Radiation Protection

Review of X-ray Interaction with Matter

Primary Beam

- High-speed electrons hit a positively charged target in a vacuum tube
- As the electrons interact with the atoms of the target, photons emerge
- X-ray photons have a broad range of energies
- Emerging x-ray photon beam is referred to as primary radiation

Primary Beam

- Two types of interactions in the anode can produce x-ray photons
  - **Characteristic**
    - Narrow range of energies
  - **Bremsstraulung**
    - Most x-ray interactions in diagnostic range

Characteristic Radiation

- Characteristic x-rays are produced after ionization of a K-shell electron.
- When an outer-shell electron fills the vacancy in the K shell, an x-ray is emitted.

Bremsstrahlung Radiation

- Results from the interaction between a projectile electron and a target nucleus.
- Electron is slowed and its direction is changed.

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Technical Factors

- Selection of optimal technical factors is critical in minimizing patient dose while producing high quality x-ray imaging.

- It is our job to understand how radiation interacts with matter so that we can select optimal techniques.

Peak Kilovoltage (kVp)

- Highest energy level of photons in the x-ray beam
- kVp controls the **quality** or penetrating power, of the photons in the beam
- Low kVp won’t make it out of the body
- High kVp will go straight through and provide no information
- Determining the optimum kVp for the patient size and body part will reduce the patient dose

Milliampere-Seconds (mAs)

- Product of electron tube current and time (in seconds) when the x-ray tube is activated
- mAs is the main determinant of how much radiation is directed toward a patient
- mAs controls the **quantity** of photons

Distance

- Distance
  - Most effective means of protection from ionizing radiation
  - More distance, less radiation intensity
    - Spreads out like a flashlight beam
  - Source to Image Distance (SID) affects the density on an image
  - Beam divergence and radiation intensity varies at different distances
  - ISL states beam intensity is inversely proportional to square of the distance

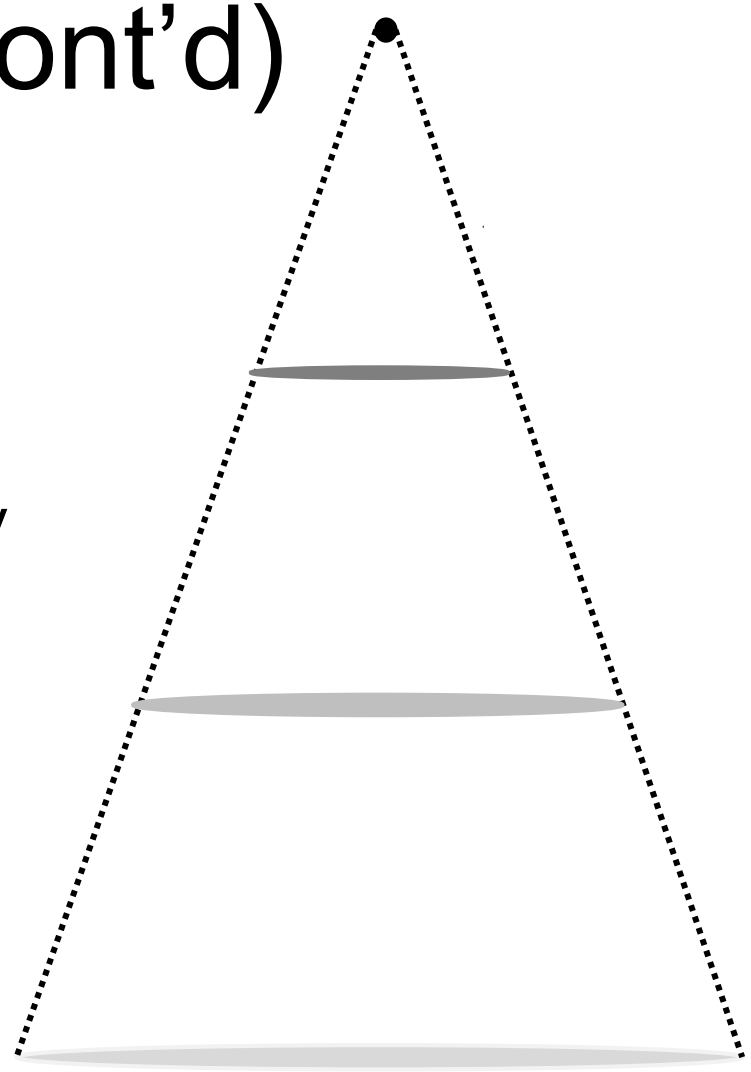
Inverse Square Law (cont'd)

$$\frac{I_1}{I_2} = \frac{(d_2)^2}{(d_1)^2}$$

- I_1 = Exposure (intensity) at original distance
- I_2 = Exposure (intensity) at new distance
- d_1 = Original distance from source of radiation
- d_2 = New distance from source of radiation

Inverse Square Law (cont'd)

- SID and Radiation Intensity
  - 2 x SID = 1/4th of radiation intensity
  - 3 x SID = 1/9th of radiation intensity
  - 4 x SID = 1/16th of radiation intensity



What Happens in the Patient ?

