# X-RAYS: INTERACTION WITH MATTER

ANIL SETHI
Department of Radiation
Oncology Loyola University
Medical Center
Maywood, Illinois

## INTRODUCTION

X-ray interaction with matter forms the backbone of medical physics. The basic interaction and its applications can be found in many subfields of medical physics. Some of the more common examples are applications in diagnosis and treatment of cancer, shielding design of accelerators, radiation detectors, biological response to radiation, and radiation protection. A thorough understanding of the interaction process is therefore mandatory to appreciate many exciting phenomena encountered in medical physics. Although the title of this article refers to X-ray interaction with a medium, the physics of the process applies equally well to gamma ($\gamma$) rays. Furthermore, in this article, all electromagnetic radiation is referred to as photons regardless of whether their origin is atomic (X rays) or nuclear ($\gamma$ rays). How a given photon will interact with matter depends on the energy of the photon and not on its birthplace.

When a beam of X rays passes through the medium, it undergoes attenuation or loss of intensity. In other words, some photons are removed from the beam. This attenuation may be due to either absorption or scattering of photons by the medium. In absorption, the energy of the photon is completely transferred to the atoms, whereas in scattering, the X-ray beam undergoes a change in direction that may be accompanied by a change in its energy. In both absorption and scattering, the net result is the transfer of energy to the medium. The amount of energy deposited per unit mass of the medium is called dose (measured in the SI

*Encyclopedia of Medical Devices and Instrumentation, Second Edition,* edited by John G. Webster

unit, gray, 1 Gy = 100 cGy), which is an important quantity in radiotherapy applications. How much energy will be transferred to the medium depends on the medium composition and the energy of X rays.

X-ray energy transfer to the medium is a two-step process. First, incident photons interact with the medium and release electrons. Next, in traveling through the medium, these electrons lose their energy via excitation or ionization of atoms. Therefore, photons are labeled as "indirectly ionizing" radiation, in contrast to charged particles, such as, electrons that are "directly ionizing." It is the latter that act as a vehicle for photon energy transfer to the medium. If the electrons have sufficient energy, they may also eject secondary electrons from atoms that form their own tracks known as δ rays.

## MODES OF PHOTON INTERACTION

A photon can interact with the medium in any one of several competing but independent processes. The main modes of interaction are as follows:

1. Coherent (or Rayleigh) scattering
2. Photoelectric effect
3. Compton scattering
4. Pair production or triplet production
5. Photodisintegration

Each of the above processes is characterized by the photon interacting with a different subatomic particle in the medium. For example, the photon interaction may be with the entire atom (as in photoelectric effect, coherent scattering), atomic electrons (Compton scattering), atomic nucleus (photodisintegration), electric field of electrons (triplet production), or nuclear field (pair production). As a result, the photon may undergo elastic (coherent) scattering, inelastic (incoherent) scattering, or complete absorption. For a beam of photons emanating from a linear accelerator and having a mixture of energies (polyenergetic beam), all of these interactions may be taking place simultaneously. Which interaction process will dominate and govern the fate of most photons in the beam depends on the energy of photons and the type (atomic number, $Z$) of attenuating material.

The interaction processes listed above are in an increasing order of importance as the photon energy increases. For example, coherent scattering is the most important interaction at very low photon energies, whereas photodisintegration occurs only at very high photon energies. In the energy domain most common in medical physics (few Kiloelectronvolts to several Megaelectronvolts), the interactions of greatest interest are photoelectric effect, Compton scattering, and pair production. It is these interactions that will be the primary focus in this article.

## SOME DEFINITIONS OF INTEREST

Before describing each interaction in further detail, it is useful to define terms that are commonly used in describing a photon beam.

### Photon Fluence ($\Phi$)

The photon fluence of an X-ray beam is the number of photons crossing a unit area. If we find that $N$ photons pass through an area $A$ perpendicular to the beam, then the photon fluence through the medium is

$$\Phi = \frac{N}{A}$$

### Fluence Rate (Flux Density, $\phi$)

The rate at which photons pass through an area is called fluence rate. If $N$ photons pass through an area $A$ in time $t$, then the fluence rate is

$$\phi = \frac{N}{At}$$

### Energy Fluence ($\Psi$)

If the energy of each photon is $h\nu$ (where $\nu$ is the frequency and $h$ is Planck's constant, $h = 4.135 \times 10^{-31}$ MeV/s), then the energy fluence is

$$\Psi = \frac{EN}{A} = \frac{dE}{dA} = h\nu\frac{dN}{dA}$$

### Energy Fluence Rate ($\psi$)

Also called the intensity of the beam, and it is defined as $\psi$ (or $I$)

$$I = \frac{EN}{At} = \frac{d\Psi}{dt}$$

### Photon Attenuation

**Linear Attenuation Coefficient ($\mu$).** Suppose that a monoenergetic beam consisting of $N_0$ photons is incident on an attenuator of thickness $x$ (Fig. 1). The number of photons $N$ that will pass through the attenuator and get registered by the detector may be written as

$$N = N_0 e^{-\mu x} \tag{1}$$

where $\mu$ is known as the *linear attenuation coefficient* of the attenuator and represents the fraction of incident photons that interact in a unit thickness of the medium. Therefore, $\mu$ represents the probability that a photon will

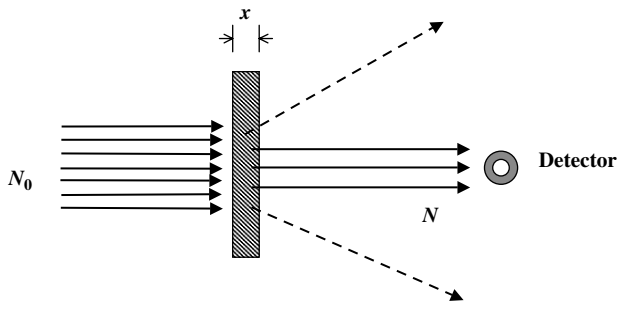


**Figure 1.** Experimental setup to determine photon beam attenuation in an absorbing medium.

interact in the absorber medium. The attenuation coefficient is a function of both the absorber material and the incident photon energy. As the incident beam is assumed to be monoenergetic, $\mu$ is a constant. Because $\mu x$ must be a dimensionless number, when $x$ is expressed in centimeters, the linear attenuation coefficient $\mu$ has units of 1/cm.

