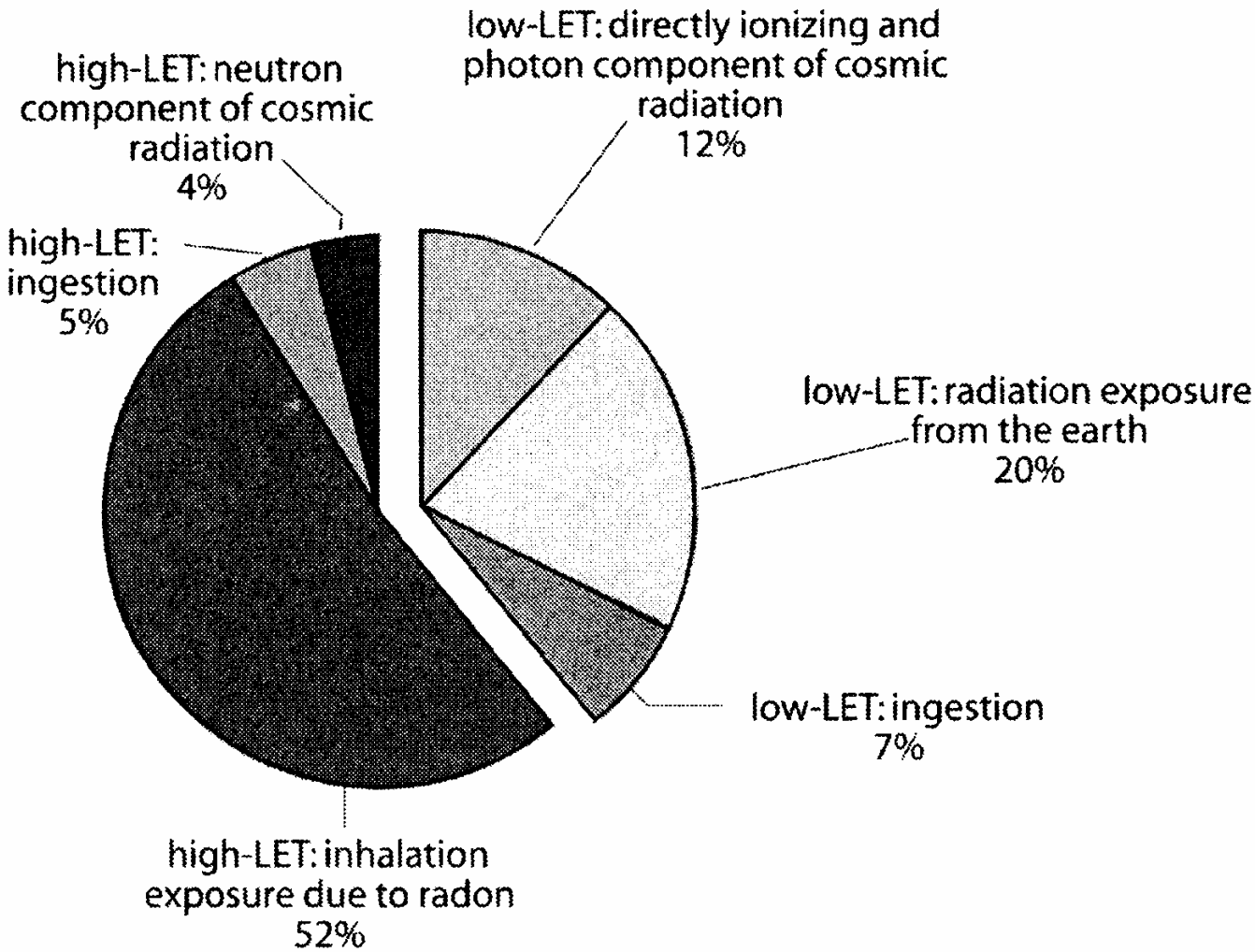
Cosmogenic
radioactive nuclides
(^{14}C, ^{7}Be, ^{3}H)

Terrestrial
(radionuclides present in the earth crust, U, Th, Ra, Rn …)



Human Body
(radionuclides present in our body, mainly ^{40}K)

Background radiation from cosmic rays and natural sources



Worldwide background radiation
2.4 mSv/year

(From BEIR 7, 2006)

