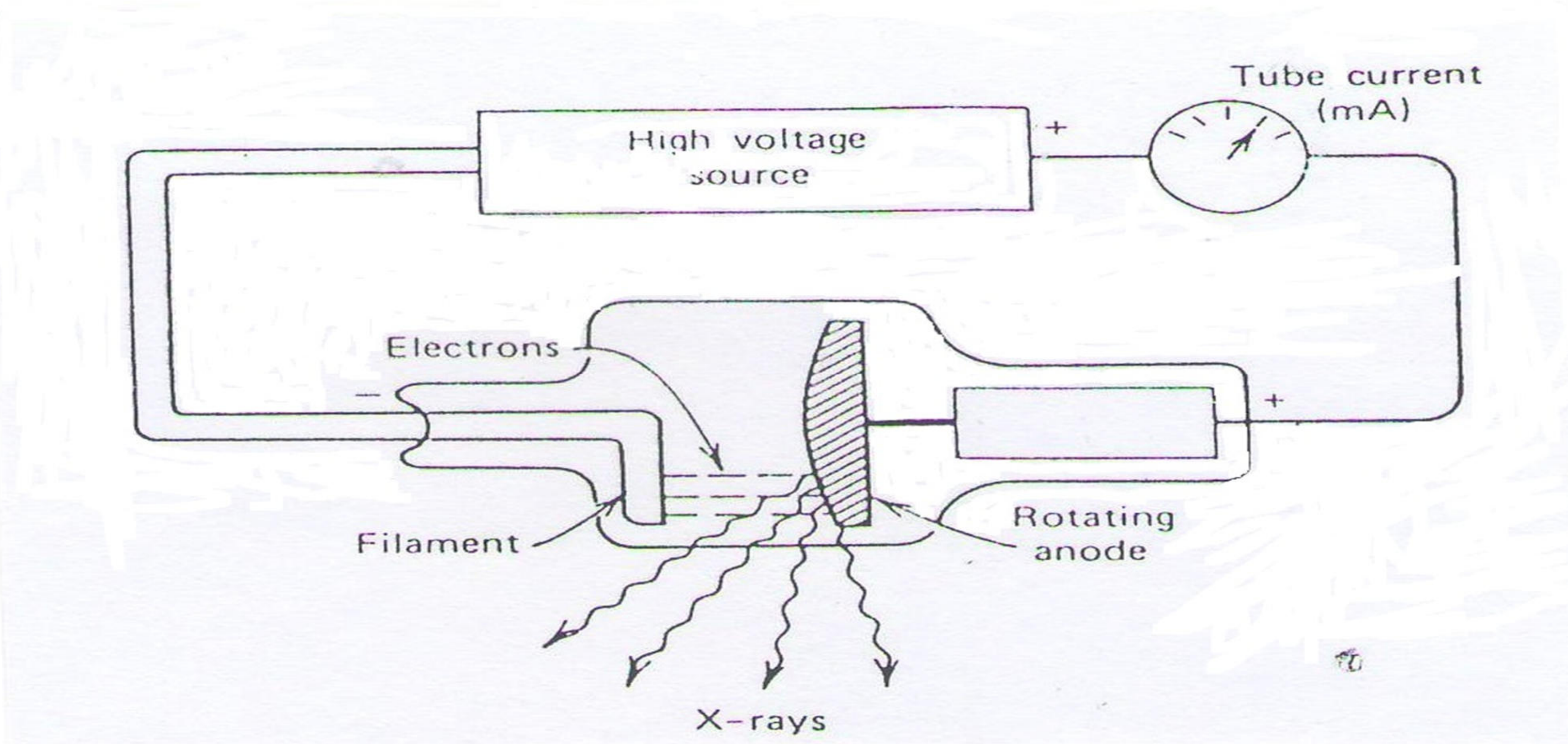
Physics of Diagnostic X-rays

1-Production of x-ray beam

- A high-speed electron can convert some or all of its energy into an x-ray photon when it strikes an atom, to us we need to speed up electrons to produce x-rays trying to speed up on electron in air is difficult since there are to many electrons on the atoms- about **4 x 10^{20}** in **1 cm^3**. Before an electron gets going it bumps into another one it in thus necessary to eliminate most of electrons, and this is done by using a glass blub (x-ray tube).

The main components of a modern x-ray unit are.

- **1- A source of electrons- a filament, or cathode.**
- **2- A n evacuated space in which to speed up the electron.**
- **3- A high positive potential to accelerate the negative electrons**
- **4- A target or a node, which the electrons strike to produce x-rays**



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 (i.e. kilovolt peak **kVp**).

e.g. : An x-ray tube operating at **80 kVp** will produce x-rays with a spectrum of energies up to a maximum of **80 keV** .

keV : is the energy an electron gains or losses in going across a potential difference of **1000 V** .

$$\mathbf{1\ keV = 1.6 \times 10^{-9}\ erg = 1.6 \times 10^{-16}\ J}\ .$$

The **kVp** used for an x-ray study depends on the thickness of the patient and the type of study being done .

e.g. mammography are usually done at 25 to 50 kVp

problems

e = charge of electron = 1.6×10^{-19} C

m= mass of electron = 9.10×10^{-31} Kg

h = plank constant = 6.63×10^{-34} Js

eV = 1.6×10^{-19} J .

Example

Compute the potential difference through which an electron must be accelerated in order that the short-wave limit of the continuous x –ray spectrum shall be exact **1A°**. The frequency corresponding to **1 A°(10^{-10}m)** is given by.

$$F = \frac{C}{\lambda} = \frac{3x10^{8}}{10^{-10}} = 3x\ 10^{18}Hz$$

The energy of the photon is

hf = 6.62 x 10^{-34} Js x 3x $10^{18}s^{-1}$ = 19.9 x 10^{-16}J

this must equal the kinetic energy of the electron, **1/2 mv^2** which is also equal to the product of the electronic charge and accelerating voltage **V**.

$$1/2\ mv^2 = eV = 19.9 \times 10^{-16} J$$

$$e = 1.6 \times 10^{-19} C$$

$$V = \frac{19.9 \times 10^{-16}}{1.6 \times 10^{-19}} J/c = 12.400 \text{ volt}$$

The efficiency of x-ray system depends on

- 1 - The atomic number of the anode material .
- The intensity of x-ray beam (I) depends on the anode material (i.e. the atomic number of the anode material Z : $I \propto Z$) .
- 2 - The melting point of the anode material.
- The target (anode) material used should have a high melting point to overcome the heat produced because of the electron stream stoppage in the surface .

e.g. Tungsten which $Z = 74$ and melting point 3400°C is common in use .

The electron current that strikes the target is typically 100 – 500 mA and the power P put into the surface of the target is quite large .

