Evaluation of Gamma Radiation Attenuation Characteristics of Different Type Shielding Materials used in Nuclear Medicine Services

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ABSTRACT

Gamma-ray radiation shielding properties such as linear attenuation coefficient (μ), mass attenuation coefficient (μ/ρ), half- value thickness (HVT), tenth value thickness (TVL) and mean free path (MFP) were calculated for different types of radiation absorbing materials such as Concrete, Aluminum, Iron, Copper, Lead, Lead-glass and Tungsten. These materials are being widely used as radiation shielding materials in different areas of nuclear medicine facilities for different purposes. The XCOM and in-house developed computer program were used to calculate the above mentioned parameters for gamma-ray energies of 100 keV, 200 keV and 511 keV. The gamma-ray energy range used in nuclear medicine is between 100 keV and 511 keV. Results show that attenuation coefficient decreases with increase of gamma-ray energy, and attenuation coefficient increases with increase of density and shows significant variation for different materials. Linear attenuation coefficient depends on the energy of incident gamma-rays and the nature of the absorbing materials. These gamma-ray attenuation parameters of different absorbing materials can be used for proper shielding design of syringe shield, isotope storage container, isotope transport container, personnel protective shield barrier, radioactive waste storage facility etc. in nuclear medicine services.

Keywords: Gamma-rays, attenuation factor, mass attenuation coefficient, absorbing materials

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INTRODUCTION

Ionizing radiation has become very important in our routine life, especially in medical applications. This radiation interacts with matter in two ways, by ionization and excitation. Studies on interaction of gamma-rays with shielding materials have been the subject of interest for the last several decades in the field of radiation protection (1). With the development of nuclear science and technology, human health has started to be exposed artificial ionizing radiation and this can damage human cell (2). In order to protect from ionizing radiation three different techniques such as time, distance and shielding are widely used. It is often necessary to provide adequate shielding for reducing radiation exposure to gamma-ray radiation in areas where people are likely to expose ionizing radiation. Either place simply shielding barrier or the attenuation of gamma-ray radiation, occurs through the interaction of the gamma-ray radiation with matter (1). The degree to which gamma-ray radiation is attenuated is dependent upon the energy of the incident gamma-ray radiation, the atomic number and density of the elements in the shielding material, and the thickness of the shielding material. Normally, the shielding design of radiation facilities, protective equipments and clothing is mainly based on lead-based absorbing materials. Recently there has been a great deal of concern expressed about the toxicity of lead (3-4). Additionally, McCaffrey (5) mentioned that the protective materials produced from the powder form of lead are poisonous and noted the decreasing lead ratio of the protective material with the use of lead alloyed or including non-lead materials. Therefore use of environment-friendly lead-free radiation shield with less weight compared to conventional lead-based shield is a challenging issue in diagnostic radiology and nuclear medicine (6). It is important to measure the radiation attenuation properties of any protective materials and demonstrate the conformity of the radiation shielding effectiveness to the requirements stipulated by the international and national standards (7-10).

Shielding is the basic method for radiation protection in all nuclear and radiation facilities. The thickness of any given material, at which 10% or 50% of the incident energy has been attenuated is known as the tenth value layer (TVL) and half value layer thickness (HVL), respectively. TVL and HVL thicknesses are expressed in units of distance (mm or cm). These are photon energy dependent, like the attenuation coeffi-cient (1). The radiation protection goal for members of the public, established by the national Nuclear Regulatory Authority is to limit exposure to ensure that no individual will receive more than 1 mSv/year total effective dose equivalent from the licensed oper-ation (2, 9). Radiation workers are limited to receiving 20 mSv total effective dose equivalent per year. Moreover, each licensee has an obligation to carry out operations so as to maintain radiation doses to both professional workers and to members of the public as low as reasonably achievable (ALARA). A radiation shield-ing plan must be developed for all radiation risk prem-ises. In medical sector, radiation risk premises include those that are mentioned below:

- diagnostic radiology
- radiotherapy and
- nuclear medicine.

