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X-rays and gamma rays interaction with matter

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Abstract
As far as treatment of cancer is concern, it is treated by either surgery or chemotherapy or radiation therapy or a combination of them. All this depend upon the type of cancer and its staging. It is found that at any point of treatment nearly 50 percent of the cancer patients undergo radiation therapy. Treatment of cancer by radiation is being done by costly medical linear accelerators based radiation therapy. Cost of treatment modality is varying from hundreds to thousands of million rupees. An advanced radio-surgery machine is even more costly. There are different kinds of techniques by which cancer is being treated by radiation therapy *viz.* conventional radiation therapy, three dimensional radiation therapy, three dimensional conformal radiotherapy, IMRT etc. Among all of these techniques, IMRT is still considered as gold standard in radiotherapy. With this technique, a very high dose can be delivered to tumor and at the same time normal tissues and OAR can be spared.

Keywords: X Rays interaction, Gamma Rays interaction, radiotherapy, radiation therapy

Introduction
The x-rays were discovered by Wilhelm Conrad Rontgen accidently while doing an experiment on 8th November 1895 [1]. Similar discovery was done by Henri Beccquerel [2], who observed the darkening of photographic plates with unknown rays from uranium salt and latter it was called spontaneous radioactivity. The news of these discoveries spread so quickly that it was observed and used by several physicians to see the effect of these radiations on malignant cancer cells. It was start of new era to use x-rays and gamma rays to treat cancer patients [3].
In 1896, first cancer patient suffering from breast cancer was treated by x- rays [4]. Later a very good response to the superficial tumor created the interest of the researchers towards x-rays to treat cancer patients. Because of its importance in medical science, x-ray equipments underwent tremendous technological advancement. This advancement happened in both diagnostics and therapeutic use of x-rays. Before 1940, superficial and orthovoltage therapeutic machine of x-rays were used [5]. Most of radiation therapy x-rays were generated at operating potential up to 300 $kV_{p.}$ The production of x-rays by hitting target with high speed electron beam accelerating in circular orbit was developed by Kerst in 1941 [6, 7]. The machine used of accelerating electrons called betatron was very large in size. It was used first time around 1950 for radiotherapy. Later it was replaced by a compact electron accelerator named linear accelerator (Linac) in late 1950s [8]. Therefore development of high energy megavoltage x-rays and cobalt-60 radiation therapy machines and their popularity gradually demise the use of kilovoltage x-rays in treatment of cancer.

Interaction of photon beam with matter
Generally x-rays and gamma rays are used in radiotherapy for treatment of cancer patients. One of the properties of these rays is its interaction with matter. The interaction in matter involve either the orbital electrons or with the nucleus of atom. Typical range of energies used in radio-diagnosis and radiotherapy is 0.01 MeV to 20 MeV [9]. There is no probability of interaction with nucleus at this energy range.
Therefore the interaction will occur either with loosely bound or free electrons or tightly bound electrons of an atom. The photon loses its energy in the interaction process resulting in photon absorption or photon scattering. In photon absorption, the energy of incident photon gets transferred to the charged particles such as electrons or positrons.

While in photon scattering either there will be an elastic scattering with no loss of energy of photon or inelastic scattering will occur to lose some part of energy get transferred to electron. The charged particle produced as a result of photon interaction with matter tends to deposit their kinetic energy to medium in the form of radiative losses or ionization losses.

Attenuation Coefficients

As the x-rays or gamma rays passes through the phantom or patient body then it is either completely absorbed or partially transmitted or scattered away from the detector. Also spectral properties of transmitted rays get changed. Narrow mono- energetic x-rays or gamma rays attenuation can be described by the exponential function as follows:

$$I(t) = I_0 e^{-\mu t} \quad (1.1)$$

Where I(t) is the intensity of photon transmitted through a thickness of attenuator t and I_0 is the intensity incident on the attenuator. μ is known as linear attenuation coefficient. It is the measure of probability per unit length in the path of absorber material. It depends on the energy (hv) of the photon and atomic mass (Z). Dividing μ by density ρ gives mass attenuation coefficient μ/ρ which is independent of density of attenuator [10].

Table 1: Different attenuation coefficients along with their relation to linear attenuation coefficients (μ); Here $n = \rho N_A/A$; N_A= Avogadro's number; A= Atomic mass of absorber; Z= Atomic number of absorber.