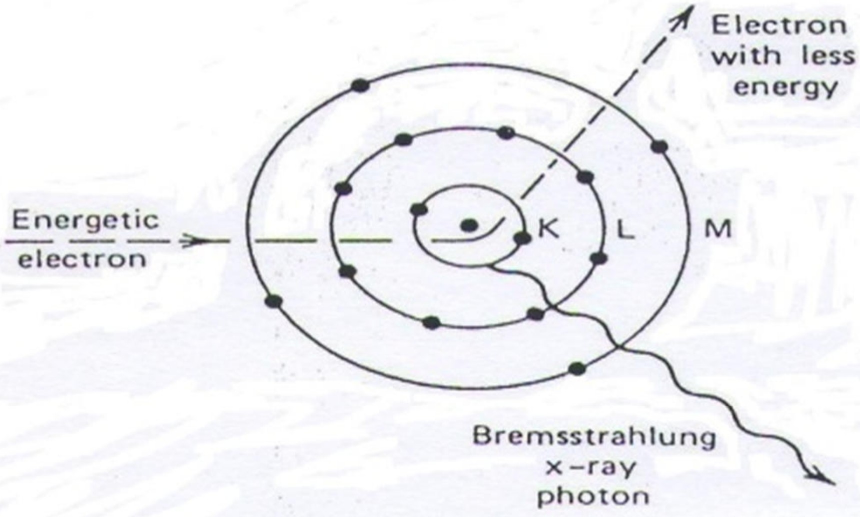
$P = IV$ where I is the current in amperes and V is the voltage in volts then P is in watts.

Example: for a system uses $I = 1$ A and $V = 100$ kV

$P = IV = 1 \times 10^5$ W = 100 kW .

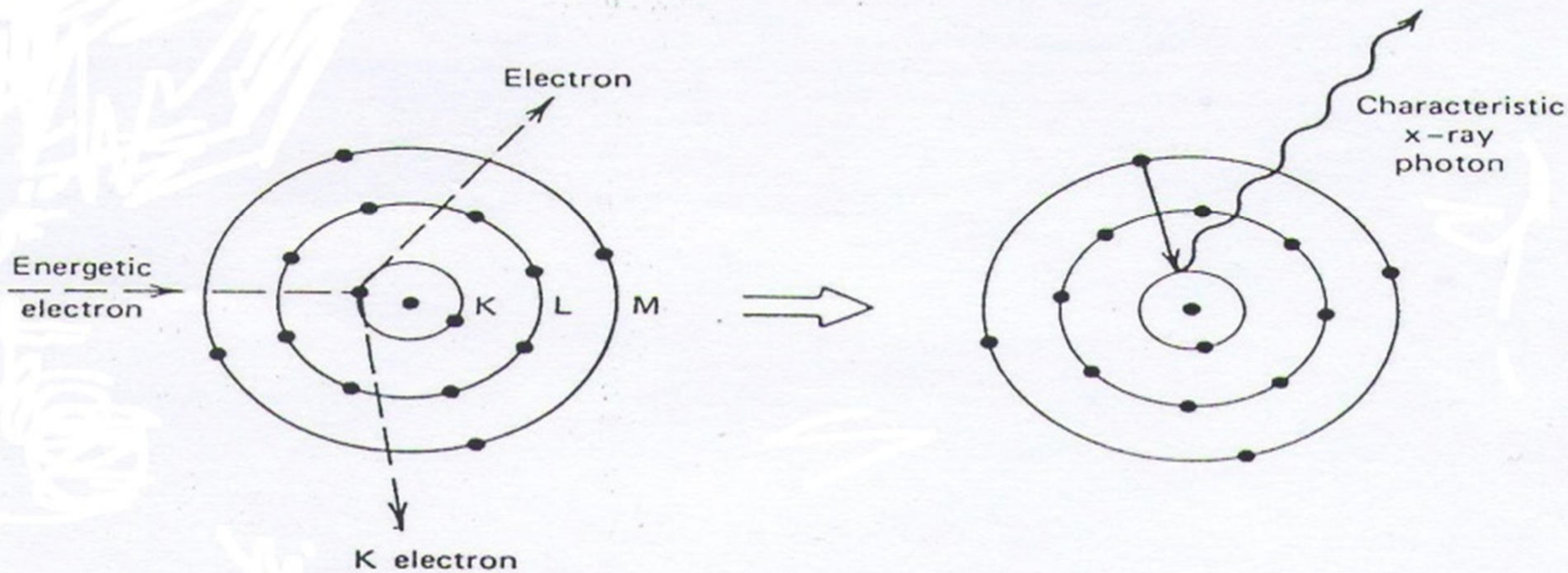
X-ray spectrum

- X-ray spectrum consists of :
- 1 - *Braking radiation or Bremsstrahlung* which is produced due to the diversion of a fast electron near the nucleus of the target atom and loss some of its energy (fig.2a)



Electron
with less
energy
Energetic
electron
K
L
M
Bremsstrahlung
x-ray
photon

(a)

