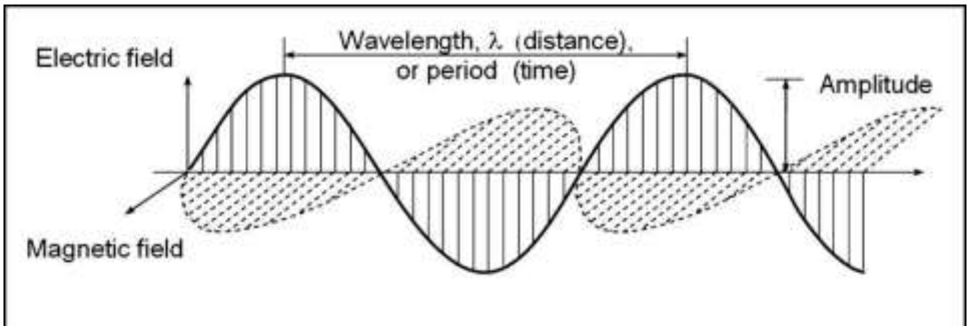
Physics of diagnostic X-ray

X-rays were discovered accidentally in the fall of 1895 by W.C. Roentgen, a physicist at the university of Wurzgurg in Germany. X-rays belong to a group of radiation called electromagnetic radiation. Electromagnetic radiation is the transport of energy through space as a combination of electric and magnetic field. The field includes radio waves, radiant heat, visible light, and gamma radiation.



Electromagnetic wave

○ X – rays production :

To produce photons of X – rays we need:

1. A filament (Cathode) as a source of electrons.
2. Target (anode) to be struck by the electrons.
3. An evacuated space in which the accelerated the electrons travel from the cathode to the anode.
4. High positive voltage to accelerate the negative electrons, 80-120 KV for diagnostic range.
5. Oil cooling or water to cool the target.

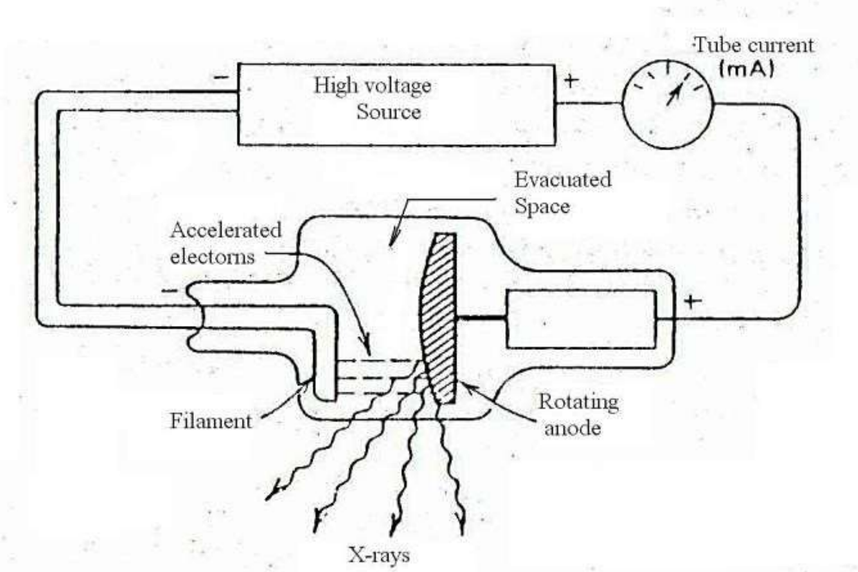


Figure: the basic components of an X-ray tube

The electrons liberated from the filament will be accelerated to a very high speed towards the anode by the high positive voltage and while passing they will not be stopped by air molecules because the tube is evacuated. These high speed electrons can convert some or all of their energy into X-ray photons when they strike the atoms of the target.

o Properties of the target:

1. It should have a high atomic number (tungsten Z=74) to be efficient in producing X-rays.
2. It should have a high melting point (for tungsten ≈3400oC).
3. It must be designed so that a relatively large area of the target struck by electrons appears as a much smaller projected focal spot.
4. It should be rotated at 3600 rpm at minimum to avoid chances of overheating and damage.