Attenuation Coefficient	Symbol	Relation with μ	Units
Mass attenuation coefficient	μ_m	μ/ρ	m2kg-1
Atomic attenuation coefficient	$_a\mu$	μ/n	$m^2 atom^{-1}$
Electronic attenuation coefficient	$_e\mu$	μ/Zn	$m^2 electron^{-1}$

(a) Narrow Beam Geometry

In ideal narrow beam geometry not any secondary or scattered particle reaches the detector. In conventional Linac the narrow beam geometry can be achieved by increasing the distance between source and detector provided beam width should be large enough to cover the detector [10]. Originated photon beam from Linac is not monoenergetic and as it passes through the medium, due to interaction with medium, it may generate charged or uncharged secondary radiation as well as scattering primaries, either with or without loss of energy. Even in conventional Linac with MLC, IMRT plans is delivered in step and shoot mode, where every beam is divided into small beamlets capable to deliver non uniform fluence to deliver homogeneous dose in tumor. Attenuation behavior of such small narrow field in medium also could be the case of narrow beam to study.

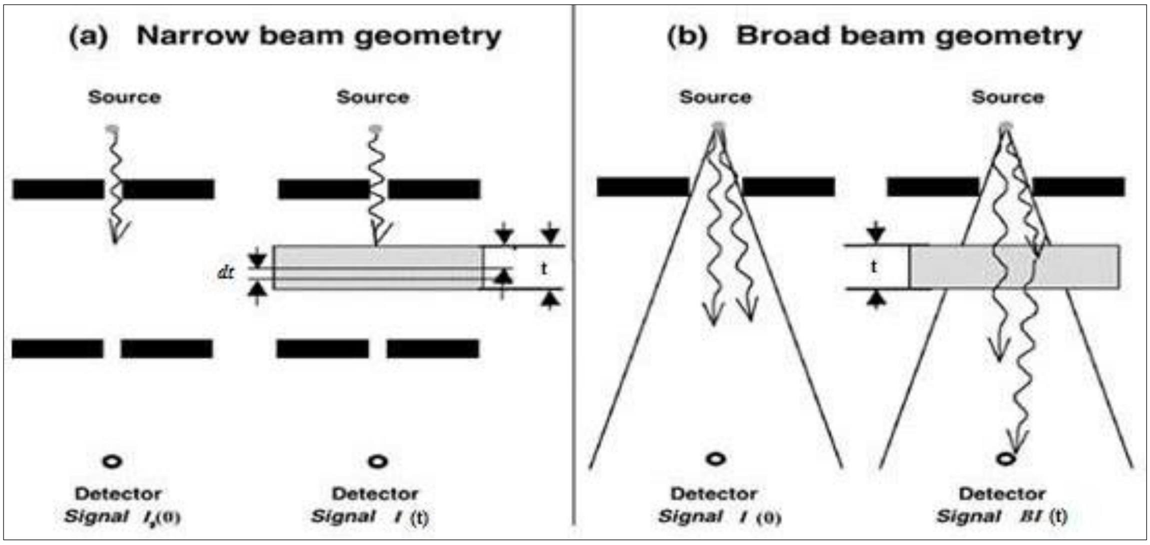

Fig 1: Sketch illustration for measurement of photon beam attenuation by detector window. (a) Narrow beam geometry and (b) Broad beam geometry [11].

(b) Broad Beam Geometry

In broad beam geometry every scattered or secondary uncharged particle strikes the detector [10]. But it is an ideal situation. Even in measurement done with detector in larger fields in conventional Linac, it is not possible to collect every scattered photon by detector however the broader radiotherapy beam may be treated as broad beam geometry.

Physical Processes of Interaction of Radiation

Attenuation of photon beam by an absorbing material is caused by five major type of inter actions *viz.* coherent scattering, photoelectric effect, Compton scattering, pair production and photo disintegration (occur at very high photon energy>10MeV) [8]. The total attenuation coefficient is the sum of individual coefficient for these processes and can be written as:

$$\mu/\rho = \sigma_{coh}/\rho + \tau/\rho + \sigma_c/\rho + \pi/\rho \quad (1.2)$$

