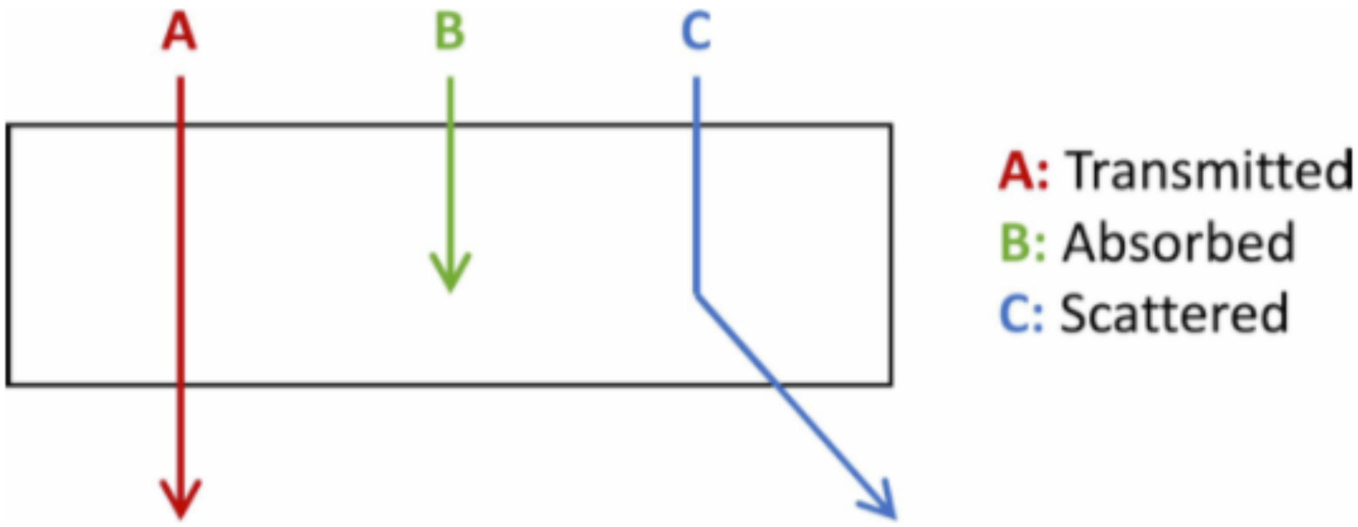
X-rays

Interaction with matter

2.2 - Interaction with matter



A beam of x-rays may be:

A. **Transmitted:** pass through unaffected or with a lower energy
B. **Absorbed:** transfer all energy to matter and not pass through the patient to the film
C. **Scattered:** diverted with or without energy loss

Attenuation

Attenuated x-rays are those that are absorbed, transmitted with a lower energy or scattered. It is an exponential process and, therefore, the **beam intensity never reaches zero**. Attenuation of the beam can be represented numerically by:

- Half value layer
- Linear attenuation coefficient
- Mass attenuation coefficient

Half value layer (HVL)

This is the measure of the penetrating power of the **x-ray beam** and is the amount of matter required to attenuate the beam to half its energy value. It differs for different materials and strengths of beams. To calculate the factor of reduction use: 2^{HVL}

e.g. if the HVL of a beam is 2 mm, by what factor is the beam attenuated if it passes through 8 mm of material?

8 mm = 4 HVLs
$2^4 = 16$
The beam is attenuated by a factor of 16

Linear attenuation coefficient (LAC)

This is the probability of the **material** to attenuate the beam. It can also be expressed as the amount of energy transferred to the material per unit of track length of the particle. The LAC (μ) is calculated by:

$\mu = 0.693 / HVL$

Key:

μ = LAC, units: cm^{-1}

Mass attenuation coefficient

The MAC is a measure of the rate of energy loss by a photon beam as it travels through an **area** of material. By dividing LAC by the density of the material the effect of density is removed. The MAC is, therefore, **independent of density** and depends only on the atomic number of the material and the photon energy.

