L37 Radiation dosimetry& Physics of Diagnostic X-rays

Radiation dosimetry is the quantitative description of the effect of radiation on living tissue .
Absorbed dose is a measure of the energy deposited in an irradiated medium by ionizing radiation per unit mass.

Used of Absorbed dose

1. **The calculation of dose uptake in living tissue in both radiation protection (reduction of harmful effects), and radiology (potential beneficial effects for example in cancer treatment).**
2. **It is also used to directly compare the effect of radiation on inanimate matter.**

- **The biological effect of the absorbed dose in tissue cells depends on the type of radiation .**
- **The SI unit of the absorbed dose is the Joule/kilogram or the gray (Gy:(1Gy = 1J/kg .We use also other unit as the rad :1Gy = 100 rad .**

The units *Sievert (Sv),(rem: röntgen equivalent man)* :

$$D_{equiv}(Sv) = RBE \times D_{abs}(Gy)$$

$$D_{equiv}(rem) = RBE \times D_{abs}(rad)$$

With 1 Gy = 100 rad, we have 1Sv = 100rem .

The unit of the RBE is Sv/Gy = rem/rad

- **QF: It is used because some types of radiation, such as Alpha Particles, are more biologically damaging internally than other types such as the Beta Particle.**
- **Low energy (E_{max} < 0.03 MeV) particles have a QF of 1.7, which reflects their inability to travel far in biological tissues and their resulting tendency to dissipate all their energy locally and therefore to cause greater biological damage.**
- **Photons and beta particles have a low linear energy transfer coefficient, meaning that they ionize atoms in the tissue that are spaced by several hundred nanometers (several tenths of a micrometer) apart, along their path**
- **Effective radiation dose, a number that provides an estimation of total danger to the whole organism, as a result of the radiation dose to part of the body.**

The oxygen enhancement ratio (OER)

It is the ratio of doses under hypoxic to aerated conditions that produce the same biologic effect. Or OER detrimental effect of ionizing radiation due to the presence of oxygen.

- **The presence or absence of molecular oxygen dramatically influences the biologic effect of x-rays.**
- **Oxygen presence (aerated cells) increases radiation effectiveness for cell killing.**
- **Lack of oxygen (hypoxic cells) results in more radio resistant cells.**

$$ORE = \frac{\text{radiation doses } in\ hypoxia}{\text{radiation doses } in\ air}$$

The maximum OER depends mainly on the ionizing density or LET of the radiation. Radiation with higher LET and higher relative biological effectiveness (RBE) have a lower OER in mammalian cell tissues. The value of the maximum OER varies from about 1-4. The maximum OER ranges from about 2-4 for low-LET radiations such as X-rays, beta particles and gamma rays, whereas the OER is unity(OER =1) for high-LET radiations such as low energy alpha particles.

Uses of OER in medicine

The effect is used in medical physics to increase the effect of radiation therapy in oncology treatments. Additional oxygen abundance creates additional free radicals (superoxide O_2^-, hydrogen peroxide H_2O_2) and increases the damage to the target tissue (DNA damage).

In solid tumors, the inner parts become less oxygenated than normal tissue, and up to three times higher dose needed to achieve the same tumor control probability as in tissue with normal oxygenation.

Radiation therapy

Radiation therapy (also called radiotherapy) is a cancer treatment that uses high doses of radiation to kill cancer cells and shrink tumors. At low doses, radiation is used in x-rays to see inside body, as with x-rays of teeth or broken bones.

- Radiation therapy may be curative in a number of types of cancer if they localized to one area of the body.
- It may also be used as part of adjuvant therapy, to prevent tumor recurrence after surgery to remove a primary malignant tumor (for example, early stages of breast cancer).
- Radiation therapy is synergistic with chemotherapy, and has been used before, during, and after chemotherapy in susceptible cancers. The subspecialty of oncology concerned with radiotherapy is called radiation oncology.

- Radiation therapy is commonly applied to the cancerous tumor because of its ability to control cell growth. Ionizing radiation works by damaging the DNA of cancerous tissue leading to cellular death. To spare normal tissues (such as skin or organs which radiation must pass through to treat the tumor), shaped radiation beams are aimed from several angles of exposure to intersect at the tumor, providing a much larger absorbed dose there than in the surrounding, healthy tissue.