where σ_{coh}, τ, σ_c and л are attenuation coefficients for coherent scattering effect, photoelectric effect, Compton scattering and pair production respectively. As we are dealing with energy energy greater than 0.511 MeV therefore Compton scattering is most prominent interaction in patient body or phantom [10]. The characteristics of an x-ray beam can be specified in terms of either its spectrum or its attenuation behavior in a medium [10]. The detailed description about all kind of photon interactions with matter are given below;

a) Coherent Scattering

When a very low energy incident photon while passing through a medium interacts with it, then it passes on its energy to loosely bound electron in outer most cell of an atom. This loosely bound electron is called a free electron. This electron then vibrates with the same energy as that of incident photon and hence emits a new photon of same energy as that of incident photon. Such interaction is known as coherent scattering. In coherent scattering, the incident photon does not impart any energy to the medium and hence it will not lead to any biological damage due to interaction [10].

b) Photoelectric Scattering

This interaction takes place when the energy of the incident photon is just equal to slightly more than the energy of orbital electron. The electron thus absorbs all the energy of the incident photon and gets ejected with energy equal to the difference in energy of incident photon and binding energy of the electron. Such interaction takes place at low energies; ≤ 1 MeV and is mainly responsible for radiographic imaging in radiology for radio-diagnosis. This phenomenon involve interaction with electron in the inner shell usually K or L. If 'v' is the frequency of incident photon and 'E_b' is the binding energy of the ejected electron, then kinetic energy of the ejected electron called photoelectron will be given by [12]:

$$KE = kv - E_b \tag{1.3}$$

The ejected photoelectron thereby forms a hole and the atom will remains in excited state. This hole is then filled by lower energy shell electron i.e. outer shell electron and in this process energy equal to difference in binding energy of the two shells i.e. outer and inner, gets released. The energy releases in the form of x-ray photon and is known as characteristic x-rays [12, 13].

The probability of absorption of this characteristics x-ray is always there. If it gets absorbed by outer orbital electron then that electron may get ejected from the atom. This ejected electron is called Auger electron. The sketch diagram showing photoelectric scattering is presented in Figure 2 [12-14].

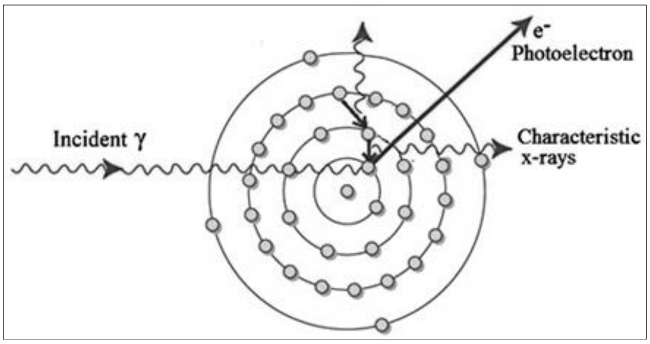

Fig 2: Diagram showing photoelectric scattering.

c) Compton Scattering

Compton scattering is found to occur when an incident photon interact with the free electron whose binding energy is much lesser than the incident photon energy. This interaction is most predominant in the energy range of 1 MeV to 10 MeV. It falls in the energy bracket of radiotherapy photon interaction. The incident photon thus impart some of its energy to the electron which is loosely bound making it free and then this photon get scatter with some angle. The sketch diagram showing Compton scattering is presented in Figure 3.

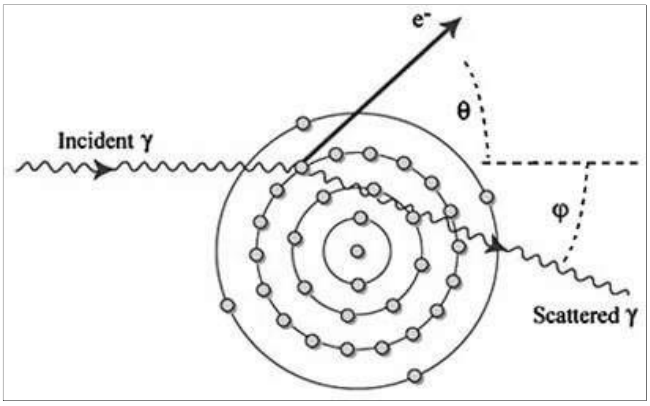

Fig 3: Diagram illustrating the Compton scattering.

