Chapter 3: Interaction of Ionizing Radiation and Matter

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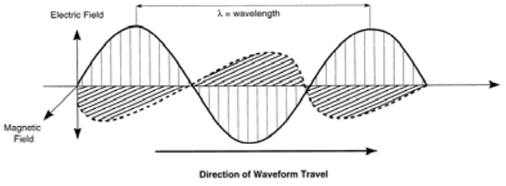
a copy of this lecture may be found at:
http://courses.washington.edu/radxphys/PhysicsCourse.html

Chapter 3 Lecture Objectives

- Describe the types of radiation - Electromagnetic and Particulate
- Particle interactions with matter
  - Excitation, Ionization and Radiative
- X-ray interactions with matter
  - Rayleigh, Compton, Photoelectric and Pair Production
- Describe the *energy dependence* of these interactions
- Describe and calculate the various *quantitative parameters* used to *characterize* x-ray *attenuation*
- Differentiate between radiographic exposure *absorbed dose* and *equivalent dose* as well as use the correct *radiological units*

Radiation

- The propagation of energy through Space or Matter
- Can be thought of as either:
  - Electromagnetic (EM) [visible light, radio waves, x-rays]
  - Particulate (e.g., electron)
- EM radiation – propagates as a pair of electric and magnetic fields
- Wave characteristics – c [speed, m/sec] = λ [wavelength, m] · ν [frequency, 1/sec]
  - As c is essentially constant, then $\nu \propto 1/\lambda$ (inversely proportional)

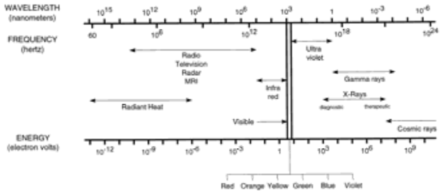


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.19.

Particulate Radiation

- When interacting with matter, EM radiation can exhibit particle-like behavior with bundles of energy known as photons, $E=h\nu = hc/\lambda$
- E (keV) = 1.24/ λ (nm)
- λ often measured in angstroms,
- 1 Å=10^{-10} m or 0.1 nm
- Multiples of the electron volt (eV) common to medical imaging are the keV (1000 eV) and the MeV (1,000,000 eV)

- The most significant charged particulate radiations of interest are:
- Alpha particles, Electrons, Positrons, Protons, Neutrons (see table 2-1 on page 20 of Bushberg)

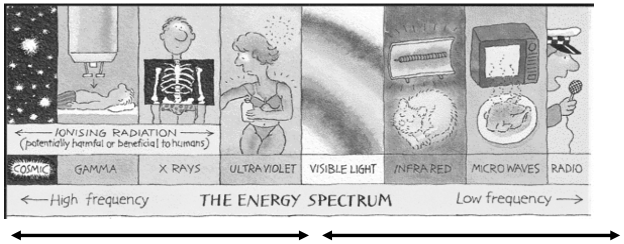


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.18

One eV is defined as the energy acquired by an electron as it traverses an electrical potential difference (voltage) of one volt in vacuum

Electromagnetic Radiation (EM)

- Physical manifestations are classified in the ĒM spectrum based on energy (E) and wavelength (λ) and comprise the following general categories:



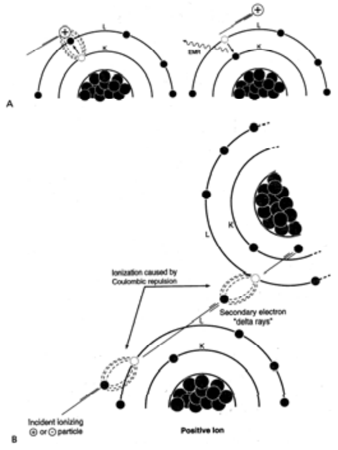
Ionizing radiation (UV, x-rays, gamma rays)

Non-ionizing radiation

Electromagnetic Radiation (EM)

- Except for nuclear medicine, the EM radiation required also interacts (via absorption, scatter) with tissues it penetrates
- In NM, radioactive agents are injected or ingested, and the metabolic or physiologic interactions of the agent give rise to the information in the images

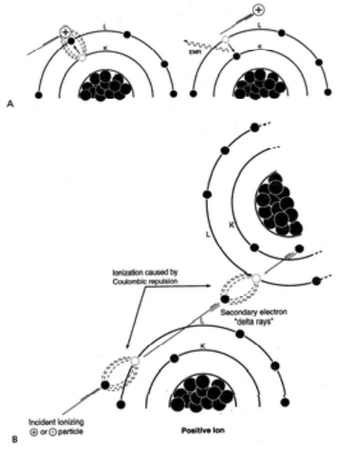
Particle Interactions
Excitation, Ionization and Radiative Losses



- Energetic charged particles interact with matter via electrical forces
- Lose kinetic energy through *excitation*, *ionization* and *radiative losses*
- <u>Excitation</u>: transfer of some of the incident particle's energy to electrons in absorbing material promoting them to higher electron orbitals
- Imparted E < E_b → emits EM (de-excitation)

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.32.

