Textbook of RADIOLOGY Physics

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3

X-ray Interactions

Aditi Dongre

There are five basic ways that an X-ray photon can interact with matter:

1. Coherent scattering
2. Photoelectric effect
3. Compton scattering
4. Pair production
5. Photodisintegration.

RELATIVE IMPORTANCE OF PHOTON INTERACTION TO RADIOGRAPHY

A radiograph is produced when an X-ray beam is incident on a specific part of a patient's body. As the X-ray beam enters the tissue many photons are transmitted and interact with the film causing the film to darken. When photons are absorbed they are completely removed from the X-ray beam and cease to exist.

1. *Coherent scattering:* When a low energy X-ray photon interacts with a relatively bound orbital electron, it sets the electron into vibration. This produces an electromagnetic wave identical in energy to that of the incident photon but differing in direction. Thus in effect the entering photon has been scattered without undergoing any change in wavelength, frequency or energy but differing in direction. There are two types of coherent scattering, Thomson scattering and Rayleigh scattering. In Thomson scattering a single electron is involved in the interaction. Rayleigh scattering results from the co-operative interaction with all the electrons of an atom. In coherent scattering there is no transfer of energy and no ionization occurs.
2. *Photoelectric effect:* Simply stated, the photoelectric effect occurs when photons interact with matter with resulting ejection of electrons from the matter. It occurs when the energy of the incident photon is slightly greater than the binding energy of the electrons in one of the inner shells. Photoelectric (PE) absorption of X-rays occurs when the X-ray photon is absorbed resulting in the ejection of electrons from the inner shell (K-shell) of the atom. The atom is left with an electron void in the K-shell but only for an instant. The electron usually comes from the adjacent L-shell occasionally from the M-shell and on rare occasions from the same or another atom. This leaves the atom in an ionized state. The ionized atom then returns to the neutral state with the emission of an X-ray characteristic of the atom (Fig. 3.1). PE absorption is the dominant process for X-ray absorption up to energies of about 500 KeV (Fig. 3.2). PE absorption is also dominant for atoms of high atomic numbers. The photoelectric effect is responsible for the production of characteristic X-rays in the X-ray tube, but the process is also important as a secondary process that occurs when X-rays interact with matter. An X-ray photon transfers its energy to an orbital electron, which is then dislodged and

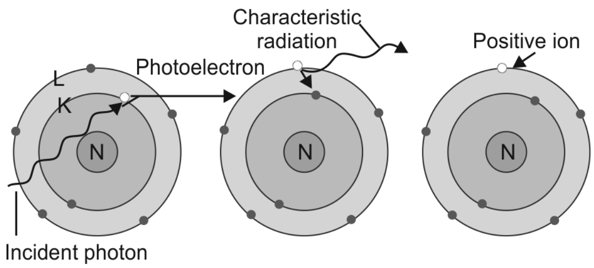

Fig. 3.1 Photoelectric effect

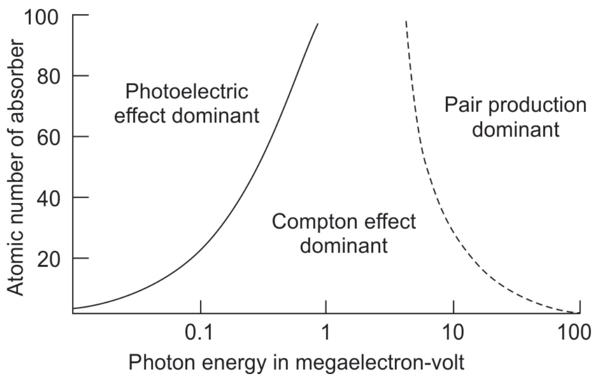

Fig. 3.2 X-ray interaction with absorber on the basis of energy of photon and atomic number of absorber

exits the atom at high speed with a kinetic energy equal to:

$$KE = E - P$$

Where, KE is the kinetic energy of the photoelectron, E is the energy of the incident X-ray photon. P is the energy required to remove the electron. This is equivalent to its binding energy in the atom.

