Dose Calculations
Absorbed Dose from a charged particle beam

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$$\dot{D} = \frac{\dot{\varphi} A(-dE/dx)\,\Delta x}{\rho A \Delta x} = \dot{\varphi}\left(-\frac{dE}{\rho\, dx}\right)$$

$\dot{D}$ = dose rate

$\dot{\varphi}$ = fluence rate ($cm^{-2}\ s^{-1}$)

ρ= density

A = area

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

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

The **absorbed dose rate** is:

$$\dot{D} = A\ \overline{E}\frac{MeV}{g\,s}x\,1.60\,x10^{-13}\,\frac{J}{MeV}\,x\,10^{3}\,\frac{g}{kg}$$

$$= 1.60 \text{ x } 10^{-10}\, A\overline{E} \text{ Gy s}^{-1}$$

Point Source of Gamma Rays

$$\dot{D} = \dot{\Psi}\frac{\mu_{en}}{\rho} = \frac{CE}{4\pi r^2}\frac{\mu_{en}}{\rho}$$

$\dot{D}$ = Dose rate

$\dot{\Psi}$ = energy fluence rate (MeV/cm^2 sec)

C = activity (Bq)

E = energy per decay (MeV)

μ_{en}/ρ = mass energy-absorption coefficient of air (cm^{2}g^{-1})

(~ same for photons between ~60keV and 2MeV)

Beam of Photons

Dose = energy absorbed/mass

$$Dose = \frac{\left(\frac{\mu_{en}}{\rho}\right)(N)(E)(\rho x)(A)}{(A)(\rho x)} = \left(\frac{\mu_{en}}{\rho}\right)(N)(E)$$

(μ_{en}/ρ) = mass energy absorption coefficient (cm^2/g)

N = photon fluence (photons/cm^2)

E = energy per photon

ρ = density

x = thickness

A = area

Absorbed dose from neutrons

- Elastic scatter (higher energies)
- Capture (thermal neutrons)

Thermal neutrons

$$D = \frac{\Phi N \sigma E}{\rho}$$

Φ = thermal neutron fluence (n/cm^2)

N = atom density (cm^{-3})
σ = capture cross section (for each element)
E = energy from capture reaction
ρ = tissue density

The major thermal neutron capture reactions in tissue

$^{14}N(n,p)^{14}C$ σ = 1.7 barns Q = 0.626 MeV

E_p = 0.58 MeV, range in water ~ 8 μm
E_C = 0.04 MeV
Energy is deposited locally

$^{1}H(n,\gamma)^{2}H$ σ = 0.33 barns 2.22 MeV gamma

(μ/ρ) = 0.05 cm^2/g
(μ_{en}/ρ) = 0.025 cm^2/g
contribution to dose depends on the size of the "target"

Principle elements in soft tissue of unit density

Element	Atoms cm^{-3}	Capture cross section, σ
H	5.98×10^{22}	0.33 barns
O	2.45×10^{22}	0.00019 barns
C	9.03×10^{21}	0.0035 barns
N	1.29×10^{21}	1.70 barns

Absorbed dose from fast neutrons

Scattering: assume average energy lost is ½ E_{max}

First collision dose

- Representative of the absorbed dose when the ***mean free path*** is large compared to the target.
- Expressed as dose delivered per individual neutron
- Units are those of dose per neutron/cm^2 (Gy cm^2)

$$D = \frac{N \sigma_S \; Q_{ave}}{\rho}$$

N = atom density (cm^{-3})
σ_S = scattering cross section (for each element)
Q_{ave} = average energy transferred in collision (½ E_{max})
ρ = tissue density

Must calculate dose for ***each element***.

E.g., Calculate the first collision dose for a 5 MeV neutron with tissue hydrogen.

5 MeV neutron σ_S = 1.61 barns
N = 5.98×10^{22} cm^{-3}
Mean energy per scattering collision, Q_{ave} = 2.5 MeV

D = 3.88×10^{-11} Gy cm^2

TABLE 12.6. Analysis of First-Collision Dose for Neutrons in Soft Tissue

Neutron Energy (MeV)	First-Collision Dose per Unit Neutron Fluence for Collisions with Various Elements (10^{-11} Gy cm^2)				
	H	O	C	N	Total
0.01	0.091	0.002	0.001	0.000	0.094
0.02	0.172	0.004	0.001	0.001	0.178
0.03	0.244	0.005	0.002	0.001	0.252
0.05	0.369	0.008	0.003	0.001	0.381
0.07	0.472	0.012	0.004	0.001	0.489
0.10	0.603	0.017	0.006	0.002	0.628
0.20	0.914	0.034	0.012	0.003	0.963
0.30	1.14	0.052	0.016	0.003	1.21
0.50	1.47	0.122	0.023	0.004	1.62
0.70	1.73	0.089	0.029	0.005	1.85
1.0	2.06	0.390	0.036	0.007	2.49
2.0	2.78	0.156	0.047	0.012	3.00
3.0	3.26	0.205	0.045	0.018	3.53
5.0	3.88	0.244	0.079	0.024	4.23
7.0	4.22	0.485	0.094	0.032	4.83
10.0	4.48	0.595	0.157	0.046	5.28
14.0	4.62	1.10	0.259	0.077	6.06

Source: From "Measurement of Absorbed Dose of Neutrons and Mixtures of Neutrons and Gamma Rays," *National Bureau of Standards Handbook 75*, Washington, D.C. (1961).