Particle Interactions
Excitation, Ionization and Radiative Losses



- Ionization: imparted E > E_b →electron ejected from atom
- Ion pair formed consisting of ejected electron and positively charged atom
- sometimes electrons with enough kinetic energy produce further ionizations (secondary ionizations)
  - Such e^- are called 'delta rays'
- Approx. 70% of electron energy deposition leads to non-ionizing excitation

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.32.

Specific Ionization

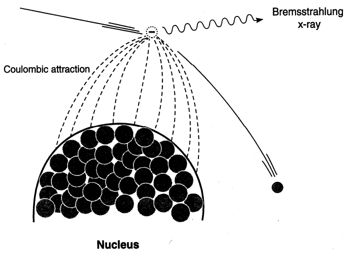
- The number of primary and secondary ion pairs produced per unit length of the charged particle is called specific ionization (IP/mm)
- SI increases as the particle charge increases and decreases as the velocity of the incident particle increases
  - SI of alpha particle can be as high as 7000 IP/mm in air
  - SI of electrons is much lower in the range of 50 to 100 IP/mm in air

Linear Energy Transfer (LET)

- Amount of energy deposited per unit length (eV/cm)
- Product of the SI (IP/cm) and energy deposited per IP (eV/IP)
- LET $\propto q^2/KE$, q = charge of particle and KE is kinetic energy
- Describes the energy deposition density which largely determines the biologic consequence of radiation exposure
- High LET radiation: alpha particles, protons etc.
- Low LET radiation:
  - Electrons (electrons, beta particles, positrons)
  - EM radiation (x-rays or γ-rays)
- High LET >> damaging than low LET radiation

Particle Interactions
Radiative Interactions - Bremsstrahlung

- Deceleration of an electron around a nucleus causes it to emit EM radiation or bremsstrahlung (German): ‘breaking radiation’
- This radiation energy loss is responsible for the majority of x-rays produced by an x-ray tube
- Probability of bremsstrahlung emission $\propto Z^2$ of the absorber
- Ratio of electron energy loss due to bremsstrahlung vs. excitation and ionization = KE[MeV]·Z/820
- Thus, for an 100 keV electron and tungsten (Z=74) ≈ 1%



Z=atomic number

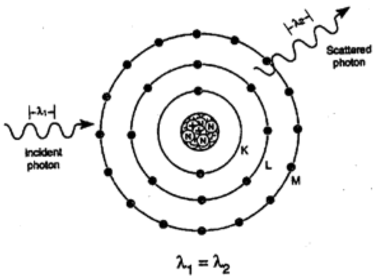
c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.35.

X- and Gamma-Ray Interactions with Matter

- There are several ways for x-rays and gamma rays to be absorbed or scattered by matter
- Four major interactions are of importance to diagnostic radiology and nuclear medicine, each characterized by a probability of interaction
  - Rayleigh (classical or coherent) scattering
  - Compton scattering
  - Photoelectric effect
  - Pair production

Rayleigh (Classical or Elastic) Scattering

- Excitation of the total atom occurs as a result of interaction with the incident photon
- No ionization takes place
- The photon is scattered (re-emitted) in different direction
- No loss of energy
- Interaction occurs at very low energy diagnostic x-rays such as in mammography
- Relatively infrequent probability ≈ 5 - 13%



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.37.