Equation 1 may also be written in terms of the beam intensity:

$$I = I_0 e^{-\mu x} \tag{2}$$

where $I_0$ is the intensity of incident photons and $I$ is the transmitted intensity. The plot of intensity ($I$) versus thickness of absorber ($x$) is an exponential curve on a linear graph or a straight line on a semilogarithmic graph (Fig. 2). The plot shows that the percentage of photons removed from the photon beam is the same with each unit increase in absorber thickness.

**Half-Value Layer.** The thickness of the absorber that will attenuate a photon beam to 50% intensity is known as the half-value layer (HVL). It can be shown from equation 2 that

$$\text{HVL} = \frac{\ln 2}{\mu} = \frac{0.693}{\mu} \tag{3}$$

HVL is a measure of the penetrability of the beam: a high-energy X-ray beam (with low $\mu$) will have a large HVL.

**Tenth Value Layer.** The tenth value layer (the thickness of the absorber required to reduce the transmitted intensity to one tenth of the original intensity) or TVL can be written as

$$\text{TVL} = \frac{\ln 10}{\mu} = \frac{2.302}{\mu} = 3.323(\text{HVL}) \tag{4}$$

The beam generated from an X-ray tube or a linear accelerator is not mono-energetic, but it is composed of a spectrum of energies. The average energy of such a beam of photons is approximately one third of the maximum photon energy. When this poly-energetic beam passes through the absorber, it is the low-energy X rays that are absorbed or filtered out first. After the low-energy photons have been removed, the filtered beam becomes more energetic or "harder." As the filter thickness increases, the average energy of the beam increases. Therefore, for an X-ray beam, the plot of beam intensity *versus* absorber thickness is not quite a straight line (Fig. 3). Instead, we see that the first HVL in the absorber is smaller than the second HVL; the second HVL is smaller than the third HVL, and so on.

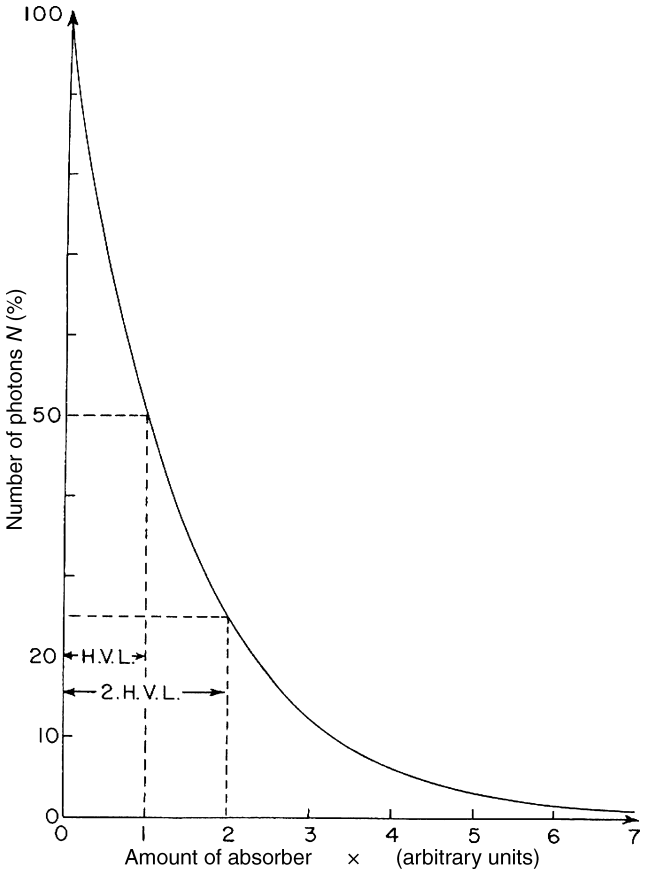


**Figure 2.** A graph of number (%) of photons transmitted through an absorber versus absorber thickness. Each HVL of absorber reduces the incident number of photons by half.

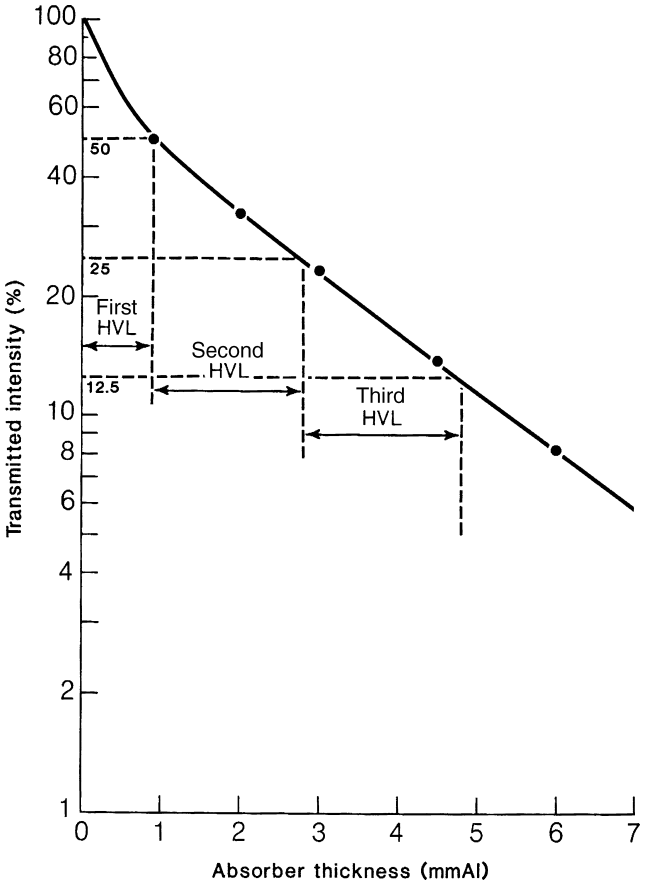


**Figure 3.** Transmitted intensity for a polyenergetic X-ray beam incident on an absorber. As the beam gets "harder" in passing through the absorber, the corresponding HVL gets larger.