NOTE: The energy of most electrons striking the target (99.3%) is dissipated in the form of heat. The remaining few energy (0.7%) produce useful x- rays. The (mA) is the electron current that strikes the target which is typically from 100 to 500 mA for diagnostic X-ray.

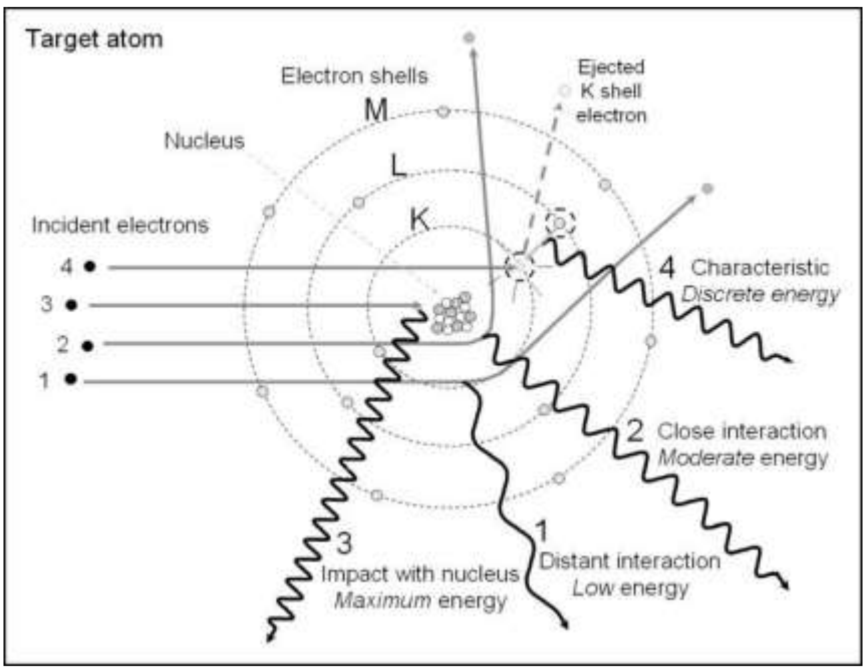
1. Bremsstrahlung (continuous) X-rays:

When the electron gets close enough to the nucleus of the target atom to be diverted from its path and emits an X-ray has some of its energy.

It is depending on:

(a) The atomic number of the target (the more protons in the nucleus, the greater the acceleration of the electron towards the nucleus.

(b) The kilovolt peak, the faster the electron, the more likely it will penetrate into the region of the nucleus.

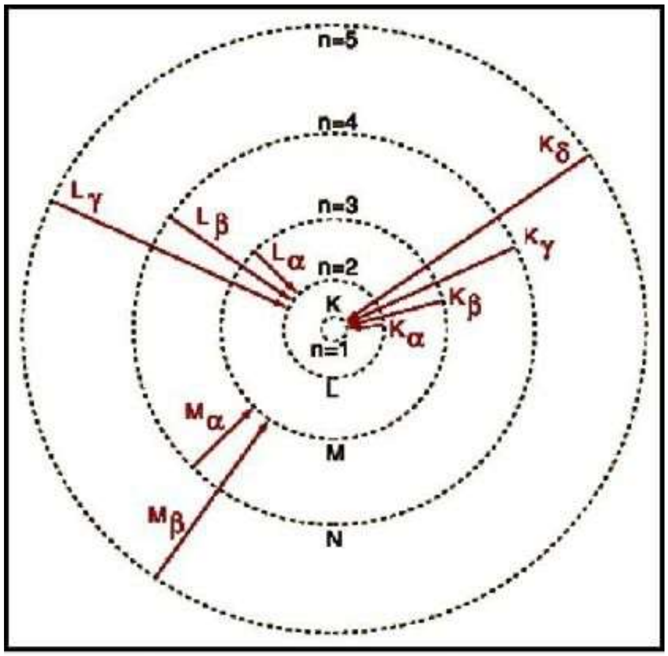


2. Characteristic X-Rays:

Sometimes a fast electron strikes a K-electron in a target atom and knocks it out of its orbit and free of the atom.

