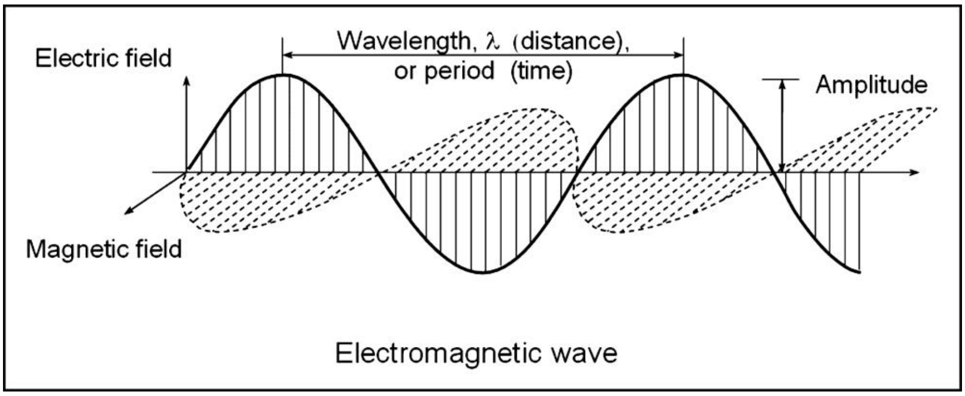
Physics of diagnostic X-ray

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.



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.

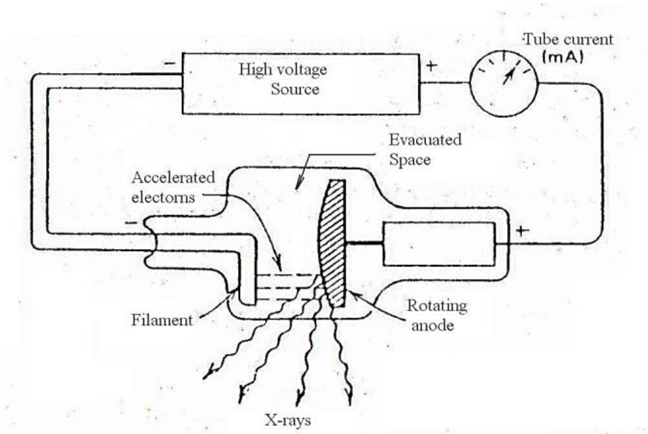
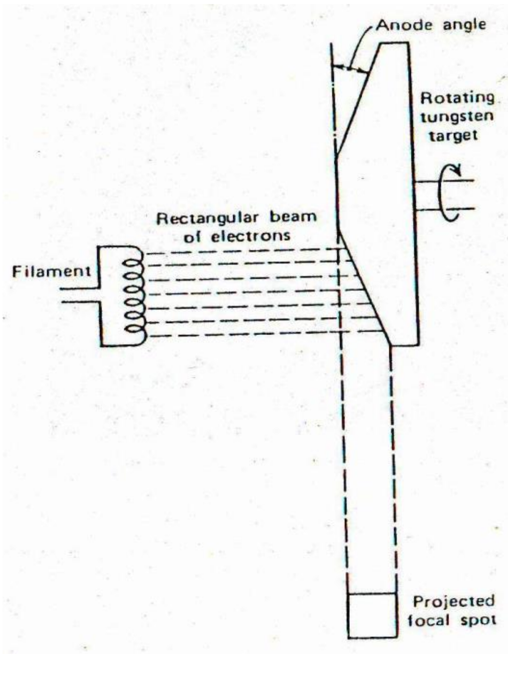


Figure: the basic components of an X-ray tube

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.

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 ≈3400°C).
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.



<u>NOTE</u>: 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.

