X-Rays and Scattering from Filters Used in Diagnostic Radiology

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Abstract- Incorporation of filters between the X-rays source and the patient in Computed Tomography helps to optimize the radiation dose and prevent unnecessary radiation; however the filters use can act as a source of secondary radiation due to angular scattering. The process of X-rays scattering, the energy transmitted and the scattered photons from such filters has is presented. This shows that the scattered photons that can contribute to unnecessary radiation are due to Compton Scattering. Only by understanding and proper collimation of the X-rays, can it be useful in diagnosis without affecting image quality or contributing to unwanted radiation to the patient and laboratory staff.

Index Terms- X-rays scattering, filters, filtration, and diagnostic radiology.

I. INTRODUCTION

X-ray radiation is of increasing interest in the diagnosis of ailment and therapy. This is because of its ability to deliver dose to a specific area under consideration while sparing most normal tissues surrounding the organ of interest. It is used in instruments like computed tomography (CT) scanner and others.

Computed Tomography is one of the most commonly used diagnostic procedures in modern medicine. It contributes a large percentage of radiation doses to the patients during medical procedure. Also, it is estimated that worldwide CT contributes 5% of the radiological examination and makes 34% contribution to the collective dose (Poonam*et al, 2011*).

A radiation attenuating material is incorporated in the path of the radiation beam to absorb preferentially the less penetrating components of the useful beam. It may consist of a permanent filter, which is an integral part of the X-ray tube housing and which cannot be removed by the user, and/or an added filter that is intended to increase the total filter thickness.

The delivery of the required dose is minimized by the use of these filters materials between the source and the patient without affecting the image quality. The filter commonly used is aluminum, but others materials of atomic number between 12 and 39 can be used e.g. magnesium, silicon and zinc.

Table 1: Minimum total filtration for X-rays tubes

Maximum rated tube potential (kVp)	Minimum total filtration (mm Al)
Less than 70	1.5
70 to and including 100	2.0
Above 100	2.5

These filter materials are meant to reduce the dose to only acceptable energy values and intensity without scattering the radiation. This is because the scattered radiation can cause unnecessary exposure to the patient and even staff in the radiation laboratory.

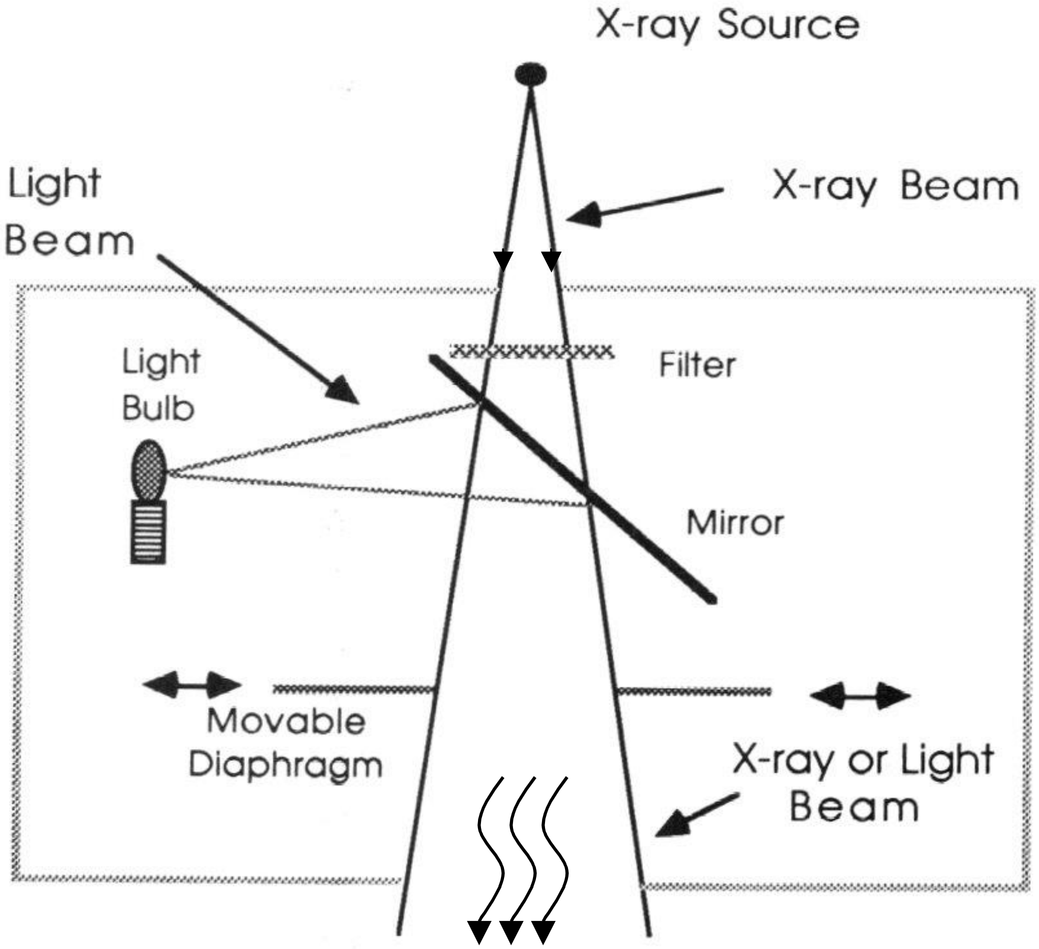

Fig. 1 A typical X-rays source showing the filter

However, the use of such filters can act as a source of secondary radiation by angular distribution (Compton Scattering).