Nuclear medicine is a specialized service that uses radioactive materials injected into the body to diagnose and treat human diseases. The application of different radioisotopes and high amounts of radioactive materials makes it necessary for the facilities where these procedures are conducted to evaluate the corresponding shielding to comply with the design radiation dose limits of a facility and avoid radiological accidents (1) as recommended and accepted in international publications (2). Nuclear medicine is a branch of medicine, which diagnoses through images and treatments by using ionizing radiations emitted by radionuclides like ^{99m}Tc, ^{131}I, ^{177}Lu, ^{188}Re, ^{90}Y, ^{67}Ga, ^{123}In, ^{32}P, ^{18}F, among others. Nuclear medicine department uses radioisotopes in a variety of ways. Some physical characteristics of radioisotopes commonly used in nuclear medicine are given in Table 1. The gamma-ray energy range emission from these radioisotopes is between 100 and 511 keV.

Table 1: Some common radioisotopes used in nucle-ar medicine.

Radionuclide	Energy (keV)	Emissivity	Half-life
^{11}C	511	2.00	20.4 min
^{13}N	511	2.00	10.0 min
^{15}O	511	2.00	2.0 min
^{18}F	511	1.93	109.8 min
^{64}Cu	511	0.38	12.7 h
^{68}Ga	511	1.84	68.3 min
^{82}Rb	511	1.90	76 s
^{124}I	511	0.50	4.2 day
^{99m}Tc	140.5	0.94	6.04 h
^{131}I	364.48	0.82	8.02 day

During the design of the facility to comply with regu-latory norms (1) in radiation protection, it is necessary to provide the shielding study, besides assuming all the security requirements, like demarcation of controlled and uncontrolled zones, limits and restric-tions for the dose rate. The International Atomic Energy Agency (IAEA) recommends within the considerations not using directly the permitted dose limit, but the following restrictions for the annual dose:

i. for controlled zones, do not exceed a dose rate of 5 m Sv/year and

ii. for uncontrolled zones, do not exceed 0.3 m Sv/year.

The shielding is the most important method in which radiation absorbing materials become important. Attenuation coefficient is an important parameter for study of interaction of ionizing radiation with shield-ing materials that gives us the fraction of energy scattered or absorbed from different absorbing materi-als like Lead, Tungsten, Iron, Aluminum, Copper, Concrete etc. These materials can be used to shield ionizing radiation from different radiation sources.

There are many useful applications of gamma-rays in medical services such as nuclear medicine, radiotherapy, brachytherapy and sterilization. In order to reduce the radiation hazards, it is necessary to know radiation attenuation properties for different shielding materials. The objective of this study is to calculate the gamma-ray attenuation properties of different shielding materials commonly used in nuclear medi-cine services. In this study, XCOM software (11-12) and in-house developed excel based computer program were used to calculate the gamma-ray radia-tion shielding characteristic such as linear attenuation coefficient, mass attenuation coefficient, half- value layer, tenth value thickness and mean free path for studied shielding materials.

MATERIAL AND METHODS

2.1 Materials

In nuclear medicine service, shielding considerations (13-14) are important for designing a positron emission tomography/computed tomography (PET/CT) imaging facility, because of the high photon energy (511 keV) of electron-positron annihilation photons. Since radiation emitted from patients administered PET radiopharmaceuticals includes lower-energy scattered photons, a given thickness of absorbing materials attenuates more of the radiation than it would for a mono energetic beam of 511 keV photons. A more accurate calculation of the effective photon attenuation coefficient of radiation shielding materials for the gamma-ray spectra of photon energies emitted from PET/CT patients could reduce the shielding requirements necessary to adequately protect occupational workers and public health. The photon energy of a positron emitter is quite different from ^{99m}Tc (140.4 keV) or ^{131}I (364.48 keV). The energy is 511 keV with two photons per atom disintegration. It is very obvious that safety for personnel and members of the public must be evaluated differently than a typical nuclear medicine department (15-17) that uses ^{99m}Tc or ^{131}I and other less hazardous radionuclides (Table 1). Five shielding materials such as concrete (ρ=2.35 g/cc), aluminum (ρ=2.72 g/cc), copper (ρ=8.24 g/cc), iron (ρ=7.42 g/cc), lead (ρ=11.42 g/cc), lead-glass (ρ =9.49 g/cc) and tungsten (ρ=19.32 g/cc) have been considered in this study. As tissue equivalent materi-als, water (ρ=1.0 g/cc) is also considered in this study for comparison. Lead, tungsten and iron materials are being widely used for syringe shield, radioisotope storage container, radioactive source transport container etc.