Cosmic radiation levels

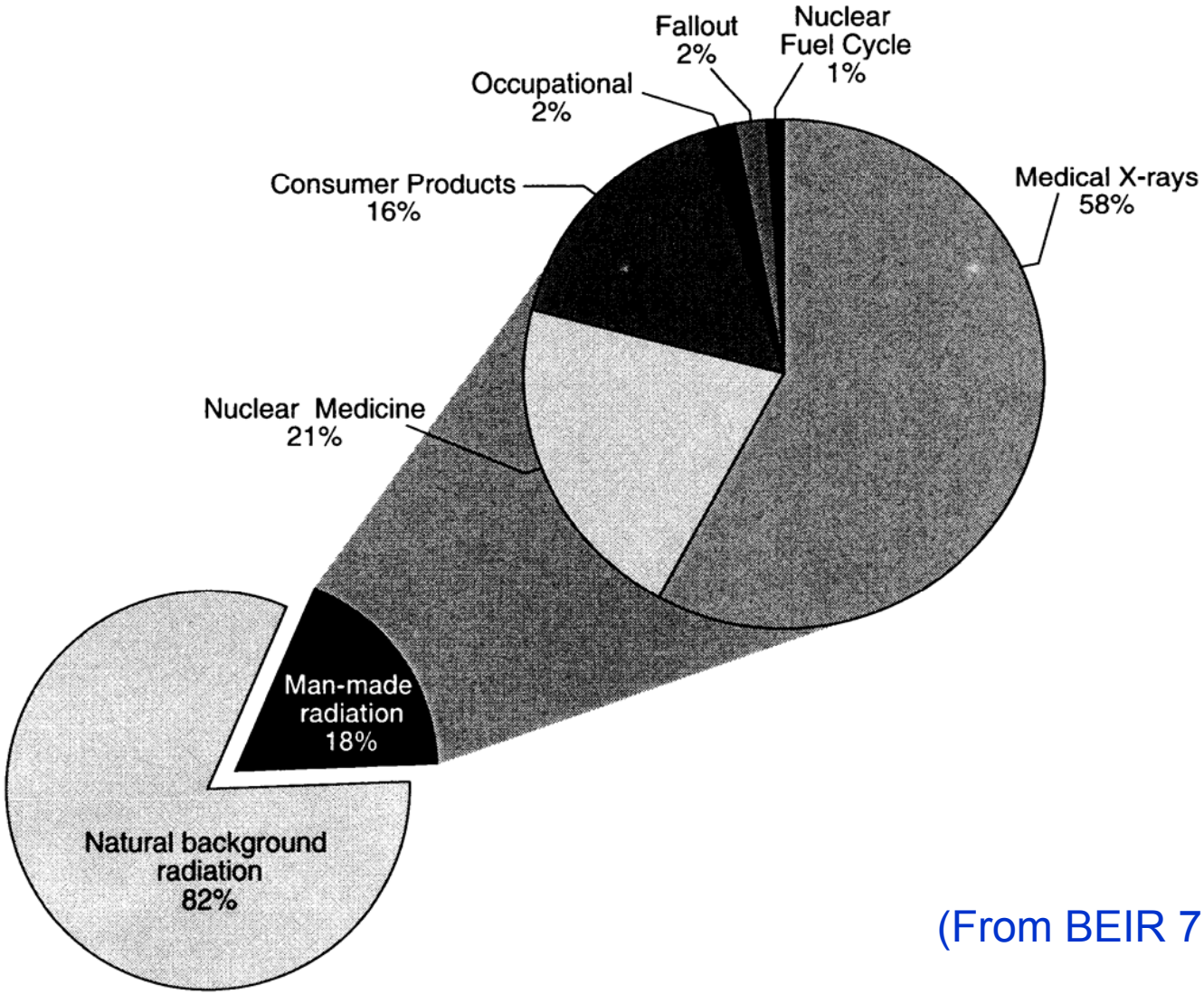
- sea level ~ 0.03 μSv/h
- 1000 m ~ 0.1 μSv/h
- 2000 m ~ 0.2 μSv/h
- civil flight altitude (13 km) ~ 5 μSv/h
- supersonic flight altitude (17-20 km) ~ 13 μSv/h
  (Concorde [† now deceased], spy planes)
- space shuttle ~ 15-30 μSv/h
- Outer space or Mars surface ~ 35-45 μSv/h
  (300-400 mSv/year)