II. THEORY OF X-RAYS

X-rays is a part of the electromagnetic spectrum. It is emitted when a solid target (atom or electron) such as copper or tungsten is bombarded with electrons whose kinetic energy is in the kilo electron-volt range. Their wavelength is of order of 1Å ($=10^{-10}$m), frequency of order 10^{18} and they travel with the speed of light ($\sim 3\times10^{8}$m/s).

A typical X-ray source has the following characteristics

i. 15 - 150 kV, rectified AC Power
ii. $\approx 2 \times 10^{3}$eV = 1.2 keV energy
iii. 50 - 400mA anode current
iv. Tungsten wire (200 µm) cathode, heated to 2200ºC
v. Anode rotating at 3000 rpm made of Molybdenum or tungsten-rhenium a
vi. Thermionic emission

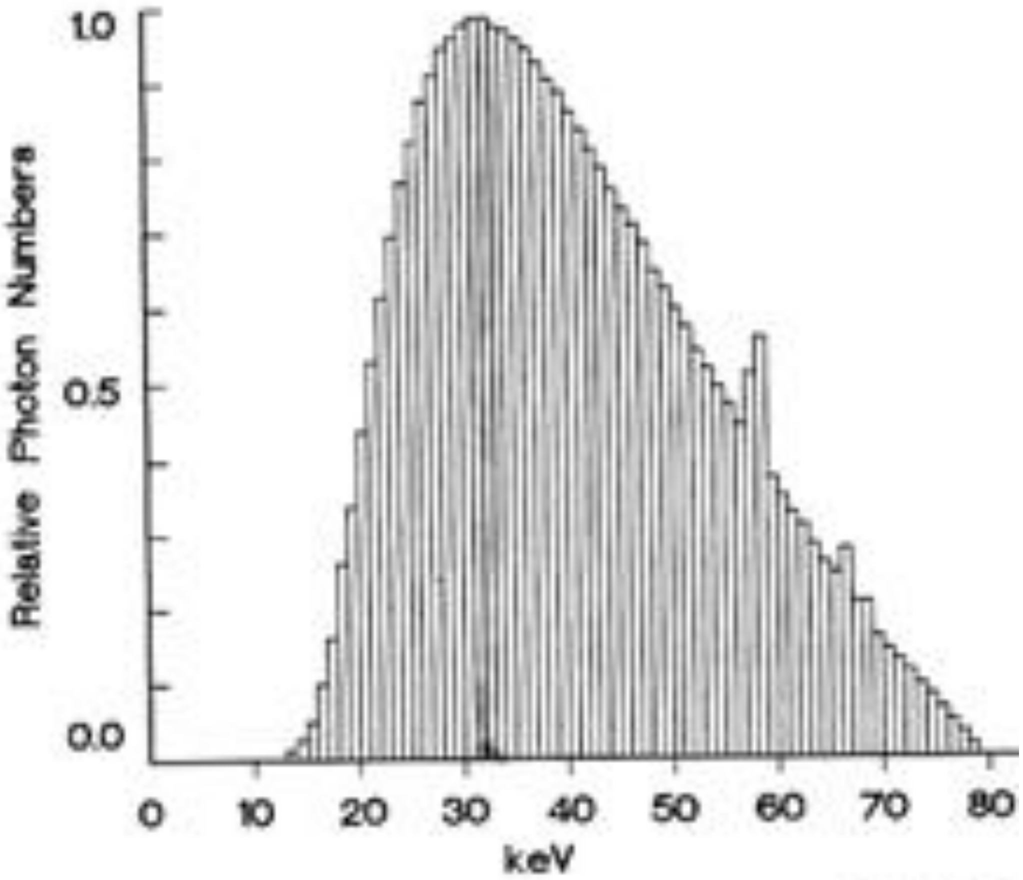

Fig. 2: The emission spectrum for X-rays for tungsten target

From the figure above, it can be seen that the overall curve is smooth shaped. The X-ray production starts at approximately15 keV and increases rapidly to 30-40% of maximum energy (peak of the curve). After the peak, there is a gradual downward slope to the x-axis (maximum energy)

X-rays propagation

Similarly to visible light, X-rays propagate linearly. The rays from a point source form a divergent beam. The number of photons passing per unit area perpendicular to the direction of motion of the photons is called the fluence, Φ. The fluence in a vacuum decreases following the inverse square law, given by

$$\Phi(r) = \frac{\Phi(1)}{r^2} \tag{1}$$

where r is the distance from the point source and Φ (1) is the fluence at r=1 (relative units). The inverse square law is illustrated in Fig 2 below.