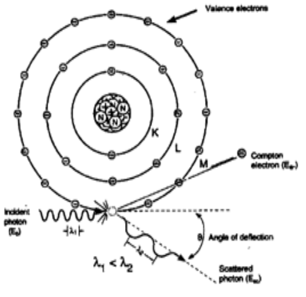
Compton (Nonclassical or Inelastic) Scattering

- Dominant interaction of x-rays with soft tissue in the diagnostic energy range (26 keV – 30 MeV)
- Occurs between the photon and a “free” outer shell electron
- $E_o >> BE_e$
- $E_o = E_{sc} + E_{e-}$ (BE_e ignored since very small)

$$E_{sc} = \frac{E_0}{1 + \frac{E_0}{m_e c^2}(1 - \cos\theta)}$$

where $m_e c^2 = 511$ keV

- The probability of Compton interaction proportional to material density (ρ)
- Max. energy transferred to electron at 180 deg backscatter
- Max energy to scattered photon is 511 keV at 90 deg



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.38.

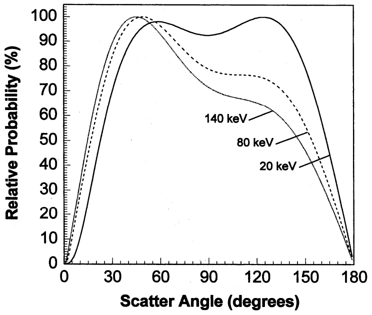
Compton (Nonclassical or Inelastic) Scattering

E_{sc} as a function of E_0 and angle (θ) – Excel spreadsheet

Eo (keV)	10	20	50	100	200	500	1000	10000
Angle (deg)								
0	10	20	50	100	200	500	1000	10000
5	9.999	19.997	49.981	99.926	199.703	498.145	992.608	9306.934
10	9.997	19.988	49.926	99.704	198.818	492.676	971.128	7708.292
20	9.988	19.953	49.707	98.834	195.388	472.139	894.440	4586.770
30	9.974	19.896	49.353	97.445	190.035	442.051	792.279	2761.049
45	9.943	19.773	48.607	94.579	179.431	388.625	635.657	1485.494
60	9.903	19.616	47.668	91.087	167.267	335.742	505.440	927.236
75	9.857	19.436	46.619	87.333	155.028	289.817	408.088	644.973
90	9.808	19.247	45.544	83.633	143.741	252.720	338.187	486.157
105	9.760	19.061	44.517	80.235	133.986	224.042	288.730	390.100
120	9.715	18.891	43.601	77.307	126.017	202.617	254.102	329.444
135	9.677	18.747	42.844	74.958	119.894	187.241	230.377	290.637
150	9.648	18.639	42.280	73.251	115.584	176.938	214.975	266.545
180	9.623	18.548	41.817	71.871	112.184	169.093	203.505	249.135

Compton (Nonclassical or Inelastic) Scattering (2)

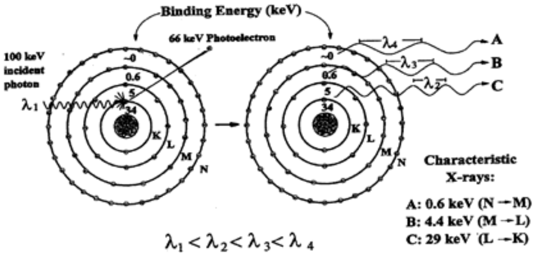
- As incident photon energy increases
  - Both scattered photons and electrons are scattered more towards the forward direction
  - For a given scattering angle, the fraction of energy transferred to the scattered photon decreases
- At low diagnostic x-ray energies, the majority of the incident photon energy is transferred to the scattered photon, which if detected by image receptor would reduce contrast



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.39.

Photoelectric Effect

- Interaction of incident photon, E_0 with inner shell electron
- All E transferred to e^- (ejected photoelectron) as kinetic energy (E_e) less the binding energy: $E_e = E_0 - E_b$
- Photon totally absorbed
- Empty shell immediately filled with e^- from outer orbitals resulting in the emission of characteristic x-rays

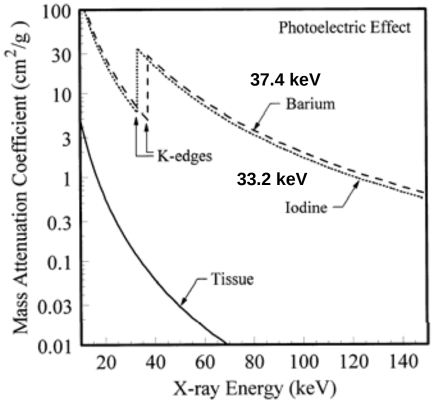


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.41.