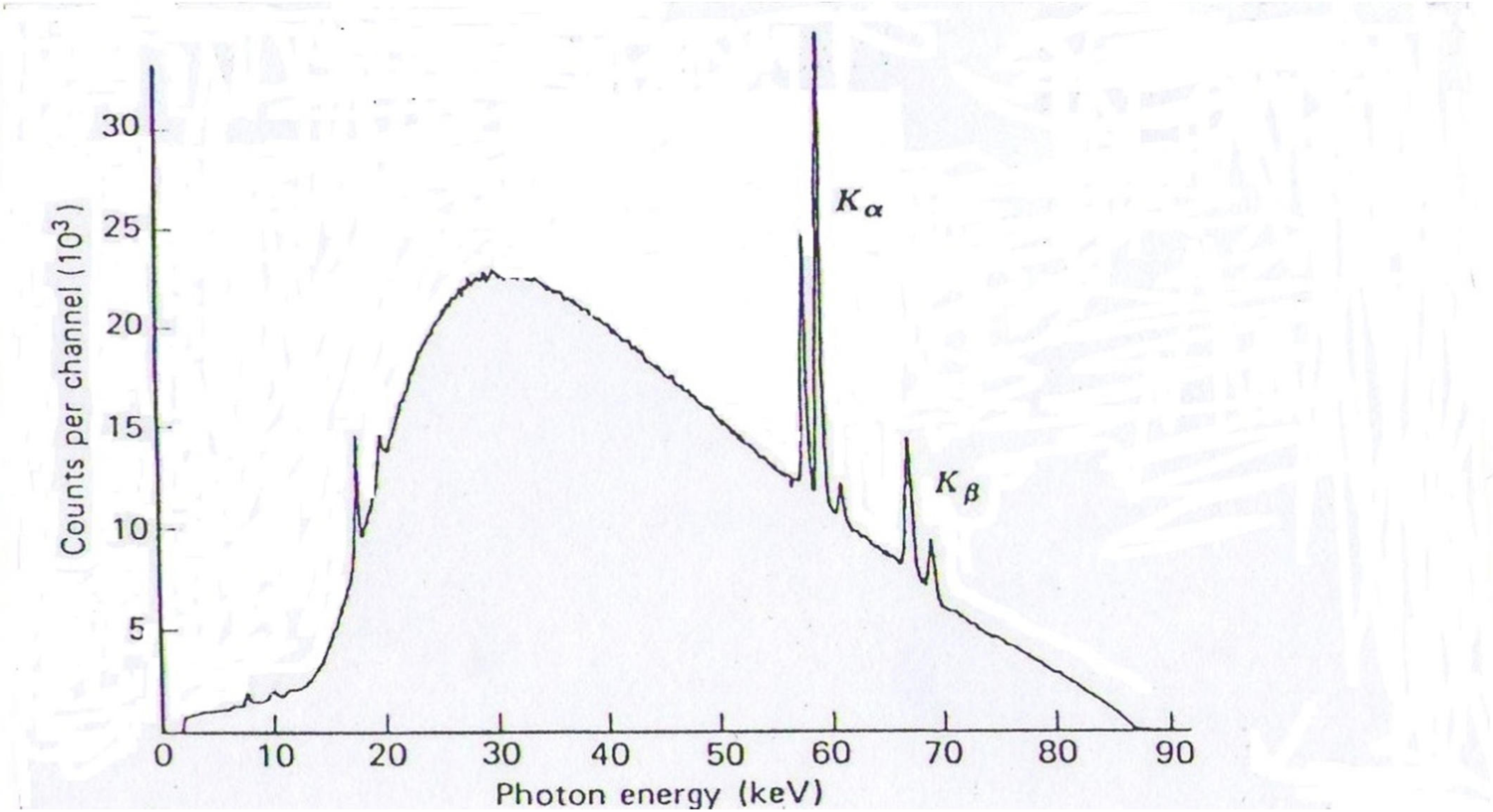


Electron
Energetic
electron
K
L
M
K electron
Characteristic
x-ray
photon

(b)

2 - *Characteristic x-rays*: which is produced due to the energy released when electron of an outer shell in the target atom falls immediately into the inner shell that has a vacancy because the accelerated electron strikes the target electron and knocks it out of its orbit and free of the atom . If the released electron is from K-shell and the vacancy is filled with electron from L-shell , the radiation produced is called K_α *characteristic x-ray* , and when the vacancy is filled with electron from M-shell, the radiation produced is called K_β *characteristic x-ray* (fig. 2b) .

the spectrum of x-rays , the broad smooth curve is due to the bremsstrahlung and the spikes represent the characteristic x-rays



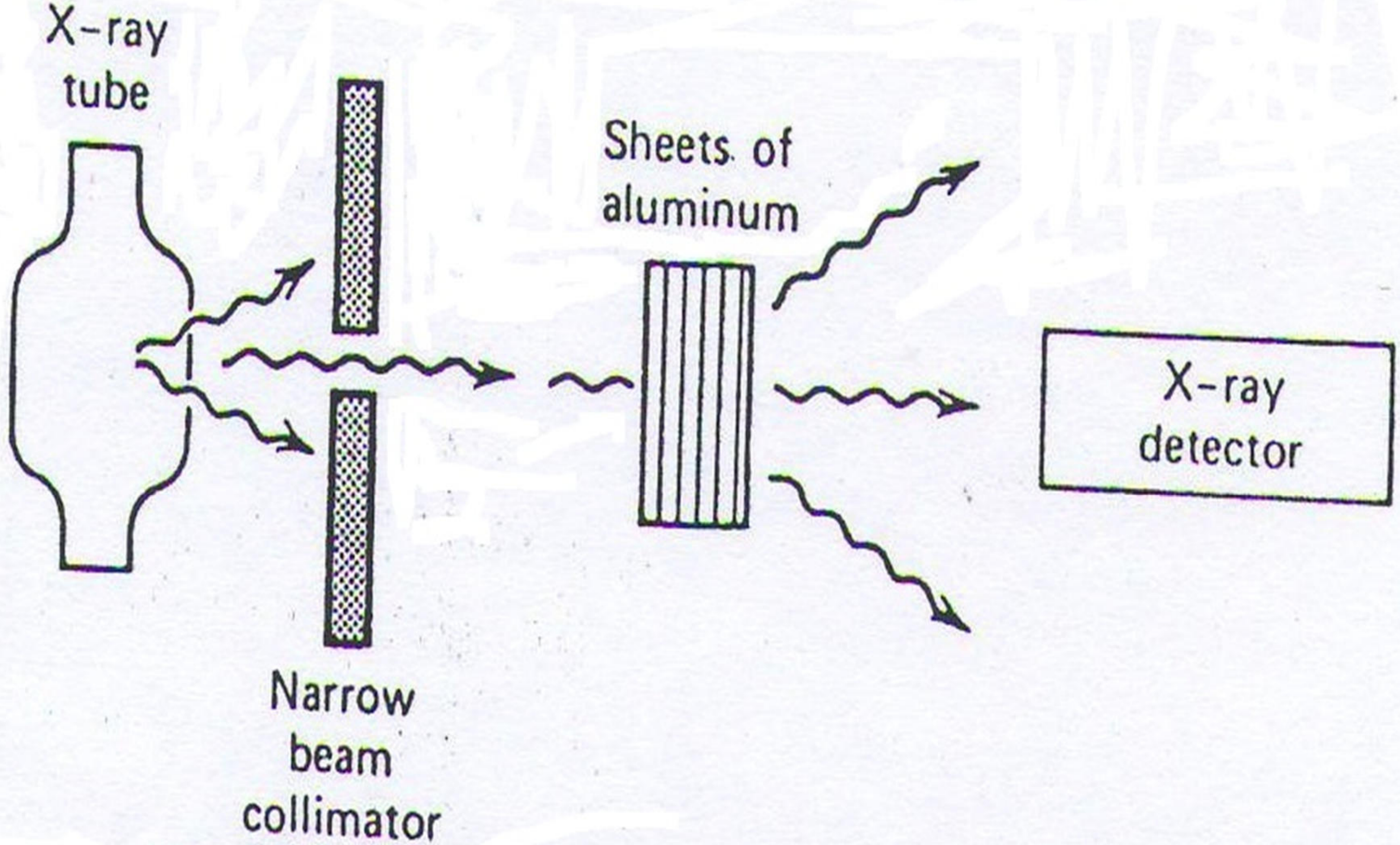
Absorption of x-rays :

X-rays absorption depends on the composition of the matter penetrated.

Heavy elements such as Ca are much better absorbers of x-rays than light elements such as C,O_2 & H_2 so the bones are the best , while the soft tissues like fat , muscles and tumors all absorb x-rays equally , thus they are difficult to distinguish from each other on an x-ray image .

The attenuation of an x-ray beam is its reduction due to absorption and scattering of some of photons out of the beam. A simple method of measuring the attenuation of an x-ray beam is shown.

$$I = I_0 e^{-\mu x}$$


X-ray
tube
Sheets of
aluminum
X-ray
detector
Narrow
beam
collimator

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

where :

$I_{\circ}$ is the intensity of un attenuated x-ray beam .

e = 2.718 .

I is the intensity of the attenuated beam.

