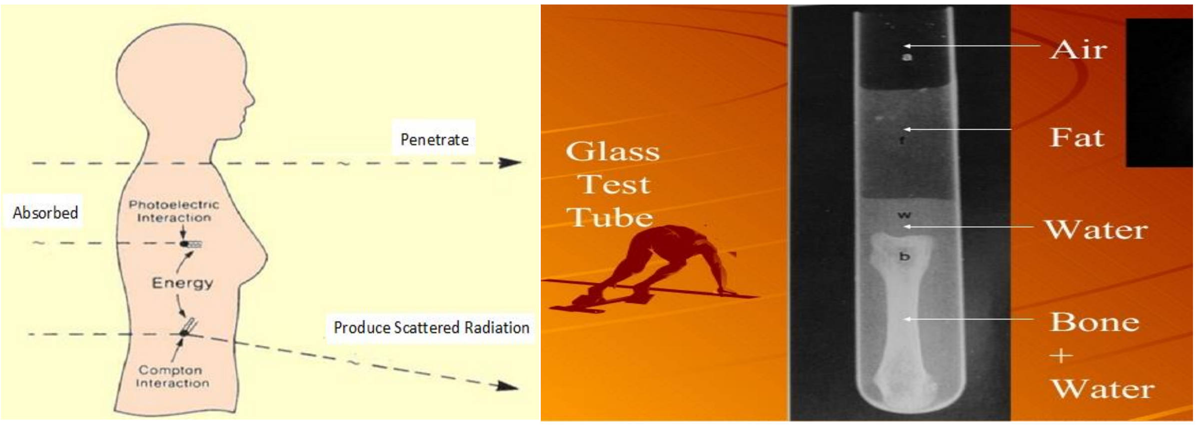
L38 Physics of Diagnostic X-rays

HOW X-RAY ARE ABSORBED

X-ray are not absorbed equally well by all materials,

- **Heavy elements such as calcium (bone)(high atomic no. Z) are better absorbers (stand out clearly)than light elements such as carbon, oxygen, hydrogen, air (fat, muscle, tumor) are poor absorbers(all absorb about equally well and are thus difficult to distinguish from each other on an x-ray image)**
- **Image formation is dependent on the phenomenon of differential absorption.**
- **Some of the x-rays are absorbed by the tissues such as bone. Other x-rays pass through the tissues and produce the diagnostic image on the film. Other x-rays pass into the tissues and are deflected or scattered in the tissues and may exit onto the film.**
- **When x-rays penetrate tissue, they are not homogeneously absorbed; some tissues absorb x-rays more efficiently than others.**
- **If x-ray absorption were uniform, the resulting radiographic image would be grey or white.**



- **The term tissue density is used to describe the degree to which a patient or object absorbs incident x-rays. In the accompanying radiograph the bone tissue is denser than the adjacent soft tissue. Penetration of the x-ray beam is dependent on tissue density.**
- **Low-density material such as air represented as black on the final radiograph.**
- **Very dense material such as metal or contrast material represented as white.**
- **Bodily tissues are varying degrees of grey, depending on density, and thickness.**

X-ray absorption

When x-rays encounter any form of matter, they are partly transmitted and partly absorbed.It was found experimentally that:

$$I \;\alpha\; x$$

I: intensity x: distance

In differential form :

$$-dI/I = \mu dx$$

Where μ :is linear absorption coefficient (linear attenuation coefficient)

After integration:

$$I_x = I_0\, e^{-\mu x}$$

I_0 :incident beam intensity

I_x :transmitted beam intensity

Let's introduce mass absorption coefficient μ/ρ (ρ:density).

It is constant and independent of physical state (solid, liquid, or gas). Then

$$I_x = I_0\, e^{-(\mu/\rho)(\rho x)}$$

μ : is the linear attenuation coefficient

μ depends on the energy of x-ray: smaller μ for harder beam

$\rho\, x$ is area density in grams per cm^2

Mass attenuation coefficient, μ_m

$$\mu_m = \frac{\mu}{\rho}$$

The intensity of a monoenergetic x-ray beam would decrease exponentially.

The linear attenuation coefficient is dependent on energy of x-ray photons ; as the beam becomes harder, it decreases.

Soft x-ray (lower energy): more absorption.

Hard x-ray (high energy): less absorption, greater penetration

Attenuation of X-rays

The half-value layer (HVL) for an x-ray beam is the thickness of the material that makes the X-ray intensity 50 % of its original value.