2.2 Gamma-ray interactions with matter

Depending upon the interacting particle/field in the matter (electrons, nucleons, electric field surrounding nuclei/electrons or meson field surrounding nucleons) with which gamma-ray photons are interacting and the result of that interaction (may be complete absorp-tion, elastic/coherent scattering or inelastic/incoherent scattering); there are many processes by which gamma-rays can interact with matter. Figure 1 gives a graphical display on the process in which gamma-rays are attenuated. The behavior of photoelectric, Compton, and pair production can be seen in Figure 2.

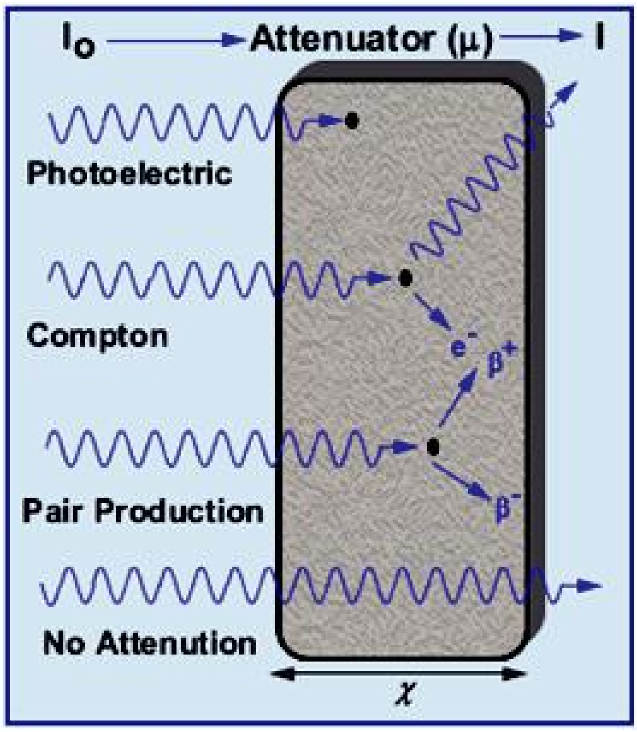

Figure 1. Gamma-ray interaction mechanism with matter.

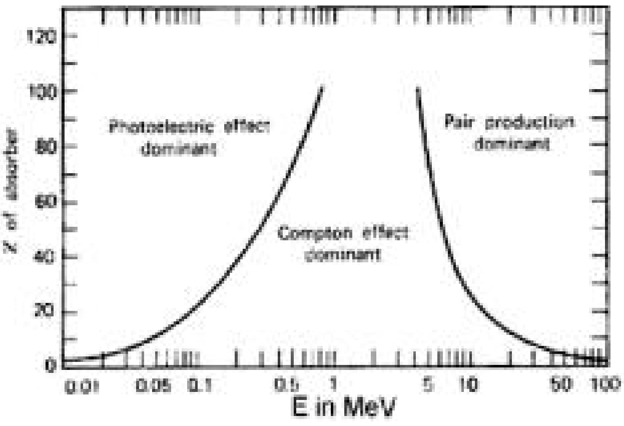

Figure 2: Relative importance of three principal modes of interaction as a function of photon energy and atomic number of absorber.

Many combinations of interacting particle/field with resultant mechanism suggest twelve processes of photon interaction. However, on the basis of probability of occurrence, only three dominant photon interaction processes (1) are discussed in next section.

2.2.1 Photoelectric Absorption

Gamma-ray photon interacts with the electron (mostly from K shell) of the matter which results in the complete absorption of the photon. The threshold energy for this process to occur depends upon the binding energy of the electron in a particular shell. Cross-section for photoelectric effect strongly depends on atomic number of an element as Z_{4-5} and energy of gamma-ray photons as $E_{3.5}$ (1). It is found that this photon interaction process is dominant for heavy elements (like lead and uranium) at lower photon energies.

2.2.2 Compton scattering

It is the process of inelastic/incoherent scattering of gamma-ray photon while interacting with an electron. As a result of this process, partial photon energy has been transferred to an electron and photon scattered with the rest of energy. Hence, this process results in only energy degradation of the gamma photon. The cross-section for Compton scattering process is least dependent on atomic number and slowly decreases with the increase in gamma-ray energy. Hence, this process is dominant at intermediate photon energy for all elements.

