Kerbala University-College of Dentistry
Medical Physics-Lecture (12)

Physics of nuclear medicine and radiation therapy

1. Gamma radiation

Gamma photons are the most energetic photons in the electromagnetic spectrum. Gamma rays (gamma photons) are emitted from the nucleus of some unstable (radioactive) atoms.

What are the properties of gamma radiation?

- Gamma radiation is very high-energy ionizing radiation.
- Gamma photons have no mass and no electrical charge--they are pure electromagnetic energy.

Because of their high energy, gamma photons travel at the speed of light and can cover hundreds to thousands of meters in air before spending their energy. They can pass through many kinds of materials, including human tissue

- **What is the difference between gamma rays and x-rays?**

Gamma rays and x-rays, like visible, infrared, and ultraviolet light, are part of the electromagnetic spectrum. While gamma rays and x-rays differ in their origin. Gamma rays originate in the nucleus. X-rays originate in the electron fields surrounding the nucleus.

- How do we use gamma emitters?

The penetrating power of gamma photons has many applications. Gamma rays penetrate many materials, they do not make them radioactive. The three radionuclides by far most useful are cobalt-60 and cesium-137 and technetium-99m.

- Uses of Cesium-137:

  cancer treatment

■ Uses of Cobalt-60:
sterilize medical equipment in hospitals
treat cancer

■ Uses of Technetium-99m:
TC-99m is the most widely used radioactive isotope for diagnostic studies. (Technetium-99m is a shorter half-life version of technetium-99.) Different chemical forms are used for brain, bone, liver, spleen and kidney imaging and also for blood flow studies.

Radioisotopes

- that are naturally occurring tend to have long half-lives.
- used in nuclear medicine have short half-lives.

Half-Lives of Some Radioisotopes

	Radioisotope	Half-life
Naturally Occurring		
	^{14}C	5730 yr
	^{40}K	1.3×10^{9} yr
	^{226}Ra	1600 yr
	^{238}U	4.5×10^{9} yr
Medical Uses		
	^{51}Cr	28 days
	^{131}I	8 days
	^{59}Fe	46 days
	^{99m}Tc	6.0 hr

2. *THE EXPONENTIAL LAW OF RADIATIVE DECAY*

Radioactive emission is a random process. Any specific radioactive isotope will decay according to the exponential function

$$-\frac{dN}{dt} = \lambda N$$

or $$\frac{dN}{dt} = -\lambda N \qquad [11.1]$$

where

λ = a (positive) constant of proportionality called the **decay constant**. (Unit = s^{-1}.)

$-dN/dt$ = the rate of decay and is called the **activity** of the source. When used in equation [11.1] the activity must be expressed in the relevant SI unit – the becquerel. One **becquerel** (Bq) is equal to an activity of one disintegration per second.

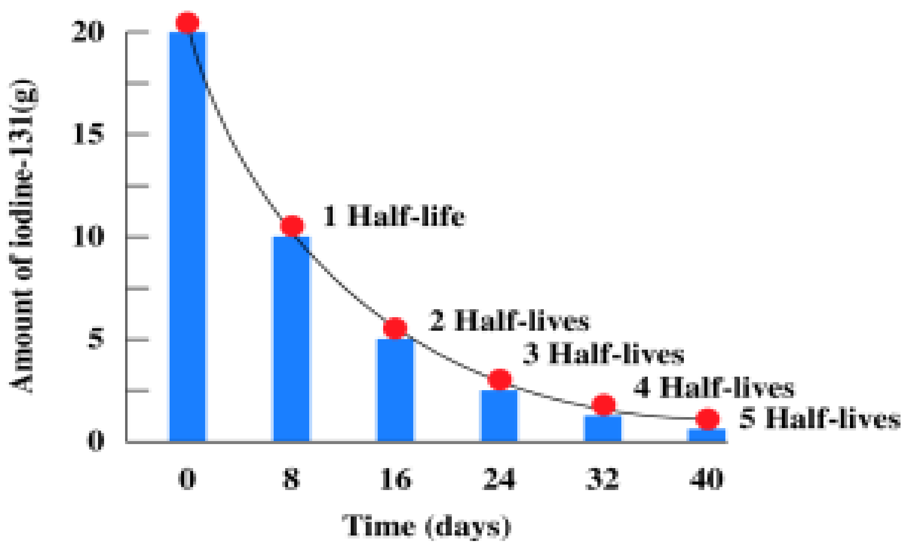
Activity used to be expressed in curies. One **curie** (Ci) is defined as (exactly) 3.7×10^{10} disintegrations per second.