**Mean Free Path.** As stated above, $\mu$ is the probability that a photon will undergo an interaction in a unit thickness of the absorber; therefore, $1/\mu$ can be thought of as the average distance a photon will travel between two successive interactions. Hence, the mean free path (MFP) is

$$\text{MFP} = \frac{1}{\mu} \tag{5}$$

It can be observed from equation 1 that approximately 37% of photons are left in the photon beam after traveling one MFP in the absorber.

**Mass Attenuation Coefficient ($\mu/\rho$).** The linear attenuation coefficient ($\mu$) varies with the density of the medium. As an example, water, water vapor, and ice have the same atomic composition, but their linear attenuation coefficients are all different due to the difference in physical density. However, if we divide the linear attenuation coefficient $\mu$ by the density $\rho$ of the medium, we get a more fundamental quantity, known as the mass attenuation coefficient (measured in squared centimeter/gram):

$$\mu_m = \mu/\rho \tag{6}$$

The absorber thickness, in this case, is $\rho x$ and has the units of gram/squared centimeter (i.e., mass of the absorber per unit area). Here the density dependence of the attenuation coefficient has been removed and $\mu_m$ is a function of the material composition only. In the aforementioned example, water, water vapor, and ice all have the same mass attenuation coefficient $\mu_m$.

The attenuation coefficient of a mixture of elements (such as water) can be calculated from the attenuation coefficients of individual elements:

$$\left(\frac{\mu}{\rho}\right) = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \tag{7}$$

where $w_i$ is the fractional weight of the $i$th element in the mixture.

As photon beam attenuation depends on the number of electrons and atoms in the path of the beam, the corresponding attenuation coefficients can be defined as follows.

**Electronic Attenuation Coefficient.** When the absorber thickness is expressed as electrons/squared centimeter, the corresponding attenuation coefficient is the electronic attenuation coefficient. If $N_e$ is the number of electrons/gram, then

$$\mu_e = \frac{\mu}{\rho}\left(\frac{1}{N_e}\right) = \frac{\mu}{\rho}\left(\frac{A}{N_A Z}\right) \tag{8}$$

where $A$ is the atomic mass number, $Z$ is the atomic number, and $N_A$ is the Avogadro's number $= 6.02 \times 10^{23}$ atoms per atomic weight in grams. The electronic attenuation coefficient, $\mu_e$ (expressed in squared centimeter/electron) represents the probability that an incident photon will have an interaction with an electron in the absorber. As $Z/A \cong 0.5$ for all materials (except hydrogen), the number of electrons/gram is a constant for all materials: $N_e = (N_A Z/A) = 3 \times 10^{23}$ (Table 1). As we will see later, the near constancy of $N_e$ across the periodic table has important implications for the Compton effect.

**Table 1. Number of Electrons Per Gram**

| Material | Density (g/cm$^3$) | Atomic Number ($Z$) | Number of Electrons/Gram |
|---|---|---|---|
| Hydrogen | 0.0000899 | 1 | $6.00 \times 10^{23}$ |
| Carbon | 2.25 | 6 | $3.01 \times 10^{23}$ |
| Oxygen | 0.001429 | 8 | $3.01 \times 10^{23}$ |
| Aluminum | 2.7 | 13 | $2.90 \times 10^{23}$ |
| Copper | 8.9 | 29 | $2.75 \times 10^{23}$ |
| Lead | 11.3 | 82 | $2.38 \times 10^{23}$ |
| | | *Effective Z* | |
| Fat | 0.916 | 5.92 | $3.48 \times 10^{23}$ |
| Muscle | 1 | 7.42 | $3.36 \times 10^{23}$ |
| Water | 1 | 7.42 | $3.34 \times 10^{23}$ |
| Air | 0.001293 | 7.64 | $3.01 \times 10^{23}$ |
| Bone | 1.85 | 13.8 | $3.00 \times 10^{23}$ |

From Johns and Cunningham, *The Physics of Radiology*.

**Atomic Attenuation Coefficient.** Similarly, the atomic attenuation coefficient may be defined as the probability that the photon will have an interaction with an atom in the absorber. The coefficient is related to linear attenuation coefficient via

$$\mu_a = \frac{\mu}{\rho}\left(\frac{Z}{N_e}\right) = \frac{\mu}{\rho}\left(\frac{A}{N_A}\right) \tag{9}$$

The atomic attenuation coefficient $\mu_a$ is expressed in squared centimeter/atom, when the absorber thickness is in the units of atoms/squared centimeter.

We now look at each interaction in more detail.

## COHERENT OR RAYLEIGH SCATTERING

Coherent scattering refers to the elastic scattering of a photon beam with atomic electrons, in which no energy transfer to medium takes place. The incident photon interacts with bound electrons as a whole (hence called coherent scattering). The electrons are temporarily set in motion (or oscillation) by the photon's electromagnetic field, and they return back to their original state by emitting a photon with the same energy as the incident photon (Fig. 4). The incident photon energy is too small to break free any electron from its shell. The scattered photon is emitted at a small angle relative to the incident photon. When a single electron from an atom participates in the process, the reaction is called Thomson scattering.

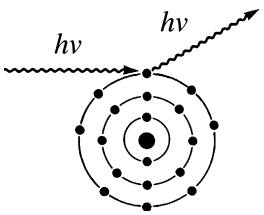


**Figure 4.** Illustration of coherent scattering: A photon with energy $hv$ scatters off an atom without transferring any energy. The scattered photon has the same energy as the incident energy.