MAC = μ / ρ
Key:
μ = LAC, units: cm^{-1}
MAC units: cm^2g^{-1}
ρ = density

Effect of beam quality on attenuation

The above only really apply to a monoenergetic (one energy value) beam of x-rays from a point source (infinitely small area) travelling in a vacuum. In reality, the x-ray beam focus is not a fine point and contains photons of different energies that, once the leave the x-ray tube, do not travel in a vacuum.

Wider beam

Increased width of beam = increased scatter produced and measured = larger measured HVL

Heterogeneous beam

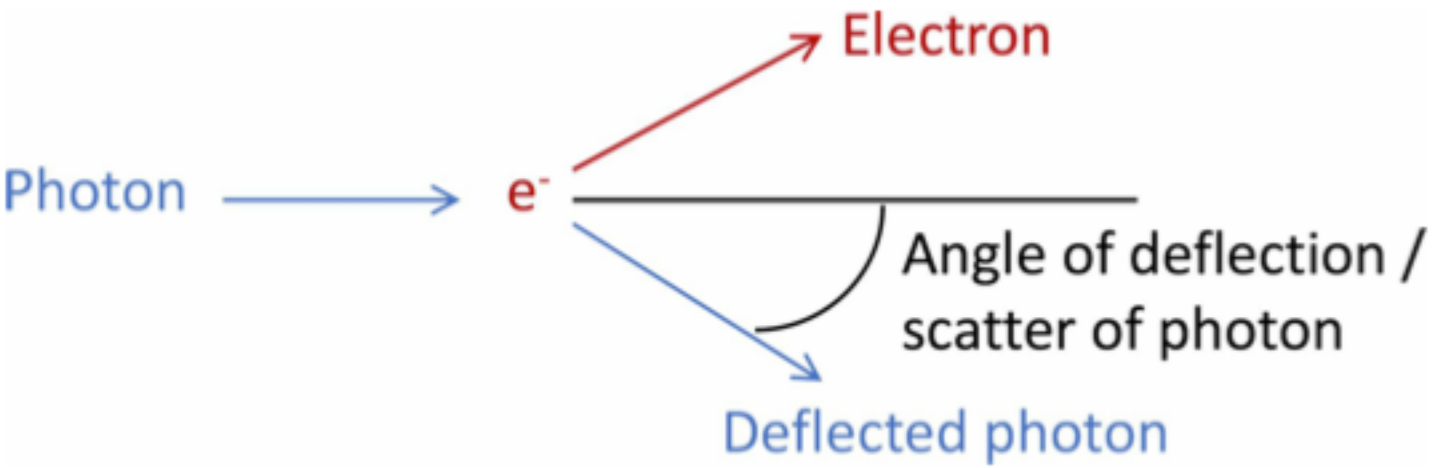
- The beams produced by x-ray tubes are photons of a wide range of energies.
- The lower-energy photons are attenuated proportionally more than the higher-energy photons and are removed, leaving behind higher energy photons aka "beam hardening".
- The resulting beam is of a higher average energy.
- It can, therefore, penetrate tissue easier and the HVL is increased.

Interactions with matter

Three processes may occur and contribute to attenuation:

- Compton effect
- Photoelectric absorption
- Elastic scatter

Compton Effect



1- Photon hits electron.

2- Electron absorbs some of the photon energy and is deflected.

3- The photon loses some of its energy and is deflected and scattered.

Notice that :

The greater the angle of scatter the:

- Lower the residual deflected photon energy
- Higher the subsequent electron energy

