Radiation Quantities and Units

B.Sc(MT) Radiography IIIrd Year

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Outline

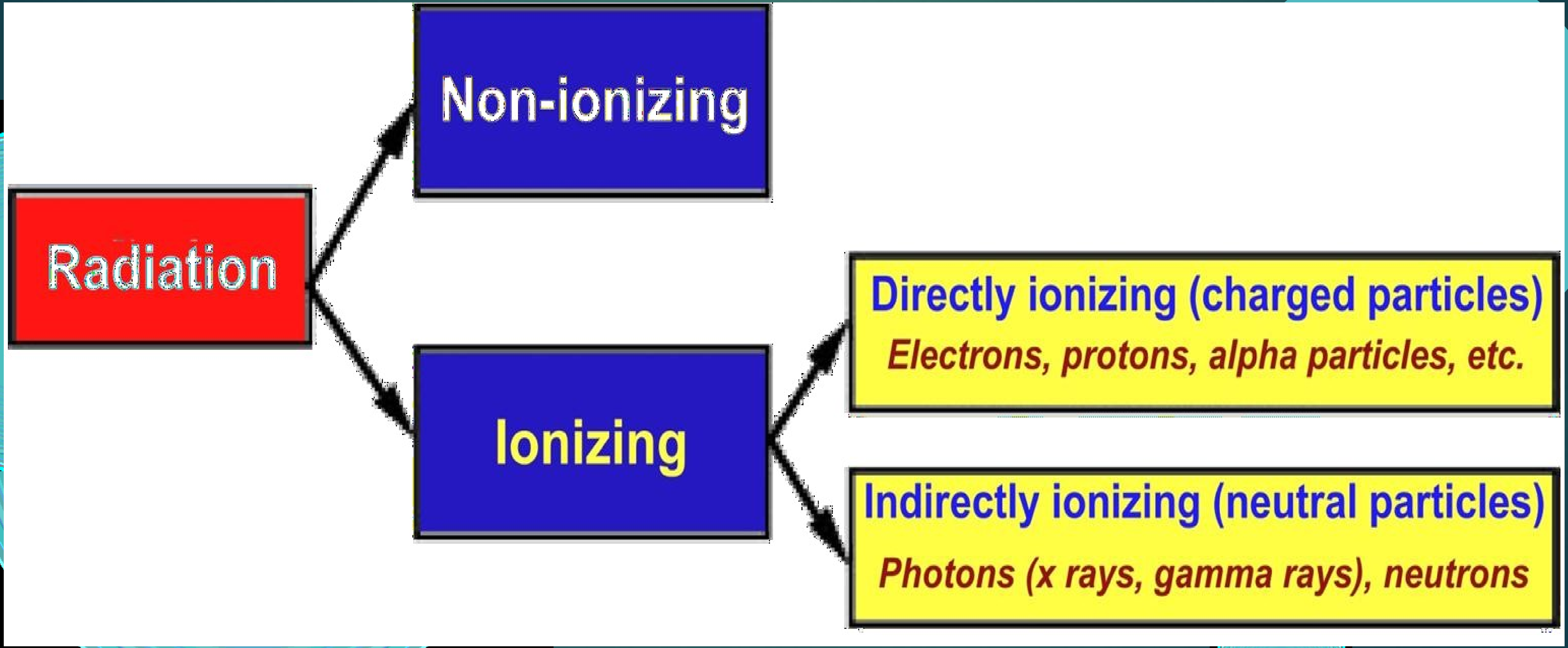
- Introduction
- Radiation Quantities
  - KERMA
  - Absorbed Dose
  - Exposure
  - Equivalent Dose
  - Effective Dose

Introduction

- Radiation dosimetry has its origin in the medical application of ionizing radiation starting with the discovery of x-rays by Röntgen in 1895.
- In particular
  - **the need of protection against ionizing radiation,**
  - **the application in medicine**
- required quantitative methods to determine a "dose of radiation".
- The purpose of a **quantitative concept of a dose of radiation** is:
  - to predict associated radiation effects (radiation detriments)
  - to reproduce clinical outcomes.