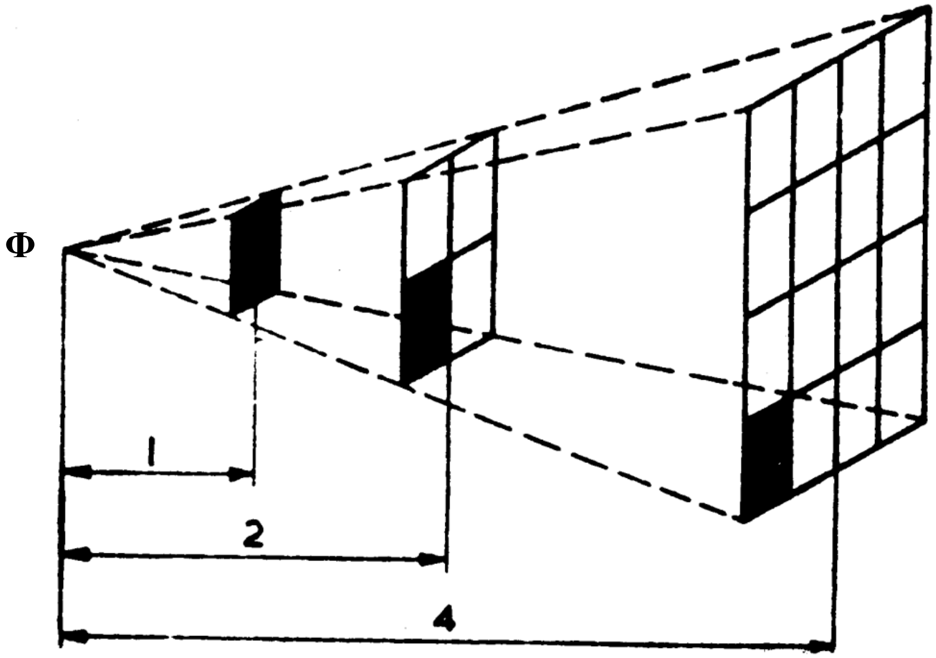

Figure 3. The fluence,Φ of X-rays decreases with the square of the distance from the source.

The Intensity of x-rays

The intensity of the X-ray beam is attenuated by absorption and scattering process as it passes through the filter and patient. The degree of attenuation depends on the energy spectrum of the X-ray, path and $\mu(x)$ i.e.the X-ray linear attenuation coefficient which varies for different materials and tissues and hence is a function of distance x through the medium.

The integral of the attenuation coefficient is given by

$$I_t = I_0 e^{-\int \mu(x)\,dx} \qquad (2)$$

The attenuation coefficient is

$$\int^{t} \mu(x)\,dx = -\frac{1}{L}\ln\left(\frac{It}{I_0}\right) \qquad (3)$$

where, I_o is incident beam intensities
I_t is transmitted beam intensities
L is the length of X-ray path
$\mu(x)$ is X-ray linear attenuation coefficient, which varies with tissue type and hence is a function of the distance (x) through the patient.

The Energy of X-rays

The production of X-rays causes electrons gain kinetic energy, which is the product of their charge and the potential difference. The unit of 1 eV is used and this is a measure of the kinetic energy of the electrons and X-ray photons. One electron volt (1 eV) is the kinetic energy of an electron that has been accelerated through a potential difference of 1 volt.

For example, If the potential difference is 100 kV, each electron gets a kinetic energy of 100 keV (i.e. 1000ev = 1 keV).

When the electron reaches the anode it imparts the main part of its energy to the atoms of the anode by ionizations and excitations. This energy will finally appear as heat energy. If an electron passes close to an atomic nucleus, it will change its direction of motion, i.e., exhibits acceleration. At each such acceleration there is a small probability that the electron looses energy in the form of a photon. These photons are called Bremsstrahlung photons and constitute the main part of the X-rays being used in X-ray diagnostic imaging.

Bremsstrahlung is generated when an electron with high energy changes its direction of motion in the neighborhood of an atomic nucleus and thereby looses energy.