The vacancy in the K-shell is filled almost immediately when an electron from an outer shell of the atom falls into it, as indicated schematically in the figure below (b), and in the process, a characteristic K X-ray photon is emitted.

The difference in energy levels of the orbits in an atom is specifying that atom; hence the emitted radiation is called characteristic.



Characteristic X-rays

Diagnostic X-rays typically have energies of 15 to 150 keV, while visible light photons have energies of 2 to 4 eV.

The number of electrons accelerated toward the anode depends on the temperature of the filament, and the maximum energy of the x-ray photons produced is determined by the accelerating voltage-kilovolt peak (kVp).

The broad smooth curve in above figure is due to Bremsstrahlung, and the spikes represents the characteristic X-rays.

Energy of X-rays

One kilo electron-volt (keV) is the energy an electron gains or losses in going across a potential difference of 1000V. 1keV=1.6*10-9 erg = 1.6*10-16 J.

The (kVp) used for an x-ray study depends on the thickness of the patient and the type of study.

- For mammography: 25 to 50 kVp
- For chest: ≈ 350 kVp

Electron current: 100 ~ 500 or 1000 mA

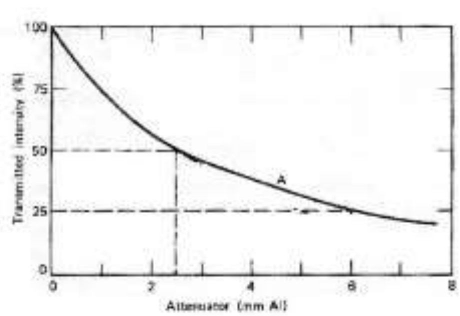
The x-ray energy produced is not monoenergetic; it is a spectrum of energies up to its maximum. The power P (watt) = I (amp.) * V (volt) = 1 A and 100 kV = 100 kW => 99% appears as heat: damaged anodes.

○ Absorption of x-ray

The attenuation of an x-ray beam is its reduction due to the absorption and scattering of some of the photons out of the beam. the intensity I decreases approximately exponentiatty as shown in the figure below

$$I = I_\circ \, e^{-\mu x}$$

I transmitted intensity,
I_0 incident intensity,
μ absorption or attenuation coefficient,
x the thickness of the material irradiated.



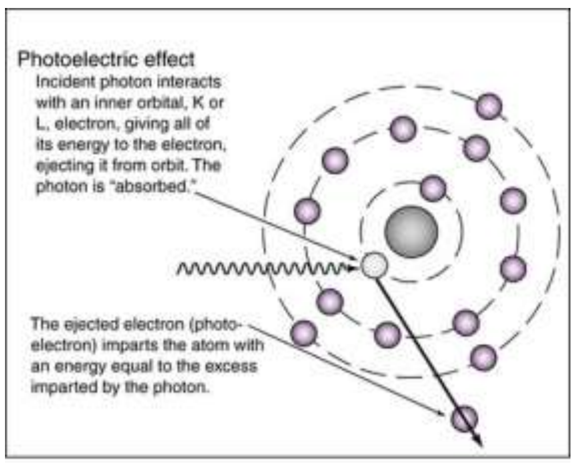
μ: linear attenuation Coefficient. It depends on:

