Absorbed Dose

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

- SI unit used to measure absorbed dose is the gray (Gy).
- 1 Gy = $\frac{1J}{kg}$
- Gy can be used for any type of radiation.
- Gy does **not** describe the biological effects of the different radiations.

Dosimetric Quantities

Quantity	**Definition**	**New Units**	**Old Units**
Exposure	Charge per unit mass of air 1 R = 2.58 x 10^{-4} C/kg	---	Roentgen (R)
Absorbed dose to tissue T from radiation of type R $D_{T,R}$	Energy of radiation R absorbed per unit mass of tissue T 1 rad = 100 ergs/g 1 Gy = 1 joule/kg 1 Gy = 100 rads	gray (Gy)	Radiation absorbed dose (rad)
Equivalent dose to tissue T H_T	Sum of contributions of dose to T from different radiation types, each multiplied by the radiation weighting factor (w_R) $H_T = \Sigma_R\ w_R\ D_{T,R}$	Sievert (Sv)	Roentgen equivalent man (rem)
Effective Dose E	Sum of equivalent doses to organs and tissues exposed, each multiplied by the appropriate tissue weighting factor (w_T) $E = \Sigma_T\ w_T\ H_T$	Sievert (Sv)	rem

Radiological Protection

For practical purposes of assessing and regulating the hazards of ionizing radiation to workers and the general population, ***weighting factors*** (previously called quality factors, Q) are used.

A radiation weighting factor is an estimate of the effectiveness per unit dose of the given radiation relative a to low-LET standard.

Weighting factors are dimensionless multiplicative factors used to convert physical dose (Gy) to equivalent dose (Sv) ; i.e., to place biological effects from exposure to different types of radiation on a common scale.

A weighting factor is not an RBE.

Weighting factors represent a conservative judgment of the envelope of experimental RBEs of practical relevance to low-level human exposure.

Radiation Weighting factors

Radiation Type and Energy Range	**Radiation Weighting Factor, W_R**
X and γ rays, all energies	1
Electrons positrons and muons, all energies	1
Neutrons:	
< 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, (other than recoil protons) and energy > 2 MeV,	2-5
α particles, fission fragments, heavy nuclei	20

[ICRU 60, 1991]

For radiation types and energies not listed in the Table above, the following relationships are used to calculate a weighting factor.

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[Fig. 1 in ICRP, 1991]

$Q = 1.0$ $\qquad L < 10 \text{ keV}/\mu\text{m}$

$Q = 0.32\,L - 2.2$ $\qquad 10 \leq L \leq 100 \text{ keV}/\mu\text{m}$

$Q = 300/(L)^{1/2}$ $\qquad L \geq 100 \text{ keV}/\mu\text{m}$

L = unrestricted LET in water (keV/ μm)

Radiation	**Typical LET values**
1.2 MeV ^{60}Co gamma	0.3 keV/µm
250 kVp x rays	2 keV/µm
10 MeV protons	4.7 keV/µm
150 MeV protons	0.5 keV/µm
14 MeV neutrons	12 keV/µm
Heavy charged particles	100-2000 keV/µm
2.5 MeV alpha particles	166 keV/µm
2 GeV Fe ions	1,000 keV/µm

Tissue weighting factors

Tissue	**Tissue Weighting Factor, W_T**
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.01
Bone surfaces	0.01
Remainder	0.05

(ICRU 60, 1991; NCRP 116, 1993)

Committed Equivalent Dose: for radionuclides incorporated into the body, the integrated dose over time. 50 years for occupational exposure, 70 years for members of the general public.

Committed Effective Dose: effective dose integrated over 50 or 70 years.

Measurement of Exposure: photons

Ionizations in air for electromagnetic radiation only

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Fig. 12.1 in Turner J. E. *Atoms, Radiation, and Radiation Protection*, 2^{nd} ed. New York, NY: Wiley-Interscience, 1995.

Measures charge (coulombs) produced by ionizations in air at STP.
The unit of exposure in air is the Roentgen: 1 R = 2.58 x 10^{-4} C/kg

Absorbed dose in air

$$1\ R = \left(2.58 x 10^{-4}\ \frac{C}{kg}\right)\left(34\frac{J}{C}\right) = 8.8 x 10^{-3}\ \frac{J}{kg}$$

1 R = 8.8 x 10^{-3} Gy in air

Image removed due to copyright restrictions.
Fig. 12.2 in [Turner].

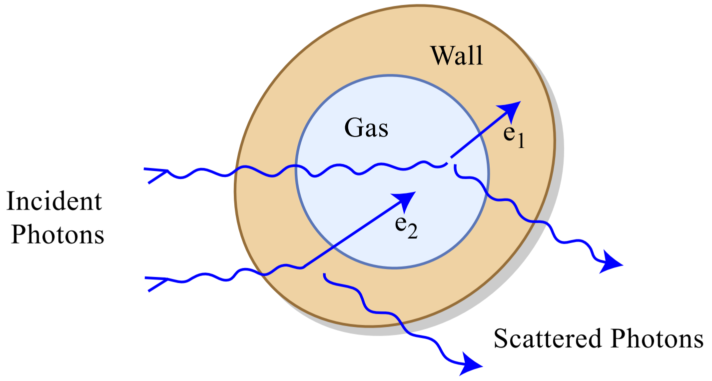
Response is energy independent (~300 keV-2 MeV)
Compton scattering dominant in air and low-Z wall

The Bragg-Gray Principle

Goal: determine absorbed dose in tissue exposed to radiation.

B-G principle relates dose in gas to dose in material.

Tissue dose:
Dosimeter material is tissue equivalent (same elemental composition).



Gas in Cavity Enclosed by Wall to Illustrate Bragg-Gray Principle

Figure by MIT OCW.

Conditions

- Electronic equilibrium: wall thickness > maximum range of secondary charged particles.
- Wall thickness not great enough to attenuate the radiation.
- Wall and gas have similar electron scattering properties.

Measurement of Absorbed Dose: photons

The tissue-equivalent ionization chamber

Graphite/CO_2 carbon is approximately tissue equivalent

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Fig. 12.4 in [Turner].

$$D_w = D_g = \frac{N_g W}{m}$$

D_W = dose to the wall
D_g = dose to the gas
N_g = number of ionizations in the gas
W = energy needed to produce an ion pair in the gas
m = mass of the gas

Absorbed Dose from a charged particle beam

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Fig. 12.9 in [Turner].

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

$\dot{D}$ = dose rate

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

ρ= density

A = area

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Fig. 12.8 in [Turner].

Dose Calculations

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:

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

$= 1.60 \times 10^{-10}$ A$\overline{E}$ 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,γ)^{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 x 10^{22} cm^{-3}
Mean energy per scattering collision, Q_{ave} = 2.5 MeV

D = 3.88 x 10^{-11} Gy cm^2

Analysis of First-Collision Dose for Neutrons in Soft Tissue
(from Table 12.6 in [Turner].

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).