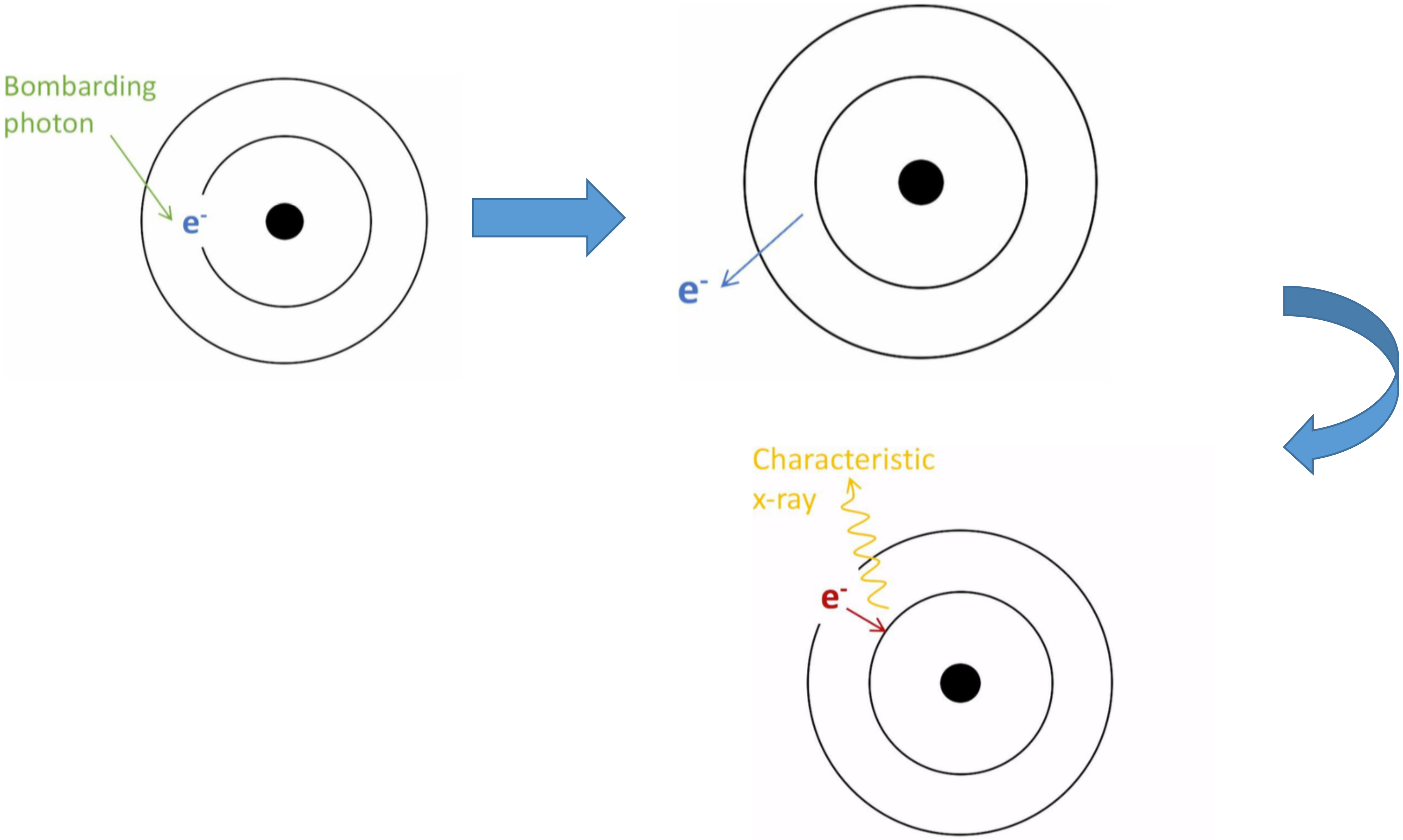
Compton Linear Attenuating Coefficient (LAC)

Compton scatter is dependent on electron density and physical density but **not on atomic number**. The amount of scatter decreases with increasing photon energies but not significantly within the range of diagnostic x-ray energies.

Compton scatter = density / energy

The Compton LAC does not change over a large range of photon energies.

Photoelectric effect



1- Bombarding photon collides with inner shell
2- K- shell electron is ejected as photoelectron
3- I- shell electron fills K-shell space and energy is released as photon of characteristic radiation EK

In low Z materials (e.g. tissue and bone) the high energy photon collides with a bound electron. The released photon has very little energy and is absorbed immediately with the ejection of a further, low-energy or "**Auger**" electron and all the energy is said to have been absorbed by the material.