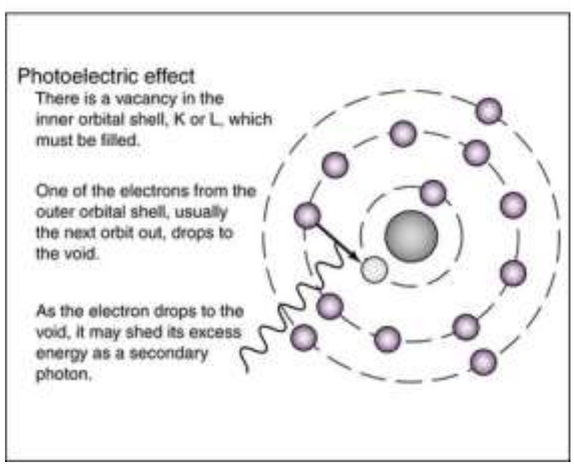
1. Energy of x-rays.
2. Atomic number (Z) of the material
3. Density of the material (ρ).

○ Interaction of X-rays with matte:

1. ***Photoelectric effect (P.E):***

In this process the incoming X-ray photon transfers all of its energy to an electron which will use it to overcome the binding energy and get away from the nucleus (which will be +ve). This free photoelectron will use the remainder of the gained energy in ripping electrons off (ionizing) surrounding atoms.



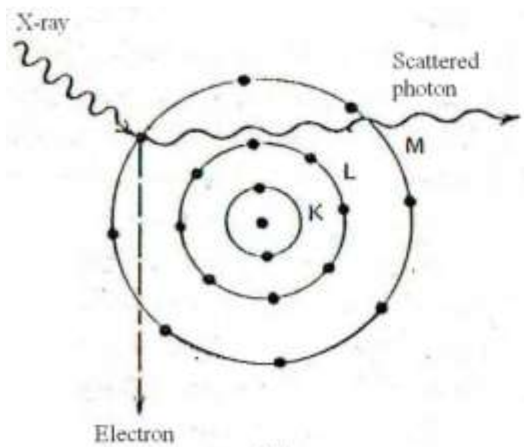


Phtoelectric is more common in the high Z elements than in those with low Z, and more apt to occur at low energies.

At 30 keV bone (as a heavy material) absorbs X-rays about 8 times better than tissue due to photoelectric effect.

2. Compton effect (C.E):

An X-ray photon collides with a loosing bound outer electron. The electron receives part of the energy and the reminder is given to the scattered photon, which then travels in a direction different from that of the original X-ray. It depends on the number of electron per gram.

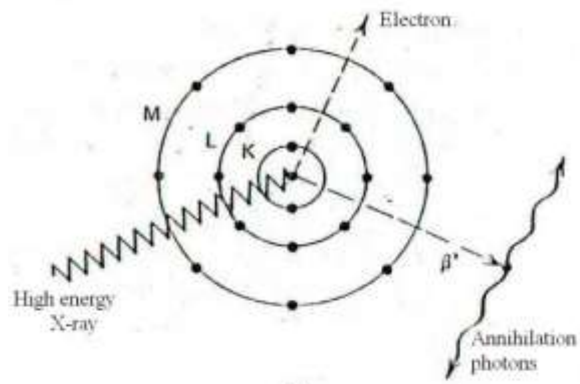


(b)

3. Pair Production (P.P):

When a very energetic photon (energy ≥1.02 MeV) enters the intense electrical field of the nucleus, it may be converted into two particles (an electron β- and a positron β+ or positive electron). After it has spent its kinetic energy ionization, the (β+) collides with an electron (e-). Both then vanish, and their mass energy appears as two photons of 511 keV each called annihilation photon.

Pair production is more apt to occur in high Z elements and it doesn't occur at energies of diagnostic procedures.