Solving equation [11.1] gives

$$N = N_0 e^{-\lambda t} \qquad [11.2]$$

or $\ln (N/N_0) = -\lambda_p t$

Where N_0 is the activity (number of disintegrations per unit time) at time zero, N is the activity after an elapsed time, t, and λ is the decay constant for the isotope concerned.



1.5 HALF-LIFE ($T_{1/2}$)

If the life of a radioactive nuclide is taken to mean the time that elapses before all the nuclei present disintegrate, then it is clear from equation [11.2] (or from Fig. 11.1) that the life of any radioactive nuclide is infinite, i.e. $N = 0$ when $t = \infty$. It is not very useful, therefore, to talk about the life of a radioactive nuclide, and instead we refer to its half-life. **The half-life of a radioactive nuclide is the time taken for half the nuclei present to disintegrate.** If the half-life is represented by $T_{1/2}$, then when $t = T_{1/2}$, $N = N_0/2$, and therefore by equation [11.2]

$$\frac{N_0}{2} = N_0\, e^{-\lambda T_{1/2}}$$

i.e. $$\tfrac{1}{2} = e^{-\lambda T_{1/2}}$$

i.e. $$\log_e\left(\tfrac{1}{2}\right) = -\lambda T_{1/2}$$

i.e. $$-0.6931 = -\lambda T_{1/2}$$

$$T_{1/2} = \frac{0.693}{\lambda}$$

EXAMPLE 1.1

A sample of a radioactive material contains 10^{18} atoms. The half-life of the material is 2.000 days. Calculate:

(a) the fraction remaining after 5.000 days,

(b) the activity of the sample after 5.000 days.

Solution

(a) Since $N = N_0\, e^{-\lambda t}$, the fraction, N/N_0, remaining after time t is given by

$$\frac{N}{N_0} = e^{-\lambda t}$$

Here $t = 5.000$ days and $\lambda = 0.6931/2.000\ \text{day}^{-1}$.

$$\therefore \quad \lambda t = \frac{0.6931}{2.000} \times 5.000 = 1.7328$$

$$\therefore \quad \frac{N}{N_0} = e^{-1.7328} = 0.1768$$

i.e. Fraction remaining after 5.000 days = 0.1768

(b) $$\frac{dN}{dt} = -\lambda N$$

Here

$$N = 0.1768 \times 10^{18} \quad \text{and} \quad \lambda = \frac{0.6931}{2.000 \times 24 \times 3600}\ \text{s}^{-1}$$

$$\therefore \quad \frac{dN}{dt} = -\frac{0.6931 \times 0.1768 \times 10^{18}}{2.000 \times 24 \times 3600}$$

$$= -7.092 \times 10^{11}\ \text{s}^{-1}$$

i.e. Activity after 5.000 days = 7.092×10^{11} Bq

1.6 PHYSICAL, BIOLOGICAL AND EFFECTIVE HALF-LIFE

Most substances that are taken into the body are subsequently removed by processes such as urination and defecation. If the substance is radioactive, its activity within the body will therefore fall more quickly than it would if it were due to radioactive decay alone, i.e. the **effective half-life** of the material will be less than its **physical (radioactive) half-life**.

The amount of substance remaining in the body often decreases exponentially with time, and in such cases it is meaningful to define a quantity called the biological half-life.

The biological half-life T_B of a material is the time taken for half the material to be removed from the body by biological processes.

If λ_B and λ_R are respectively the fractions of the radioactive nuclei removed per unit time by biological processes and by radioactive decay, then the total fraction removed per unit time, λ_E, is given by

$$\lambda_E = \lambda_B + \lambda_R$$

Bearing in mind that the fraction removed per unit time is the decay constant (see section 1.4), it follows that

$$\frac{0.6931}{T_E} = \frac{0.6931}{T_B} + \frac{0.6931}{T_R}$$

$$\therefore \quad \boxed{\frac{1}{T_E} = \frac{1}{T_B} + \frac{1}{T_R}}$$

where T_E and T_R are the effective half-life and the physical (radioactive) half-life respectively.

Example : For iodine, the physical half-life is 8 days, and its biological half-life in the thyroid is 180 days. Calculate its effective half-life and effective elimination constant.