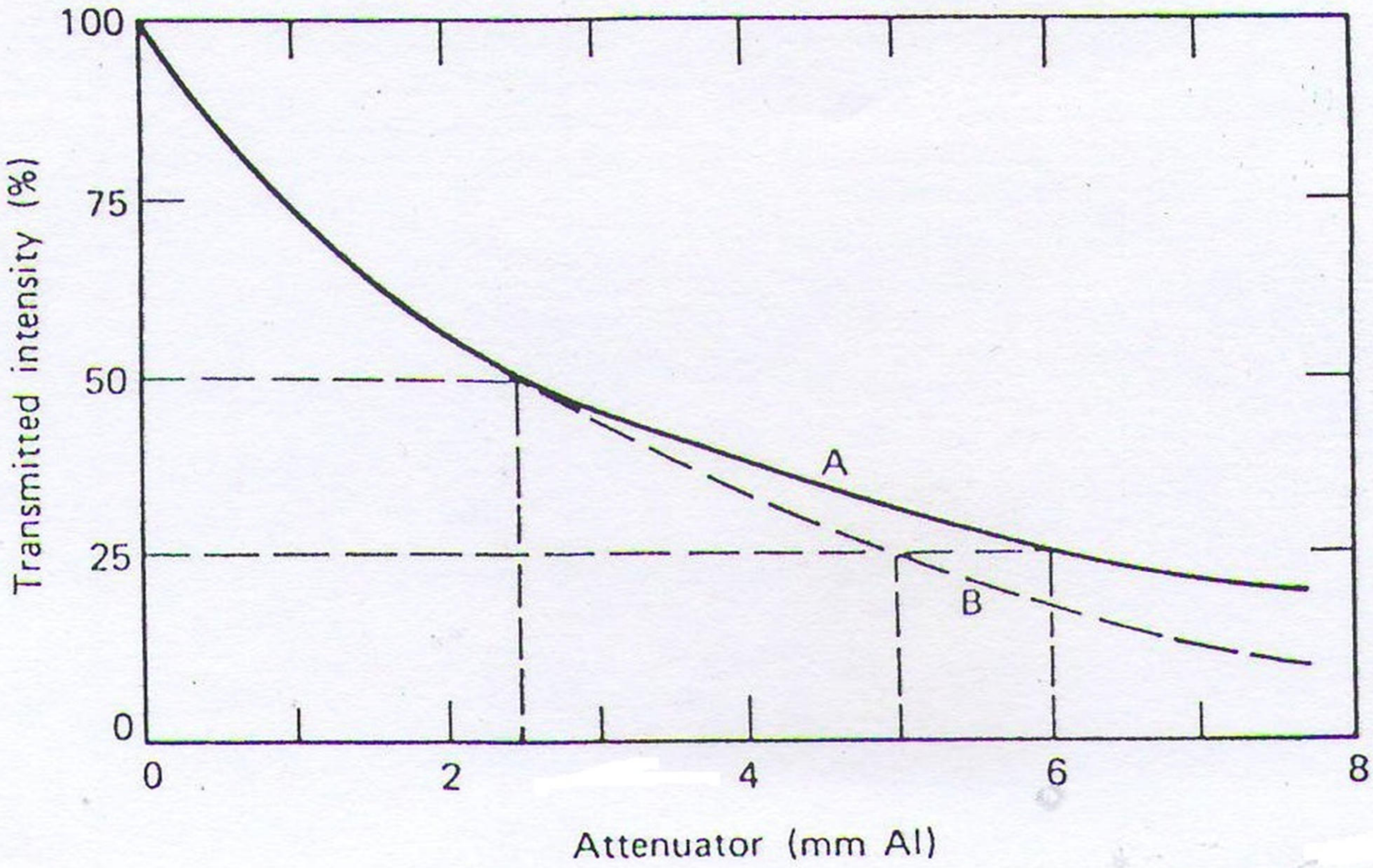
X is the thickness of the attenuator, and μ is the linear attenuation coefficient of the attenuator which is dependent on the energy of x-rays (as the beam become harder μ decreases).

The equation above means that the attenuation is exponentially

The half value layer (HVL) :-

The half value layer (HVL) for an x-ray beam is the thickness of a given material that will reduce the beam intensity by one –half. Fig. 4 shows HVL at certain transmitted intensity of x-rays for (Al) used as attenuator. For a monoenergetic x-ray beam, the second HVL equals the first HVL while, in general, x-rays consists of several energies in the spectrum so HVLs are not equal.

$$\mathbf{HVL = 0.693 / \mu}$$


100
75
50
25
0
Transmitted intensity (%)
A
B
0
2
4
6
8
Attenuator (mm Al)

The equivalent energy :

The equivalent energy of an x-ray beam is the energy of a monoenergetic x-ray beam with the same HVL .

e.g. : A typical x-ray set operating at 80 kVp with a filter of 3 mm Al would have a HVL of about 3mm Al . Since a beam of monoenergetic 28 keV x-rays also has a HVL of 3 mm Al , the equivalent energy of x-ray beam would be 28 keV .

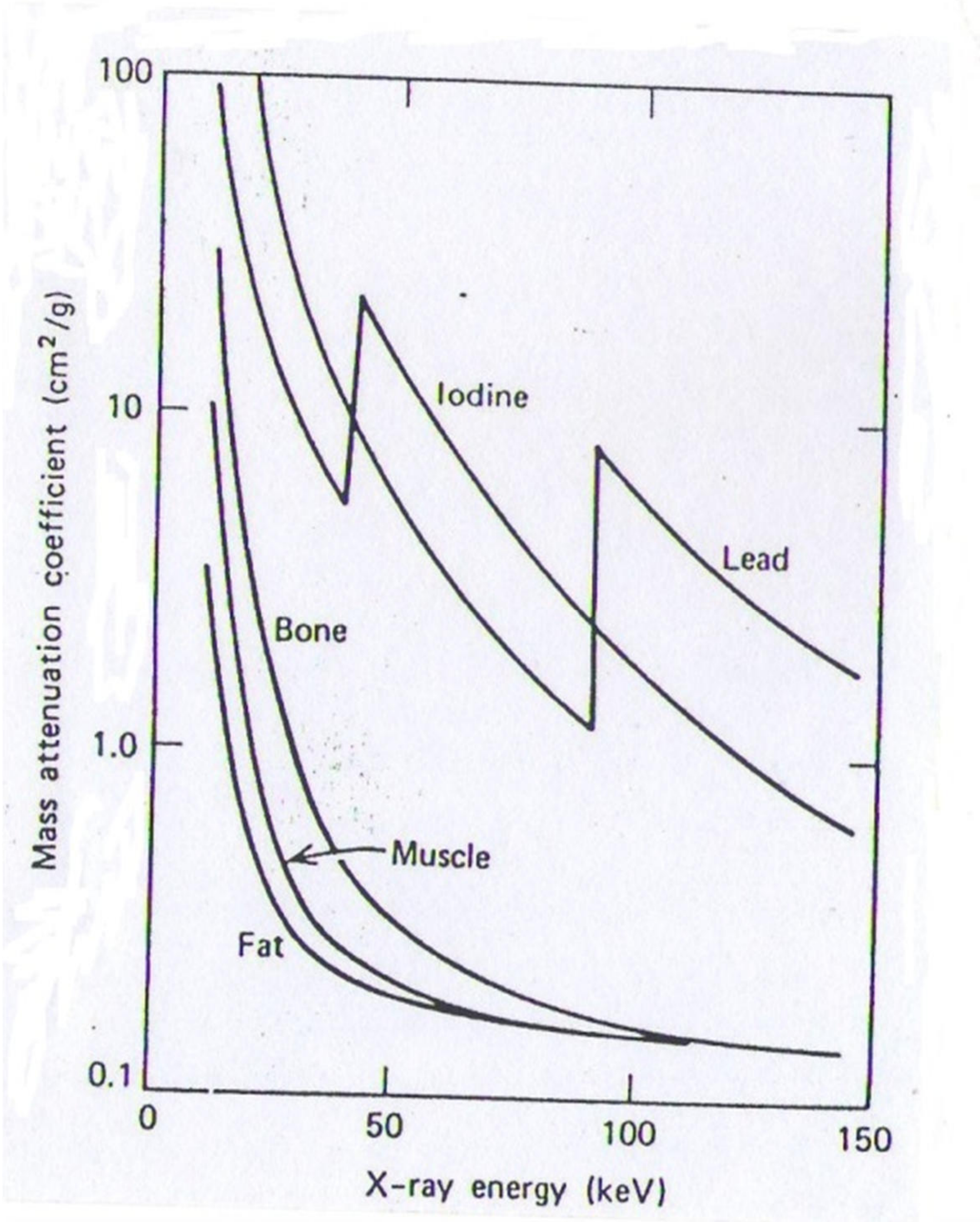
The mass attenuation coefficient (μ_m)