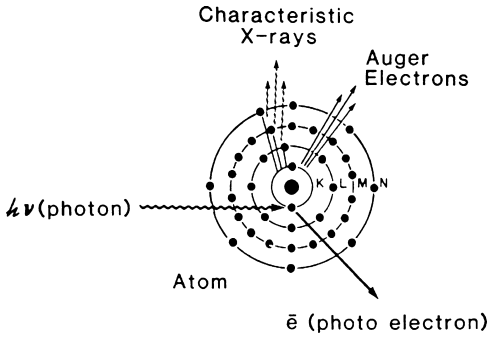


**Figure 5.** Photoelectric effect: A photon incident on an atom is absorbed with the emission of photoelectron. In the process, characteristic X rays and Auger electrons may also emitted.

The probability of coherent scattering ($\sigma_{coh}$) is highest when photon energy is very small and the medium atomic number $Z$ is very large. Likewise, the probability of coherent scattering is lowest when $Z$ of the medium is small and the photon energy is large. Consequently, coherent scattering is not very likely to occur in tissue and therefore is not of much interest in medical physics.

## PHOTOELECTRIC EFFECT

In the photoelectric effect, the incident photon interacts with an atom and ejects one of the bound electrons (from K, L, M, or N shells) (Fig. 5). The photon disappears by transferring all of its energy to the atom. Some of the photon's energy is used to overcome the binding energy of the electron, and the rest changes into the kinetic energy of the electron:

$$K.E. = h\nu - E_b \tag{10}$$

where $h\nu$ is the incident photon energy and $E_b$ is the binding energy of the electron. For the photoelectric effect to take place, the energy of the incident photon *must* be larger than the binding energy of the bound electron.

For example, suppose that the incident photon ejects an electron from the K-shell. After the photoelectron is ejected, a vacancy is created in the electron shell and the atom goes into an excited state. The vacancy left by the electron is filled by an outer shell electron (say, from an L-shell) with a lower binding energy. This leads to emission of characteristic X rays with energy $= E_K - E_L$. If the characteristic X rays have sufficient energy, they may also knock out electrons (called Auger electrons) from the surrounding shells. These Auger electrons leave behind more vacancies that in turn leads to generation of more X rays. The cycle is repeated until all of the photon energy is absorbed by the medium. In the tissue, the binding energies of electron shells are very small. Therefore, the characteristic X rays released in tissue are of very low energy and hence are locally absorbed. In the photoelectric energy range, all incident radiation on tissue is locally absorbed with no scatter radiation. In contrast, the characteristic radiation produced in high $Z$ material (e.g., lead) is more energetic and is absorbed some distance away from the site of photoelectric effect.

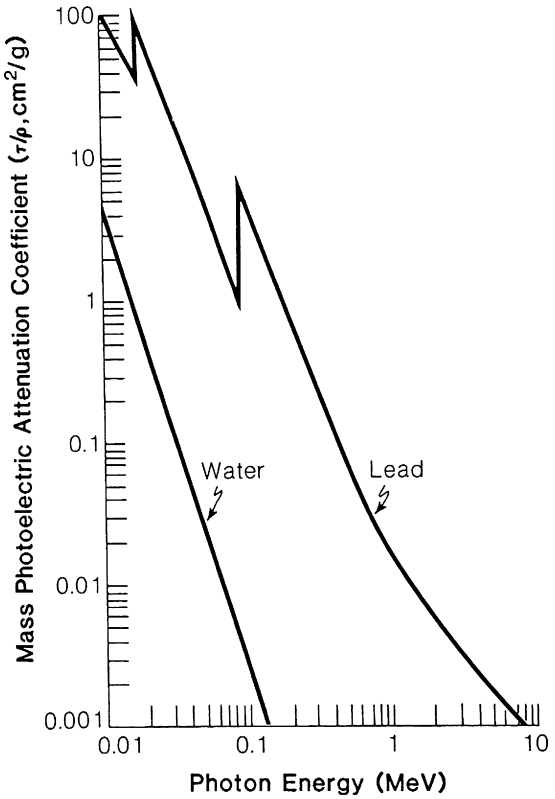


**Figure 6.** Variation of photoelectric mass attenuation coefficient with incident photon energy. Curves shown are for water ($Z = 7.82$) and lead ($Z = 82$).

The probability that a photon will undergo photoelectric effect depends strongly on its incident energy $E = h\nu$ and the atomic number $Z$ of the absorbing material. In fact, the photoelectric mass attenuation coefficient $\tau/\rho$ varies directly as the cube of atomic number and inversely as the cube of photon energy ($Z^3/E^3$). Figure 6 shows a plot of $\tau/\rho$ versus energy for water ($Z = 7.5$) and lead ($Z = 82$). Due to the $Z^3$ dependence, a photon is 1000 times more likely to undergo photoelectric interaction in lead than in a water-like medium (e.g., tissue). Also, if it has sufficient energy to knock out an electron, a low-energy photon is more likely than a high-energy photon to participate in the photoelectric effect. It can be observed from the figure that as the photon energy increases, the probability of photoelectric interaction decreases rapidly (as $1/E^3$). The curve for lead also shows sharp discontinuities for incident photon energies of 15 keV and 88 keV. These peaks correspond to the binding energies of L- and K-shells, respectively, for lead and are called absorption edges. A photon having energy less than the electron's binding energy cannot undergo a photoelectric effect with electrons in that shell. However, as soon as the photon energy exceeds the binding energy of the electron, the probability of the photoelectric effect increases dramatically (like a resonance) and a sudden jump (or discontinuity) is observed in the plot of photoelectric attenuation coefficient versus energy. The discontinuity is greatest for the K-shell and becomes weaker for higher shells (L, M, N, etc.). Therefore, it is noticed that the most tightly bound

electrons have the greatest chance of undergoing photoelectric interaction. For water, the plot of $\tau/\rho$ again shows the same steady decline with energy, although the curve is much smoother. As the K-shell binding energy for a low $Z$ medium is only about 0.5 keV, no discontinuities are observed.