Photoelectric Effect (2)

- Products:
  - Characteristic x-rays and/or auger electrons
  - Negative ion (photoelectron) and positive ion (atom)
- Probability of photoelectric absorption $\propto Z^3/E^3$
- Due to the absorption of the incident x-ray without scatter, maximum subject contrast arises with a photoelectric effect interaction
- Explains why contrast ↓ as higher energy x-rays are used in the imaging process
- If photon energies are doubled, the probability of photoelectric interaction is decreased by a factor of 8
- Increased probability of photoelectric absorption just above the E_b of the inner shells cause discontinuities in the attenuation profiles (e.g., K-edge)

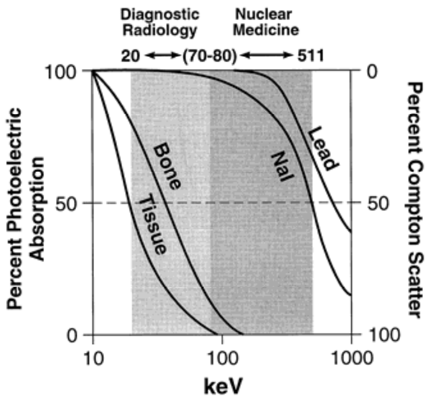
Photoelectric Effect (3)



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.43.

Photoelectric Effect (4)

- Edges become significant factors for higher Z materials as the E_b are in the diagnostic energy range:
  - Contrast agents – barium (Ba, Z=56) and iodine (I, Z=53)
  - Rare earth materials used for intensifying screens – lanthanum (La, Z=57) and gadolinium (Gd, Z=64)
  - Increased absorption probabilities improve subject contrast and quantum detective efficiency
- At photon E << 50 keV, the photoelectric effect plays an important role in imaging soft tissue, amplifying small differences in tissues of slightly different Z, thus improving subject contrast (e.g., in mammography)



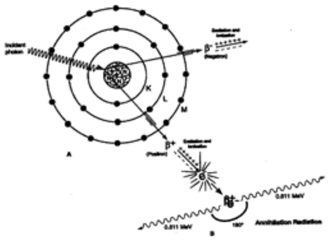
c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.43.

- The photoelectric process dominates when lower energy photons interact with high Z materials. This it the primary mode of interaction of x-rays with screen phosphors, contrast materials and bone.
- Compton scattering will dominate at most photon energies in materials of lower atomic number such as tissue and air.

Pair Production

- Conversion of energy to mass occurs upon the interaction of a high E photon (> 1.02 MeV; rest mass of e^- = 511 keV) in the vicinity of a nucleus
- Creates a negatron (β^-) - positron (β^+) pair
- The β^+ annihilates with an e^- to create two 511 keV photons separated at an θ of 180°
- Not important in diagnostic x-ray imaging because of the high energy threshold requirement for this to occur

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.44.



Question

- In comparison to 20 keV photons, the probability of photoelectric interaction in bone at 60 keV is approximately:
  - A. 27 times as great.
  - B. 3 times as great.
  - C. The same.
  - D. 3 times less.
  - E. 27 times less.

- remember: PE $\propto Z^3/E^3$
- $\approx (Z/60)^3/(Z/20)^3 = (20/60)^3 = (1/3)^3 = 1/27$

Question

- Electrons lose energy when passing through matter by:
  - 1. Production of bremsstrahlung.
  - 2. Photoelectric interactions.
  - 3. Collisions with other electrons.
  - 4. Production of delta rays.

  - A. 1 and 2
  - B. 3 and 4
  - C. 1, 3 and 4
  - D. 1, 2 and 3
  - E. All of the above.

Question

Which is characteristic of photon interaction with soft tissue?

A. Some Compton, some PE, no pair production.
B. Some Compton, some pair production, no PE.
C. Brehmstralung only.
D. Pair production only.
E. Compton only.

- Answer: A

Question

- In Compton interactions, the primary x ray will interact with an outer electron resulting in
- A) ejected electron + positron
- B) ejected electron + characteristic x ray
- C) recoil electron + photon of less energy
- D) conversion electron + photon of less energy
- E) auger electron + photon of less energy