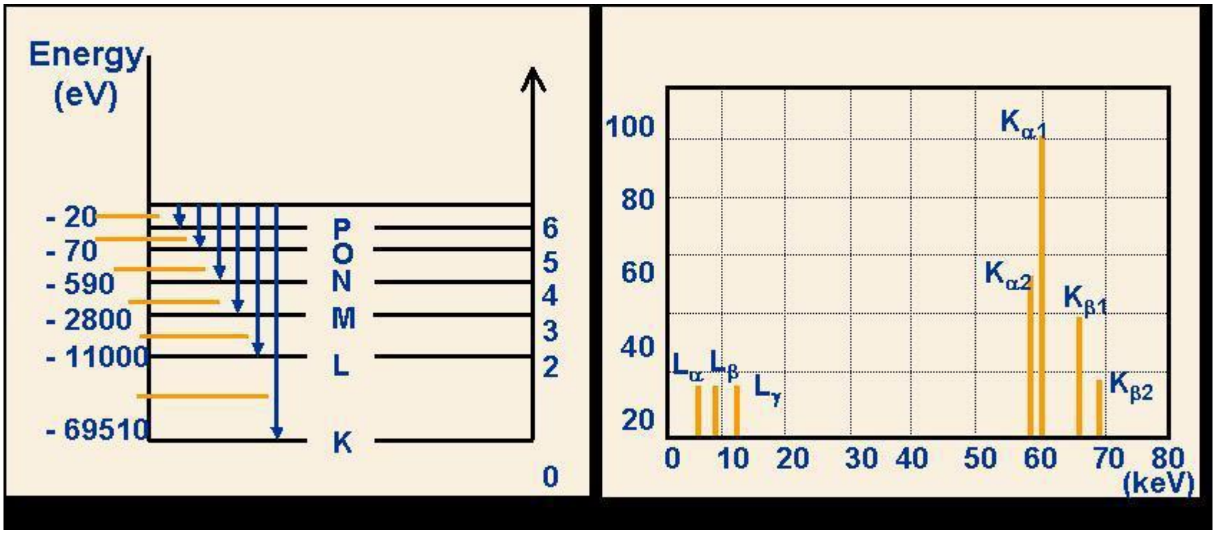

Fig. 4: Characteristic of X-rays

From figure 3 above, it shows the energy chart from The energy of X-rays and their wavelength are inversely proportional (higher energy = lower wavelength), and the continuous spectrum minimum wavelength decreases as the accelerating voltage (kV) of the X-ray source increases. It is important to understand that an increase in filament current (ma) and kV (beyond the minimum value required to produce characteristic radiation for the target) will result in an increase in the intensity of the generated X-rays, but will not change their energy.

The bremsstrahlung photon can obtain an arbitrary energy between zero and the whole of
the kinetic energy of the electron, E_T.

$$E_T = hv_{max} \qquad (4)$$

The relative amount of bremsstrahlung emitted increases with increasing electron kinetic energy and with increasing atomic number, Z, of the anode material. Since the major part of the energy of the electrons is converted into heat in the anode (about 1% will appear as X-rays), the anode material should have a high melting point and good heat conduction ability. To get a high relative amount of X-ray energy, the anode material should be of high atomic number. Tungsten is the dominating anode material and is in modern X-ray tubes often mixed with rhenium (ZW=74; ZRe=75). Modern X-ray imaging requires a small focal spot and high X-ray fluence rates (number of photons per unit area and unit time). To meet these requirements, technical solutions with a line shaped focal spot and rotating anode have been introduced.

History of X-rays

X-rays was discovery by Professor Wilhelm Conrad Roentgen as a new, invisible and unknown ray in November 1895 hence the name (X-unknown).

He continued to experiment doggedly to test its properties. He noted quickly that solid objects placed in the beam between the Crookes' tube and the fluorescent screen serving as an image receptor attenuated or blocked the beam, depending upon their density and structure.

Then, in a heart-stopping moment, he chanced to pass his hand through the beam. As he looked at the screen, the flesh of the hand seemingly melted away, projecting only the outlines of the bones. The hand was intact, unharmed. But on the screen, only the bones showed up. With that observation, the science of medical radiology was born.

The discovery of a new form of energy that could penetrate solid objects and record their structure excited Roentgen's scientific contemporaries. But it was the skeletal hand that captured the imagination of the public and of physicians, who recognized instantly that this discovery could change medical practice forever.

Roentgen's discovery was artificial ionization radiation. Two years later, a French physicist Henri Becquerel, discovered that certain rocks emitted natural ionizing radiation with characteristics much like Roentgen's X-rays. Pierre and Marie Curie refined the natural radioactive ores to derive uranium, polonium and radium. Then radium was perceived the most valuable due to its use in cancer treatment. But with the coming of World War II, uranium and polonium was considered of primary interest since they could be used to make atomic bombs. But continual experiment, results and data have been presented to prove its immense benefit of X-rays to man. Medical usage of X-ray photon is more likely to be formed by the process of transfer of an electron from higher energy to lower energy level (Cunningham *et al*). This process occurs in the X-ray tubes, to produce characteristic X-ray with different energy and intensity. The spectra widely used are those given by Fewell *et al.* This is due to its reliability and popularity among diagnostic imaging community (Ay *et al*). According to Ay *et al*, the spectra by Fewell *et al* were measured without adding filtration. Thus, giving the opportunity to continuously modify the spectrum using known attenuation properties of any particular material as additional filter.

Linton W. O reported that trials in the treatment of cancers with neutrons melted away due to the high energy and different biological characteristics than high energy X rays. Advancements in medical radiation uses came from gradual improvements in equipment and techniques. The availability of X-ray machines in hospitals can be used to diagnose more ailments such as tuberculosis, cancer and bone abnormalities or fractures. With the advances in Fluoroscopy, radiation can be fed directly unto screens, which help to view and record motion e.g. heartbeat. For most physicians diagnostic radiology made a huge leap into cross-sectional imaging with the development of computed tomography (CT). The rapid development of the computers which saw them shrank in size, grew in power, dropped in price and began to be available in research centers helped scientist understand the application of X-rays. And with the complex mathematical algorithms of computers, three-dimensional images could be drawn in seconds by reconstructing the body.