The above behavior of the photoelectric effect has many important applications in medical physics:

1. Due to the $Z^3$ dependence, differential absorption of photons by bone, muscle, and fat is exaggerated and provides excellent X-ray film contrast in mammography and other diagnostic applications.
2. High $Z$ materials, such as, $BaSO_4$ and Hypaque, are ideally suited for contrast enhancement in CT scanning.
3. As lead is a good absorber of low-energy photons, it is commonly used for shielding in diagnostic radiology procedures (for example, lead aprons).

The angular dependence of emitted photoelectron is a function of the photon's energy. For a low-energy photon, the electron has small kinetic energy and is emitted at 90° relative to the direction of the incident photon. As the photon energy increases, the photoelectrons also have higher energy and are emitted in a more forward direction.

## COMPTON SCATTERING

As the incident photon energy increases (beyond 30–40 keV in tissue-like medium), the probability that it will undergo photoelectric effect decreases and the Compton effect becomes the dominant mode of interaction. This is the most important mode of interaction for tissue like materials.

In Compton scattering, the incident photon with energy $hv_0$ interacts with a loosely bound (or "free") electron from an outer shell and transfers some of its energy to it. The photon is scattered at a lower energy ($hv'$) and scattering angle $\theta$, and the recoil (or Compton) electron is ejected with an energy $E$ at an angle $\phi$ relative to the incident photon's direction (Fig. 7). From conservation of energy and momentum, the following relations can be obtained:

$$\begin{aligned} E &= hv_0 \frac{\alpha(1-\cos\theta)}{1+\alpha(1-\cos\theta)} \\ hv' &= \frac{1}{1+\alpha(1-\cos\theta)} \\ \cot\phi &= (1+\alpha)\tan\theta/2 \end{aligned} \tag{11}$$

where $\alpha = hv_0/m_0c^2$ and $m_0c^2 = 0.511$ MeV is the rest mass energy of the electron.

In terms of a photon's wavelength, after undergoing a Compton interaction, the scattered photon has a longer wavelength $\lambda'$ than that of the incident photon $\lambda$. The change in wavelength or "Compton shift" is independent of the incident photon energy and depends only on the scattering angle $\theta$:

$$\Delta\lambda = \lambda' - \lambda = h/m_0c(1-\cos\theta) = \lambda_C(1-\cos\theta) \tag{12}$$

where $\lambda_C = h/m_0c = 0.02426$ Å $= 2.426 \times 10^{-10}$ m is the Compton wavelength, or the wavelength of a photon whose energy is just equal to the rest mass energy of the electron.

The scattered photon's energy, and therefore how much energy is imparted to Compton electron, depends on the scattering angle and incident photon energy. Let us first consider the dependence of transferred energy on the photon's scattering angle $\theta$ (Fig. 8). If the photon undergoes a "head-on" collision with the electron, the photon is scattered backward ($\theta = 180$) and the electron moves forward ($\phi = 0$). In this case, the photon transfers most of its energy to the electron ($hv' = hv'_{min}$ and $E = E_{max}$). If the photon makes a "glancing" hit with the electron ($\theta = 0$), the electron receives very little energy and the scattered photon continues forward with the same energy as the incident photon ($hv' = hv$ and $E = 0$). In summary, when a photon is scattered at small angles ($\theta \to 0$), very little of its energy is transferred to the electron. However, as the photon scattering angle increases ($\theta = 0 \to 180$), a greater fraction of the incident energy is imparted to the electron.

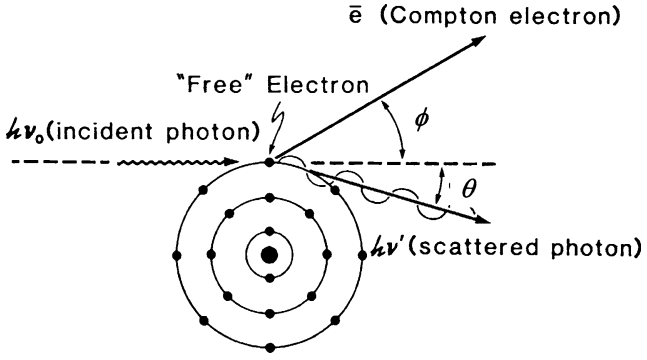


**Figure 7.** Compton effect: Incident photon scattering off a free electron.

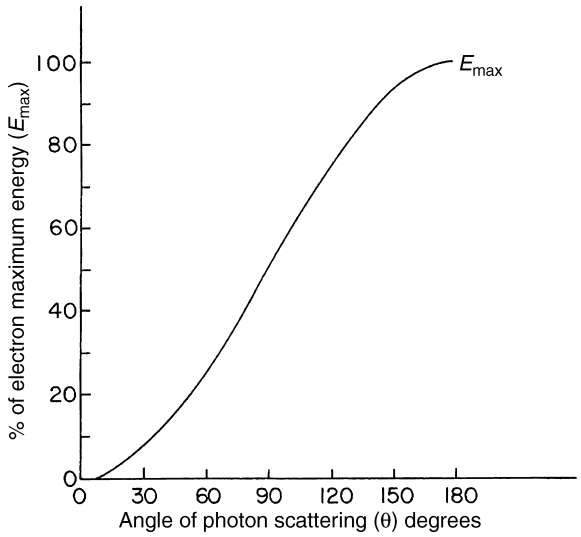


**Figure 8.** Compton scattering: Relationship between energy transferred to Compton electron and the scattering angle.

Unlike the photoelectric effect, however, the photon does not give all of its energy to the electron. The directional dependence of scattered electron and photon is governed by equation 11.

We next study the dependence of Compton effect on incident photon energy. For a low-energy photon, only a small portion of its energy is imparted to the electron. The scattered photon's energy is almost the same as the incident photon. Note that in the limiting case ($h\nu_0 \rightarrow 0$), this reduces to Rayleigh scattering where the incident photon suffers no loss of energy. As the photon energy increases, the fraction of energy transferred to the electron increases. For a very high-energy photon, the photon loses almost all of its energy to the electron and is emitted with a low energy.