- **Answer: C**

Attenuation of X- and Gamma Rays

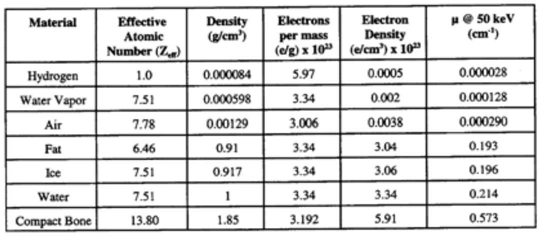
- *Attenuation* is the removal of photons from a beam of x- or gamma rays as it passes through matter
- *Attenuation is c*aused by both absorption and scattering of the primary photons
- Linear Attenuation Coefficient (μ)
  - *Fraction of photons removed from a monoenergetic beam of x- and gamma rays per unit thickness of material* (cm^{-1})
- The number of photons removed from the beam traversing a very small thickness Δx can be expressed as:
    - $n = \mu N \Delta x$
    - n = number of photons removed from beam
    - N = number of photons incident on the material

Attenuation of X- and Gamma Rays (2)

- $n = \mu N \Delta x$
- However, as the thickness increases, the relationship is not linear
- Thus for a monoenergetic beam of photons incident upon either thick or thin slabs of material, an exponential relationship exists between the number of incident photons (N_0) and transmitted photons (N) through thickness x without interaction
  - $N = N_0 e^{-\mu \cdot x}$
  - $\mu_{total}(E) = \mu_{RS}(E) + \mu_{PE}(E) + \mu_{CS}(E) + \mu_{PP}(E)$
- Energy dependent, $\mu(E) \downarrow$ as E $\uparrow$ (except at k-edge),
- e.g., for soft tissue
  - $\mu(30\text{ keV}) = 0.35\text{ cm}^{-1}$ and $\mu(100\text{ keV}) = 0.16\text{ cm}^{-1}$
  - Multiply by 100% to get % removed from the beam/cm

Attenuation of X- and Gamma Rays (3)

- At low x-ray E: $\mu_{PE}(E)$ dominates and $\mu(E) \propto Z^3/E^3$
- At high x-ray E: $\mu_{CS}(E)$ dominates and $\mu(E) \propto \rho$
- Only at very-high E (> 1MeV) does $\mu_{PP}(E)$ contribute
- The value of $\mu(E)$ is dependent on the phase state:
    - $\mu_{\text{water vapor}} < \mu_{\text{ice}} < \mu_{\text{water}}$

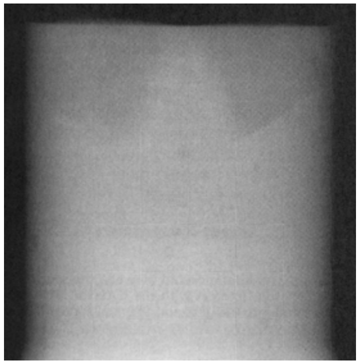


Material	Effective Atomic Number (Z_{eff})	Density (g/cm³)	Electrons per mass (e/g) x 10^{23}	Electron Density (e/cm³) x 10^{23}	μ @ 50 keV (cm⁻¹)
Hydrogen	1.0	0.000084	5.97	0.0005	0.000028
Water Vapor	7.51	0.000598	3.34	0.002	0.000128
Air	7.78	0.00129	3.006	0.0038	0.000290
Fat	6.46	0.91	3.34	3.04	0.193
Ice	7.51	0.917	3.34	3.06	0.196
Water	7.51	1	3.34	3.34	0.214
Compact Bone	13.80	1.85	3.192	5.91	0.573

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.46.

Attenuation of X- and Gamma Rays (4)

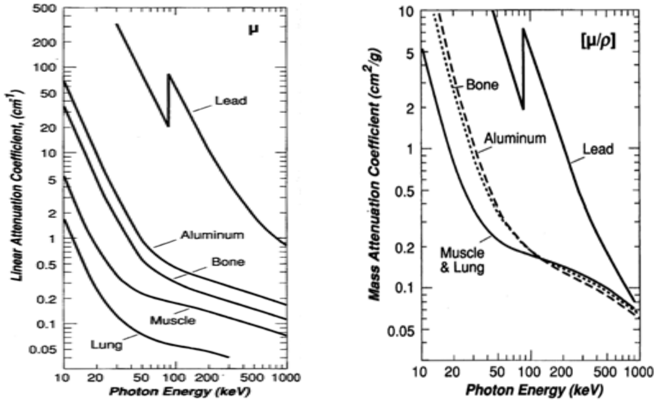
- The linear attenuation coefficient, normalized to unit density is called the mass attenuation coefficient
- $\mu_m = \mu\ [cm^{-1}] / \rho\ [g/cm^3]$
- $\mu_m\ [cm^2/g]$
- Independent of density (ρ)
- $N = N_0 e^{-(u/\rho) \cdot \rho x}$
- ρx - mass thickness or areal thickness



125 kVp Radiograph of two ice cubes

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.47.