Average annual effective dose to aircrew 3 mSv
(250000 monitored persons)

The integral dose equivalent received during a return flight Geneva - Los Angeles is about 100 μSv

(if the pilots pay attention to the route and you manage to get there…)

Natural and man-made radiation exposures



(From BEIR 7, 2006)

Medical exposures

	Type of examination	Absorbed dose (mSv)
Conventional X rays	Chest (AP – Lat.)	0.02 - 0.04
	Skull (AP – Lat.)	0.03 - 0.01
	Lumbar spine (AP)	0.7
	Mammogram (4 views)	0.7
	Dental (Lat.)	0.02
	Dental (Panoramic)	0.09
	Abdomen	1.2
CT scan	Head	2.0
	Chest	8.0
	Abdomen	10.0
	Pelvis	10.0
Interventional procedures	Angioplasty (heart study)	7.5 - 57.0
	Coronary angiogram	4.6 - 15.8
	Intravenous pyelogram (kidney 6 films)	2.5

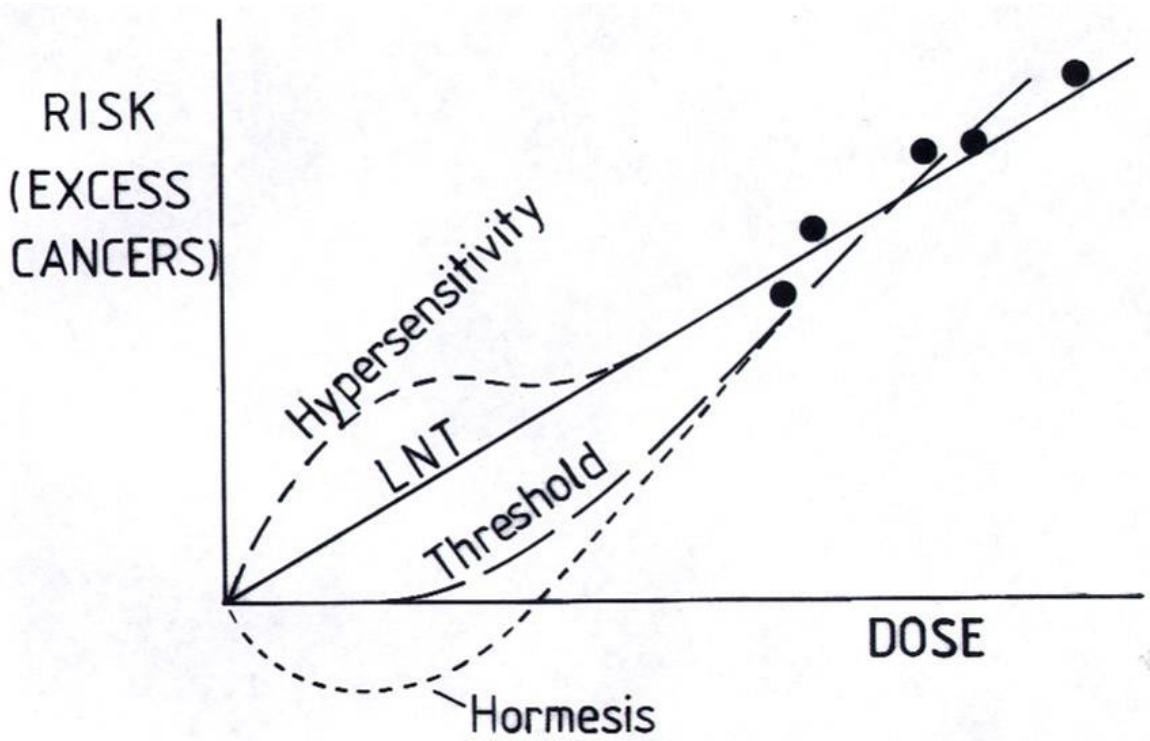
From: Health Physics Society 2006

- Low Doses 0 – 100 mGy
- Medium Doses >100 mGy – 1 Gy
- High Doses > 1 Gy

  Including doses used in radiation therapy (localized irradiation, 20-60 Gy)

Assumptions:

- No threshold
- Dose response is linear at low doses



Risk and rates are the basic measures to compare disease occurrence in exposed and unexposed population.