It can be shown that a photon scattered at 90° can have energy of no more than 0.511 MeV regardless of the incident photon energy. If the photon is scattered backward, its maximum energy is only 0.255 MeV. These results are independent of the incident photon energy and have important consequences in the shielding design for treatment rooms in radiotherapy. For example, for side-scattered radiation (90° scatter), one needs to only shield for 0.511 MeV photons, and for backscattered radiation (180° scatter), the maximum required shielding is for 0.255 MeV photons. However, a photon scattered in the forward direction can have any energy up to that of the incident photon. As the incident photon energy increases, the recoil electron angle $\phi$ becomes smaller; i.e., the electron is more likely to be ejected in the forward direction.

As the Compton interaction involves a free electron, it is independent of the atomic number $Z$ of the medium and depends only on the number of electrons per gram, which is constant for almost all materials (Table 1). Thus, the Compton mass attenuation coefficient $\sigma/\rho$ is the same for all materials. In other words, gram for gram all materials will undergo the same Compton interaction. However, the linear attenuation coefficient $\sigma$ will be larger for denser materials: In the Compton energy range, 1 cm of bone will attenuate more than 1 cm of tissue. The inherent contrast in the Compton range is due to density difference and not due to $Z$ dependence as observed in the photoelectric effect. This fact, coupled with the presence of scattered photons, causes the mega-voltage X ray film quality to be inferior to that of kilovoltage films. In the soft tissue, the Compton effect is most important for photons with incident energy 0.1–10 MeV. As the photon energy increases, the probability of Compton interaction decreases.

## PAIR PRODUCTION

A photon with energy more than 1.02 MeV may interact with the medium through pair production. In this reaction, the photon interacts with the field of the nucleus and disappears with the creation of a positive and negative electron ($e^+/e^-$) pair (Fig. 9). This reaction is an example of energy converting into mass. As the rest mass energy for electron or positron is $m_0c^2 = 0.511$ MeV, the threshold for pair production is 1.022 MeV. The total kinetic energy of the electron–positron pair is

$$h\nu - 1.022 = E^+ + E^- \tag{13}$$

The excess energy is generally shared equally between $e^+$ and $e^-$; however, any ratio is possible. As the products have equal and opposite charge, the net charge is conserved in the reaction.

The above reaction can also take place in the presence of an electron: a process known as triplet production ($e^+/e^-$ pair and the interacting electron). The threshold energy for triplet production is 2.04 MeV. However, the likelihood of triplet production is small compared with pair production.

The electron and positron formed in the pair- (or triplet-) production lose their energy in passing through matter via ionization and excitation of atoms, until they come to rest. Near the end of its track, a positron combines with an available electron to produce two annihilation photons, each with an energy of 0.511 MeV (Fig. 9). The photons are emitted in opposite directions (180 degrees apart) to conserve momentum. This reaction is opposite to the pair production in that matter is now converted into energy.

The likelihood of pair production is very small when the photon energy is about 1–2 MeV. However, it increases rapidly with energy and becomes the dominant interaction for photons with an incident energy above 10 MeV. This behavior is in contrast to the other photon interaction processes considered so far that decrease in likelihood with increasing photon energy. The pair production interaction also increases with $Z$ of the atomic nucleus.

It varies as $Z^2$/atom or $Z$/g. This implies that high-energy X rays will be readily absorbed in high $Z$ materials, leading to "beam-softening." For this reason, lead is not recommended as a flattening filter in high-energy linear accelerators. For the same reason, HVL is not a useful concept in specifying beam quality of high-energy X rays. This can be explained by recalling that HVL is related to the attenuation coefficient as HVL = $0.693/\mu$. In the high-energy range, $\mu$ increases (or HVL decreases) as the photon

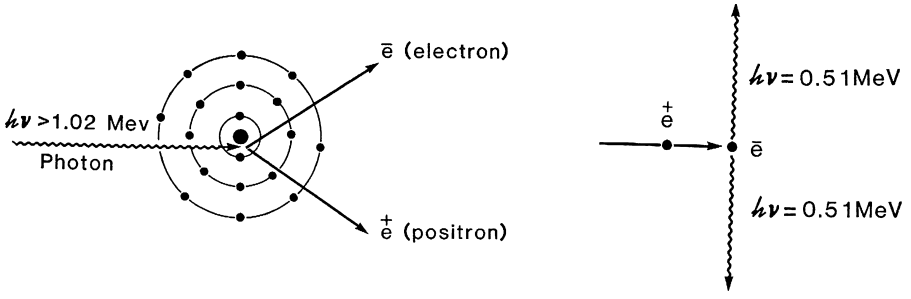


**Figure 9.** Illustration of pair production process and subsequent production of annihilation radiation.

energy increases. Therefore, HVL is not a meaningful quantity in describing a beam of high-energy photons.

## PHOTODISINTEGRATION

A photon with still higher energy may penetrate the nucleus and knock out one of its constituents: a proton, neutron, or alpha particle along with more gamma rays. The incident photon is absorbed, and the nucleus is transformed into an unstable reaction product. The latter next returns back to a stable state via radioactive decay of a nuclear particle, for example, as in $(\gamma, p)$ and $(\gamma, n)$ reactions.

The threshold for the photodisintegration reaction is essentially the binding energy of nucleons in the nucleus. For low $Z$ nuclei, this is above 10 MeV (except for Be: 2 MeV and $^2$H: 1.5 MeV). For heavy nuclei, the nuclear binding energy is about 7 MeV. Due to Coulomb repulsion, the threshold for $(\gamma, p)$ is lower than that for the $(\gamma, n)$ reaction. Beyond the threshold energy, the probability for photodisintegration increases rapidly with increasing incident photon energy, reaches a maximum value, and then drops with further increase in energy. This peak is referred to as the *nuclear giant resonance* and is due to the electric dipole absorption of the incident photon.

Compared with the other reactions described above, the probability for photodisintegration is small and hence does not contribute significantly to photon attenuation. However, the interaction has great importance in shielding considerations for radiotherapy room design.