Absorption of Energy

- Energy from a heat source can be absorbed by matter and increase its temperature
- Nuclear radiation can transfer energy from a radiation source to an absorbing medium
- The body can detect harmful levels of heat, but it can not detect absorbed energy from nuclear radiation – even in lethal quantities
- Nuclear radiation differs from heat and other types of radiation in that it has sufficiently high energy to cause ionisation



Radiation
Non-ionizing
Ionizing
Directly ionizing (charged particles)
Electrons, protons, alpha particles, etc.
Indirectly ionizing (neutral particles)
Photons (x rays, gamma rays), neutrons

Ionisation

- Removal of an orbital electron from an atom gives
  - an electron
  - remainder of atom (an ion)
  - positively charged
- This is an ion pair
- The energy needed to remove the electron is the ionization energy

Indirectly ionizing & Directly ionizing Radiation

- **Indirectly ionizing** radiation means:
  - the energy is imparted to matter in a two step process.
    - In the first step (resulting in KERMA), the indirectly ionizing radiation transfers energy as kinetic energy to secondary charged particles.
    - In the second step, these charged particles transfer a major part of their kinetic energy to the medium (finally resulting in absorbed dose).
- **Directly ionizing** radiation means:
  - charged particles transfer a major part of their kinetic energy directly to the medium (resulting in absorbed dose).

"Energy Transfer" and "Energy absorption"

- For charged particles, most of the energy loss is directly absorbed

  → **Energy Absorption**

- For uncharged particles, energy is transferred in a first step to (secondary) charged particles

  → **Energy Transfer**

- In a second step, the secondary charged particles lose their energy according to the general behavior of charged particles (again **Energy Absorption).**

- **The energy of uncharged particles like photons or neutrons is imparted to matter in a two stage process.**

KERMA

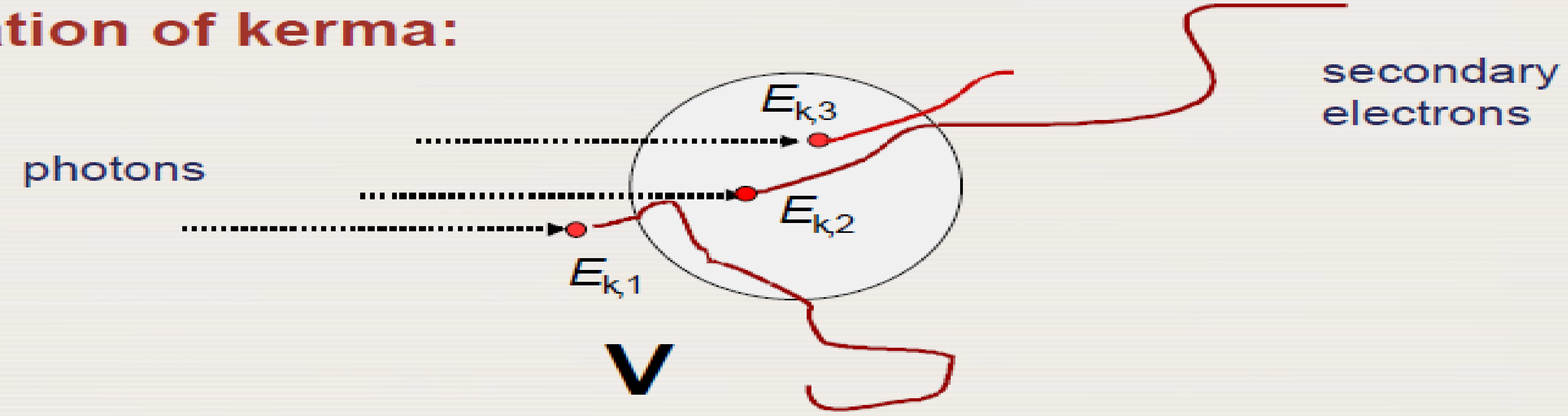
- Kerma is an acronym for Kinetic Energy Released per unit MAss.
- It quantifies the average amount of energy transferred in a small volume from the indirectly ionising radiation to directly ionising radiation without concerns to what happens after this transfer.

$$K = dEtr/dm$$

- The unit of kerma is joule per kilogram (J/kg).
- The name for the unit of kerma is the gray (Gy), where 1 Gy = 1 J/kg.
- Kerma is a quantity applicable to indirectly ionizing radiations, such as photons and neutrons

KERMA

Illustration of kerma:



Collision energy transferred in the volume: $E_{tr} = E_{k,2} + E_{k,3}$

where E_k is the initial kinetic energy of the secondary electrons.

Note: $E_{k,1}$ is transferred **outside the volume** and is therefore not taken into account in the definition of kerma!

Absorbed dose

Absorbed dose is a quantity applicable to both indirectly and directly ionizing radiations.