Rate = incidence of new cases of a disease related to a population of 100000. It is time dependent and depends also on the starting point and the length of the interval.

It is function of age at exposure, sex, type of cancer

Excess Absolute Risk = rate of disease in an exposed population minus the rate of disease in an unexposed population

Lifetime absolute risk (40 years following irradiation)

$$EAR = 5\%\ Sv^{-1}$$

- Hiroshima & Nagasaki (86572 individuals)
- Chernobyl (2240000 under control in 2005, 94% of liquidators, 89% of evacuees, 85% of residents of radioactively contaminated territory, 79% of children directly or indirectly (643000 children born to the accident liquidators) affected by the accident)
- Accidents
- Occupational exposures (600000 workers in the nuclear industry)
- Radiation therapy patients

- Young have higher cancer relative and absolute risks than older people
- Women have higher cancer risk for most solid cancers than men

86572 individuals from 1950-1990

334 cancers due to radiation exposure / 7578 deaths for solid tumours.

87/249 Leukaemia deaths due to radiation

By 1991 48000 people alive

Life span follow-up

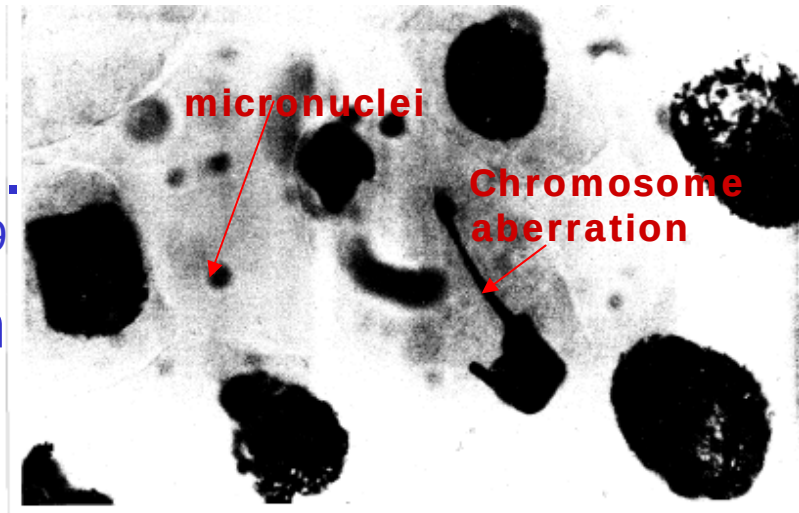
Atomic bomb survivors

Group Degree of severity	First week	Second week	Third week	Approximate mortality Time of death (weeks)
Very severe (5-6 Gy)	Nausea, vomiting Fever, apathy, delirium, diarrhoea, Oropharingeal lesions	Fever, Emaciacion, Leukopenia, Haemorrhagic diathesis, epilation		100% First and second
Severe (2-4.5 Gy)	Nausea, vomiting, anorexia, fatigue	Fever, Leukopenia Anaemia	Anorexia, emaciacion, fever, diarrhoea, epilation, oropharingeal lesions, Haemorragic diathesis +++, Leukopenia ++, Anaemia ++	50% Third to sixth
Moderately severe (2-3 Gy)	Gastrointestinal syndrome	Leukopenia	Anorexia, emaciacion , fever, diarrhoea , epilation, oropharingeal lesions + to ++, Haemorragic diathesis + to ++, Leukopenia ++, Anaemia +	Less than 10% Sixth or later
Mild (1-2 Gy)	Gastrointestinal syndrome	Leukopenia	Fever +, epilation +, oropharingeal lesions +, Haemorragic diathesis +, Leukopenia +	None

Source: UNSCEAR

1. P53 protein arrests the cell cycle and controls apoptosis (programmed cell death) preventing damaged cells to progress into a proliferation or malignant state. Human tumours show deficiency in apoptotic response. Specific DNA damage by radiation signals apoptosis.
2. Activation of proto-oncogenes by chromosomal translocation.
3. Onset of genomic instability (critical event for tumor genesis)
4. Repair of DNA lesions may be error prone

- DNA single and double strand breaks damage.
- Failure to repair DNA damage produce mutations (point mutations, deletions, insertions, translocations)
- Humans inherit 3 x 10^9 base pairs of DNA from each parent. Each cell has therefore 6 x 10^9 base pairs of DNA. It has been estimated that in normal conditions each new cell contains some 120 new mutations.
- Ionizing radiations and chemicals have proved mutational capability.