To remove the effect of density when comparing attenuation in several materials , mass attenuation coefficient (μ_m) can be used which is the linear attenuation coefficient (μ) divided by the density (ρ) of the material , so that :

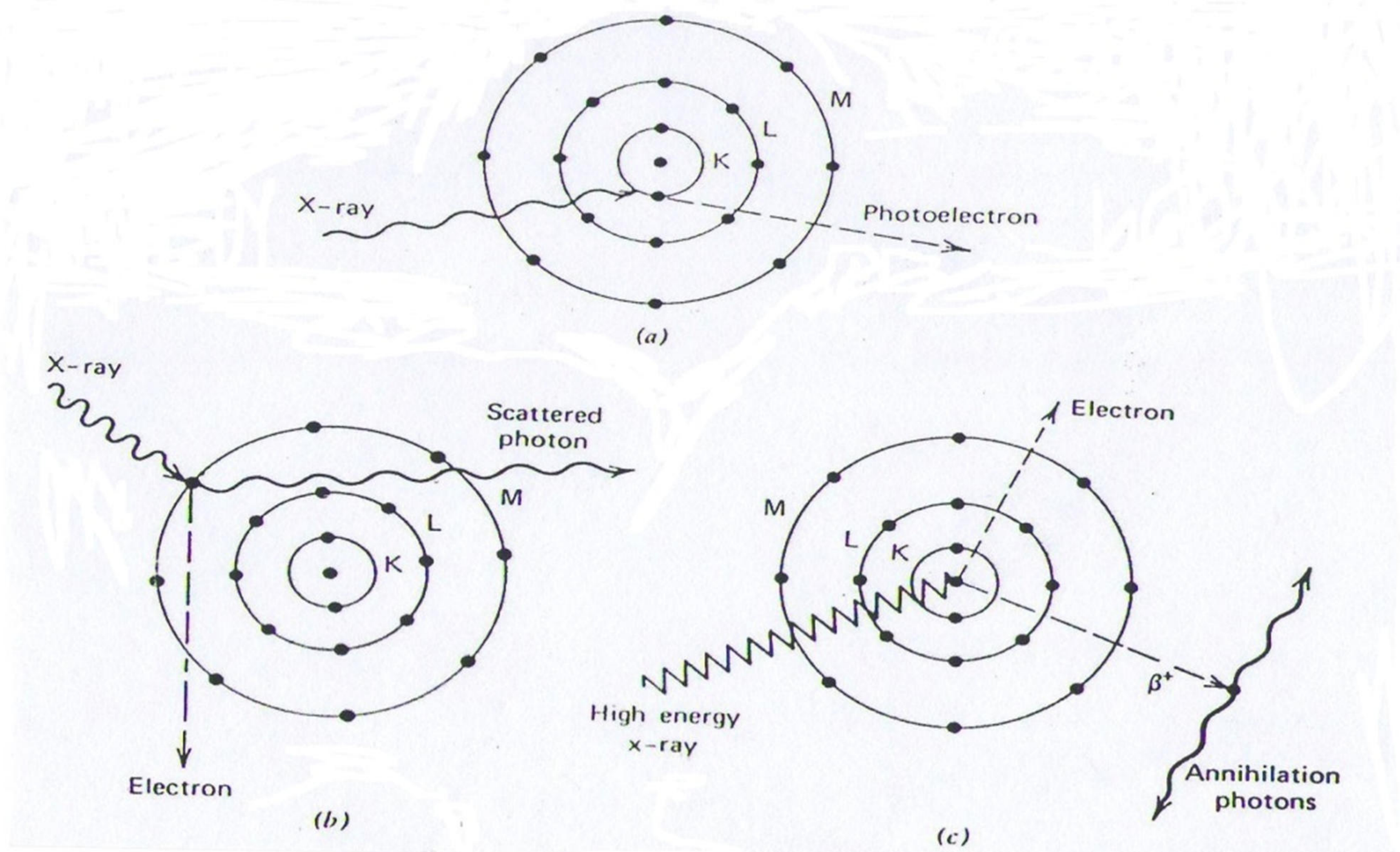
$$\mathbf{I = I_{\circ}\ e^{-(\mu/\rho)(\rho x)} = e^{-(\mu m)(\rho x)}}$$

Where ρx is in g / cm^2 and called the area density .
Again HVL = 0.693 / μ_m

Fig shows the mass attenuation coefficients of fat, muscle, bone, iodine, and lead as function of x-ray energy. Iodine is better absorber than lead from about 30 to about 20 kev. This phenomenon is due to the photoelectric effect. The mass attenuation coefficients of bone greater than muscle and fat but on mass basis all tissues attenuate about the same above 100 kev.



Interaction of x-rays with the matter :



X-rays lose energy in three ways :

1- <u>Photoelectric effect</u> : It occurs when an x-ray photon transfers all of its energy to an electron in an inner shell which then escapes from the atom (fig. 7a).

The photoelectron uses some of its energy (the binding energy) to get away from the positive nucleus and spends the remainder ripping electrons of (ionizing) surrounding atoms. The photoelectric effect is more apt to occur in the intense electric field near the nucleus than the outer levels of the atom, and in the elements with high **Z** more than with low **Z**.

K-edges *:* are sharp rises in the curve of x-rays energy versus mass attenuation coefficient $\boldsymbol{\mu_m}$ (fig. 7), when the energy of the x-rays is just slightly greater than the binding energy so the probability of photoelectric effect increases greatly

2 – Compton effect :

It occurs when an x-ray photon collides with a loosely bound outer electron which receives part of the energy and the remainder is given to a Compton (scattered photon), then this photon travels in a direction different from the original x-ray (fig.7b). Compton Effect depends on the number of electron per cubic centimeter which is proportional to the density

The energy transferred to the electron can be calculated in the same way as the energy transferred during a billiard ball like collision by using the laws of conservation of energy and momentum.

The effective mass of x-ray (m)= E/c^2 (Einstein's equation $E=mc^2$)

The momentum = E/c

The energy equivalent of electron mass is 511 keV so Compton Effect needs to occur an

X-rays with this energy.

Compton Effect is common in low Z elements. e.g. in water or soft tissue at energies

Above 30 keV and in bone at energies above 100 keV.