Solution :

We know, the effective half-life

$T_E = T_p \, T_b / (T_p + T_b)$

Here, T_p = 8 days, T_b = 180 days , therefore

$T_E = T_p \, T_b / (T_p + T_b)$ = 8 days x 180 days /(8 days + 180 days)

= 1440 $(\text{days})^2$ /188 days = 7.7 days

Again, we have

The effective elimination constant

$\lambda_E = \ln 2 / T_E = 0.693 / 7.7 \text{ days} = 0.09 \text{ day}^{-1}$

5. Common radioactive emission particles

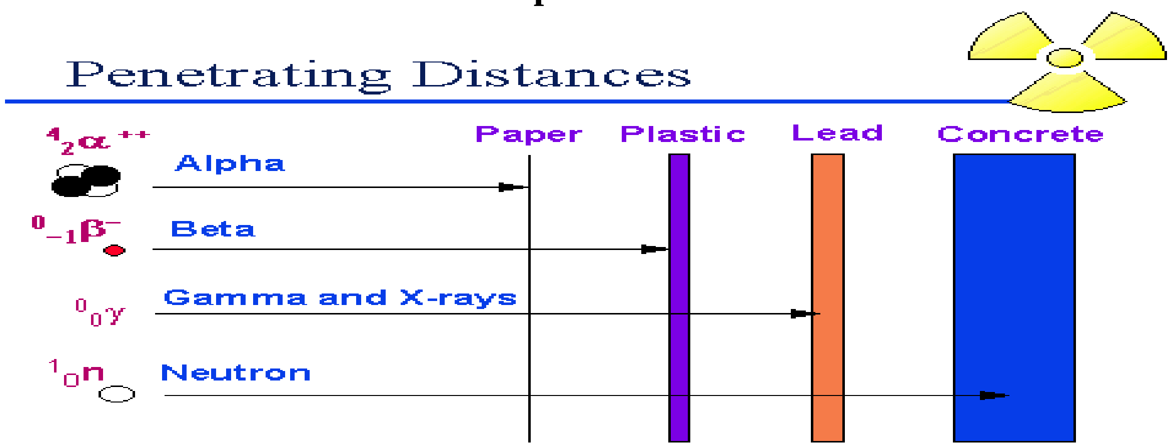


Figure 1 Effective Shielding Materials for Various Radiation Types

The diagram above shows the important qualitative difference in material penetration between charged (alpha and beta) and uncharged (gamma and neutron) particles, and also that slow-moving charged particles (alpha) lose energy much more rapidly than

fast (beta). More detailed discussion is needed to understand origin of the various radiation types and the important variation of their interaction rate with energy and with absorber element.

The cells of the body may become damaged through exposure to ionizing radiation. **The extent of the damage depends on:**

(i) **the nature of the radiation**

(ii) **the part of the body exposed** (rapidly dividing cells are the most susceptible),

(iii) **the dose received,**

(iv) **the rate at which the dose is received** (a given dose acquired over a long period allows the body time to recover and is likely to be less harmful than the same dose acquired over a shorter period).

6. Radiation Units

Units of radiation include

- **Curie**

- measures activity as the number of atoms that decay in one second.

- **rad** (radiation absorbed dose)

- measures the radiation absorbed by the tissues of the body.

- **rem** (radiation equivalent)

- measures the biological damage caused by different types of radiation.

Units of Radiation Measurement

Measurenent	Common unit	SI Unit
Activity	Curie (Ci)=3.7×10^{10} disintegration/s	Becquerel (Bq) =disintegration/s
Absorbed Dose	rad	Gray =J/kg
Biological damage	rem =rad x factor	Sievert (Sv)

7. Exposure to Radiation

Exposure to radiation occurs from

- naturally occurring radioisotopes.
- medical and dental procedures.
- air travel, radon, and smoking cigarettes.

Exposure and absorbed dose

Exposure is defined by

$$x = \frac{Q}{M}$$

where

X = exposure (unit = $C\,kg^{-1}$)

Q = the total charge on all the ions of any one sign (+ or −) produced in a mass m of air.

Absorbed Dose

Exposure applies only to X-rays and γ-rays in air. Absorbed dose is a more useful quantity because it applies to all forms of ionizing radiation in all materials.

$$D = \frac{E}{m}$$

where

D = absorbed dose. The unit is the **gray** (**Gy**). 1 Gy = 1 J kg^{-1}.