In less than a decade from the 1970s, magnetic resonance (MR) imaging burst on the scene with even more promising-and even more expensive- technology. MR image analysis technology was comparable to CT but no X rays were needed. Instead, MR units relied on strong magnets, as much as 8000 times as strong as the earth's magnetic field.

However the high cost of MR scans is factor that will see the continuous use of the CT scan and other instruments in demand. Also, the characteristic of the radiation used is necessary for radiation protection and especially if it is ionizing.

Applications of X-rays

The uses of X-rays are as diverse as the whole of the scientific world. Some major applications include

1. Medical Imaging
2. X-rays diffraction in the study of crystals and other solids

Table 2: The advantages and disadvantages of using X-rays in medical imaging is given below

Advantages		Disadvantages
1	Widely used and available	Radiation exposure
2	Experts available	Difficulty in imaging soft-tissues
3	High-spatial resolution	2D projection, hidden parts
4	Excellent imaging of hard tissues (bones)	

Energy transfer

There are two basic types of energy transfer that may occur when X-rays interact with matter:

1. Ionization, in which the incoming radiation causes the removal of an electron from an atom or molecule leaving the material with a net positive charge.
2. Excitation, in which some of the X-ray's energy is transferred to the target material leaving it in an excited (or more energetic) state.

Theoretically there are twelve processes that can occur when X-rays interact with matter,

Which process dominates is dependent on the mass absorption characteristics of the target (directly related to the atomic weight, Z) and the energy of the X-rays. The fig 4 below shows the most important of these.

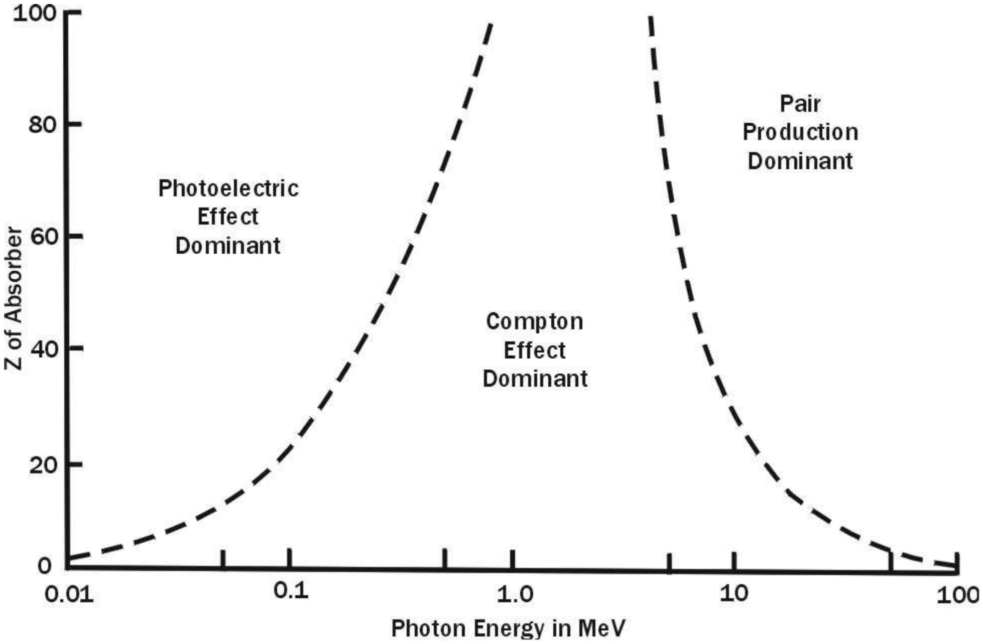

Fig 5: Photon interactions as a relation between photon energy and atomic number of filters

The major interaction between X-rays and matter occurs in the following ways;

- Coherent (Rayleigh) scattering
- The photoelectric effect
- The Compton effect
- Pair Production
- Photodisintegration

Coherent (Rayleigh) scattering

This is a photon to photo interaction usually at a lower energy strikes by an electron, to produce a characteristic X-rays. Low-energy radiation is thus produced. It constitutes about 5 - 10 % of tissue interactions.

