CHAPTER 3: INTERACTION OF RADIATION WITH MATTER

PARTICLE INTERACTIONS

Excitation – charged particle transfers energy to orbital electron not exceeding its binding energy, which moves to a higher energy level then returns to the lower energy level (de-excitation), emitting EM radiation

Ionization – charged particle transfers energy to orbital electron
exceeding its binding energy à electron is ejected from the atom,forming an ion pair (ejected electron and positively charged atom)
- Secondary ionizations can be produced by sufficiently high energy ejected electrons (delta rays)
- Specific Ionization = # ion pairs produced per mm of charged particle's path; increases with electrical charge and decreases with incident particle velocity
- Linear Energy Transfer = energy deposited per cm path length; proportional to square of charge and inversely proportional to incident particle kinetic energy

Scattering – interaction resulting in deflection of particle or photon from its original trajectory

Bremsstrahlung (Braking Radiation) – electron decelerated by interaction with positively charged nucleus à lost kinetic energy is emitted as a photon

X- AND GAMMA-RAY INTERACTIONS

Coherent (Rayleigh) scatter – low energy photon excites an total atom but passes through without any net transfer of energy to the atom à scattered photon has same energy but a slightly different direction than incident photon
- Scattered photon usually emitted in forward direction
- Minimal concern in diagnostic radiology

Compton scatter – incident photon interacts with loosely bound outer shell electron àelectron is ejected from atom and photon is scattered with some reduction in energy and a new direction
- Scattered photon may participate in additional tissue interactions or reach the image receptor and degrade image quality
- Scatter more likely to be in forward direction with higher incident photon energy
- Energy of scattered photon increases as angle of deflection decreases
- Energy of incident photon = energy of scattered photon + ejected electron
- Accounts for most scattered radiation in diagnostic radiology
- Probability increases with number of outer shell electrons (density of material) and decreases with increasing incident photon energy

PHOTOELECTRIC EFFECT

In the photoelectric interaction, a photon transfers all its energy to an electron located in one of the atomic shells. The electron is ejected from the atom by this energy. Photoelectric interactions usually occur with electrons that have a relatively high binding energy, but only slightly less than the energy of the photon. If the binding energy is more than the energy of the photon, a photoelectric interaction cannot occur. The photon's energy is divided into two parts by the interaction. A portion of the energy is used to overcome the electron's binding energy and to remove it from the atom. The remaining energy is transferred to the electron as kinetic energy and is deposited near the interaction site. This interaction opens one of the electron shells, and an electron moves down to fill in. The drop in energy of the filling electron often produces a characteristic x-ray photon. The energy of the characteristic radiation depends on the binding energy of the electrons involved.
Pair Production:

Pair production is a photon-matter interaction that is NOT encountered in diagnostic imaging because it can occur only with photons with energies in excess of 1.02 MeV. In a pair-production interaction, the photon interacts with the nucleus in such a manner that its energy is converted into matter. The interaction produces a pair of particles, an electron and a positively charged positron. These two particles have the same mass, each equivalent to a rest mass energy of 0.51 MeV.

ATTENUATION

Attenuation is the removal of photons from a beam of x- or gamma rays as it passes through matter. This is caused by both absorption and scattering of the primary photons.

Linear Attenuation Coefficient:
The linear attenuation coefficient (μ) is the actual fraction of photons interacting per 1-unit thickness of material. In the example below, the fraction that interacts in the 1-cm thickness is 0.1, or 10%, and the value of the linear attenuation coefficient is 0.1 per cm.

Linear attenuation coefficient values indicate the rate at which photons interact as they move through material and are inversely related to the average distance photons travel before interacting. The rate at which photons interact (attenuation coefficient value) is determined by the energy of the individual photons and the atomic number and density of the material.

Mass Attenuation Coefficient:
The mass attenuation coefficient is the rate of photon interactions per 1-unit (g/cm2) area mass. The area mass is the product of material thickness and density: Area Mass (g/cm2) = Thickness (cm) x Density (g/cm3).

The relationship between the mass and linear attenuation coefficients is Mass Attenuation Coefficient (μ/r) = Linear Attenuation Coefficient (μ) / Density (r).

The total attenuation rate depends on the individual rates associated with photoelectric and Compton interactions. The respective attenuation coefficients are related as follows: μ(total) = μ(photoelectric) + μ(Compton).

* Half value layer (HVL) is the thickness of material required to reduce intensity of x- or gamma-ray beam to 1/2 of initial value and is an indirect measure of photon energy or quality of a beam. HVL = 0.693/u where u is the linear attenuation coefficient. The HVL for soft tissue is about 3 cm.
* Effective energy is an estimate of the penetration power or hardness of an x-ray beam as if it were monoenergetic and can be derived from the HVL and expressed as mm of aluminum.
* Tenth value layer (TVL) is the thickness of material to reduce intensity of beam to 1/10 of initial value.
* Mean free path (MFP) is the average distance traveled before interaction of a photon with matter; MFP = 1.44 HVL= 1/u.
* Beam hardening is the shift of the x-ray spectrum to higher effective energies as the low-energy (soft) beams are removed while travelling through the subject.
* Fluence is the number of photons or particles passing through a cross-sectional area; Photons / Area.
* Flux is the rate at which photons pass through a unit area per unit time; Photons / (Area x Time).
* Energy fluence is the amount of energy passing through a unit of cross-sectional area and is in KeV / cm2 or joules / m2.
* Kerma is kinetric energy released in media and represents the kinetic energy transferred from uncharged particles to charged particles and has units of joules / kg. It is calculated from the mass energy transfer coefficient.
* Exposure is the amount of ionization per unit mass of air due to x- and gamma rays and has a traditional unit of Roentgen (R) and SI unit of C/kg.
* Absorbed dose is the energy depositied by ionizing radiation per unit mass of material and has units of gray (Gy) where 1 Gy = 1 J / kg. The traditional units had been rad; there are 100 rads in 1 gray. This is the preferred metric in radiobiology and depends on the particular material, such as different organs, being considered.
* Imparted energy is the total radiation imparted to matter and has units of Joule.

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* Equivalent dose is a measure of radiation specific biologic damage in numans and has SI units or Sievert (Sv) of traditional units of rem.

* Effective dose is a measure of radiation and organ system specific damage in humans and has SI units of Sievert (Sv) or tradiational units of rem.

* Activity is the amount of radioactive material expressed as the nuclear transformation rate and has SI units of Becquerel (Bq) or traditional units of Curie (Ci).