<u>There are two types of X-rays:</u>

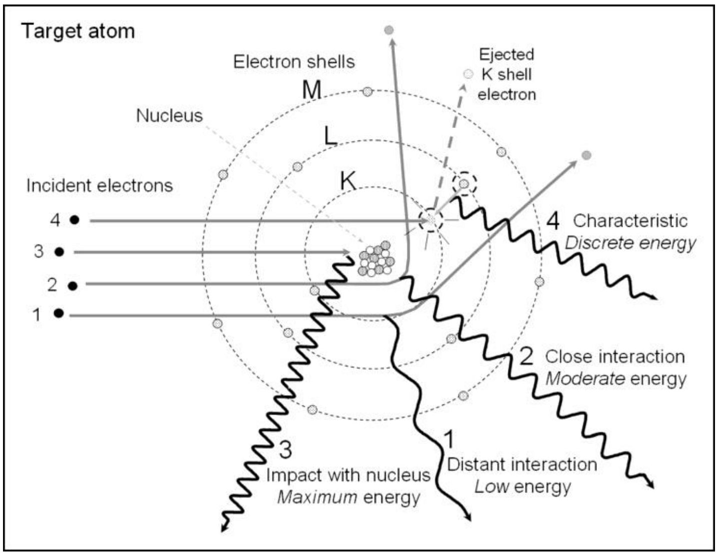
1. **<u>Bremsstrahlung (continuous) X-rays:</u>**

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:

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

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

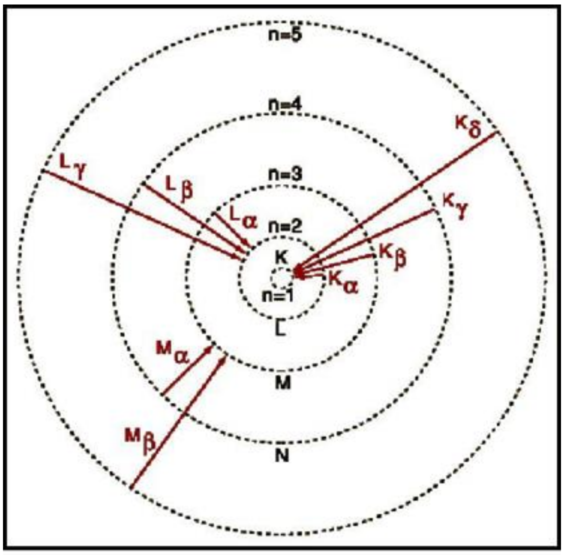


1. **<u>Characteristic X-Rays:</u>**

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.

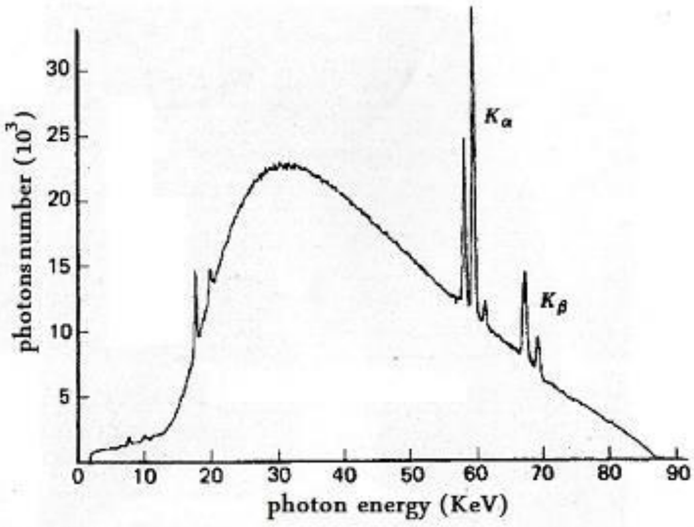
The difference in energy levels of the orbits in an atom is specifying that atom; hence the emitted radiation is called characteristic.