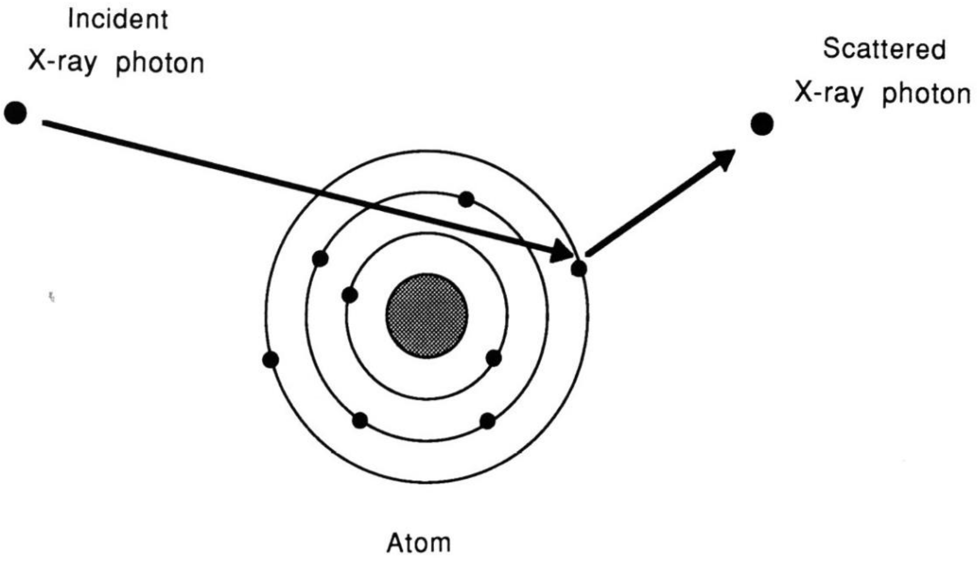

Fig. 6: Diagram of Rayleigh scattering

Compton Scattering

Compton scattering occurs when the incident X-ray photon is deflected from its original path by an interaction with an electron. The electron gains energy and is ejected from its orbital position while the X-ray photon losses energy. The X-ray continues to travel in a different path with less energy than the incident photon and is known as incoherent scattering because the photon energy change is not always orderly and consistent. At energies of 100 keV -- 10 MeV the absorption of radiation is mainly due to the Compton effect.

The Compton effect or Compton scattering (C), also known as 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 process1 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 -- 10 MeV the absorption of radiation is mainly due to the Compton effect.

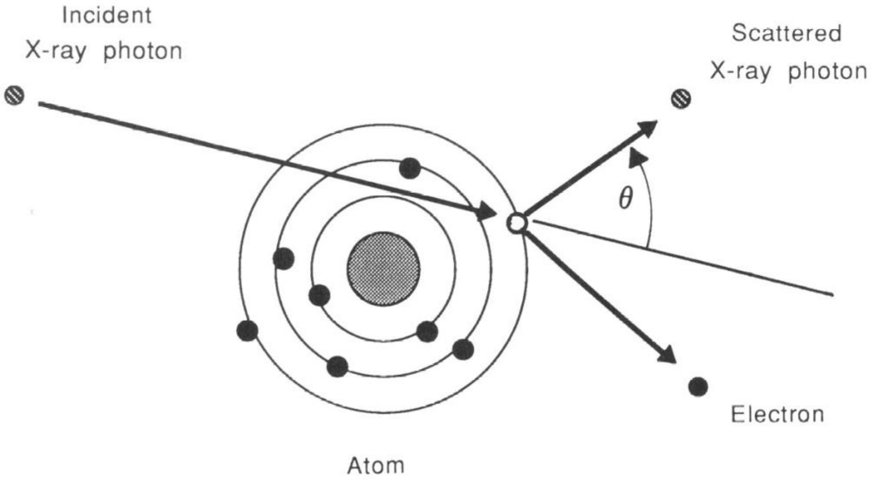

Fig. 7: Diagram of Compton scattering

The energy of shift depends on the angle of scattering and original photon energy and not the nature of the scattering medium.

The change in wavelength of the scattered photon is given by

$$\lambda' - \lambda = \frac{h}{m_0}(1 - \cos\theta) \quad (6)$$

Where λ′ is wavelength of the scattered photon
λ is wavelength of the incident photon

h is Planck's constant
m_o is rest mass of electron
c is the speed of light
θ is the scattering angle

The quantity $^{h}/_{me}$ is known as the Compton Scattering of the electron; it is equal to 2.43×10^{-12} m. The wavelength shift $\lambda' - \lambda$ is at least zero (for $\theta = 0°$) and at most twice the Compton wavelength of the electron (for $\theta = 180°$).

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).

The Compton electron will typically interact with other atoms producing secondary ionizations. Since they possess relatively low energy, the x-rays produced will generally be low energy also.

The maximum possible energy, *E*, of a Compton electron (the "Compton edge") is equal to:

$$E = \frac{Ex}{1+4Ex} \qquad (7)$$

Where *Ex* is the energy of the incident photon. Qualitatively, it is easy to see that the Compton electrons will be significantly less energetic than photoelectrons for an equal value of *Ex*.

In x-ray diffraction, Compton scatter will contribute to the overall background in the x-ray data produced, but because of the relatively low energies of the incident x-rays and the higher mass of the specimens and specimen holders, the contribution will usually be very small.

The Photoelectric Effect

The photoelectric effect occurs when photons interact with matter with resulting ejection of electrons from the matter. Photoelectric (PE) absorption of x-rays occurs when the x-ray photon is absorbed resulting in the ejection of electrons from the atom. This leaves the atom in an ionized (i.e., charged) state. The ionized atom then returns to the neutral state with the emission of an x-ray characteristic of the atom. PE absorption is the dominant process for x-ray absorption up to energies of about 500 KeV. PE absorption is also dominant for atoms of high atomic numbers.