## RELATIVE IMPORTANCE OF VARIOUS TYPES OF INTERACTIONS

Up to now we have considered how a monoenergetic beam of photons interacts with a medium having an atomic number $Z$. However, an X-ray beam from a radiotherapy machine is not monoenergetic, but it consists of a mixture of photons with various energies. Such a beam, in passing through an absorber, will undergo all of the above interactions to various degrees. The *total linear attenuation coefficient* may be written as the sum of the photoelectric, coherent, Compton, and pair production coefficients:

$$\mu_{\text{total}} = \tau + \sigma_R + \sigma_C + \kappa \tag{14}$$

Figure 10 shows a plot of $\mu_{\text{total}}$ versus photon energy along with contributions from individual component interactions.

The *total mass attenuation coefficient* may be written as

$$\frac{\mu_{\text{total}}}{\rho} = \frac{\tau}{\rho} + \frac{\sigma_R}{\rho} + \frac{\sigma_C}{\rho} + \frac{\kappa}{\rho} \tag{15}$$

The relative probability of various interactions depends on the incident photon energy and the $Z$ of the material. In general, the photoelectric interaction is most common at low photon energies; the Compton effect dominates at intermediate energies and the pair production at high energies. As explained above, as coherent scattering is significant for low-energy photons (<10 keV) incident on high $Z$ materials, it may be ignored.

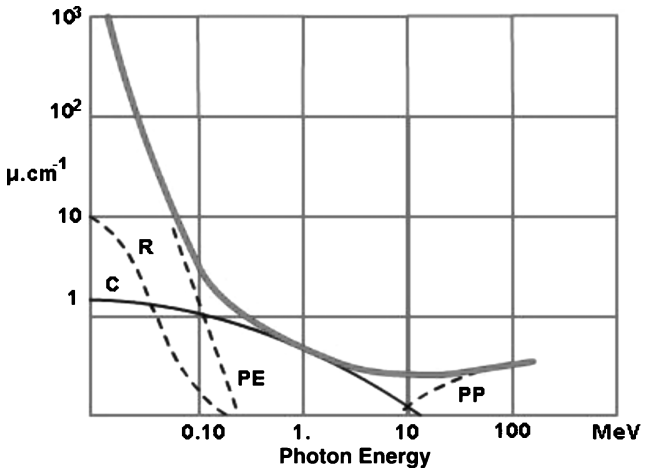


**Figure 10.** A plot of total linear attenuation coefficient that is composed of Rayleigh, photoelectric, Compton, and pair production processes.

Let us consider the plot of total mass attenuation coefficient as a function of photon energy for water and lead, which, respectively, represent a low $Z$ and high $Z$ material (Fig. 11). At low energies ($\geq$10 keV), the photoelectric effect is dominant. The attenuation coefficient displays $Z^3/E^3$ behavior in this region. Therefore, $\mu$ is much higher for lead ($10^3$ times) compared with water and decreases rapidly with increasing photon energy.

As the photon energy exceeds electron binding energy ($\sim$100 keV and higher), the Compton effect takes over. As the Compton interaction is independent of $Z$ of medium, lead and water have practically the same attenuation. As the photon energy is further increased, the attenuation coefficient decreases until the pair production becomes the dominant mode of interaction (for photon energies higher than 1 MeV).

In the pair production range, the attenuation coefficient increases with energy as log $E$. Also, the likelihood of interaction is higher in lead than in water because of the $Z$ dependence of pair production interaction. The above behavior of various modes of interactions is summarized in Table 2 for tissue-like material.

Another way to discuss the relative importance of various interactions is to look for them as regions of dominance in the plot of $h\nu$ versus $Z$ (Fig. 12). The curves display points in the $h\nu$ and $Z$ space for which the Compton effect equals the photoelectric effect and pair production. The Compton effect is most dominant between 1 and 5 MeV

**Table 2. Relative Importance of Photoelectric, Compton, and Pair Production Processes in Water**

| Energy | Photoelectric | Compton | Pair Production |
|---|---|---|---|
| 10 keV | 95 | 5 | 0 |
| 25 keV | 50 | 50 | 0 |
| 150 keV | 0 | 100 | 0 |
| 4 MeV | 0 | 95 | 5 |
| 24 MeV | 0 | 50 | 50 |
| 100 MeV | 0 | 16 | 84 |

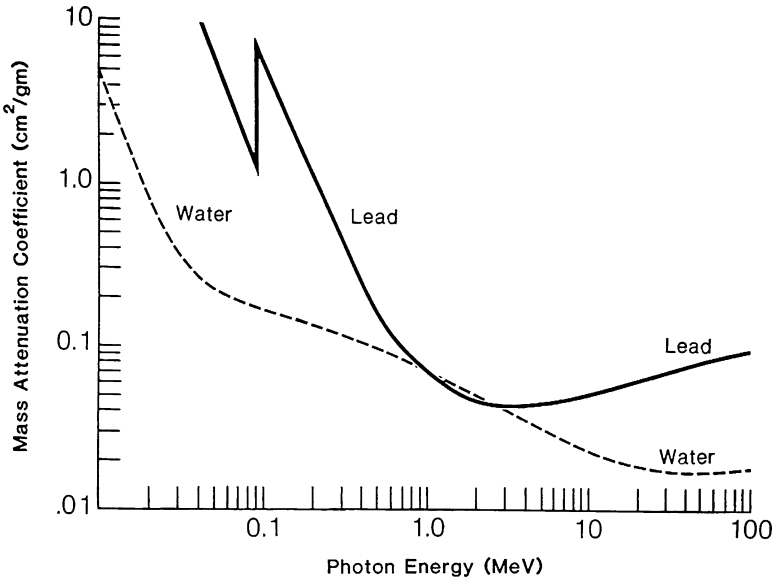


**Figure 11.** A plot of total mass attenuation coefficient as a function of incident photon energy for lead and water.

regardless of the type of material. According to this figure, for low $Z$ (tissue-like materials), the Compton effect is the main interaction over a much wider energy range. For high $Z$ materials, however, the photoelectric effect is dominant at low photon energies and pair production is the main interaction at high energies.