$I_x = I_0\, e^{-\mu x}$

$0.5 = 1 \times e^{-\mu x}$

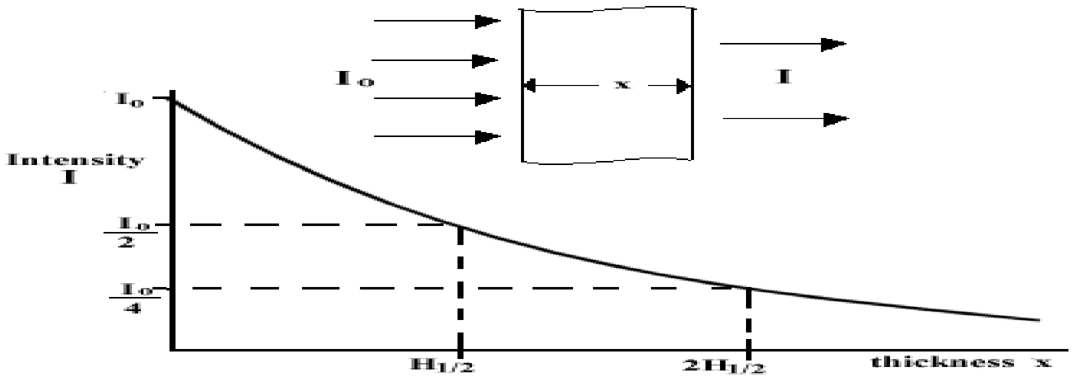
HVL = 2.5 mm for Al

HVL = 0.1 mm for lead, good shielding material for x-ray: 1.5 mm lead plate reduces x-ray energy by a factor of 2^{15} ~30000

Example :

What is the HVL for a material with attenuation coefficient of 0.4/cm

$$HVL = \frac{0.693}{\mu} = 0.693/0.4 = 1.73 \text{ cm}$$



The attenuation of the x-ray beam by tissue has been shown to be dependent on:-

1. Atomic number (Z) of the tissue.
2. Density of the tissue.
3. Thickness of the tissue.
4. Wavelength of the incident x-ray photon.

Methods of Absorption of X-Rays by Tissues

When X-rays pass through materials the energy of the beam is reduced or attenuated by :

1. **Photoelectric effect**
2. **Compton effect (scattering):**
3. **Pair production**
4. **Scattering**

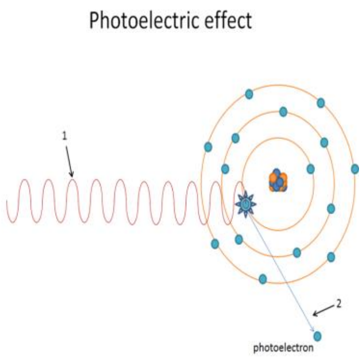
1. **Photoelectric effect:** is the emission of **electrons** or other free carriers when **light(photon)** shines on a material.

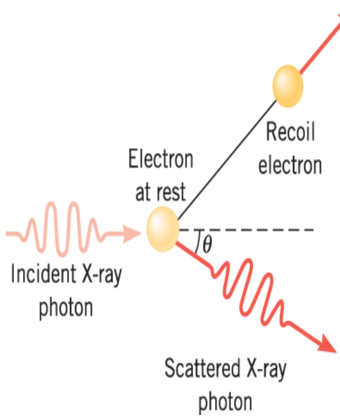
a) **When the incoming x-ray photon with energy (E= hν). transfers all of its energy to an electron which then escapes from the atom**

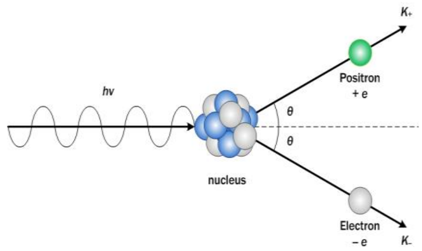
b) **The photoelectron uses some of its energy (the binding energy) to get away from the positive nucleus and spend the remainder ripping off (ionizing) surrounding atoms.**

Photoelectric effect

- **Is occur in the intense electric field near the nucleus than in the outer levels of the atom.**
- **Is more common in elements with high Z than in those with low Z.**







2. **Compton effect (scattering):**

Is the scattering of a **photon** by a **charged** particle, usually an **electron.** It results in a decrease in **energy** (increase in **wavelength**) of the photon (which may be an X-ray or gamma ray **photon**), Part of the energy of the photon is transferred to the recoiling electron.

- **The x-ray photon can collide with a loosely bound outer electron,**
- **At the collision, the electron receives part of the energy and remainder is given in a Compton (scattered) photon ,which then travels in a direction from that of the original x-ray.**
  - **The x-ray has an effective mass m of E/c^2 ($E = m c^2$)**

And its momentum is E/c,

We can calculate the energy equivalent of electron mass to be 511 keV, and Compton effect is most likely to occur when the x-ray has this energy

- **The number of Compton collisions depends only on the number of electrons per cubic centimeter, which is proportional to the density.**

$$\lambda' - \lambda = \frac{h}{m_e C}(1 - cos\theta)$$

Where

λ : initial wavelength, λ' : wavelength after scattering, h: Planck constant, m_e : electron rest mass , c :speed of light, and θ : scattering angle.