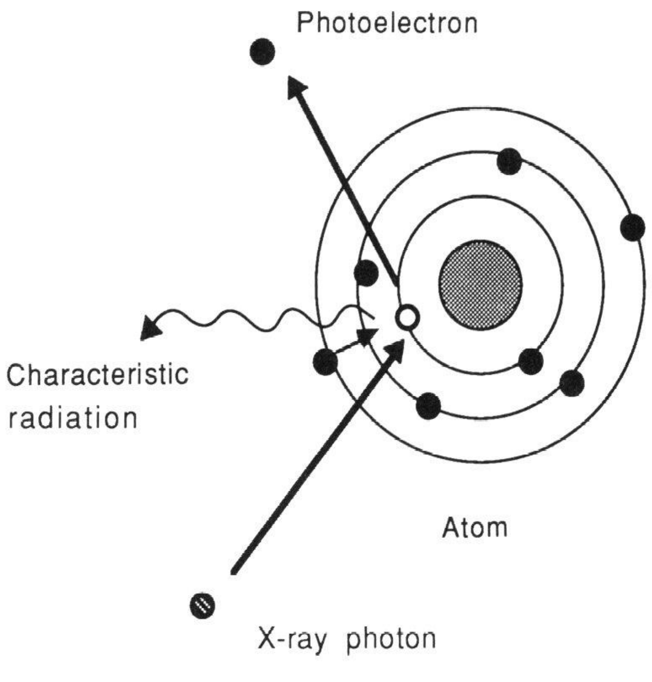

Fig. 8: Diagram of photoelectric effect

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

$$T = Ex - P \qquad (8)$$

Where T is the kinetic energy of the photoelectronExis the energy of the incident X-ray photon andP is the energy required to remove the electron. This is equivalent to its binding energy in the atom.

The energy equivalent of the rest mass of an electron is m_oc^2, and is equal to about 0.51 MeV ($m_o$is the rest mass of an electron and c is the speed of light). When $E_x$is much lower than this value, the electron will exit at a high angle to the incident beam; when Ex is closer to this value, the electron will exit at close to parallel with the beam.

When the photoelectron is ejected, it has the capability, depending on its energy, to interact with subsequent electrons in other molecules or atoms in a chain reaction until all its energy is lost. If that interaction results in the ejection of an outer orbital electron, this is known as the Auger effect, and the electron called an Auger electron. The probability of producing a secondary photoelectron vs. an Auger electron is directly proportional to the T of the photoelectron.

The production of photoelectric and Auger electrons is shown diagrammatically in the following figure from Jenkins and Snyder (1996). In the diagram (a) shows the incident X-ray photon, (b) shows the production of a high-energy primary photoelectron. In (c) a lower energy electron moves into the vacated K-shell resulting in the production of an X-ray photon that leaves the atom, and in (d) the X-ray photon is absorbed by an outer shell electron resulting in the emission of a Auger electron.

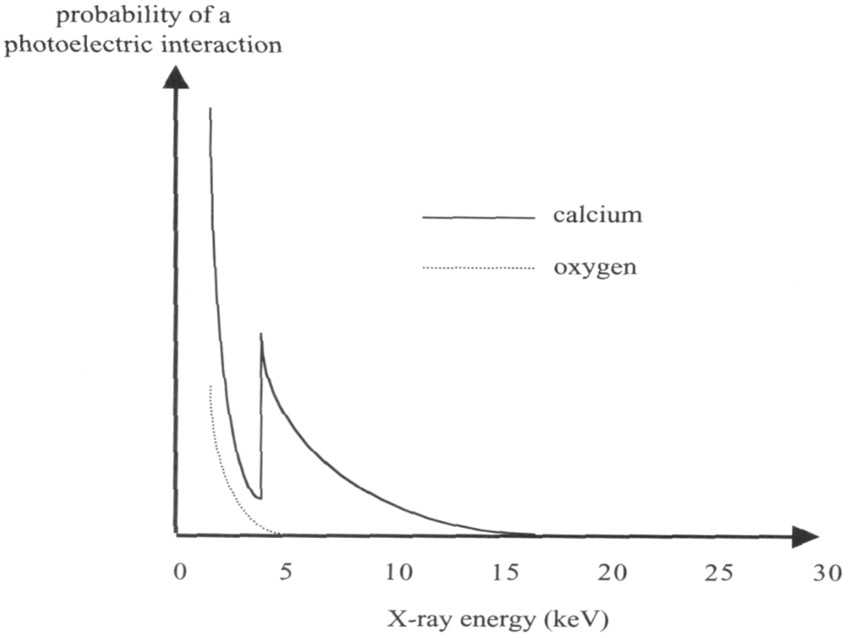

Fig. 9: Photoelectric interaction wrt energy

It is easy to see how the photoelectric (and Auger) effect can significantly damage the molecular structure of soft tissues encountered by an X-ray beam.

Pair Production

Pair Production (PP) can occur when the x-ray photon energy is greater than 1.02 MeV, when an electron and positron are created with the annihilation of the x-ray photon. Positrons are very short lived and disappear (positron annihilation) with the formation of two photons of 0.51MeV energy. Pair production is of particular importance when high-energy photons pass through materials of a high atomic number.

Pair production is a rare process and only occurs at high X-ray photon energies with high atomic weight targets. It is virtually nonexistent at the low-energies involved in X-ray diffraction work. Pair production is impossible unless the incident X-rays exceed 1.02 MeV and does not become important until this exceeds about 2 MeV.