## ENERGY TRANSFER AND ENERGY ABSORPTION COEFFICIENTS

When a beam of photons passes through an attenuator, either part or all of its energy is transferred to the medium (Table 3). The exact fraction of energy transferred depends on the incident photon energy and $Z$ of the medium. If part of the incident energy is transferred, then the remaining photon energy is emitted as scattered photons. The scattered photons may further interact with the medium and lose some or all of their energy. Thus, a photon may undergo *multiple* interactions with electrons in the medium before it is absorbed or escapes out. Suppose $hv$ is the incident photon energy, out of which, $\bar{E}_{tr}$ is the average energy transferred to the medium. Let $E_{\text{scat}}$ be the energy of scattered photons; then

$$h_v = \bar{E}_{tr} + \bar{E}_{scat} \tag{16}$$

The fraction of photon energy transferred to electrons kinetic energy per unit absorber thickness can be written as

$$\mu_{tr} = \frac{\bar{E}_{tr}}{hv}\mu \tag{17}$$

where $\mu_{\text{tr}}$ is the linear energy transfer coefficient. The corresponding mass energy transfer coefficient is $\mu_{\text{tr}}/\rho$.

Most of the energy transferred to the electrons is deposited in the medium at the site of interaction via ionization and excitation of atoms and is referred to as the absorbed energy $E_{\text{ab}}$ (related to radiation dose delivered). However, a portion of the transferred energy is radiated away in the form of bremstrahlung radiation ($E_{\text{rad}}$):

$$\bar{E}_{tr} = \bar{E}_{ab} + \bar{E}_{rad} \tag{18}$$

Therefore, the energy absorption coefficient may be written as

$$\mu_{ab} = \frac{\bar{E}_{ab}}{hv}\mu \tag{19}$$

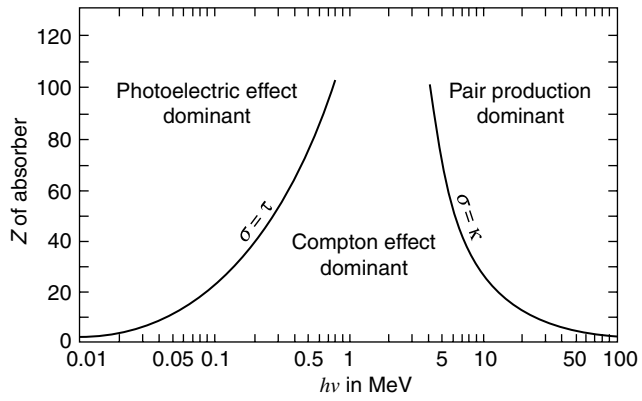


**Figure 12.** Relative importance of the three major types of X-ray interactions. The curves show the values of Z and $hv$ for which two neighboring effects are equal.

**Table 3. Depth of Maximum Dose and Percent Depth Dose at 10 cm Depth for Megavoltage Photon Beams**

| Photon Beam Energy | Depth of Maximum Dose (cm) | Percent Depth Dose at 10 cm depth (%) |
|---|---|---|
| 1.25 MV ($^{60}$Co) | 0.4 | 58.7 |
| 4 MV | 1 | 63 |
| 6 MV | 1.6 | 66.7 |
| 10 MV | 2.5 | 73.2 |
| 18 MV | 3.5 | 79.2 |
| 25 MV | 5 | 84.5 |

## X-RAY BEAM ENERGY PARAMETERS

As we have noted, the type of interaction an X-ray beam will undergo with a medium depends on its energy. This section presents some ways of defining energy of incident radiation.

The most comprehensive description of an X-ray beam is obtained via spectral energy distribution, i.e., a graph showing the relative population of different energy photons in the beam. The spectral distribution can be measured by several methods, including magnetic spectrometry, photoactivation, Cerenkov detection, and total-scintillation spectrometry, or it can be approximated by computational techniques based on bremstrahlung interaction in a target. Although useful, the exact determination of the spectra is labor intensive. In addition, the spectral distribution consists of a vast amount of information that makes it difficult to compare two X-ray beams using this information. Instead, alternative simpler methods may be used to describe the quality of the X-ray beam and its spectra.

### Beam Energy, Maximum Energy, or Peak Energy

Typical X-ray spectrum consists of photons with energy ranging from 0 to a maximum energy ($E_{max}$). X-ray energy as nominally specified by the manufacturer is generally the energy of the peak intensity. This energy is the energy of the most probable electrons incident on the patient. The peak energy, however, is not a good indication of the X-ray spectrum, as two beams with same peak energy may have different spectrum.

### Effective Energy

The X-ray beam is usually composed of photons of a mixture of energies. These will attenuate differently in matter. The effective energy of such a heterogeneous beam is defined as the energy of a monoenergetic beam that has the same HVL as the beam in question.

### Half-Value Layer

HVL is the thickness of the absorber required to attenuate the beam intensity to half its original value.

### Weighted Mean Energy

The weighted mean energy of a heterogeneous X ray beam is found from the mean mass-attenuation coefficient weighted by the energy fluence of the photons. The mean energy of the heterogeneous beam is approximately one third of the peak energy.

## FURTHER READING

Khan FM. The Physics of Radiation Therapy. 3rd ed. Philadelphia, PA: Lippincott Williams and Wilkins; 2003.

Johns HE, Cunningham JR. The Physics of Radiology. 4th ed. Springfield, IL: Thomas; 1984.

Evans RD. The Atomic Nucleus. Malabar, FL: Krueger; 1955.

Cember H. Introduction to Health Physics. 3rd ed. New York: McGraw-Hill; 1996.

Ter-Pogossian MM. The Physics Aspects of Diagnostic Radiology. New York: Harper & Row; 1967.

Hendee WR, Ritenour ER. Medical Imaging Physics. 4th ed. New York: Wiley Science; 2002.

See also RADIATION THERAPY, QUALITY ASSURANCE; SCREEN-FILM SYSTEMS; THERMOGRAPHY.