E = the energy absorbed by a mass m of irradiated material.

8. DOSE EQUIVALENT

The biological damage produced by ionizing radiation depends not only on the absorbed dose but also on the type of radiation involved. Neutrons and α-particles, for example, dissipate their energy over a much shorter distance than X-rays, γ-rays and β-particles and therefore can cause much more damage even when the absorbed dose is the same. A quantity called the dose equivalent has been introduced to take account of this.

The dose equivalent (***H***) is defined by

$$H = Q \times D$$

where

Q = a (dimensionless) quantity called the **quality factor** of the radiation (see Table 12.1)

D = the absorbed dose (Gy)

The unit of dose equivalent is the **sievert** (**Sv**). (1 Sv = 1 J kg^{-1}.) Until recently the unit was the **rem**. (1 rem = 0.01 Sv.)

Table 3 shows the values of Q for different radiation types

Type of Radiation	Q
X and γ rays	1
Electrons	1
Thermal neutrons	2.3
Fast neutrons	10
α particles	20

The value of Q for neutrons depends on the neutron energy.

Example: *In one year a worker receives a gamma dose of 2 rad, a thermal neutron dose of 0.5 rad a fast neutron dose of 0.1 rad and an alpha particle dose of 0.2 rad. What is his total dose equivalent?*

Solution :

We know,

Dose equivalent = Absorbed dose x quality factor

Therefore,

Gamma dose equivalent = 2 x1 = 2 rem

Thermal neutron dose equivalent = 0.5 x 2.3 = 1.15 rem

Fast neutron dose equivalent = 0.1 x 10 = 1.0 rem
Alpha particle dose equivalent = 0.2 x20 = 4.0 rem

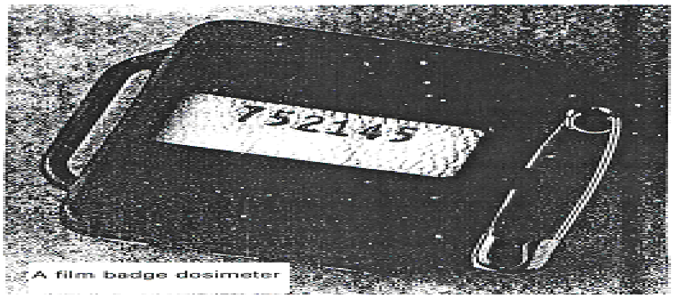
Hence, Total dose equivalent = 8.15 rem = 0.0815 Sv (since 1Sv = 100 rem)

9. *Radiation detection*

1. Film badge dosimeter

Photographic film is affected by exposure to all forms of ionizing radiation – the greater the exposure, the greater the blackening when the film is developed.

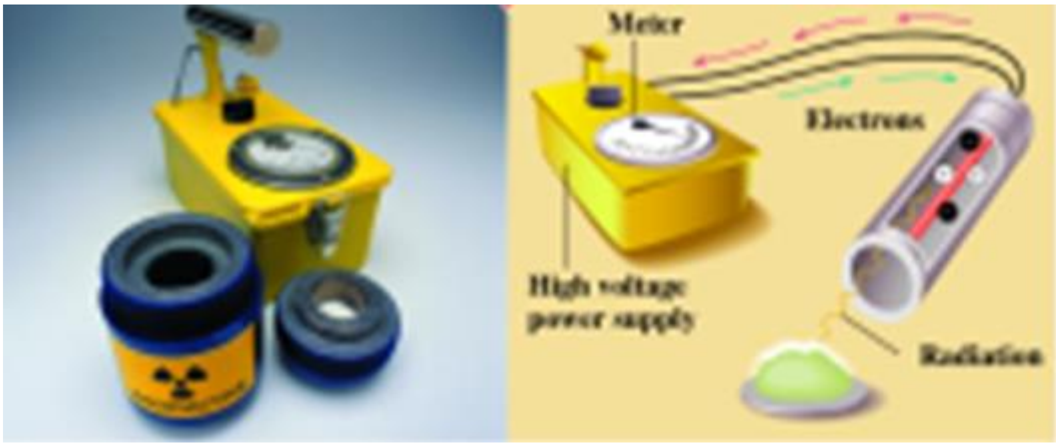
The film-badge dosimeter is commonly used to monitor personnel exposed to radiation. It consists of a piece of photographic film in a light–tight envelope inside a specially designed plastic case that can be attached to the person's clothing. The film is replaced after about a month and is then processed to determine the extent of the blackening.