- The fundamental dosimetric quantity D, defined as:

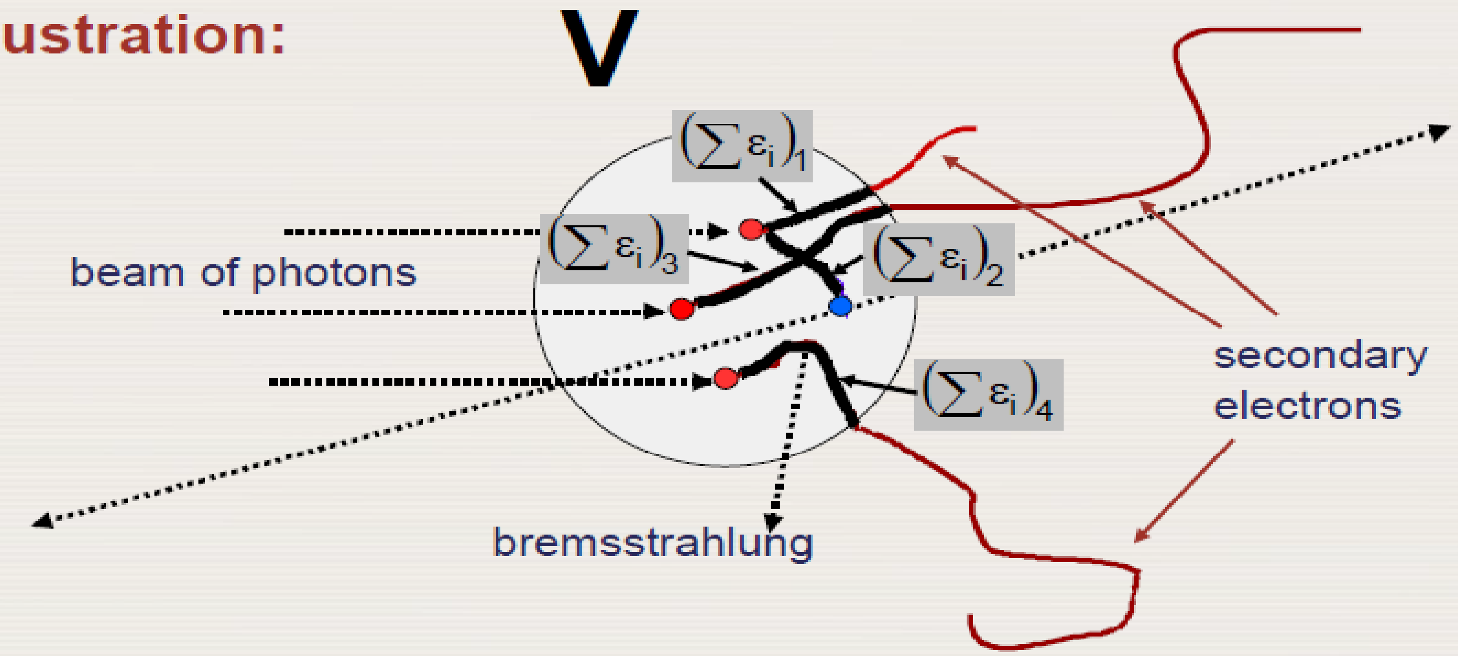
  $$D = dE/dm$$

  where dE is the mean energy imparted by ionizing radiation to matter in a volume element and dm is the mass of matter in the volume element. The energy can be averaged over any defined volume, the average dose being equal to the total energy imparted in the volume divided by the mass in the volume.

- The SI unit of absorbed dose is the joule per kilogram (J/kg), termed the gray (Gy).

Absorbed dose

Illustration:



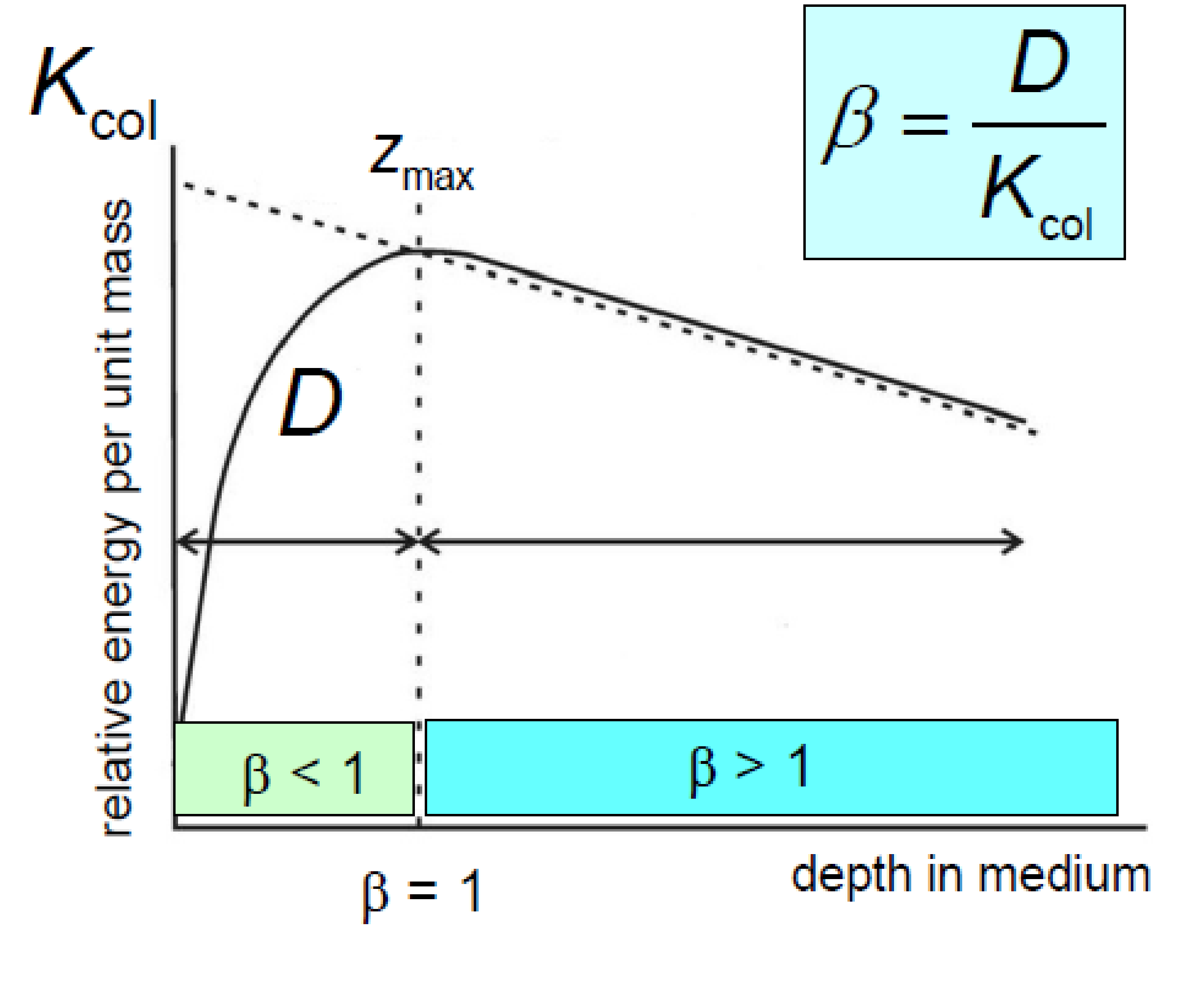
energy absorbed in the volume $= (\sum \varepsilon_i)_1 + (\sum \varepsilon_i)_2 + (\sum \varepsilon_i)_3 + (\sum \varepsilon_i)_4$

where $(\sum \varepsilon_i)$ is the sum of energy lost by collisions along the track of the secondary particles **within the volume V**.

IAEA

Note:
Because electrons are traveling in the medium and deposit energy along their track, the absorption of energy(=)
does not take place at the same location as the transfer of energy described by kerma (=).

Relationship between collision KERMA and absorbed dose



In the buildup region:
$\beta < 1$

In the region of a transient charged particle equilibrium:
$\beta > 1$

At the depth $z = z_{max}$, a true charged particle equilibrium exists.
$\beta = 1$

$$D = K_{col} = K \cdot (1 - \bar{g})$$

Exposure *X*

Exposure *X* is the quotient of d*Q* by d*m*, where d*Q* is the absolute value of the total charge of the ions of one sign produced in air when all the electrons and positrons liberated or created by photons in mass d*m* of air are completely stopped in air

X = dQ/dm

The unit of exposure is coulomb per kilogram (C/kg)

The old unit used for exposure is the roentgen R, where 1 R = 2.58 ×10–4 C/kg

In the SI system of units, roentgen is no longer used and the unit of exposure is simply 2.58 × 10–4 C/kg of air.