2.2.3 Pair production

It is the process of complete absorption of gamma-ray photon in the electric field of nuclei/electrons, which results in the formation of an electron-positron pair. The threshold value for this process to occur is 1.022 MeV (which is equivalent to the sum of rest mass of an electron and positron). For gamma photon with higher energy, the excess energy is transferred as kinetic energy to electron–positron pair. This process is the best example for transformation of energy into mass. The cross-section for pair production in the electric field of a nucleus varies directly with atomic number as Z_2 and with photon energy as log(E). Hence, it is a dominant process for heavy elements at higher photon energies.

2.3 Radiation attenuation properties

Materials to be used for gamma-ray radiation shield-ing should have homogeneity of density and composi-tion, and sufficient thickness to absorb the radiations to a safe level. It must have high atomic number. Linear attenuation coefficient (μ), mass attenuation coefficient (μ/ρ), mean free path (λ), half value thick-ness (HVT) and tenth value thickness (TVT) are the basic quantities which determine the scattering and absorption of photons in matter. For a narrow beam of mono-energetic photons (1), the change in photons beam intensity at some distance in a material can be expressed in the form of an equation as:

$$I\,(x)= I_o\, e^{-\mu x} \qquad (1)$$

I is the gamma-ray intensity transmitted through an absorber of thickness x.

I_o is the gamma-ray intensity at zero absorber thickness.

x is the absorber thickness

μ is slope of absorption curve - linear attenuation coefficient.

$I(x)/I_0$ is the radiation attenuation factor

2.3.1 Mass attenuation coefficient

Linear gamma-ray attenuation coefficient measures the number of photons interacted (may be scattered or absorbed) with the shielding material. The density dependence of linear attenuation coefficient (μ) has been removed by introducing another parameter known as mass attenuation coefficient (μ/ρ), which is obtained by dividing μ by the density ρ of the shield-ing materials. It is usually expressed in cm$_2$/g. The gamma-ray attenuation parameters such as mass attenuation coefficient (μ/ρ) was calculated for some shielding materials in the energy region from 1 keV to 10 MeV using XCOM program (6,7). The XCOM package provides total as well as partial attenuation coefficients and cross sections for various interaction processes (Rayleigh scattering, Compton scattering, photoelectric absorption.

2.3.2 Mean free path

The mean free path (mfp) is the average distance a photon can travel in the shielding material before being interacted. The mean free path has been obtained from the linear attenuation coefficient by the relation

$$mfp = 1/\mu \qquad (2)$$

where μ is the attenuation coefficient (cm$_{-1}$)

2.3.3. Half value thickness

Half value thickness (HVT) is the thickness of the interacting material at which the intensity of the photon beam entering it is reduced by one half. The lower is the value of HVT, the better is the radiation shielding material in terms of thickness requirement. Half value thickness can be estimated by the relation

$$HVT = 0.693/\mu \qquad (3)$$

2.3.4. Tenth value thickness

Tenth value thickness (TVT) is the thickness of the interacting material at which the intensity of the photon beam entering it is reduced by one tenth. The lower is the value of TVT, the better is the radiation shielding material in terms of thickness requirement. Tenth value thickness can be estimated by the relation

$$TVT = 2.301/\mu \qquad (4)$$

3. Results and discussions

The shielding effectiveness of materials can be exam-ined on the basis of different parameters which includes attenuation factor, mass attenuation coefficient (μ/ρ), half value thickness (HVT), tenth value thickness (TVT) and mean free path (mfp). Gam-ma-ray attenuation factors (I/I_0) for different shielding materials are calculated by using computer program based on excel sheet. The results are shown in Fig. 3 for a typical 511 keV photon energy, which is the maximum energy used in nuclear medicine services. The gamma-ray mass attenuation coefficient was calculated with XCOM software and the results for iron are shown in Fig. 4. Gamma-ray mass attenuation coefficient depends on the energy of incident photons and the nature of the shielding materials. From Fig. 4, it is observed that mass attenuation coefficient decreases with increasing energy and attenuation coefficient increases with increasing density of the material. Similar nature of mass attenuation curves were found for other studied shielding materials.

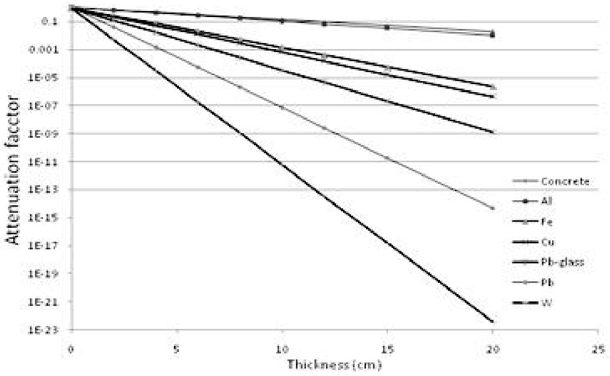

Figure 3. Gamma-ray transmission factor of differ-ent shielding materials.