Linear and Mass Attenuation Coefficients



c.f. Wolbarst. Physics of Radiology, pp. 108, 110.

Half Value Layer

- Thickness of material required to reduce the intensity of the incident beam by ½
- $\frac{1}{2} = e^{-\mu(E) \cdot HVL}$ or $HVL = 0.693/\mu(E)$
- Units of HVL expressed in mm Al for a Dx x-ray beam and is a surrogate measure of the average energy of the photons in the beam
- Reduction in beam intensity can be expressed as $(\frac{1}{2})^n$
- The HVL is function of photon energy, geometry and attenuating material

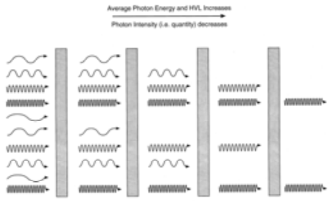
Question

- If the linear attenuation coefficient is 0.05 cm^{-1}, the HVL is:
  - A. 0.0347 cm
  - B. 0.05 cm
  - C. 0.693 cm
  - D. 1.386 cm
  - E. 13.86 cm

- HVL = $0.693/\mu = 0.693/0.05\ cm^{-1} \approx 0.7 \times 20\ cm = 14\ cm$

Effective Energy, Mean Free Path and Beam Hardening

- The effective (avg.) E of an polychromatic x-ray beam is ⅓ to ½ the peak value (kVp) and is essentially an estimate of the penetration power of the x-ray beam
- Mean free path (avg. path length of x-ray) = $1/\mu$ = HVL/0.693 = 1.44 HVL
- Beam hardening
  - The Bremsstrahlung process produces a wide spectrum of energies
  - As lower E photons have a greater attenuation coefficient, they are preferentially removed from the beam, thus the mean energy of the resulting beam is shifted to higher E
  - Homogeneity coefficient = 1st HVL/2nd HVL



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.51.

Question

- The intensity of a beam is reduced by 50% after passing through x cm of an absorber. Its attenuation coefficient, μ, is:
  - A. (0.693)·x
  - B. x/0.693
  - C. 0.693/x
  - D. 2x
  - E. $(0.693)\cdot x^2$

- HVL = $0.693/\mu$, so $\mu = 0.693/\text{HVL} = 0.693/x$

Fluence, Flux and Energy Fluence

- Fluence (Φ) = number of photons/cross sectional area [cm^{-2}]
- Flux ($d\Phi/dt$) = fluence rate = fluence/sec [cm^{-2}-sec^{-1}]
- Energy fluence (Ψ) = (photons/area)·(energy/photon) = $\Phi \cdot E$ [keV-cm^{-2}] or [J-m^{-2}]
- Energy flux ($d\Psi/dt$) = energy fluence rate = energy fluence/sec [keV-cm^{-2}-sec^{-1}]

Kerma

- Kerma = Kinetic Energy Released in MAtter
    - Defined as the kinetic energy transferred to charged particles by indirectly ionizing radiation, per mass matter.
    - Units are J/kg or gray

Absorbed Dose

- Absorbed Dose = energy deposited by ionizing radiation per unit mass of material
- ΔE/Δm [J/kg]
- SI units of absorbed dose = gray (Gy); 1 Gy = 1 J/kg
- Traditional dose unit: rad (*r*adiation *a*bsorbed *d*ose) = 10 mGy; 100 rads = 1 Gy

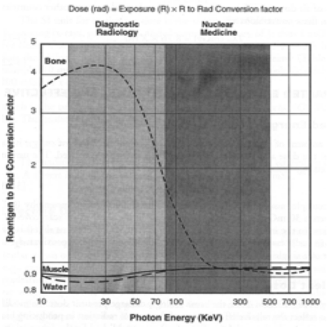
c.f. http://www.uic.com.au/ral.htm

Exposure and Dose

- Exposure (X): the amount of electrical charge (ΔQ) produced by ionizing radiation per mass (Δm) of air = ΔQ/Δm [C/kg]
- Traditional units: Roentgen (R) = 2.58×10^{-4} C/kg
    - also mR = 10^{-3} R
- Measured using an air-filled ionization chamber
- Output intensity of an x-ray tube (I) = X/mAs [mR/mAs]