Let electron is ejected at the angle θ and the scattered photon with residual energy get scattered at angle φ with respect to direction of motion of incident electron as shown in Figure 1.3. Then according to the law of conservation of energy, total energy before collision would be equal to the total energy after collision. It can be expressed with following equation:

$$hv + m_o c^2 = hv' + mc^2 \tag{1.4}$$

Where, hv - Energy of incident photon,
$m_o c^2$ - Rest mass energy of electron
hv ' - Energy of scattered photon
mc^2 - Total energy of scattering electron.

Additionally, according to principal of conservation of angular momentum total momentum before scattering must be equal to total momentum after scattering. It can be expressed as following equation:

$\frac{hv}{c} + 0 = \frac{hv'}{c} \times \cos\varphi + mv \times \cos\theta$ (in the direction of motion) (1.5)

$0 = \frac{hv'}{c} \times \sin\varphi - mv \times \sin\theta$ (perpendicular to direction of motion) (1.6)

From equations (1.4), (1.5) and (1.6), we will get

$$v = v/(1 + \frac{2\alpha\, \mathrm{Sin}^2\varphi}{2}) \tag{1.7}$$

$$\text{and } \tan\theta = \frac{1}{(1+\alpha)\tan\varphi/2} \tag{1.8}$$

Where, $\alpha = hv / m\_o\, c^2$

Equation 1.7 shows that frequency of scattered photon is lesser than frequency of incident photon i.e. v ' < v

The total Compton cross-section falls in the range of high energy beam used in radiotherapy. It is clear from Equation 1.8 that angular distribution of scattered photons depends on the energy of the incident photon i.e. hv. The scattering is almost symmetric about 90° at low energy incident photons. As the energy of incident photon increases, the probability of scattered photon will be more peaked in forward direction. The recoil electrons will also peaked in forward direction with increase in energy of incident photon [10].

d) Pair Production

Probability of pair production depends on the energy of incident photon. In this phenomenon, the incident photon interact with the orbital electron surrounding the nucleus and its entire energy get absorbed in this process and resulted in emission of a positron- electron pair. For energy of incident photon greater than or equal to 1.02 MeV, there is always possibility of this phenomenon. The rest mass of electron is 0.511 MeV and therefore the probability of pair production is zero below this energy. The process follows law of conservation of energy and hence energy of the pair is equal to the energy of incident photon. The pair production energy distribution can be represented as:

Energy of Incident Photon, hv = Total enegy of e^- +Total energy of e^+

$$h = KE_{e^-} m_o c^2 + KE_{e^+} + m_o c^2 = KE_{e^-} + 2m_o C^2 + KE_{e^+} \quad (1.9)$$

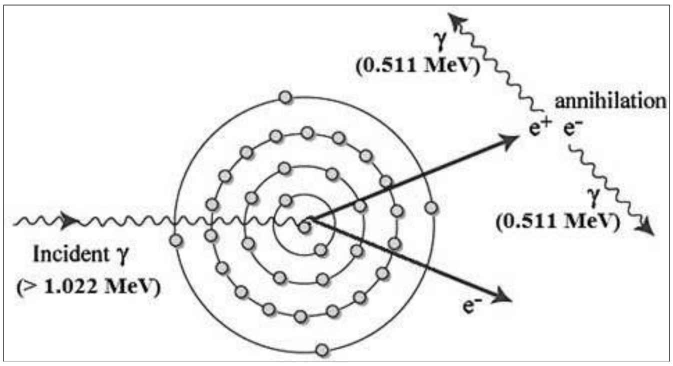

Fig 4: Diagram illustrating the pair production.

Therefore, threshold energy require for pair production to happen is 0.511 MeV × 2 = 1.02 MeV. The excess of energy of incident photon will be shared by the pair to attain kinetic energy. The electron of pair production electron interact with the matter and loses all of it energy to get absorbed while the positron of pair production interact with matter to combine with a free electron and in this process two photons each of energy 0.511 MeV produced and they tend to travel in opposite direction as shown in Figure 1.4. These photons are called annihilation photons. The probability of pair production is directly proportional to the atomic number and log of energy of incident photon [10].

Conclusion

All these process has an important role in radio-diagnosis and radiation therapy. The low energy x-rays play a crucial role in diagnostics with Compton scattering is major interaction mechanism happened in computed tomography. The high energy x-rays, electron beam and gamma radiation are integral part of radiation therapy.

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