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

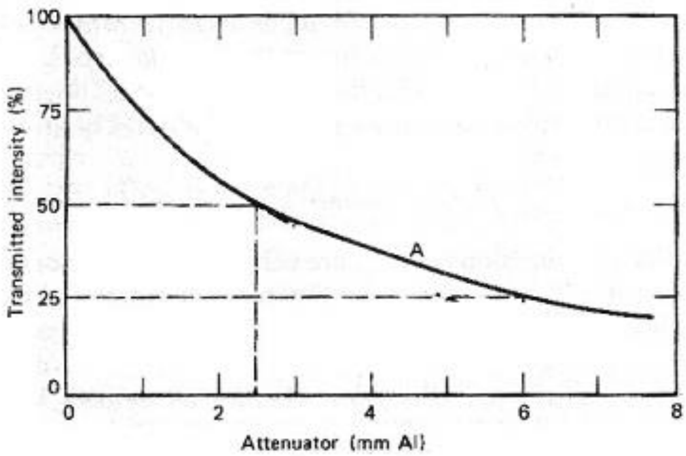
Electron current: 100 ~ 500 or 1000 mA
The x-ray energy produced is not monoenergetic; it is a spectrum of energies up to its maximum.
The power P (watt) = I (amp.) * V (volt) = 1 A and 100 kV = 100 kW => 99% appears as heat: damaged anodes.

3. 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).

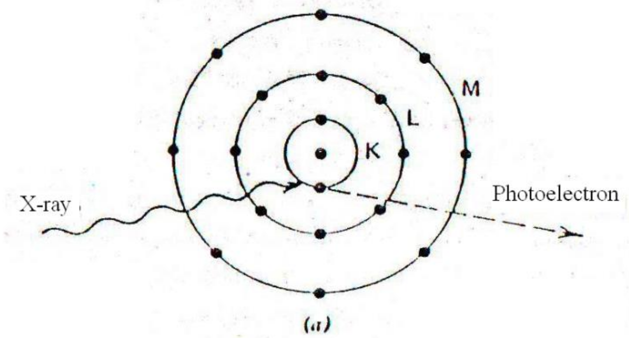
Interaction of X-rays with matte:

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.

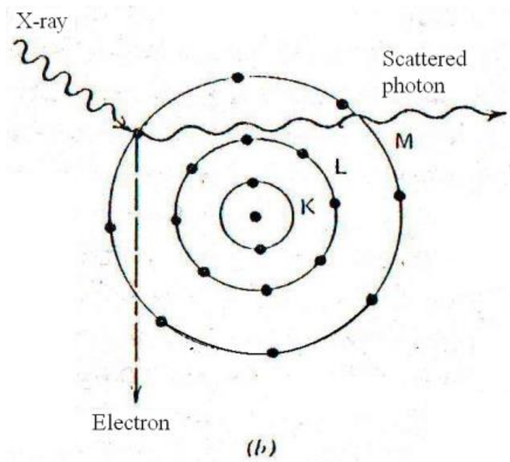
At 30 keV bone (as a heavy material) absorbs X-rays about 8 times better than tissue due to photoelectric effect.



2. Compton effect (C.E):

An X-ray photon collides with a loosing bound outer electron.

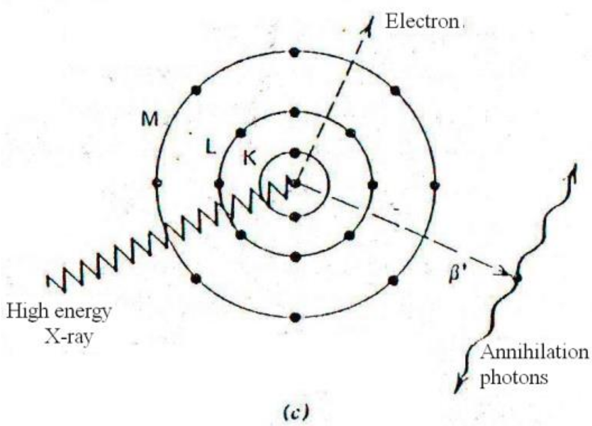
The electron receives part of the energy and the reminder is given to the scattered photon, which then travels in a direction different from that of the original X-ray. It depends on the number of electron per gram.