Exposure and Dose

- Dose (Gy) = Exposure (R) · (R to or Gray conversion factor)
    - R to Gray conversion factor = 0.00876 ≈ 1 for air
- D_{air} (mGy) = 8.76 · X (R)
- D_{air} (μGy) = 8.76 · X (mR)
- Exposure is nearly proportional to dose in soft tissue over the diagnostic radiology range
- For bone, the roentgen-to-rad conversion factor approaches 4



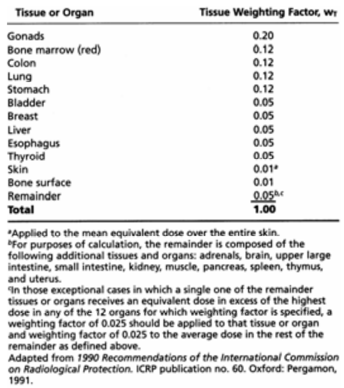
c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.55.

Imparted Energy and Equivalent Dose

- Imparted Energy [J] = Dose [J/kg] · mass [kg]
- Equivalent Dose (H) [Sievert or Sv]
  - In general, 'high LET' radiation (e.g., alpha particles and protons) are much more damaging than 'low LET' radiation, which include electrons and ionizing radiation such as x-rays and gamma rays and thus are given different radiation weighting factors (w_R)
    - X-rays/gamma rays/electrons: LET ≈ 2 keV/μm; $w_R = 1$
    - Protons (< 2MeV): LET ≈ 20 keV/μm; $w_R = 5\text{-}10$
    - Neutrons (E dep.): LET ≈ 4-20 keV/μm; $w_R = 5\text{-}20$
    - Alpha Particle: LET ≈ 40 keV/μm; $w_R = 20$
  - $H = D \cdot w_R$; 1 Sv = 100 rem (traditional unit), 1 rem = 10 mSv
- Replaced the quantity formerly known as dose equivalent

Effective Dose

- Not all tissues equally radiosensitive
- ICRP publication 60 (1991): tissue weighting factors (w_T)
- First calculate the equivalent dose to each organ: (H_T) [Sv]
- Effective Dose (E) [Sv]
- $E = \sum w_T \cdot H_T$
- Replaces the quantity formerly known as effective dose equivalent (H_E) using different w_T per ICRP publication 26 (1977)



Tissue or Organ	Tissue Weighting Factor, w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01^{a}
Bone surface	0.01
Remainder	$0.05^{b,c}$
Total	**1.00**

[a] Applied to the mean equivalent dose over the entire skin.
[b] For purposes of calculation, the remainder is composed of the following additional tissues and organs: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, and uterus.
[c] In those exceptional cases in which a single one of the remainder tissues or organs receives an equivalent dose in excess of the highest dose in any of the 12 organs for which weighting factor is specified, a weighting factor of 0.025 should be applied to that tissue or organ and weighting factor of 0.025 to the average dose in the rest of the remainder as defined above.
Adapted from *1990 Recommendations of the International Commission on Radiological Protection*. ICRP publication no. 60. Oxford: Pergamon, 1991.

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.58.

Summary

Used to compare assessment of equipment performance etc.

Used to calculate organ dose such as dose to uterus

Used to compare risk of stochastic effects, compare different imaging proc.