3 – <u>Pair production</u> : It occurs when a very energetic photon enters the intense electric field of the nucleus , it may be converted into two particles :an *electron* and a *positron* (β^+) . X-ray photon energy must be at least 1.02 MeV which is equivalent to the mass of the two produced particles . If the energy is more than 1.02 MeV the remainder is given to the particles as kinetic energy.

After the positron spent its kinetic energy in ionization it does a death dance with an electron (annihilation), then both vanish and their mass energy appears as two photons of 511 keV called annihilation radiation.

Pair production is common in light Z materials with an x-ray energy more than 1.02 MeV

Pair production is no use in diagnostic radiology because of the high energies needed and that photoelectric effect is more useful than the Compton effect because it permits use to see bones and other heavy materials such as bullets in the body. At 30 kev bone absorbs x-rays about 8 times better than tissue due to photoelectric effect.

Compounds containing iodine are often injected into the blood stream to show arteries, and only mist containing iodine is some time sprayed into lungs to make airways visible.

Radiologists give barium compounds oral to see parts upper gastrointestinal trace (upper GI) and barium enemas to view the other end of digestive system (lower GI), since gases are poorer absorbs of x-rays than liquids and solids.

Computed tomography (CT)

Computed tomography (CT) scanners have been available since the mid-1970s and have revolutionized medical imaging.

The most prominent part of a CT scanner is the gantry – a circular, rotating frame with an X-ray tube mounted on one side and a detector on the opposite side. A fan-shaped beam of X-rays is created as the rotating frame spins the X-ray tube and detector around the patient. As the scanner rotates, several thousand images are taken in one rotation resulting in one complete cross-sectional image of the body

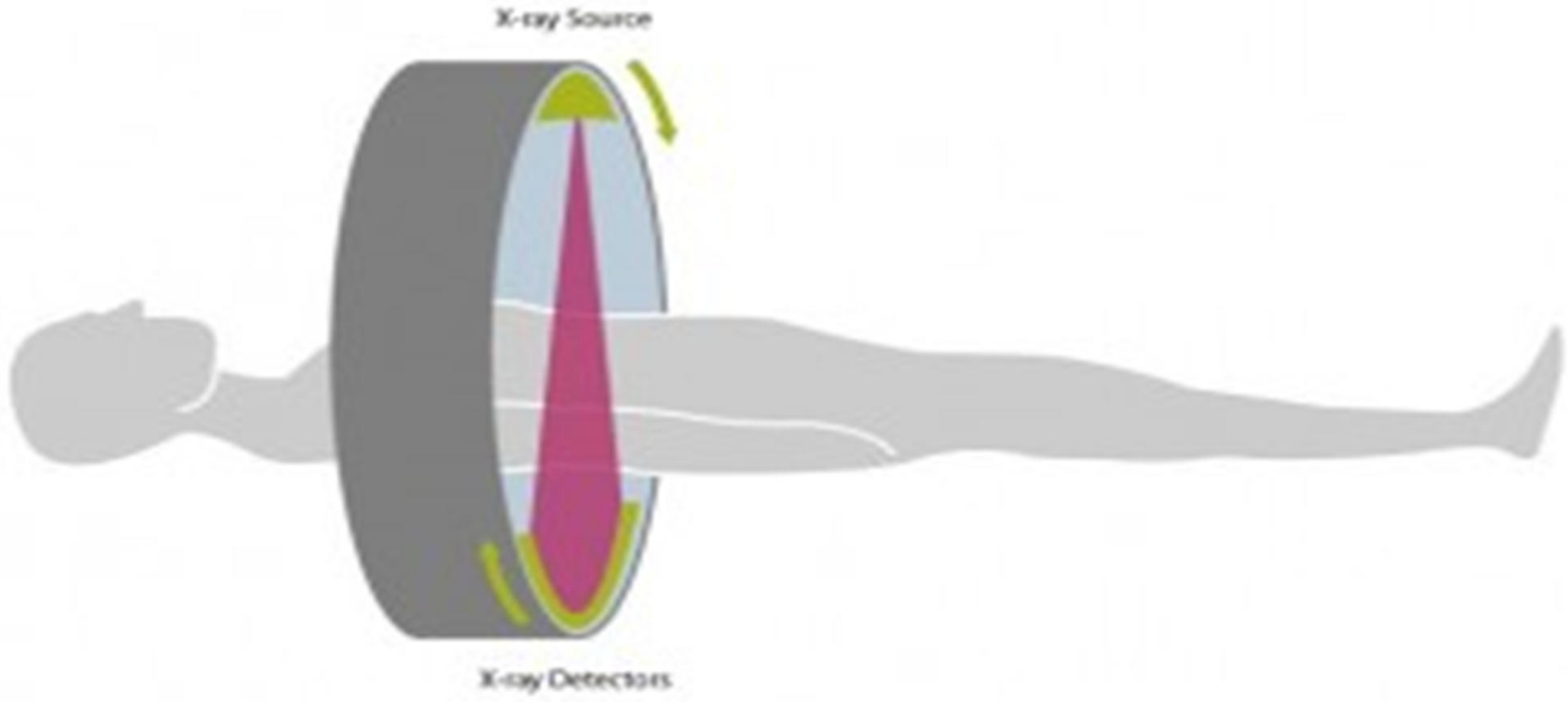


Fig: The principle of computed tomography with an X-ray source and detector unit rotating synchronously around the patient. Data are acquired continuously during rotation.

CT scans provide far more detailed images than with conventional X-rays, especially in the case of blood vessels and soft tissue such as internal organs and muscles.