APPLICATIONS OF PHOTOELECTRIC EFFECT IN DIAGNOSTIC RADIATION

The photoelectric effect gives two types of radiation, photoelectrons and characteristic X-rays. The photoelectric effect is very important in radiography because the chance of its occurrence varies directly with the atomic number of the irradiated tissue and indirectly with the photon energy.

Basically it produces radiographic images of excellent quality. The quality is good for two reasons: first the photoelectric effect does not produce scatter radiation and second it enhances natural tissue contrast. So from the point of view of the film quality, photoelectric effect is desirable while from the point of view of the patient exposure it is undesirable because patients receive more radiation.

The Compton Effect or Compton scattering (C), also known an incoherent scattering, occurs when the incident X-ray photon ejects an electron from an atom and an X-ray photon of lower energy is scattered from the atom. Relativistic energy and momentum are conserved in this process and the scattered X-ray photon has less energy and therefore greater wavelength than the incident photon. Compton Scattering is important for low atomic number specimens. At energies of 100 keV to 10 MeV (Fig. 3.1) the absorption of radiation is mainly due to the Compton Effect.

The Compton Effect will occur with very low atomic weight targets even at relatively low X-ray energies. The effect may be thought of as a scattering of the photons by atomic electrons. In the process, also called Compton scattering, the incident X-ray changes direction and loses energy, imparting that energy to the electron (now called a Compton electron or recoil electron). This phenomenon was discovered by renowned physicist, A. H. Compton. The emerging photon, having undergone a change in direction is called a scattered photon.

Scatter radiation: It refers to those X-ray photons that have undergone a change in direction after interacting with atoms. The primary X-ray beam leaving the X-ray tube is polyenergetic, i.e. it contains photons of various energies. As the primary beam passes through the patient some of the radiation is absorbed while the rest is scattered in many directions. In the diagnostic range the scattered radiation generated in the body consists mainly of scattered photons produced by Compton scattering, but also includes characteristic radiation resulting from photoelectric interaction. The multidirectional scattered radiation is a noise factor which seriously impairs radiographic quality by its fogging effect diffusing X-rays over the surface of the film and thereby lessening the contrast. Radiographic image contrast is less with compton reactions than with the photoelectric effect.

Factors affecting scatter radiation: Scatter radiation is maximum with high kvp techniques, large fields and thick parts. Three factors determine the quantity of scatter radiation. These are: Field size; Part thickness and Kilovoltage**.**

- *Field size* is the most important factor in the production of scatter radiation. A small X-ray field (usually called a narrow beam) irradiates only a small amount of tissues so it generates only a small amount of scattered photons. A large X-ray field is enlarged; the quantity of scatter radiation increases rapidly at first and finally tapers off and reaches a plateau.
- *Part thickness:* The number of scattered photons increases with increase in the part thickness. It is difficult to control this factor as patients are of different thickness.
- *Kilovoltage:* The effect of kilovoltage is not as important as field size and part thickness. In low energy range (20 to 30 keV) in which the photoelectric effect predominates, extremely little scatter radiation is produced. As the radiation energy increases the percentage of Compton reaction increases so does the production of scatter radiation.
- *Pair production:* It does not occur in diagnostic energy range. In this process a high energy (Fig. 3.1) photon (1.02 MeV) interacts with the nucleus of an atom, the photon disappears and its energy converted into matter in the form of two particles. One is an ordinary electron and the other is a positron, a particle with the same mass as an electron but with a positive charge.
- *Photo disintegration:* In this process part of the nucleus of an atom is ejected by a high energy photon. The ejected portion may be a neutron, a proton, an alpha particle or cluster of particles. The photon should have sufficient energy to overcome nuclear binding energies of the order of 7 to 15 MeV.

ATTENUATION

Attenuation is defined as the process of removal of photons from an X-ray beam as it passes through an absorber which results from photoelectric absorption, compton scattering, pair production or photo disintegration.

The attenuation of monochromatic radiation is exponential that is each layer of absorber attenuates the same percentage of the photons remaining in the beam. The attenuation of polychromatic radiation is not exponential. A large percentage of the low energy photons are attenuated by the first few centimeters of the absorber so the quality of the remaining photons increases as the beam passes through an absorber.

