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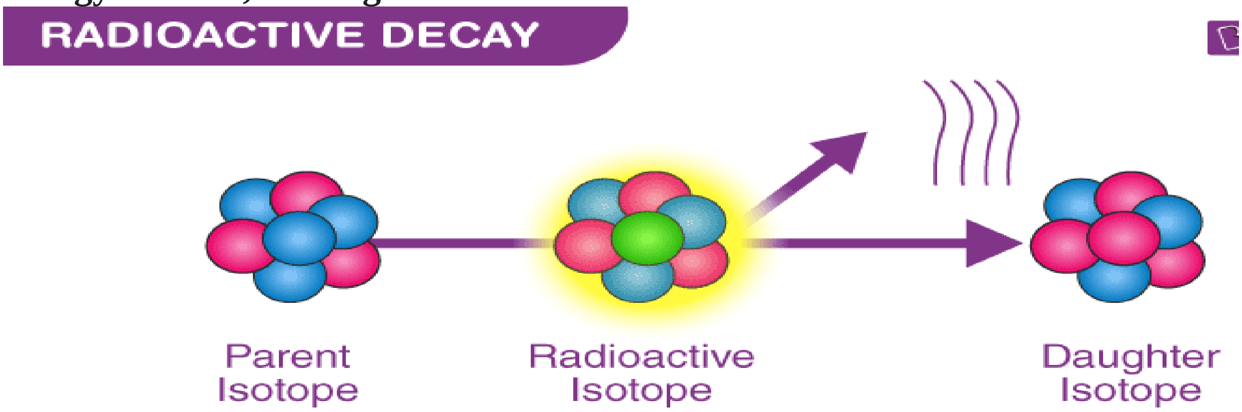
L36 - Radioactive Decay ,Half-life , Linear Energy Transfer (LET) and Relative Biological Efficiency (RBE)

Radioactive Decay : is the random process in which a nucleus loses energy by emitting radiation. This is usually in the form of alpha particles (Helium nuclei), beta particles (electrons or positrons), or gamma rays (high energy photons). The nucleus' energy reduces, making it more stable.



The equation describing radioactive decay is

$A_t = A_o . e^{-\lambda . t}$ = Activity after time t

A_0 : original activity

A_t : is the activity in disintegration per second (activity after time t)

λ : is decay constant (hours^{-1})

t : is the time since the activity was A

if λ = 0.01 hr^{-1} 0.01 (or 1%) decay per hour

$A = \lambda N$

N is the number of radioactive atoms

$N_t = N_o . e^{-\lambda . t}$ = number of atoms at time t

N_0 = original atoms

The decay constant is related to the half – life by :

$T_{1/2} = 0.693/\lambda$ (0.693 =ln 2 natural logarithm)

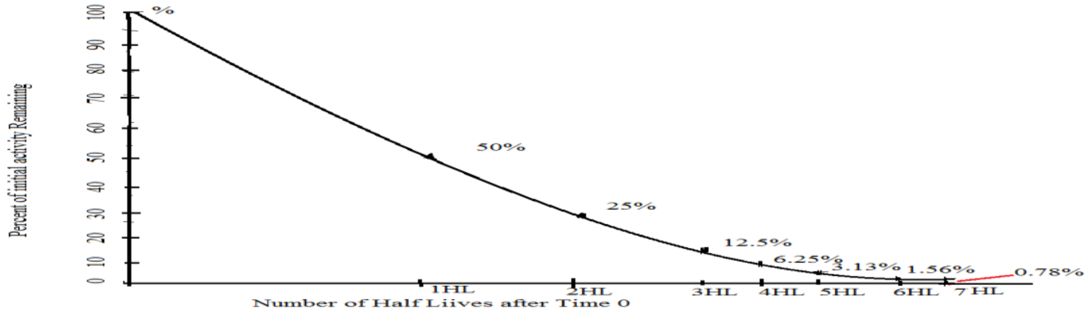
The half-life: is the amount of time it takes half of the atoms to release radiation and make the change from a very unstable configuration to a more stable configuration. For example Iodine 131. It has a half life of eight days, uranium 238 has a half life of 4.5 billion years. It is because of this that it takes so long for an area that was nuked to get rid of the radiation; a lot of the elements used in nuclear weapons have much longer half-lives.