A film badge dosimeter

2. **Geiger counter**

- detects beta and gamma radiation.
- uses ions produced by radiation to create an electrical current.



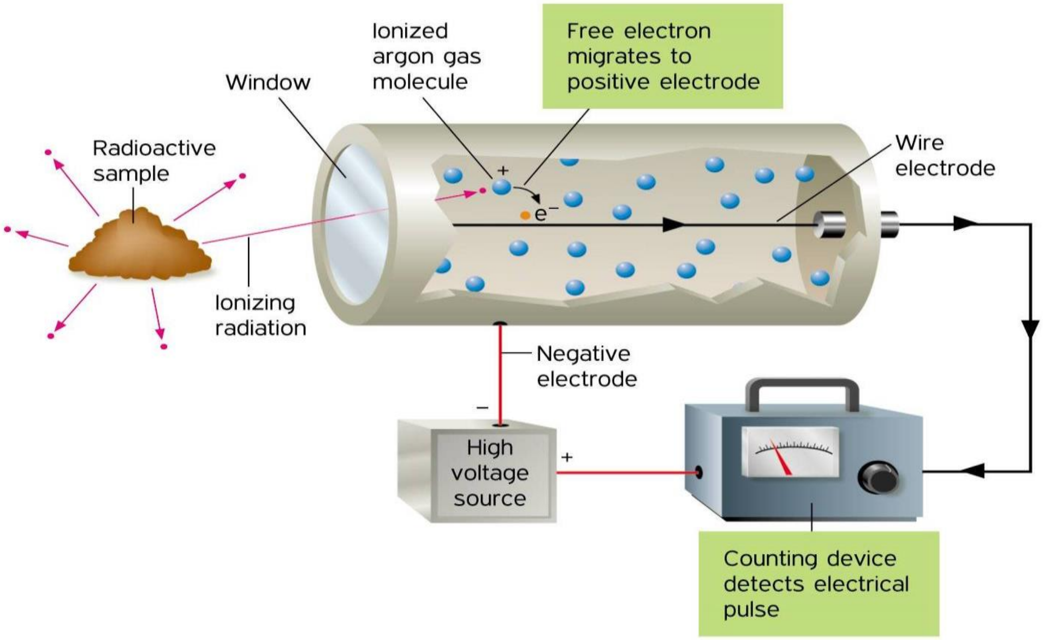
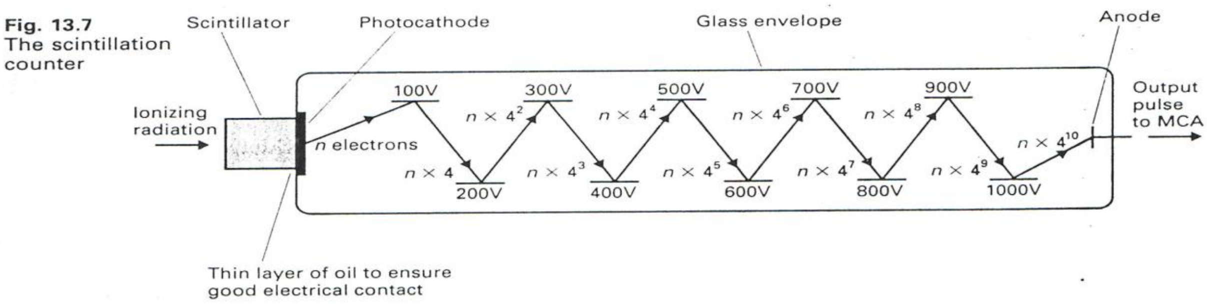


Figure 13.6 : A Geiger tube detector. The center wire operates at + voltage, attracting primary electrons released in the counter gas. For high enough voltage, a very strong field near the wire accelerates electrons to produce secondaries, resulting in an avalanche and a large voltage pulse, independent of initiating electron number.

3.Scintillators

Inorganic scintillators. The most common scintillation crystal used as a radiation detector is NaI(Tl). They are used for the detection of x-ray and gamma-ray radiation with medium resolution. Photoelectric absorption or Compton scattering in the crystal leads to scintillation light that is usually converted to an electrical pulse by a photomultiplier tube.