As a photon makes its way through matter, there is no way to predict precisely either how far it will travel before engaging in an interaction or the type of interaction it will engage in. In clinical applications we are generally not concerned with the fate of an individual photon but rather with the collective interaction of the large number of photons. In most instances we are interested in the overall rate at which photons interact as they make their way through a specific material.

Attenuation coefficient: An attenuation coefficient is a measure of the quantity of radiation attenuated by a given thickness of an absorber. Two are important in diagnostic radiology; linear and mass attenuation coefficient.

Let us observe what happens when a group of photons encounters a slice of material that is 1 unit thick, as illustrated in the Figure 3.3. Some of the photons interact with the material, and some pass on through. The interactions, either photoelectric or Compton, remove some of the photons from the beam in a process known as attenuation. Under specific conditions, a certain percentage of the photons will interact, or be attenuated, in a 1-unit thickness of material.

Linear attenuation coefficient (Fig. 3.3): The linear attenuation coefficient (μ) is the actual fraction of photons interacting per 1-unit thickness of material. In our example the fraction that interacts in the 1 cm thickness is 0.1, or 10%, and the value of the linear attenuation coefficient is 0.1 per cm. Linear attenuation coefficient values indicate the rate at which photons interact as they move through material and are inversely related to the average distance photons travel before interacting. The rate at which photons interact (attenuation coefficient value) is determined by the energy of the individual photons and the atomic number and density of the material.

Mass attenuation coefficient: In some situations it is more desirable to express the attenuation rate in terms of the mass of the material encountered by the photons rather than in terms of distance (Fig. 3.4). The quantity that affects attenuation rate is not the total mass of an object but rather the area mass. Area mass is the amount of material behind a 1-unit surface area, as shown below. The area mass is the product of material thickness and density:

Area Mass (g/cm^2) =
Thickness (cm) × Density (g/cm^3)

The mass attenuation coefficient is the rate of photon interactions per 1-unit (g/cm^2) area mass.

The figure compares two pieces of material with different thicknesses and densities but the same area mass. Since both attenuate the same fraction of photons, the mass attenuation coefficient is the same for the two materials. They do not have the same linear attenuation coefficient values.

The relationship between the mass and linear attenuation coefficients is

Mass Attenuation Coefficient (μ/ρ) =
Linear Attenuation Coefficient (μ)/Density (ρ).

The symbol for mass attenuation coefficient (μ/ρ) is derived from the symbols for the linear attenuation coefficient (μ) and the symbol for density (ρ). We must be careful not to be misled by the relationship stated in this manner. Confusion often arises as to the effect of material density on attenuation coefficient values. Mass attenuation coefficient values are actually normalized with respect to material density, and therefore do not change with changes in density. Material density does

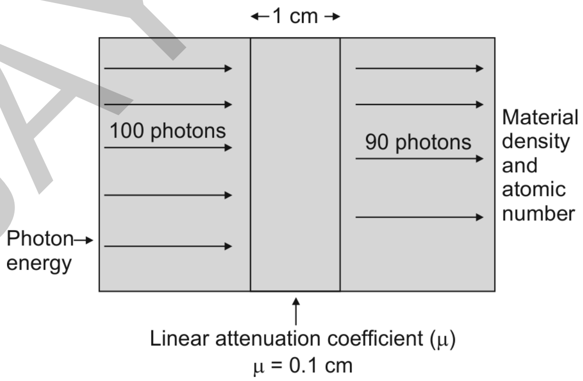

Fig. 3.3 Linear attenuation coefficient depends on material density, atomic number and photon energy

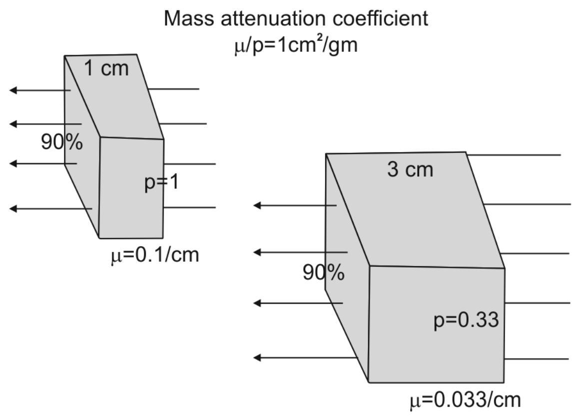

Fig. 3.4 Mass attenuation coefficient

have a direct effect on linear attenuation coefficient values.