The dose to a particular organ of body depends on :-

1. the physical characteristics of the radionuclide (what particles it emits and their energies)

2. the length of time the radionuclide is in the organ (Effective half-life $T_{1/2eff}$

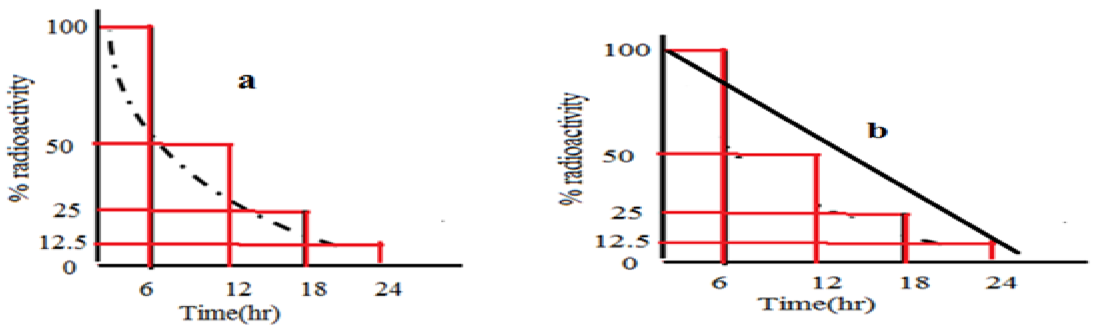
Each radionuclide decays at a fixed rate commonly indicted by the half –life ($T_{1/2}$)



$A=A_0.e^{-\lambda.t}$ $N=N_0.e^{-\lambda.t}$ $A=-\lambda.N=dN/dt$

$N=N_0(1/2)^m$ m=(no. of half-life) since t=0 $T_{1/2}=0.693/\lambda$

$$N(t)=N_0\left(\frac{1}{2}\right)^{t/T_{\frac{1}{2}}}$$



Radioactivity versus time for the common radionuclide ^{99m}Tc plotted in

(a) *a log scale .* (b) *a linear scale .*

Two factors the length of time the radionuclide is in the organ ($T_{1/2eff}$):

1- **The physical half life $T_{1/2phy}$ and**

2-**The biological half life $T_{1/2bio}$ of an element**

The biological half life $T_{1/2bio}$ is the time needed for one-half of the original atoms present in an organ to removed from the organ . and it is independent of whether the element is radioactive .

The combination of the biological and physical ($T_{1/2}$) half-lives, the *effective half-life*, $T_{½eff}$,

The Effective half-life $1/T_{1/2eff} = 1/T_{1/2phy} + 1/T_{1/2bio}$

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Is less than either half-life and is calculated by the equation:-.

$$T_{1/2_{eff}} = \frac{T_{1/2phy} \times T_{1/2bio}}{T_{1/2phy} + T_{1/2bio}}$$

Example (1):

a- If you have 1 gm of pure potassium 40 (^{40}K) that is experimentally determined to emit about 10^5 beta rays per second, what is the decay constant λ?

b- Estimate the half-life of ^{40}K from the decay constant

Solution

40 gm of ^{40}K contains 6.02×10^{23} (Avogadro's number) potassium atoms.