Organic (plastic) scintillators. These low mass detectors are used for the detection of many types of radiation with generally low energy resolution. They are often used in coincidence systems where a particle or gamma-ray loses a small part of its energy to the detector. The scintillation light is usually converted to an electrical pulse by a photomultiplier tube.



10. Medical uses of radioisotopes

The Gamma Camera

This consists of a large diameter (40 cm) crystal of sodium iodide about 1 cm in thickness with an array of up to 75 photomultiplier tubes mounted just above it. Immediately beneath the crystal is a collimator – a circular slab of lead pierced with thousands of narrow channels whose axes are at right angles to the crystal face (Fig. 4.1). This arrangement ensures that all the γ-rays that reach any particular part of the crystal have come from a point directly below that part. It follows that the amount of light produced at any particular point in the crystal corresponds to the γ-ray activity in that part of the patient which is directly below that point.

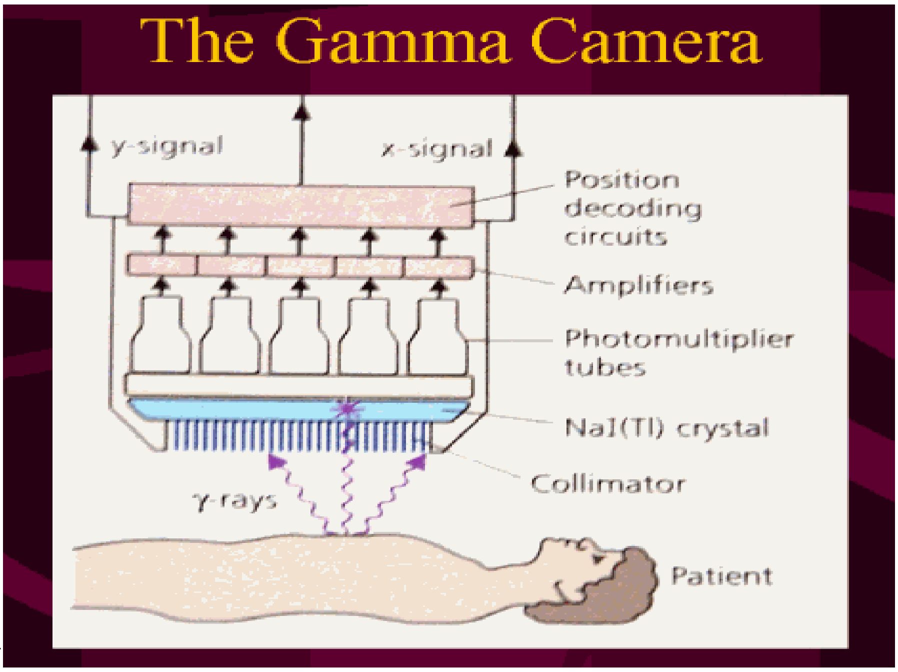
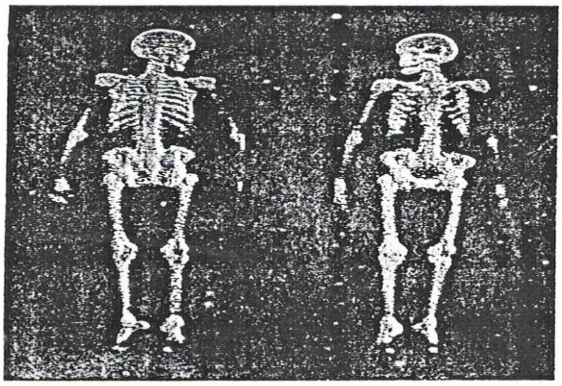


Fig.4.1 Gamma camera.

Image produced using a gamma camera



11.Treatment of Cancer

- Radioactivity is very effective in the treatment of certain cancers.
- The choice is basically do you administer the radiotherapy externally or internally.

External Beam Therapy

- External beam therapy (EBT) is a method for delivering a beam of high-energy x-rays to the location of the patient's tumor.
- The beam is generated outside the patient and is targeted at the tumor site.
- These x-rays can destroy the cancer cells and careful treatment planning allows the surrounding normal tissues to be spared.

These cancers are commonly treated.

- Breast Cancer
- Colorectal Cancer (Bowel Cancer)
- Head and Neck Cancer
- Lung Cancer
- Prostate Cancer