When radiation enters matter it can be:

1. **Attenuated** - interact with atoms in the patient
2. **Transmitted** – pass through without interaction

- Factors affecting photon interactions include:
  - **Incident photon energy**
  - **Density, thickness and atomic number of the matter, tissue or organ in which it interacts**

X-ray Photons

- **Absorption** and **scatter** both contribute to attenuation

- May be absorbed and transfer their energy to the tissue
- May be scattered, change direction and possibly lose energy

Radiation Protection

- Absorption: **patient dose**

- Scatter: **technologist dose**

Interactions that Attenuate the Primary Beam

- Photoelectric absorption
- Compton scattering
- Coherent, Classical, Elastic and Unmodified scattering (all the same)
- Pair Production
- Photodisintegration

Two most important to us are **photoelectric absorption** and **Compton scattering**

Compton and Photoelectric Interactions

- In these interactions incident photons either:
  - Interact and are absorbed by the atom (Photoelectric Interaction)
  - Interact and change direction, called “Scattering” (Compton Interaction)

Photoelectric Absorption

- Photoelectric absorption or effect
- Responsible for **patient dose** and **image contrast**
- Results when a photon interacts with a **k-shell** electron
- Total absorption of the incident photon
- Occurs if the energy is equal to or slightly greater than the binding energy of the atom

Photoelectron

- Negative ion
- Quickly absorbed, micrometres in tissue
- Photoelectron’s kinetic energy is equal to the energy of the incident photon, less the binding energy of the electron shell
- May interact with other atoms until all the energy is gone

Reaction in the Atom

- Atom is **ionized**, unstable energy
- Electron will drop from an outer shell to fill the void left by the photoelectron
- Radiation is produced when an electron from the “L” shell jumps into the “K” shell and releases energy
- Radiation given off is **“characteristic radiation”** with energy equal to the difference in binding energy

Photoelectric Effect Facts

- Increase probability of PE effect :
  - Decrease of energy of incident photon
  - Higher atomic number of irradiated tissue

- Good for image quality, increased contrast

Patient dose factors

- Lower kVp = more photoelectric interaction
- Higher atomic number = more PE absorption

Low kVp and high atomic numbers = increase patient dose

Products of the Photoelectric Effect Interaction in the Body

1. **Photoelectron**

2. **Positive Ion**

3. **Characteristic Radiation**

Three Rules of PE Interaction

1. **Incident photon energy must be greater than the binding energy of the inner shell electron.**

2. **More likely when the photon energy and electron binding energy are close.**

3. **More likely to occur with an electron more tightly bound in its orbit.**

PE conclusion

- Increased photoelectric effect provides increased contrast

- Increased photoelectric effect increases patient dose

Compton Interaction

- Compton scattering is also known as:
  - **Incoherent scattering**
  - **Inelastic scattering**
  - **Modified scattering**

- Responsible for most of the scattered radiation during radiographic procedures

Compton Interaction

- Interaction between **incident** photon and **loosely-bound outer shell** electron
- Incident photon ejects the electron from its shell, giving up some of its energy and resulting in **ionization** of the atom
- Incident photon is scattered in a different direction
- Ejected electron can be called **a Compton or secondary scatter or recoil electron**

Characteristics of Compton

- Energy and direction of scatter depends on **energy** of incident photon
- As **mass density** of tissue being irradiated increases, so does the increase of Compton Scatter
- Not always totally absorbed and can leave the body, causing less patient dose
- Image quality is **decreased** if it hits the IR, adds no useful information

Characteristics of Compton

- Scatter provides the biggest safety hazard for us!
- Increased Compton scattering relative to photoelectric effect as x-ray energy increases
- Free electrons from Compton scatters can cause biological damage
- Scattered radiation in a diagnostic exam consists mainly of the Compton effect

Energy Dispersion

- After collision, the energy of the incident photon is distributed between energy of scattered photon and ejected electron that may be capable of ionizing other atoms
- Incident photon will lose energy
- The Compton Electron may recombine with an atom needing an electron
- Two factors determine the energy the photon retains:
  - Initial energy of the incoming photon
  - Angle of deflection

Products of Compton Interaction in the Body

1. Scattered photon

2. Compton/secondary/recoil electron

3. Positive ion (remaining atom)

Principle factors of Compton scatter

1. kVp

2.Mass density of irradiated material

Coherent, Classical, Elastic and Unmodified Scatters

- All mean the same thing
- Interaction that occurs between very low energy photons and whole atom
- Occurs with photons at 10 keV or less
- Photon changes direction less than 20° with **no change in energy**
- **Insignificant in diagnostic imaging**

Pair Production

- Interaction between a very high energy incident photon (1.02 MeV) and the nucleus
- Photon gives up all its energy
- Does not occur in the diagnostic range
- Two particles are formed:
  - Negatron
  - Positron
- Annihilation—mass totally disappears

Photodisintegration

- Interaction is between extremely high energy photon (10 MeV) and the nucleus
- All energy of the photon is absorbed by nucleus, exciting the nucleus
- Excited nucleus emits a nuclear fragment
- Part of the nucleus ejected may be in the form of a neutron, proton or alpha particles

Attenuation

- Attenuation will be greater with:
  - **Decreased average energy of the beam**
  - **Increased thickness of the body part**
  - **Higher atomic number of the matter**
  - **Increased tissue density**

Human Body

- Variable thickness and density throughout the body
- Air, fat, muscle and bone all have different atomic numbers and densities

Matter	Effective Atomic #	Mass Density
Lung	7.4	320 kg/m³
Fat	6.3	910 kg/m³
Muscle	7.4	1000 kg/m³
Bone	13.8	1850 kg/m³

Bushong, 2013, pp. 152, 157; Statkiewicz Sherer, et al., 2013, pp. 50–51