Roentgen is defined as the exposure that produces, in air, one esu of charge of either sign per 0.001293g of air(i.e. mass contained in 1cc at 760 Torr, 0C) irradiated by photons.

(1C= 2.998 x 10^9esu)

X(C/kg) = 2.58 x 10-4 X(R)

Exposure X

- The average energy expended in air per ion pair formed W_{air} is the quotient of E_K by N, where N is the mean number of ion pairs formed when the initial kinetic energy E_K of a charged particle is completely dissipated in air:

$$W_{air} = \frac{E_K}{N}$$

- The current best estimate for the average value of W_{air} is 33.97 eV/ion pair or $33.97 \times 1.602 \times 10^{19}$ J/ion pair.
- It follows:

$$\frac{W_{air}}{e} = 33.97 \text{ J/C}$$

- Multiplying the collision kerma K_{col} by (e/W_{air}), the number of coulombs of charge created per joule of energy deposited, one obtains the charge created per unit mass of air or exposure:

$$X = (K_{col})_{air} \cdot \left(\frac{e}{W_{air}} \right)$$

Linear Energy Transfer (LET)

- Rate at which energy transferred from radiation beam to the medium
- Density of ionisation along the track of radiation
- High LET radiations are more easily stopped

Radiation	LET (keV per μm)
1 MeV gamma rays	0.5
100 keV x-rays	6
20 keV betas	10
5 MeV alphas	50

Relative Biological Effectiveness (RBE)

- Different types of radiation can be more or less damaging

$$RBE = \frac{\text{Dose of 220 kV x-rays}}{\text{Dose of radiation under test}}$$

- Both doses cause same biological end point e.g. 10% cell survival
- RBE increases with LET

Radiation Weighting Factors
(from ICRP103)

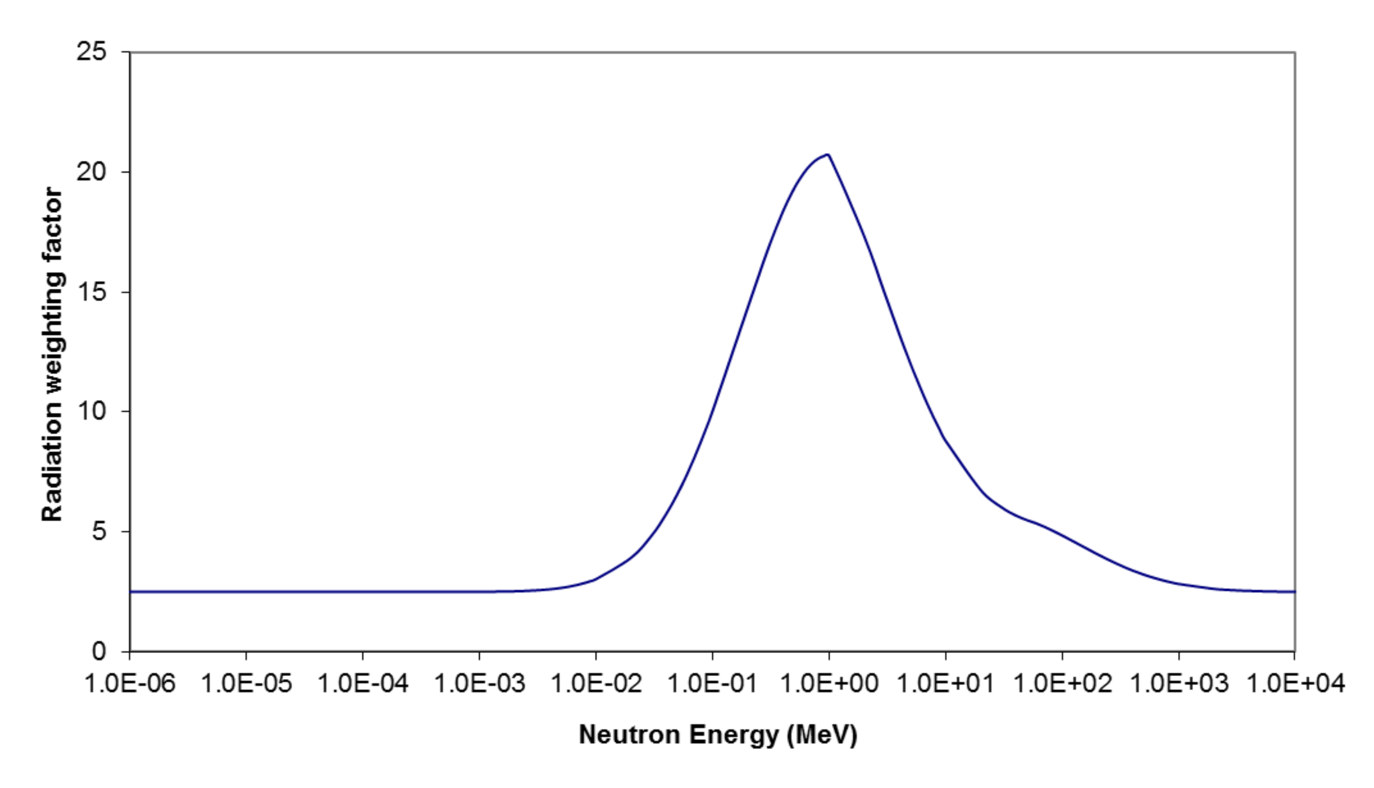
Type of radiation	wR
X-rays, γ-rays and electrons	1
Protons	5
Thermal neutrons	2.5
Fast neutrons	2.5 to 20 *
Alpha particles, fission fragments	20