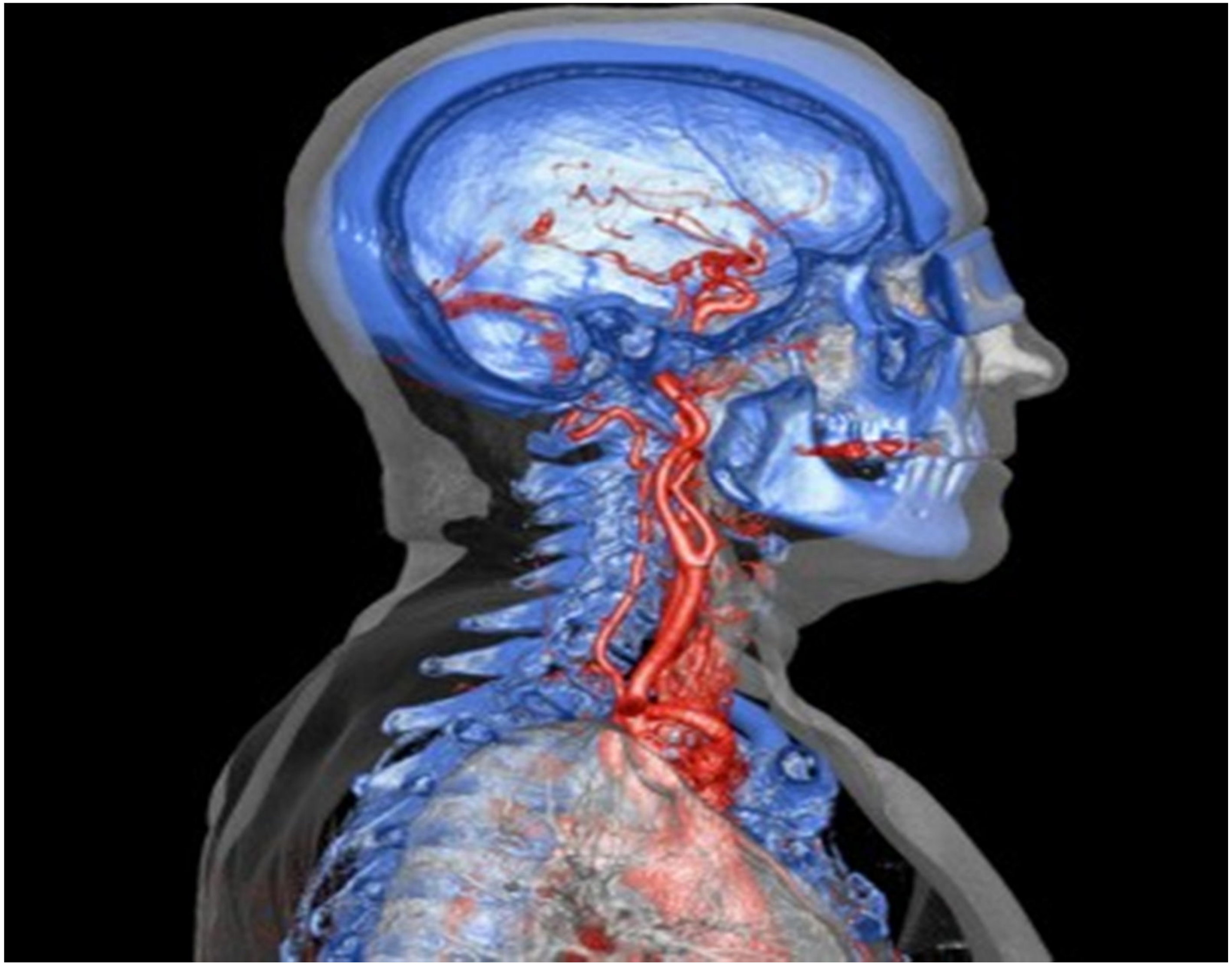
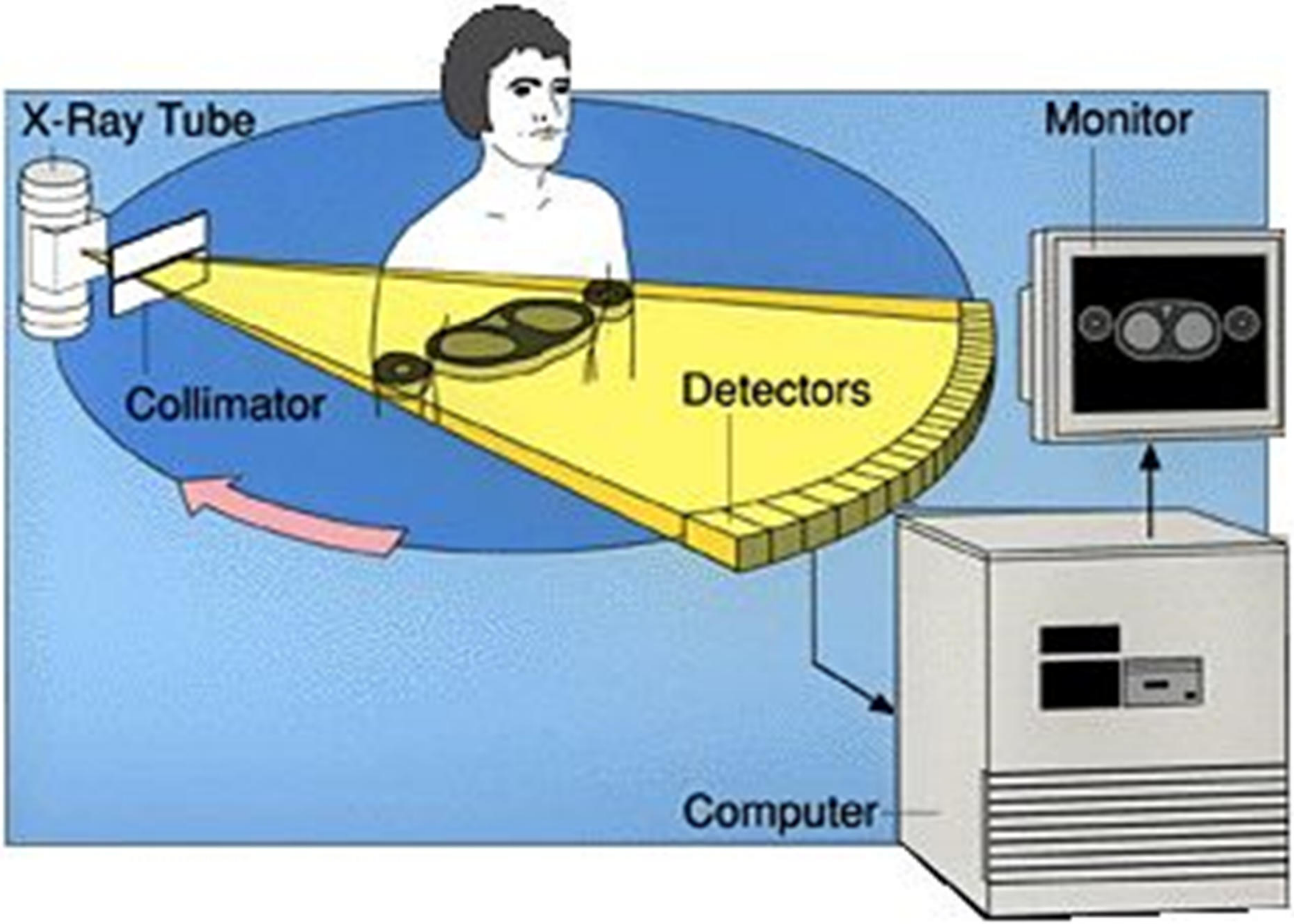
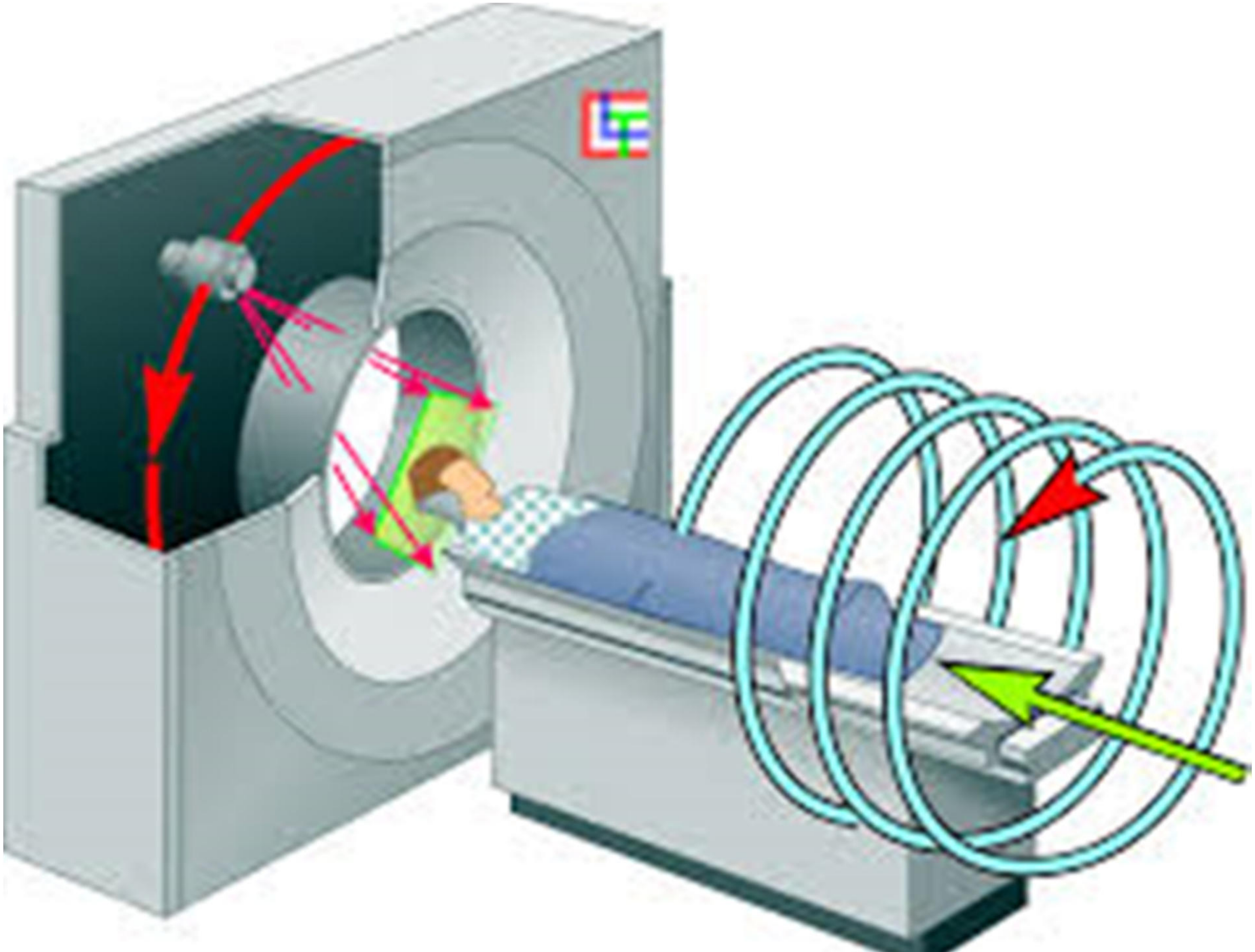