Therefore ,

1gm contains $(6.02 \times 10^{23} \times 1\ gm)/40\ gm = 1.5\times 10^{22}\ atoms$

$\lambda = A/N = 10^5 / 1.5\times 10^{22} = 6.7\times 10^{-18}\ sec^{-1}$

b- The half-life of ^{40}K

$T_{1/2} = \frac{0.693}{\lambda} = \frac{0.693}{6.7 \times 10^{-18}} = 10^{17}$ sec

Since there are 3.15×10^{17} sec/year,

$T_{1/2} = \frac{10^{17} sec}{3.15 \times 10^{17} sec/yr} = 0.317$ year

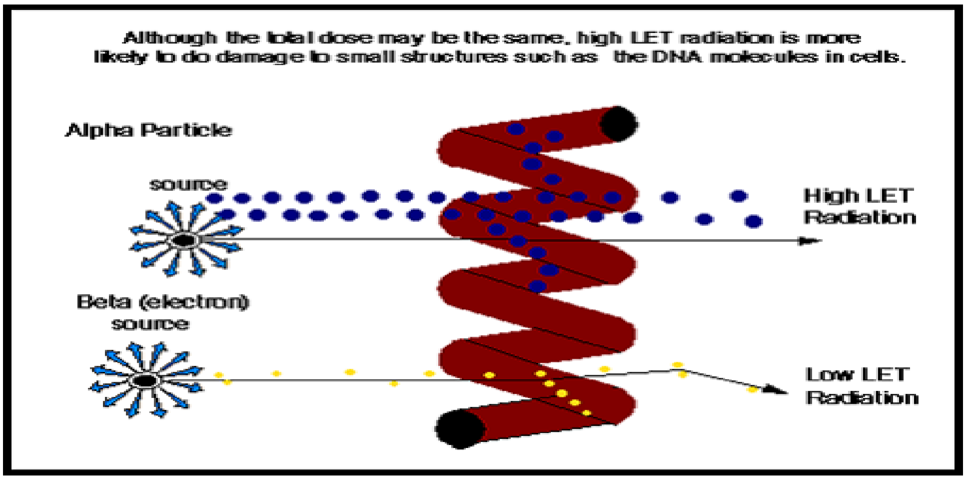
Linear Energy Transfer (LET) and Relative Biological Efficiency (RBE)

Linear energy transfer (LET)

It describes how much energy an ionizing particle transfers to the material (transverse per unit distance). Or the amount of energy a radiation deposits per unit of path length (i.e., kilo electron volts/micron - Kev/µm).It describes the action of radiation into matter.

LET is a positive quantity, depends on the nature of the radiation as well as on the material traversed.

LET increases with the square of the charge on the incident particle. When ionizing radiation interacts within cells, it deposits ionizing energy in the cell .The higher the charge of the particle and the lower the velocity, the greater likelihood to produce ionization.



Linear energy transfer (LET)

A measure of the rate at which energy is transferred from ionizing radiation to soft tissue **Mass, charge and velocity of a particle all affect the rate at which ionization occurs and is related to range.** **(Heavy, highly charged particles (e.g., α-particle) lose energy rapidly with distance and do not penetrate deeply. In general, radiation with a long range (e.g., x-/γ-rays, high energy ß- particles) usually has a low LET, While large particulate radiations with short range (e.g., α-particles, neutrons, protons) have a high LET.**

- **LET is number of ionizations which radiation causes per unit distance as it traverses the tissue**
- **Medical x-rays and gamma rays are low LET. LET of diagnostic x-rays is 3.0**
- **Alpha particles are high LET - about 100.0**
- **LET varies with type of radiation**
- **LET is potential ionization**

Relative Biologic Effectiveness, RBE

It is the ratio of biological effectiveness of one type of ionizing radiation relative to another, given the same amount of absorbed energy. The RBE is an empirical value that varies depending on the particles, energies involved, and which biological effects are deemed relevant.

The higher the RBE of radiation, the more damaging is the type of radiation, per unit of energy deposited in biological tissues.

Different types of radiation have different biological effectiveness because they transfer their energy to the tissue in different ways

In tissue, the biologic effect of a radiation depends upon the amount of energy transferred to the tissue volume or critical target (i.e., the amount of ionization) and is therefore a function of LET.