Photoelectric LAC

The probability of a photoelectric effect increases:

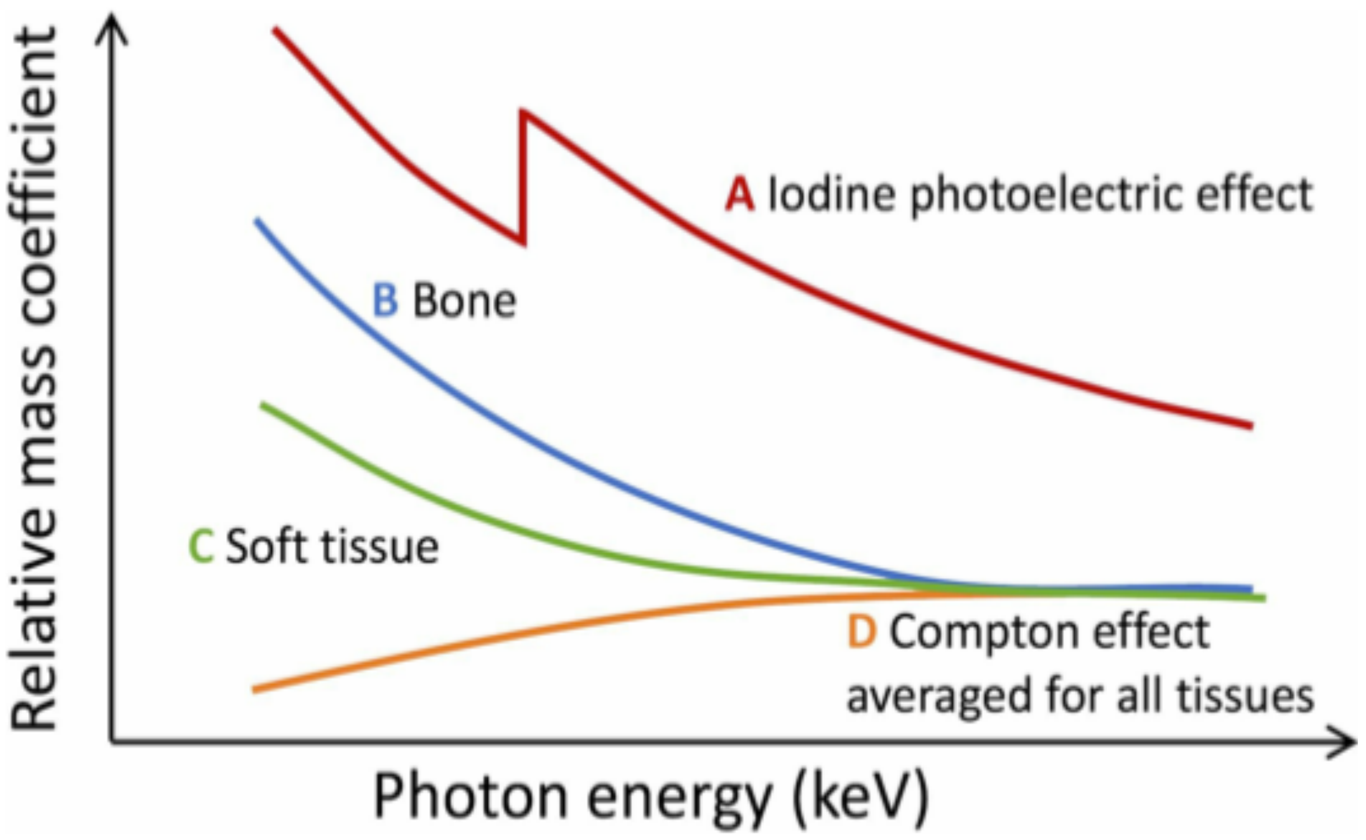
- When electrons are more tightly bound (i.e. higher Z)
- When photon energy closer to binding energy. The higher the photon

  energy the less likely the photoelectric effect.

$$\tau = \rho Z^3 / E^3$$

Key:
τ = photoelectric LAC
ρ = density
Z = atomic number
E = photon energy

Absorption edges



Whenever the photon energy is just slightly greater than the energy required to remove an electron from a particular shell around the nucleus, there is a sharp increase in the photo- electric absorption coefficient. This is known as an absorption edge, and absorption edges associated with K shell electrons have a number of important applications in radiology (see Table 1.1). The edges associated with the L shell and subsequent outer shells are at energies that are too low to be of any practical significance.