Pair production is not a significant process at the X-ray energies involved in X-ray diffraction.

Other Effects

Thomson scattering (R), also known as Rayleigh, coherent, or classical scattering, occurs when the x-ray photon interacts with the whole atom so that the photon is scattered with no change in internal energy to the scattering atom, nor to the x-ray photon. Thomson scattering is never more than a minor contributor to the absorption coefficient. The scattering occurs without the loss of energy. Scattering is mainly in the forward direction. ***This effect is minor to when related to absorption, but is the primary effect, which makes x-ray diffraction possible.***

Photodisintegration (PD) is the process by which the x-ray photon is captured by the nucleus of the atom with the ejection of a particle from the nucleus when all the energy of the x-ray is given to the nucleus. Because of the enormously high energies involved, this process may be neglected for the energies of x-rays. It is the process harnessed in the development of nuclear fission.

Of all these processes, Compton scattering is of prime importance to radiology, as it is the most probable interaction of gamma rays and high energy X-rays with atoms in living beings and is applied in radiation therapy. It is also the main process that contributes to unnecessary radiation to the patient and laboratory staff during computed tomography scan.

According to Okunade*et al* “For optimum benefit from X-rays in diagnostic radiology, the entire imaging process must be assessed objectively”. These processes which involve precise steps in succession have been studied over time and outlined as follows:

i. X-rays production

ii. Filtration
iii. Photo interaction with the object (patient)
iv. Anti-scatter device
v. Image detection

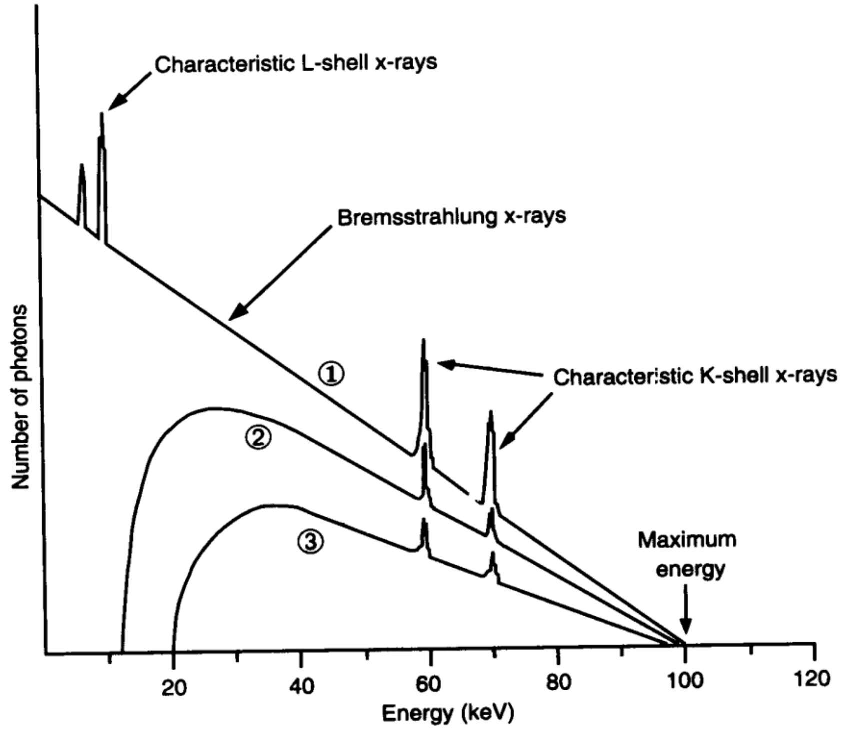

Fig. 10: Characteristics X-rays 1- Spectrum out of anode
2- After window tube housing (INHERENT filtration)
3- After ADDITIONAL filtration

III. CONCLUSION

What radiation effect will be dominant is a function primarily of the energy of the radiation and the mass of the absorbing medium. The photoelectric effect, Compton scattering, pair production, Thomson or Rayleigh scattering, and photodisintegration are the main processes that can occur. At the low energies involved in X-ray diffraction, the processes are limited to Compton scattering, Thomson/Rayleigh scattering and the photoelectric effect.

The common product of these types of x-ray interaction with matter is the production of high-speed electrons and x-rays that can cause secondary effects in the matter with which they interact. The “end” effect (which can cause significant damage in tissues, particularly at the low X-ray energies involved in diffraction) of heat production is preceded by interactions, which create excited atoms, additional free electrons from ionization, and low-energy X-rays. These can do significant molecular damage (including chromosomal damage in tissues) leading to a number adverse health effects. Also to note is that the kV determines type of interaction in the body

- As kV increases photoelectric decreases (everything is penetrated)
- As kV decreases photoelectric increases (more absorption by thicker or denser tissues)
- As kV increases Compton increases but Compton occurs throughout the diagnostic range.

When the X-ray is scattered within a cone of 15° or less (i.e. Rayleigh Scattering), it will contribute to useful beam with comparable energy of primary source. But photons that undergo Compton interactions (wide-angle scattering) can cause unnecessary dose. This will contribute to radiation of other sensitive part of the patient and or staff if not properly collimated.

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