The quantity h/m_ec is known as the Compton wavelength of the electron; it is equal to 2.43×10^{-12} m

The Compton shift or wavelength shift(The amount by which the light's wavelength changes ($\lambda' - \lambda$) is at least zero (for $\theta = 0°$) and at most twice the Compton wavelength of the electron (for $\theta = 180°$).

3-Pair production

Here a photon passes by a nucleus and converts to a particle- anti particle pair. Examples include creating an electron and a positron, a muon and an ant muon, or a proton and an antiproton.

When a very energetic photon enters the intense electric field of the nucleus, it may be converted into two particles: an electron and positron(β), or positive electron. Providing the mass for the two particles requires a photon with an energy of at least 1.02 MeV, and the remainder of the energy over 1.02 MeV is given to the particles as kinetic energy.

X-ray imaging

X-ray imaging utilizes the ability of high frequency electromagnetic waves to pass through soft parts of the human body largely unimpeded.

2D Images produced by passing the x-rays radiation through the patient's body. This process is described as attenuation of the X-ray beam. On the opposite side of the body, detectors or a film capture the attenuated X-rays, resulting in a clinical image). Different organs and tissues have a different sensitivity to radiation. This is why the actual risk to the body from X-ray procedures varies depending on the part of the body being X-rayed. "Effective dose" is a parameter of the dose absorbed by the entire body that takes account of these differing sensitivities.

The proper film exposure can be obtained from the so-called characteristic curve of the film material. The blackening of the film after X-ray exposure is expressed in terms of its optical density

$$D = \log_{10}\frac{I_0}{I}$$

Where I_0 and I is the light intensities before and after passing through the exposed film material

Additionally the contrast can be affected by the energy absorption efficiency of the image receptor material which in general decreases with energy.

Efficiency and / or sensitivity of film material

The film material consist of :

1. **The base:the base of a typical radiographic film is made of a clear polyester material about 150 μm thick. It provides the physical support for the other**

film components and does not participate in the image-forming process. In some films, the base contains a light blue dye to give the image a more pleasing appearance when illuminated on a viewbox.

2. **The emulsion** is the active component in which the image is formed and consists of many small silver halide crystals suspended in gelatin. The gelatin supports, separates, and protects the crystals. The typical emulsion is approximately 10 µm thick.

The sensitivity of film material depends on

- The size and shape of the silver halide grains have some effect on film sensitivity. Increasing grain size generally increases sensitivity.
- density of grains,
- emulsion thickness
- X-ray absorption efficiency.

The noise in the receptor image arises from several sources:

- Fluctuations in the number of absorbed X-ray photons per unit area
- Fluctuations in the absorbed photon energy
- Fluctuations in the number of silver halide per unit area of emulsion

The first and the last are the main sources for noise.

The noise in the image may limit the contrast.

X-ray computed tomography (X-ray CT) (CT-scan)

Makes use of computer-processed combinations of many X-ray images taken from different angles to produce cross-sectional (tomographic) images (virtual 'slices') of specific areas of a scanned object, allowing the user to see inside the object without cutting.

In Computed Tomography, the tube and the detector are both rotating around the body during the examination so that multiple images can be acquired, resulting in a 3D visualization. by computerized tomography (CT scan) (CT).

Digital geometry processing

Is used to generate a three-dimensional image of the inside of the object from a large series of two-dimensional radiographic images taken around a single axis of rotation.

Contrasting

This technique is made to make further use of the photoelectric effect. This done by injected high Z material into different parts of the body which are called (Contrasting media).

Examples:

1. Compound containing iodine is injected into a blood stream to show the arteries.
2. Oily mist containing iodine is sometimes sprayed into the lungs to make the airways visible.
3. Barium enemas to view lower GI system.
4. Barium compound is given orally to see parts of the upper gastrointestinal tract.
5. Air is used to replace some of the fluid in ventricles of the brain

The risks of medical X-rays

The risks of medical X-rays include

- **a small increase in the chance of developing cancer later in life**
- **developing cataracts and skin burns following exposure to very high levels of radiation**