Fig. 2: Modern CT scans provide very detailed images by using relatively low radiation doses, e.g. blood vessels, and internal organ.

As the x-ray tube and detector make this 360Â° rotation, the detector takes numerous snapshots (called profiles) of the attenuated x-ray beam. Typically, in one 360Â° lap, about 1,000 profiles are sampled. Each profile is subdivided spatially (divided into partitions) by the detectors and fed into about 700 individual channels. Each profile is then backwards reconstructed (or "back projected") by a dedicated computer into a two-dimensional image of the "slice" that was scanned.



X-Ray Tube
Monitor
Collimator
Detectors
Computer



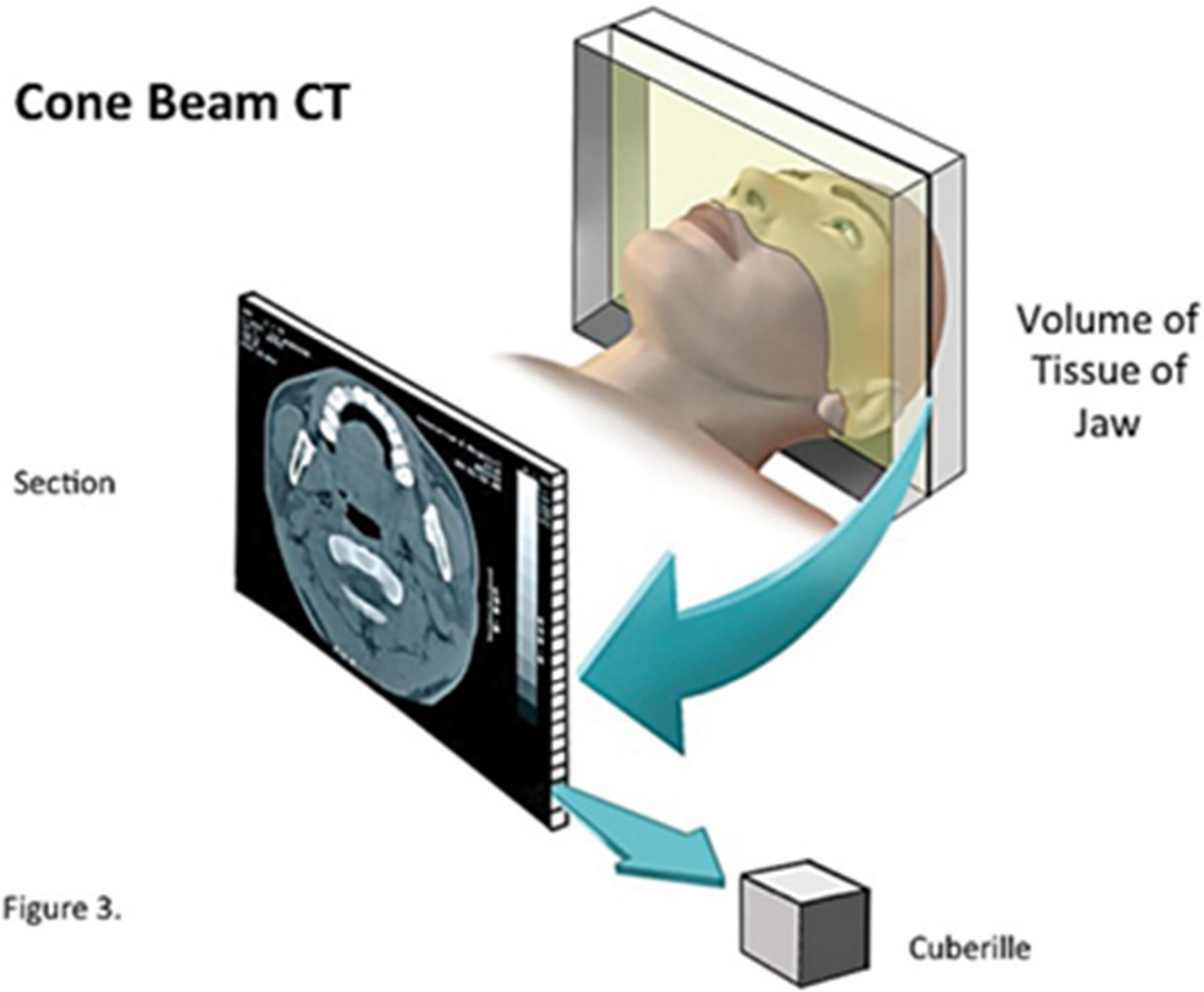


Figure 3.