(c)

o Contrasting:

This technique is made to make further use of the photo-electric effect Radiologists often inject high Z material into different part of the body (contrasting media). e.g.:

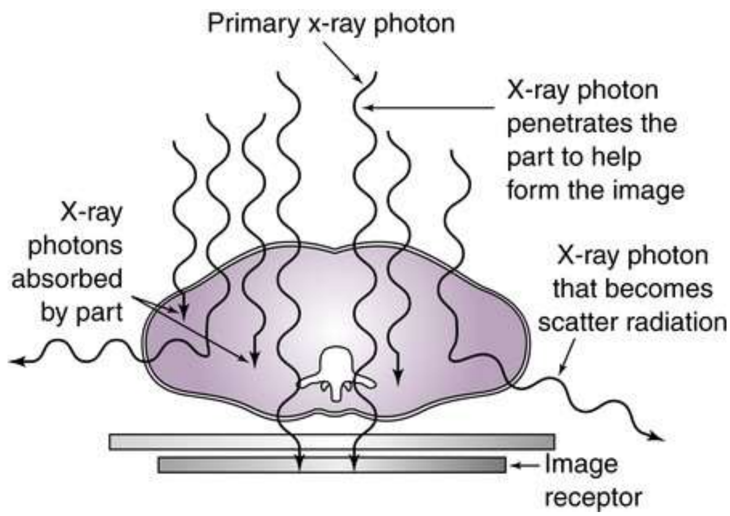
1. Compounds containing iodine injected into the blood stream to show the arteries.
2. Oily mist containing iodine is sometimes sprayed into the lungs to make airways visible.
3. Barium compound is given orally to see parts of the gastrointestinal tract (upper GI).
   a. Air is used to replace some of fluid ventricles of the brain, when a pneumoecephalgram is taken.

   b. Barium enemas to view the other end of the digestive system (lower GI).
   c. Air & barium are used separately to show the same organ in a double contrasting study.

o Making an X-ray image:

Medical diagnosis is essentially the extraction of anatomical and physiological information from a subject (the patient) and the interpretation of this information in such a way that corrective treatment may be prescribed. The radiographic image presents the information in a visual form, which is relatively easy for a trained observer to understand.

Different parts of the body absorb the x-rays in varying degrees. Dense bone absorbs much of the radiation while soft tissue, such as muscle, fat and organs, allow more of the x-rays to pass through them. As a result, bones appear white on the x-ray film, soft tissue shows up in shades of gray and air appears black.



<u>How to increase the sharpness of an X-ray image?</u>

X-ray images are basically images of shadows cast on film of various structures in the body. So we are in need to make these shadows as sharp as possible. This can be done by:

1. blurring in the image can be reduced by using a small focal spot.
2. positioning the patient as close to the film as possible.

3. Increasing the distance between the X-ray tube and the film as much as possible.

4. Reducing the scattered radiation striking the filmby using grids consisting of a series of lead and plastic strips.

5. Holding breath when having a chest X-rays to reduce motion which in turn reduces bluring.

X- ray Image Formation

The basic requirements for X-ray image production are X-ray source and image receptor. There are three types of image receptors:

1. *Film-screen technique* : X-ray film accommodated inside special cassette was used as image receptor. On both inner sides of the cassette there was a screen (cardboard coated with phosphor layer) used to convert the X-ray photons to visible light photons which form the image on the X-ray film.

2. *computed radiography (CR)* phosphor detectors are used inside special cassettes as image receptor. Exposing detector to X-rays resulted in an excitation process through the movement of valence band electrons to the conduction band forming the latent image. The exposed detector is scanned with a laser in the reader converting the image information (latent image) to blue light. Then a photomultiplier system inside the reader will convert the blue light to electronic signal which can be displayed on monitor.

3. *In digital radiography (DR)*, digital detectors made from amorphous selenium (a-Se) mounted on the image plate . Before exposing the a- Se to X- ray, its surface is charged with a uniform positive charge. The uniform surface charge pattern is partially discharged when the X-rays are absorbed by the a- Se. This charge distribution forms the latent image as an electronic signal. This type of detectors avoids the multiple conversions of signals (light to electronic signal) eliminating the light scattering problem.