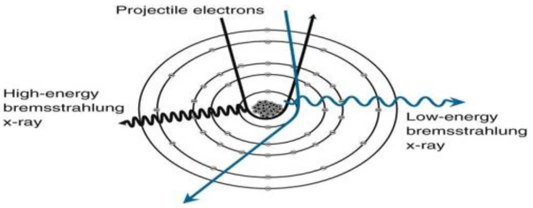
Types of radiation therapy : There are two main types of radiation therapy, external beam and internal. The type of radiation therapy that patient may have depends on many factors, including:

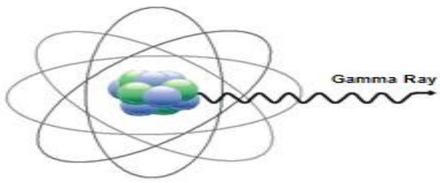
- The type of cancer
- The size of the tumor
- The tumor's location in the body
- How close the tumor is to normal tissues that are sensitive to radiation
- General health and medical history
- Whether the patient will have other types of cancer treatment
- Other factors, such as age and other medical conditions

Physics of Diagnostic X-rays

What are x-ray

- X-rays and gamma rays are both forms of ionising radiation
- Both are forms of electromagnetic radiation, but they differ in their source of origin.
- Gamma rays are produced in the nucleus
- X-rays are produced through interactions in electron shells.





X-ray are electromagnetic radiation of exactly the same nature as light but of very much shorter wavelength.

Unit of measurement in x-ray region is A° and nm.

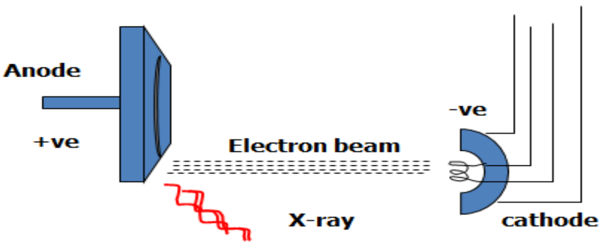
1 A° = 10^{-10} m , 1nm = 10 A° = 10^{-9} m

X-ray wavelength are in the range 0.5-2.5 A°.

Wavelength of visible light ~ 6000 A°

Formation of X-rays

To produce x-rays projectile electrons accelerated from the negative cathode to the positive anode.



When the electrons from the cathode accelerated at high voltage to the anode:

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

Peak kilovoltage (kVp) is the maximum voltage applied across an X-ray tube. It determines the kinetic energy of the electrons accelerated in the X-ray tube and the peak energy of the X-ray emission spectrum.

- **The actual voltage across the tube may fluctuate.**
- **An x-ray tube operating at 80 kVp will produce x-ray with spectrum of energies up to maximum of 80 keV (1 keV= 1.6× 10^{-9} erg =1.6× 10^{-16} J)**
- **Diagnostic X-rays typically have energies of 15 to 150 keV,**
- **While visible light photons have energies of 2 to 4 eV**

The kVp used for an x-ray study depends on :

- **Thickness of the patient**
- **Type of study being done.**

X-ray studies of the breast (mammography) are usually done at 25 to 50 keV , While some hospitals use up to 350 keV for chest x-ray

The intensity of the X-ray beam produced when the electrons strike the anode is highly dependent on

1. The anode material(the higher the atomic number (Z) of target the more efficiently x-rays are produced).
2. The target material used should also a high melting point since the heat produced when the electrons are stopped in the surface of the target is substantial.

- Nearly all x-ray tubes use tungsten target (Z=74, melting point =3400ºC)
- The electron current that strike the target is typically 100 to 500 mA, some units even have current of over 1000 mA.
- The power put into surface of the target can be quite large.

$$P=IV$$

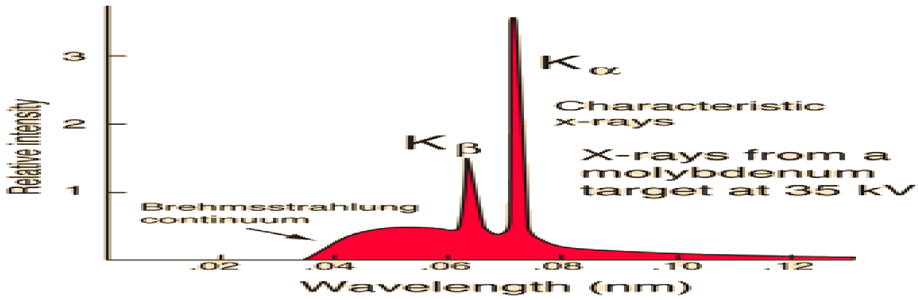
Where I is in amperes ,V in volts and P in watts.

Ex: The power at the target of an X-ray tube with a current of 1A operating at 100 kV (10^5 V) is $P=1\times10^5$ W or 100 kW

- 99% of the energy is dissipated as heat (the ratio of energy that goes into X-ray tube to the energy that goes into heat is approximately 10^{-9} ZV)
- 1% is given off as X-rays.