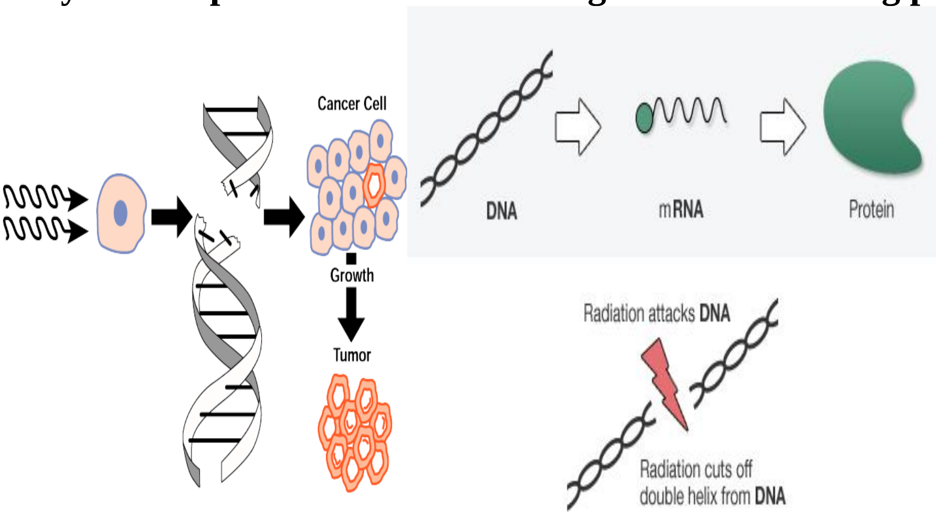
The small risk of cancer depends on several factors:

- **The lifetime risk of cancer increases as a person undergoes more X-ray exams and the accumulated radiation dose gets higher.**
- **The lifetime risk is higher for a person who received X-rays at a younger age than for someone who receives them at an older age.**
- **Women are at a somewhat higher lifetime risk than men for developing cancer from radiation after receiving the same exposures at the same ages.**

Radiation protection

How Radiation Damages Tissue

When ionizing radiation strikes the atoms in a substance, some of its molecules may break apart or become stuck together in the wrong places.



Proteins and other biological molecules may have many thousands of atoms arranged in complex structures; damage to them can result in the breakdown of a cell's normal functions.

Radiation effects are divide into

1. **Somatic effects : affects the function of cells and organs(Somatic cells refers to all the cells in the human body except the germ cells (genetic cells). is biologic damage to the exposed individual caused by exposure to ionizing radiation**

Early somatic effects: Effects that appear within minutes, hours, days or weeks after exposure to ionizing radiation.

Late somatic effects:Effects that appear months, years, or decades after exposure to ionizing radiation. May result from previous whole or partial body high radiation doses, or they may be the product of individual low-level doses sustained over the years.

Radiation affects rates of cell division. Hastening and slowing down cell division affect embryonic tissues. Damages to cell membranes, mitochondria and cell nuclei result in abnormal cell functions, affecting their division, growth and death.

Exposure to radiation strongly affects the rapidly dividing tissues and cell. For example:

- **Skin - skin disease and cancer**
- **Lining of the gastrointestinal tract - hinders digestion and absorption**
- **Bone marrow – anemia**
- **Embryonic developments - mature to have disproportionate parts**

2. Genetic Effects: affects the future generations.

When ionizing radiation causes DNA damage (mutations) in male or female reproductive (“germ”) cells, that damage can be transmitted to the next generation (F_1). This is in contrast to mutations in somatic cells, which are not transmitted.

Detection of human germ cell mutations is difficult, especially at low doses. While high doses in experimental animals can cause various disorders in offspring (birth defects, chromosome aberrations, etc.), no evidence of clinical or subclinical effects has yet been seen in children of A-bomb survivors.

Radiation protection

Is defined by the International Atomic Energy Agency (IAEA) as :
"The protection of people from harmful effects of exposure to ionizing radiation,

Protection groups

Radiation protection can be divided into

- ***Occupational radiation protection*, which is the protection of workers,**
- ***Medical radiation protection*, which is the protection of patients**
- ***Public radiation protection*, which is protection of individual members of the public, and of the population as a whole**

The types of exposure, as well as government regulations and legal exposure limits are different for each of these groups, so they must be considered separately.

What are the basic measures in radiation protection?

Shortening the time of exposure, increasing distance from a radiation source and shielding are the basic countermeasures (or protective measures) to reduce doses from external exposure.

1. **Time: The less time that people are exposed to a radiation source, the less the absorbed dose.**
2. **Distance : The farther away that people are from a radiation source, the less the absorbed dose.**
3. **Shielding: Barriers of lead, concrete or water can stop radiation or reduce radiation intensity.**

- **To reduce doses from intake of radioactive substances, the following basic countermeasures can be considered:**

1. **Shortening time of exposure to contaminants;**
2. **Preventing surface contamination;**
3. **Preventing inhalation of radioactive materials in air; and**
4. **Preventing ingestion of contaminated foodstuffs and drinking water.**
5. **The need to use personal protection equipment necessary for protection from radiation hazards: gloves – glasses – the flagstones**