Higher LET , higher ability to produced damage

In radiation biology research, many different types and energies of radiation are used and it become difficult to compare the results of the experiments based solely on LET

a more general term, the *relative biologic effectiveness , RBE*, was developed

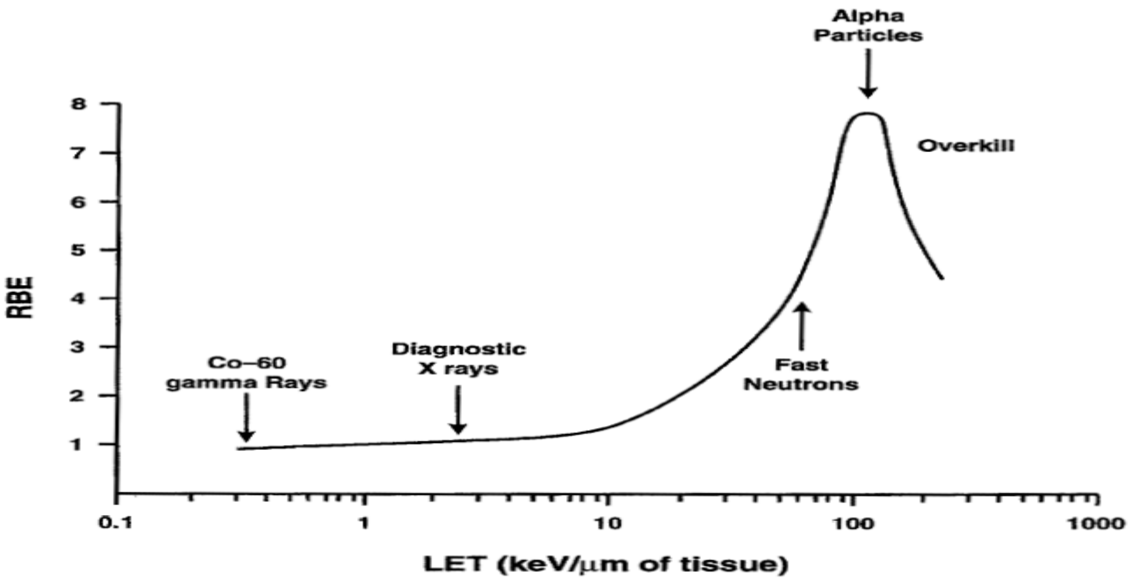
In using RBE ,it has become customary to use either 250 keV x-rays or 1.17/1.33 MeV ^{60}Co gamma rays. as the standard reference radiation . The formula definition is :

$$RBE = \frac{Dose\ of\ standard\ radiation}{Dose\ of\ test\ radiation} \quad \text{for a given effect}$$

For example ,if 10 Gy of ^{60}Co gamma rays kills 50 % of the mice in a group, and 1 Gy of heavy ion radiotherapy kills the other group, the RBE would be:

$$RBE= \frac{Dose\ of\ standard\ radiation}{Dose\ of\ test\ radiation} \quad =10/1 =10$$

RBE is initially proportional to LET and, as the LET for ionizing radiation increases, so does the RBE.



For low LET radiation, ⇒ RBE ∝ LET, for higher LET the RBE increases to a maximum, the subsequent drop is caused by the overkill effect.

Quality Factor (QF) (weighting factors)

Different types of radiation do different amounts of biological damage,

Quality factor of the radiation a factor express the effectiveness of the absorbed dose; for ease of calculation, the QF of most of the radiation are:

Gamma Rays =1, Alpha Particles =20

X-rays =1, Thermal Neutron =3

β- Particles =1, Fast Neutron =10

- **The Quality Factor is used to modify the Absorbed Dose in Gray (Gy) by multiplying to obtain a quantity called the Equivalent Dose**
  Equivalent Dose = Quality Factor(RBE)* Absorbed Dose

$$D_{equiv} = RBE \times D_{abs}$$