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.



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).

1. Air is used to replace some of fluid ventricles of the brain, when a pneumoecephalgram is taken.

2. Barium enemas to view the other end of the digestive system (lower GI).

3. Air & barium are used separately to show the same organ in a double contrasting study.

Fig. Barium meal as a contrast medium.

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.

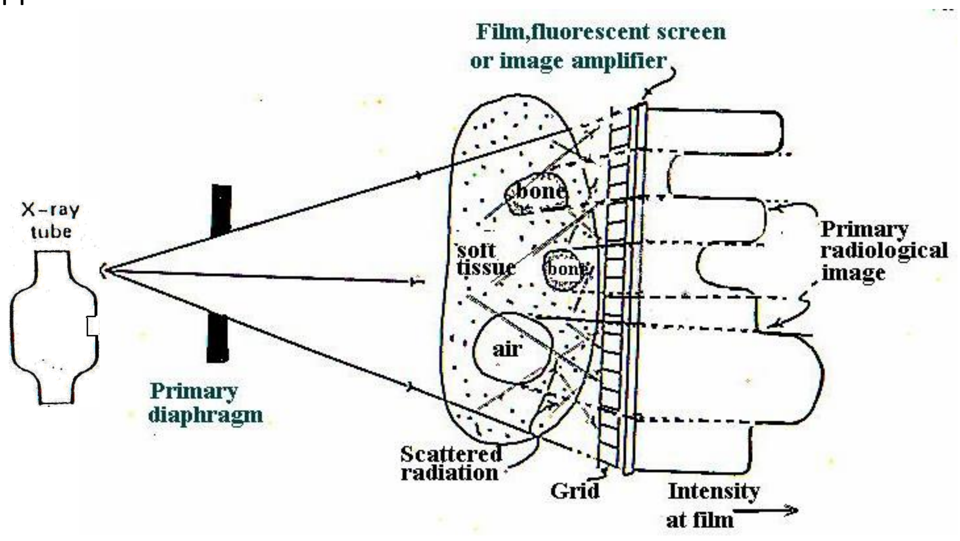


Figure: Diagram showing how the primary radiological image is produced

How to increase the sharpness of an X-ray image?

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.

Photographic film

It is a sheet of plastic coated with an emulsion containing light-sensitive salts (such as silver salts) with variable crystal sizes that determine the sensitivity, contrast and resolution of the film.

When the emulsion is sufficiently exposed to X-ray, it forms a latent (invisible) image. Chemical processes can then be applied to the film to create a visible image, in a process called film developing.

The most problem concerned with x-ray image is recording sharp x-ray shadows (as small as penumbra or blurring) with keeping the x-ray exposure at a minimum, Fig.7.

In the case of a sample of significant thickness is placed adjacent to the film, the width of the penumbra ***P*** in the image can be calculated by:

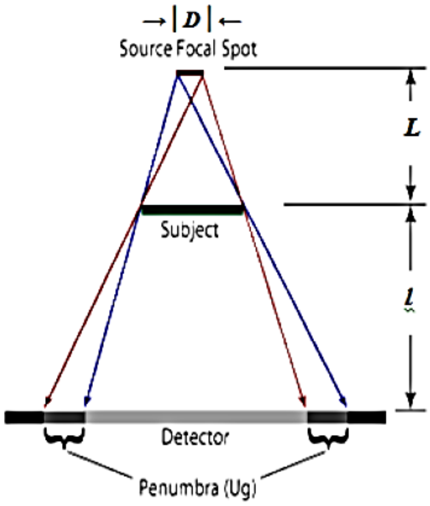


Fig. 7: Traditional x-ray image.

$$P = D \cdot \frac{l}{L}$$

Where, ***D*** diameter of the source focal spot, ***L*** distance between focal spot and object and ***l*** distance between object and film.

