

Electromagnetic Radiation

Ionizing radiation: shown here for photon energies greater than about 1 keV.

Different types of ionizing radiation:

- Photons
- neutrons
- charged particles

← **visible spectrum**

[Image removed due to copyright concerns]

[Alpen, 1998]

Absorbed Dose

- Dose is a measure of the amount of energy from an **ionizing radiation** deposited in a mass of some material.

Formally, **absorbed dose** at a point is defined by the ICRU as

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

where $\Delta \varepsilon$ is the mean energy transferred by the radiation to a mass Δm .

- The biological effect is related to the dose and depends on the **nature** of the radiation.

Units

RAD (Radiation Absorbed Dose)

- Old, but still commonly used.
- 1 rad = 100 ergs/g

Gray (Gy)

- SI unit used to measure absorbed dose is the gray (Gy).

- $1 \text{ Gy} = \frac{1 \text{ J}}{\text{kg}} = \frac{10^7 \text{ erg}}{10^3 \text{ g}} = 10^4 \frac{\text{erg}}{\text{g}} = 100 \text{ rad}$

- Gy can be used for any type of radiation.
- Gy does **not** describe the biological effects of the different radiations.

Dose Calculations: Example

Alpha and Low energy Beta emitters distributed in tissue.

A radionuclide, ingested or inhaled, and distributed in various parts of the body is called an **internal emitter**.

Many radionuclides follow specific metabolic pathways, acting as a chemical element, and localize in specific tissues.

E.g., **iodine** concentrates in the thyroid
radium and **strontium** are bone seekers
tritium will distribute throughout the whole body in body water
cesium tends to distribute throughout the whole body.

If an internally deposited radionuclide emits particles that have a short range, then their energies will be absorbed in the tissue that contains them.

Let:

A = the activity concentration in Bq g^{-1} , of the radionuclide in the tissue

\bar{E} = the average alpha or beta particle energy, in MeV per disintegration

The rate of energy absorption per gram tissue is $A\bar{E}$ ($\text{MeV g}^{-1} \text{s}^{-1}$).

The **absorbed dose rate** is:

$$\begin{aligned}\dot{D} &= A\bar{E} \frac{\text{MeV}}{\text{g s}} \times 1.60 \times 10^{-13} \frac{\text{J}}{\text{MeV}} \times 10^3 \frac{\text{g}}{\text{kg}} \\ &= 1.60 \times 10^{-10} A\bar{E} \text{ Gy s}^{-1}\end{aligned}$$

Health effects depend on how radiation interacts with biological material at the microscopic level.

Radiation delivers energy in “small packets”, not uniformly distributed throughout the entire mass.

[Image removed due to copyright concerns]

[Hall, 2000]

Energy Deposition by Ionizing Radiation

- The biological effects of radiation are the end product of this long series of phenomena, which are set in motion by the passage of radiation through the medium.
- The interaction of radiation with matter produces excited and ionized atoms and molecules as well as large numbers of secondary electrons.
- The secondary electrons produce additional ionizations and excitations until the energies of all electrons fall below the threshold necessary for further interactions.

Dose must be applied to different endpoints... at vastly different scales.

organism
tissue
cell
DNA
(atom?)

Deficiency of the dose concept at the microscopic level

As early as the 1920s, experiments with irradiation of virus particles with x-rays illustrated the paradox that continues today.

- The viruses appeared to be both sensitive and highly resistant at the same time.
- Even at low doses some were killed.
- On average they tolerated very large doses.
- A paradox? Responding differently?
- No, actually receiving different doses.
- The radiation is actually delivered in small packets.
- Dose was seen to be a statistical expectation of being hit.
- The virus particles were demonstrating this random statistical fluctuation.
- “Protection by virtue of being small.”

[Image removed due to copyright concerns]

Distribution of absorbed energy and ionization on a microscopic scale.

[Tubiana, 1990]

Given: 1 Gy = 1 J/kg; 1 eV = 1.6×10^{-19} J

Assume: 1 ionization = 33 eV; 1 nucleus = 10^{-10} gram or about $5 \mu\text{m}^3$

Therefore:

$1 \text{ Gy} \approx 2 \times 10^{17}$ ionizations/kg $\approx 2 \times 10^{14}$ ionizations/g $\approx 20,000$ ionizations / 10^{-10} g

In crossing the $5 \mu\text{m}$ nucleus:

1 MeV electrons lose 200 eV in 6 ionizations/ μm ,
700 tracks $\approx 20,000$ ionizations ≈ 1 Gy

30 keV electrons lose 1 keV in 30 ionizations/ μm ,
140 tracks $\approx 20,000$ ionizations ≈ 1 Gy

4 MeV protons lose 10keV in 300 ionizations/ μm
14 tracks $\approx 20,000$ ionizations ≈ 1 Gy

The dose to the nucleus is the same. *The biological effect is very different.*

- In reality, $\Delta\varepsilon$ depends on the number of particles traversing the mass Δm and the energy that these particles deposit.

The Problem:

- Dose represents the density of energy absorbed per unit mass at a point in the medium.
- On a very small scale (on the order of μm) the energy distribution is not uniform.
- Energy is localized near the tracks of particles.
- Energy transfer takes place in a discontinuous manner, in discrete amounts.
- Dose is a statistical quantity and does not express these characteristics.
- Dose gives a **global value** determined in a mass sufficiently large that the statistical fluctuation is not significant.

However, the biological effect is related to the dose deposition at the microscopic level.

At the level of the cell or the DNA, where the size of the “target” is measured in μm or nm , the non-uniform and discontinuous nature of the energy deposition can be very important.

At the microscopic level, the biological effect depends on the nature and the energy of the ionizing particles.