- Irradiated cells transmit damage signals to non irradiated cells that received no radiation (oxidative stress modulating signal transduction and micronucleus formation). 90% of mutations in bystander cells after low doses of α rays are point mutations, whereas in DNA repair deficient cells 80% of the mutants show partial or total gene deletions.
- Second neoplastic transformations events with transmissible genetic instability (visible as micronuclei) which is dose dependent.
- Delayed reproductive failure many generations after irradiations.
- Possible trans-generational effects of radiations due to induction of genomic instability in germ cells.

Factors influencing the response of a biological system

- Physical:
  - type of radiation [x, γ, n, α]
  - type of exposure
    - internal [by inhalation or ingestion]
    - external
  - local or total body irradiation
  - absorbed dose
  - spatial distribution of the absorbed dose (track structure)
  - time distribution of the absorbed dose

- Biological:
  - intrinsic characteristics of the irradiated biological system: radiation sensitivity (or resistance), number of cells exposed to radiation, kinetics/metabolism, repair capability
  - biological environment: oxygenation, nutrition, etc.

Effects of whole body irradiation

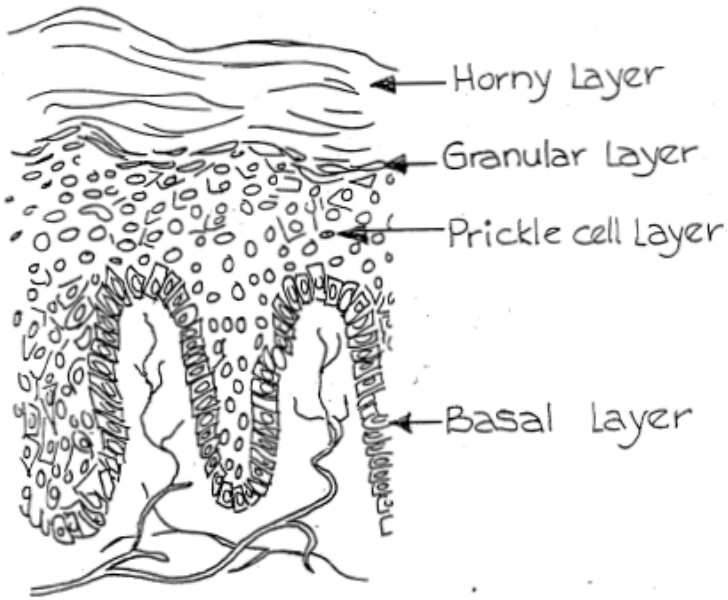
Dose Limits	< 1 Gy	1-2 Gy	2-6 Gy	6-10 Gy	10-15 Gy	>50 Gy
Vomiting	No	5-50 %	100 %	100 %	100 %	100 %
Delay	-	3	2	1	30 min	30 min
Therapy	Psycho-therapy	Psycho-therapy Haematological observation	Blood-Transfusion Antibiotics	Bone Marrow Transplant	Electrolyte balance	Symptomatic
Prognosis	Excellent	Excellent	Guarded	Guarded	Poor	Hopeless
Lethality	0	0	0-80 %	80-100 %	90-100 %	100 %
Time of Death	-	-	2 months	2 months	2 weeks	2 days

Whole body dose (Gy)	Organ or tissue failure responsible for death	Time at which death occurs after exposure (days)
3-5	Bone marrow	30-60
5-15	Intestine and lungs	10-20
>15	Nervous system	1-5

Lethal effects: LD50 for humans 3-5 Gy due to damage to bone marrow, in absence of bone marrow transplantation

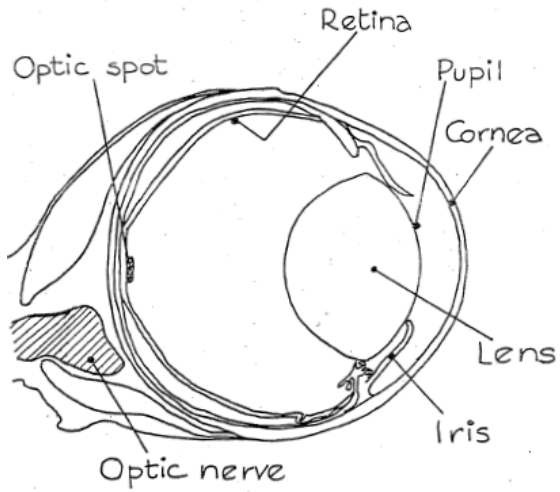
- Skin: 8-30 days

Initial erythema: 1-3 days
Desquamation: 2-3 weeks
Deep erythema: 3-4 weeks
Necrosis: 2-3 weeks