X-ray beam Filtration

Low-energy x-rays will not penetrate the entire thickness of the body; thus they will increase the patient radiation dose without increasing the diagnostic quality of the image. Most of this low energy radiation will be removed with filters, thin plates of aluminum, copper, or other materials placed in the beam in front of X- ray tube window.

Radiation Risk of X-ray Examinations

The radiation risk refers to the damage produced by ionising radiation due to energy deposition in tissues. This energy may result in ionisation within the tissues. The radiation interactions with tissue are either:

- Direct, wherein the radiation energy is directly transferred to the DNA causing structural changes in its molecules; or

- Indirect interaction, where the radiation energy is absorbed by water molecules forming free radicals which in turn cause damage to DNA molecules.

The adverse health effects of radiation can be classified into two groups:

1) Deterministic effects which follow high radiation doses and result in relatively immediate damage (within minutes, hours, days and even weeks).

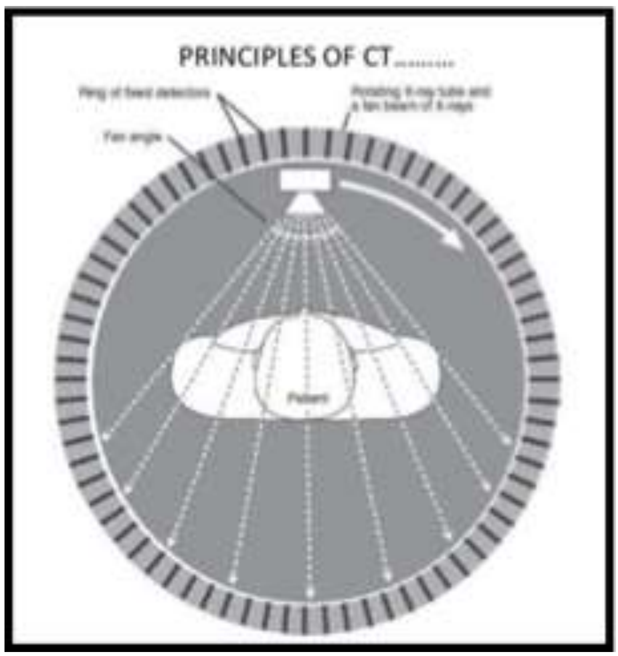
2) Stochastic effects which follow low radiation doses and may result in cancer development. The lag period between irradiation and cancer development for stochastic effects is at least 5 years and may reach to 10 or 20 years.

Fluoroscopy

Fluoroscopy refers to the continuous acquisition of a sequence of X-ray images over time (real-time X-ray movie of the patient). Fluoroscopic systems use X- ray detector systems capable of producing images in rapid sequence. Fluoroscopy is used for positioning catheters in arteries, visualising contrast agents and invasive therapeutic procedures (surgery). It is also used to make X-ray movies of anatomic motion, such as of the heart or the oesophagus.

○ Computed tomography (CT scan)

CT images are produced by passing X-rays through the body at a large number of angles, by rotating the X-ray tube around the body. A detector array, opposite the x-ray source, collects the transmission projection data. The numerous data points collected in this manner are synthesised by a computer into tomographic images of the patient. The term tomography refers to a picture (graph) of a slice (tomo). The advantage of CT over radiography is its ability to display three-dimensional (3D) slices of the body eliminating the superposition of anatomical structures.



○ Magnetic Resonance Imaging (MRI)

♣ In MRI, the patient is placed in strong magnetic field to utilise magnetic resonance properties of the proton in hydrogen nuclei of water molecules within the body.

♣ Then a pulse of radio waves is generated by coils positioned around the patient.

♣ The protons in the patient absorb the radio waves, and subsequently re-emit this radio wave energy after a period of time.

♣ The radio waves emitted by the protons in the patient are detected by the coils that surround the patient. The returning radio waves signal carry