The total attenuation rate depends on the individual rates associated with photoelectric and Compton interactions. The respective attenuation coefficients are related as follows:

$$\mu_{(total)} = \mu_{(photoelectric)} + \mu_{(Compton)}$$

Factors affecting attenuation: Factors determine the degree of attenuation of an X-ray beam as it passes through matter include the nature of the radiation and the composition of matter. Increasing the radiation energy increases the number of transmitted photons while increasing the density, atomic number or electrons per gram of the absorber decreases the number of transmitted photons.

Applications to Diagnostic Radiology

- The transmitted and attenuated photons are equally important. If all photons were transmitted the film would be uniformly black; if all photons were attenuated then film would be uniformly white. In neither case would there be an X-ray image. Image formation depends on a differential attenuation between tissues.
- The higher the linear attenuation coefficient, the greater the attenuation .Therefore X-ray attenuation is greater in bone than in water.
- At low photon energies most of the difference in X-ray attenuation between bone and soft tissues results from a difference in the number of photoelectric reaction while at high photon energies the difference in X-ray attenuation between bone and soft tissues is almost entirely the result of the difference in the number of Compton reactions.

SCATTERED RADIATION

Scatter radiations arise from interactions of the primary radiation beam with the atoms in the object being imaged. When X-ray radiation passes through a patient, three types of interactions can occur, including coherent scattering (coherent scatter), photoelectric absorption and Compton scattering. Of these three events, the great majority of scattered X-rays in diagnostic X-ray imaging arise from Compton scattering. Because the scattered radiation deviates from the straight line path between the X-ray focus and the image receptor, scattered radiation is a major source of image degradation. This scattered radiation reduces image contrast. The degree of contrast loss depends on the scatter content of the radiation emerging from the patient's body. Scattered radiation is a noise factor which seriously impairs radiographic quality by its fogging effect and lessening contrast.

Techniques to Minimize Scattered Radiation

Collimation: The amount of scattered radiation is generally proportional to the total primary X-ray beam. This is, in turn, determined by the thickness of the patient and the area or field size being exposed. Increasing the field size increases the total amount of scattered radiation and the value of the scatter contrast-reduction factors. Therefore, one method of reducing scattered radiation and increasing contrast is to reduce the field size with X-ray beam collimators, cones, or other beam-limiting devices. Contrast can be improved by reducing the field size to the smallest practical value in some situation.

Air gap: The quantity of scattered radiation in an X-ray beam reaching a receptor can be reduced by separating the patient's body and receptor surface. This separation is known as an air gap. Scattered radiation leaving a patient's body is more divergent than the primary X-ray beam. The reduction of scattered radiation in proportion to primary radiation increases with air-gap distance. Patient exposure is increased because of the inverse-square effect. The use of an air gap introduces magnification. Therefore, a larger receptor size is required to obtain the same patient area coverage. If the air gap is obtained by increasing the tube-to-receptor distance, the X-ray equipment must be operated at a higher output to obtain adequate receptor exposure.

Grid: The most effective and practical method of removing a portion of the scattered radiation is to use a grid. The grid is placed between the patient's body and the receptor. It is constructed of alternate strips of an X-ray-absorbing material, such as lead, and a relatively nonabsorbing interspace material, such as fiber, carbon, or aluminum. The grid strips are aligned with the direction of the primary X-ray beam. The focal point of the grid should coincide with the focal spot of the X-ray tube. Because the X-ray beam direction is aligned with the grid, much of the primary radiation passes through the interspaces without encountering the lead strips. Since scattered radiation is not generally lined up with the grid strips, a large portion of it is absorbed by the grid. The ideal grid would absorb all scattered radiation and allow all primary X-rays to penetrate to the receptor.

Textbook of
RADIOLOGY
Physics

Salient Features

- Presents short, snappy and length-restricted text, developed especially for students of radiology preparing for assessment or examination and are short of time
- Teaches the essential physics of diagnostic radiology and its applications in contemporary medicine
- Covers most questions asked in and during examination
- Helps radiology residents, radiologists and technical staff.

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