B 1.24. THE EPIDERMIS

- Lens opacities in the posterior part of the lens followed by cataract. Latency inversely related to dose.
- Cataract 2-10 Gy single dose or fractionated doses
- Radiation opacities observed at Chernobyl, astronauts, CT scan, occurs after 250 mSv
- Retinopathy and other ocular damage at doses < 5 Sv

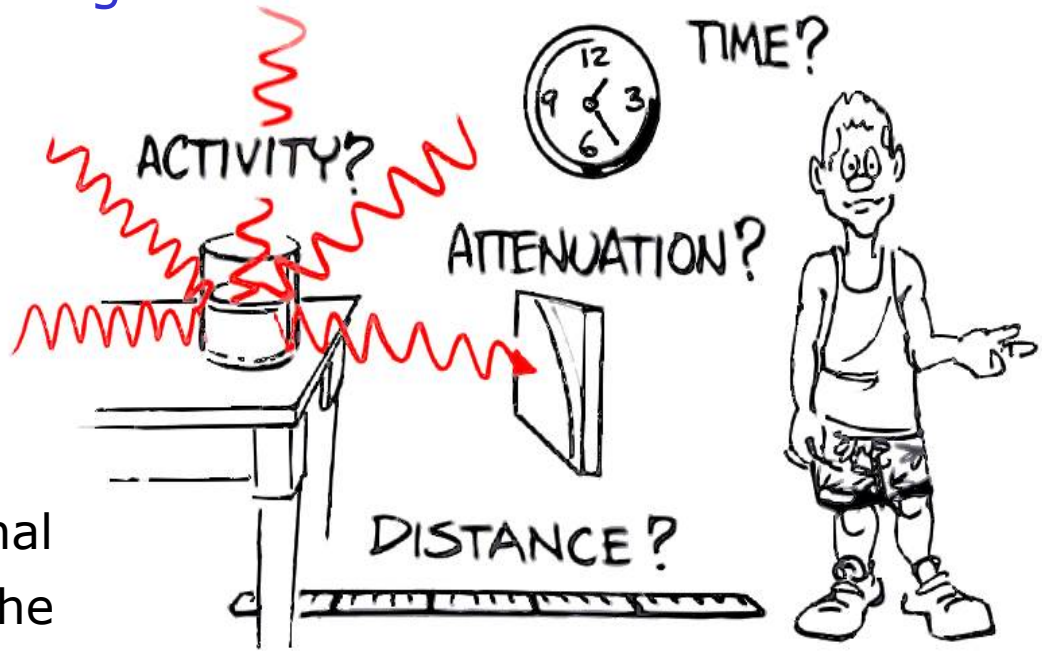


B 1.38. HUMAN EYE

- Leukemia
- Solid cancers
- Thyroid cancers
- Cardiovascular diseases

- Justification: any practice involving exposure to radiation should produce sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes
- Optimization: process to keep the magnitude of individual doses, the number of people exposed As Low As Reasonably Achievable (ALARA) below the appropriate dose limits, economic and social factors being taken into account.
- Limits: exposure of radiation workers and individuals of public must not exceed Dose Limits
  - E < 20 mSv / 12 months
  - annual limits for skin and extremities (150 mSv for the lens of the eye, 500 mSv for the skin, hands and feet)

When in presence of a source of radiation, make use of distance, time, shielding



- Distance: the dose rate decreases with the inverse squared of the distance (from a point-like source)
- Time: the dose is proportional to the time spent close to the source $D = dD/dt \times t$
- Shielding: the dose rate approximately reduces as $\exp(-d/\lambda)$
  λ = shielding properties of the material

for β radiation: plexiglass
for γ radiation: iron or lead
for n: concrete

I am indebted to my colleague Marilena Streit-Bianchi (CERN) from providing me with the radiobiology material I have shown you today