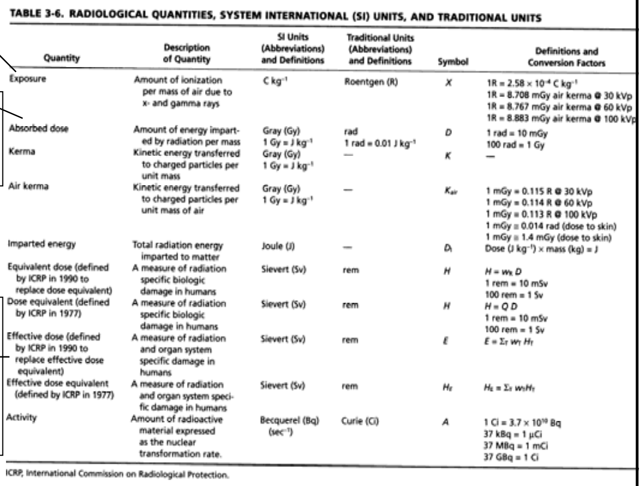


TABLE 3-6. RADIOLOGICAL QUANTITIES, SYSTEM INTERNATIONAL (SI) UNITS, AND TRADITIONAL UNITS

Quantity	Description of Quantity	SI Units (Abbreviations) and Definitions	Traditional Units (Abbreviations) and Definitions	Symbol	Definitions and Conversion Factors
Exposure	Amount of ionization per mass of air due to x- and gamma rays	C kg^{-1}	Roentgen (R)	X	1R = 2.58 × 10^{-4} C kg^{-1} 1R = 8.708 mGy air kerma @ 30 kVp 1R = 8.767 mGy air kerma @ 60 kVp 1R = 8.883 mGy air kerma @ 100 kVp
Absorbed dose	Amount of energy imparted by radiation per mass	Gray (Gy) 1 Gy = J kg^{-1}	rad 1 rad = 0.01 J kg^{-1}	D	1 rad = 10 mGy 100 rad = 1 Gy
Kerma	Kinetic energy transferred to charged particles per unit mass	Gray (Gy) 1 Gy = J kg^{-1}	—	K	—
Air kerma	Kinetic energy transferred to charged particles per unit mass of air	Gray (Gy) 1 Gy = J kg^{-1}	—	K_{air}	1 mGy = 0.115 R @ 30 kVp 1 mGy = 0.114 R @ 60 kVp 1 mGy = 0.113 R @ 100 kVp 1 mGy ≅ 0.014 rad (dose to skin) 1 mGy ≅ 1.4 mGy (dose to skin)
Imparted energy	Total radiation energy imparted to matter	Joule (J)	—	D_i	Dose (J kg^{-1}) × mass (kg) = J
Equivalent dose (defined by ICRP in 1990 to replace dose equivalent)	A measure of radiation specific biologic damage in humans	Sievert (Sv)	rem	H	$H = w_R D$ 1 rem = 10 mSv 100 rem = 1 Sv
Dose equivalent (defined by ICRP in 1977)	A measure of radiation specific biologic damage in humans	Sievert (Sv)	rem	H	$H = Q D$ 1 rem = 10 mSv 100 rem = 1 Sv
Effective dose (defined by ICRP in 1990 to replace effective dose equivalent)	A measure of radiation and organ system specific damage in humans	Sievert (Sv)	rem	E	$E = \Sigma_T w_T H_T$
Effective dose equivalent (defined by ICRP in 1977)	A measure of radiation and organ system specific damage in humans	Sievert (Sv)	rem	H_E	$H_E = \Sigma_T w_T H_T$
Activity	Amount of radioactive material expressed as the nuclear transformation rate.	Becquerel (Bq) (sec^{-1})	Curie (Ci)	A	1 Ci = 3.7 × 10^{10} Bq 37 kBq = 1 μCi 37 MBq = 1 mCi 37 GBq = 1 Ci

ICRP, International Commission on Radiological Protection.

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.59.

Question

- Match the type of radiation with its description.
  - A. Ionizing elementary particles
  - B. Non-ionizing elementary particles
  - C. Ionizing photons
  - D. Non-ionizing photons
  - E. Other

  - **G46**. Betas
  - **G47**. Heat radiation
  - **G48**. Visible light
  - **G49**. X-rays
  - **G50**. Ultrasound

Question

- Match the quality factor (Q) or radiation weighting factor (w_R) used in radiation protection with the type of radiation:
  - A. 10
  - B. 2
  - C. 1
  - D. 0.693
  - E. 20

  - **G2**. 1.25 MeV gammas
  - **G3**. 100 keV x-rays
  - **G4**. 200 keV neutrons

Question

- Match the following units with the quantities below:
  - A. Bq
  - B. Sv
  - C. C/kg
  - D. Gy
  - E. J

  - **G3**. Absorbed dose
  - **G4**. Activity
  - **G5**. Exposure
  - **G6**. Equivalent Dose

Question

- Equivalent Dose is greater than absorbed dose for __________.
  - A. X-rays above 10 MeV
  - B. Kilovoltage x-rays
  - C. Electrons
  - D. Neutrons
  - E. All charged particles

  - Remember: $H = D \cdot w_R$
  - X-rays/gamma rays/electrons: LET ≈ 2 keV/μm; $w_R = 1$

Question

- Match the unit with the quantity it measures. (Answers may be used more than once or not at all.)
  - A. Frequency.
  - B. Wavelength.
  - C. Power.
  - D. Absorbed dose.
  - E. Energy.

  - **G2**. Electron volt
  - **G3**. Hertz
  - **G4**. Joule
  - **G5**. Gray