To obtain a good x-ray image (without blurring) it should be:

1. Small focal spot, small ***D***, to reduce the penumbra,
2. Positioning the patient as close to the film as possible, small ***l***,
3. Increasing the distance between the x-ray tube and the film as much as possible, large ***L***,
4. Reducing the amount of scattered radiation striking the film as much as possible by using a grid consisting of a series of lead and plastic strips, as shown in Fig. 8,
5. It's necessary to avoid motion during the exposure, since motion causes blurring.

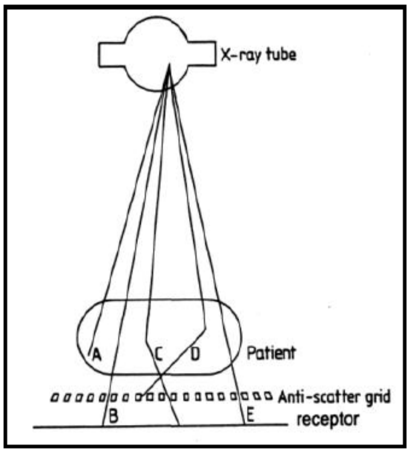


Fig. 8: The grid that used in x-ray imaging.

7. Units of measure and exposure

The measure of X-rays ionizing ability is called the exposure. The unit used for radiation exposure is the roentgen (**R**), a measure of the amount of electric charge produced by ionization in air, since, $1\ R = 2.58\times10^{-4}$ C/kg of air.

Since an exposure to a large area is more hazardous than the same exposure to a small area, a useful quantity for describing radiation to the patient is the exposure-area product (EAP), which is given by:

EAP (rap) = exposure (roentgen) $\times$ area (cm^2)

Where, 1 rap = 100 R cm^2

So, if one receive an exposure of 0.6 R to an area of 33 cm^2 (a typical dental exposure), he will receive 20 R cm^2 (or 0.2 rap). Typical exposures received by an adult are given in the following Table,

X-ray study	Exposure (mR)	Exposure-Area product (raps)
Chest	23	0.5
Skull	270	1.3
Abdomen	560	4.7
Dental bitewing	650	0.2

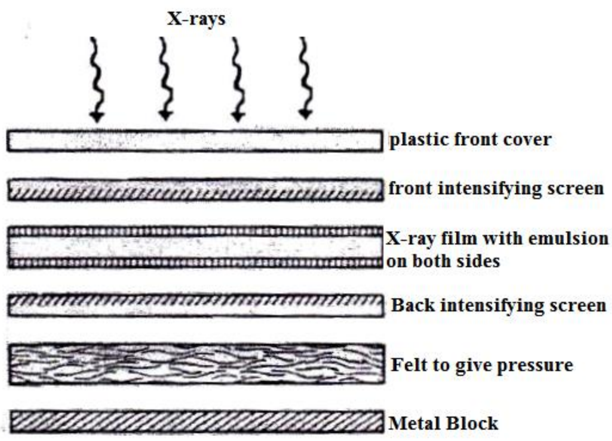
X-ray Film: It is sensitive photographic plate, which is easily effected by X-rays. This is because of containing Silver halogens **(Agcl, AgI, AgBr)** which may suffer an interaction like the following:

$AgBr \xrightarrow{x\text{-}ray} Ag^{+} + Br$

$4Ag + O_2 \rightarrow 2Ag_2O$ (Black)

AgBr: is the emulsion layer of the film. If more x-rays photons incident on the film, more blacking color occur in the film.

if less X-rays photons incident on the film, more whiting color occur in the film. Since bones are strong attenuator for X-rays, they appear as white on the X-ray film.



Photographic process: as follows:

1. Immerse the exposed film in the developer solution to free the silver atoms in those grains which have received sufficient exposure & contain latent image center.
2. Fixing to neutralize the developer on the film & stop the developing action.
3. Washing the film in running water to remove the fixing chemicals &dissolve silver halides.