TABLE 1.1

K Shell Energies for Various Elements and the Aspect of Radiology Where They Are Important

Element	Area of Application	Z Number	K Shell Energy (keV)
Carbon	(a)	6	0.28
Oxygen	(a)	8	0.53
Aluminium	(b)	13	1.6
Silicon	(c)	14	1.8
Phosphorus	(a)	15	2.1
Sulphur	(a)	16	2.5
Calcium	(a)	20	4.0
Copper	(f)	29	9.0
Germanium	(c)	32	11.1
Selenium	(c)	34	12.7
Molybdenum	(b and e)	42	20.0
Rhodium	(e)	45	23.2
Palladium	(e)	46	24.4
Caesium	(c)	55	36.0
Barium	(d and f)	56	37.4
Iodine	(c and d)	53	33.2
Gadolinium	(c)	54	50.2
Erbium	(b)	68	57.5
Ytterbium	(c)	70	61.3
Tungsten	(e)	74	69.5
Lead	(f)	82	88.0

(a) Body tissue components—but the X-rays associated with these K shells have too low an energy to have any external effect and are absorbed in the body.
(b) Used to filter the beam emerging from the X-ray tube.
(c) Used as a detector (in a monitor) or an image receptor of X-ray photons.
(d) Used as a contrast agent to highlight a part of the body.
(e) Used to influence the spectral output of an X-ray tube.
(f) Used as shielding from X-ray photons.

When the photon energy is as strong as the binding energy of the k-shell electrons (Ek; for iodine this is 33 keV) the probability of photoelectric absorption jumps to a higher value resulting in a sharp increase in attenuation (the k-edge).

For iodine this k-edge is in the diagnostic x-ray energy range and is utilised to massively increase the photoelectric effect and therefore give greater tissue contrast. Soft tissues and bone also have a k-edge but these occur at 1 keV or less so the k-edge doesn't appear in the diagnostic energy range. As you can see from the graph above, the Compton effect does not change significantly over the range of photon energies for tissues.

Elastic Scatter

Coherent, classical or Rayleigh scattering

- Photon bounces off an electron that is firmly bound to its parent atom
- Occurs if photon energy less than binding energy of electron
- No secondary electron is set moving and no ionisation or other effect is produced in the material
- Little significance in radiology

Σ Summary

- Attenuation is an exponential process - beam intensity never reaches zero
- Penetrating power of a beam is measured by its half value layer (HVL) - the depth of material that results in a 50% reduction in the beam intensity - factor of reduction = 2^{HVL}
- Mass attenuation coefficient independent of density of material - depends only on atomic number of material and photon energy
- Wide beam - increases measured HVL due to increased scatter
- Heterogeneous beam - HVL increases with distance travelled due to beam hardening

Compton effect	Photoelectric effect
Interactions with free / outer shell electrons	Interactions with inner shell electrons
Part of electron energy transferred	Whole of photon energy transferred
Depends on: • Electron density of target	Depends on: • Atomic number of target

Compton effect	Photoelectric effect
• Physical density of target • Photon energy (minimally) • NOT atomic number	• Photon energy • Physical density of target
More important in low density structures (e.g. air, water, soft tissues) and with high energy photons	More important in high Z structures (e.g. iodine, lead) and with low photon energy
Both processes occur equally at: • 30 keV for air, water and tissue • 50 keV for aluminium and bone • 300 keV for iodine and barium • 500 keV for lead	