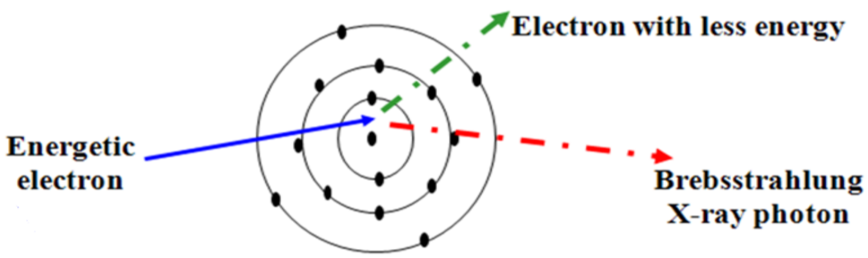
The x-ray radiation is emitted as:

- Bremsstrahlung x-ray radiation and/or
- Characteristic x-ray radiation.



Bremsstrahlung radiation

- While the energy of most of the electron striking the target is dissipated in the form of heat, the remaining few electrons produce useful x-ray.
- Many times one of these electrons gets close enough to the nucleus of a target atom to be diverted from its path and emits an x-ray photon that has some of its energy.



As the electrons pass through the target atom they slow down, with a loss in kinetic energy. This energy is emitted as x-rays.

- The process is known as *bremsstrahlung* or "braking energy".

- Approximately 80% of the population of X-rays within the X-ray beam consists of X-rays generated in this way.

The amount of bremsstrahlung produced for a given number of electron striking the anode depends upon two factors:

1. The Z of target, the more protons in the nucleus, the greater the acceleration of electrons.
2. The kilovolt peak kVp, the faster the electrons, the more likely they will penetrate into the region of the nucleus

Properties of the Continuous Spectrum (bremsstrahlung)

- Smooth, monotonic function of intensity vs wavelength.
- The intensity is zero up to a certain wavelength –short wavelength limit (λ_{SWL}).

The relationship between wavelength and frequency:

$v = c/\lambda$ c:velocity of light ($\sim 3\times 10^{8}$m/s)

Each photon has associated with it an amount of energy:

$E=h\nu$ $h= 6.63\times 10^{-34}$ Js

$K.E=eV=\frac{1}{2}mv^{2}$ e:electron charge (1.6×10^{-19} C) K.E:kinetic energy,

V: applied voltage, m: mass of the electron (9.11×10^{-31} kg), v:electron velocity (m/sec)

The electrons transfer all their energy into photon energy

$eV=h\nu_{max}$

$$\lambda_{SWL} = c/\nu_{max} = hc/eV = \frac{12.398\times 10^{3}}{V}$$

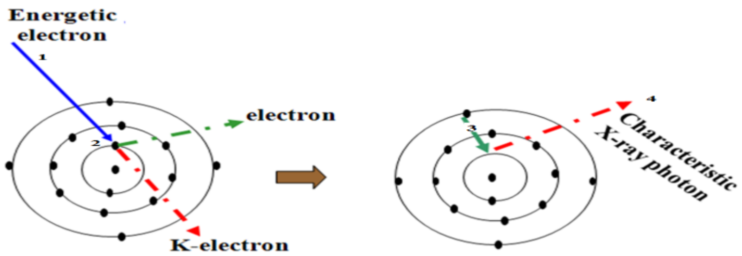
λ in A° V in volt

The total x-ray energy emitted per second depends on the atomic number Z of the target material and on the x-ray tube current. This total x-ray intensity is given by

$$I_{cont} = A\, iZV^{m}$$

A: proportionality constant, i: tube current (measure of the number of electrons per second striking the target) , m:constant ~2

Characteristic X-ray generation



- When a high-energy electron (1), collides with an inner shell electron (2) both are ejected from the tungsten atom leaving a 'hole' in the inner layer. This is filled by an outer shell electron (3) with a loss of energy emitted as an X-ray photon (4).
- When another electron fails immediately from the upper energy level such as M or L shell to fill the vacancy, it will give energy in the form of electromagnetic waves (photons) if these in the range of X –ray energy it will show as an X –ray and it is called the characteristic X –ray.
- If the electrons falls from L shell to k shell it will emit Kα characteristic X-ray
- And if it fall from M level to K it will be Kβ characteristic X-ray.

It is called characteristic because it is characteristic of the target element in the energy of the photon produced which can be seen as lines in the X- ray spectrum.

The Characteristic X-ray Used in mammography

Interactions of X-rays with matter

Interaction in the body begins at the atomic level, Atoms, Molecules, Cells, Tissues, Organ structures.

Photons entering the human body will either: penetrate, absorbed, produce scattered radiation

- **Penetrate (No interaction);** X-ray passes completely through tissue and into the image recording device.
- **Complete absorption;** X-ray energy is completely absorbed by the tissue. No imaging information results.
- **Partial absorption with scatter;** Scattering involves a partial transfer of energy to tissue, with the resulting scattered X-ray having less energy and a different trajectory. Scattered radiation tends to degrade image quality and is the primary source of radiation exposure to operator and staff.