* Depending on energy

Set from a study of RBE and using organ dose concept

Neutron Radiation Weighting Factors

(from ICRP103)



Equivalent Dose (H)

$$H = \text{Absorbed Dose (in Grays)} \times \text{Radiation Weighting Factor } (w_R)$$

Strictly speaking this is the absorbed dose averaged over the organ or tissue

Dimensionless quantity

$$\text{Total } H_T = \sum w_R \times D_{T,R}$$

where $D_{T,R}$ is the average absorbed dose to the organ for a particular radiation type

Equivalent Dose (H)

Unit:

Sievert (Sv)

Still dimensionally J / kg as w_R is just a number

Rolf Sievert – 1929

(from Karolinska Institutet – http://ki.se)

Conversion factor: 1 Sv $\approx$ 100 rem

Example No. 1

- What is the total equivalent dose to the organ (H_T) if the absorbed dose to the lungs is 0.2 mGy from x-rays?

H_T = Absorbed Dose x radiation weighting factor

Radiation weighting factor for x-rays (w_R) = 1 (for any energy)

$$H_T = 0.2 \text{ x } w_R = 0.2 \text{ x } 1 = 0.2 \text{ mSv}$$

Note that the units change from mGy to mSv

Example No. 2

- What is the total equivalent dose to the organ (H_T) if the absorbed dose to the lungs is 0.2 mGy from x-rays and 0.01 mGy from alpha radiation?

$$H_T = \sum \text{Absorbed Dose x radiation weighting factor}$$

Radiation weighting factor for x-rays (W_R) = 1 (for any energy)
Radiation weighting factor for alpha (W_R) = 20 (for any energy)

$$H_T = 0.2 \times 1 + 0.01 \times 20 = 0.4 \text{ mSv}$$

Note that the units change from mGy to mSv

Effective Dose (E)

- Accounts for uneven irradiation of the body and represents overall risk from whole body exposure

$$E = \sum_{T} w_T \times H_T$$

H_T = Equivalent dose to tissue or organ 'T'
w_T = tissue weighting factor

- Tissue weighting factors represent risks of detrimental radiation effects to different organs or tissue

Tissue Weighting Factors
(from ICRP103)

Organ	w_T for organ
Gonads	0.08
Red bone marrow, colon, lung, stomach, breast	0.12
Bladder, liver, oesophagus, thyroid	0.04
Skin, bone surface, brain, salivary glands	0.01
Remainder (in total)	0.12

Example No. 3

- A patient receives the following equivalent (organ) doses as a result of a chest PA x-radiograph:

Bone Marrow	0.01 mSv (W_T=0.12)
Thyroid	0.05 mSv (W_T=0.04)
Lungs	0.17 mSv (W_T=0.12)
Breast	0.09 mSv (W_T=0.08)

- What is the effective dose resulting from this examination?

$$E = \sum w_T \times H_T$$

$$E_T = 0.01 \times 0.12 + 0.05 \times 0.04 + 0.17 \times 0.12 + 0.09 \times 0.08 =$$

$$0.0308 \text{ mSv or } 30.8 \ \mu\text{Sv}$$