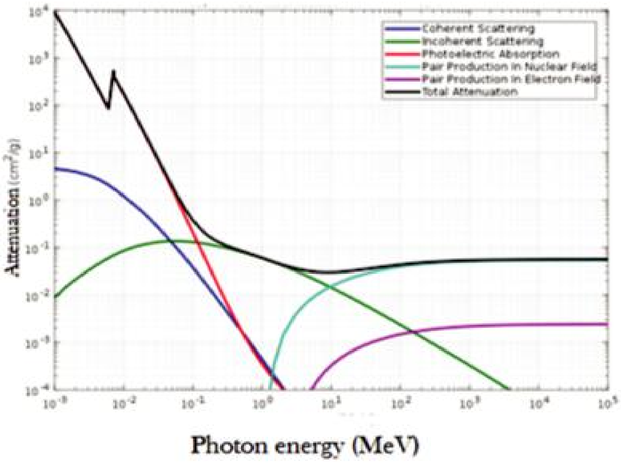

Figure 4. Photon mass attenuation coefficients for iron

Shielding effectiveness against gamma-ray radiation mainly involves the interaction of gamma radiation with absorbing materials via three main processes: 1) photoelectric effect, 2) Compton scattering, and 3) pair production. In case of photoelectric effect, a gamma-ray interacts with an atom resulting in the ejection of an orbital electron from the atom. The orbital electron receives all of the energy of the gamma-ray, minus its atomic binding energy, and may induce secondary ionization events. The interaction probability of the photoelectric effect is proportional to the atomic number (Z) of the absorbing material and inversely related to the energy of the gamma-ray. The different contributions of Compton scattering, photoelectric absorption and pair production to the total mass absorption coefficient (μ/ρ) for each type of shielding materials, calculated using the XCOM (11) program as shown in Fig. 4. Shielding of 100-1000 keV gamma-ray radiation with absorbing materials containing high Z components, such as lead and tungsten, is achieved with a significant contribution from both Compton scattering and photoelectric absorption. It may be mentioned here that the shielding with materials containing low Z components, such as aluminum and iron, is achieved primarily with Comp-ton scattering.

The HVT and TVT values were calculated for different shielding materials at 100 keV, 200 keV and 511 keV photon energies by using in-house developed computer program based on excel sheet. The results of HVT and TVT values are given in Figures 5 and 6.

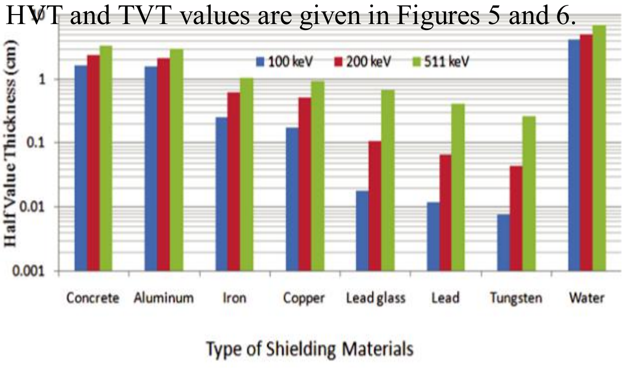

Figure 5: Comparison of HVT of some shielding materials for different photon energies.

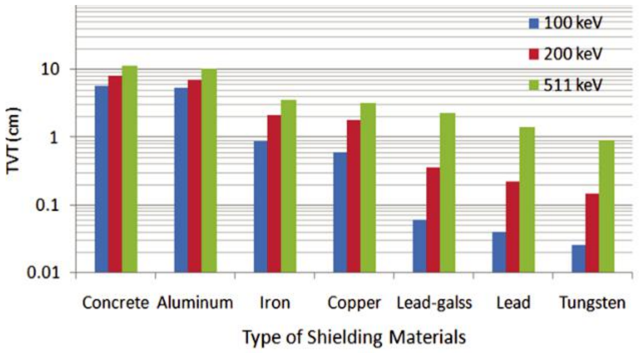

Figure 6: Comparison of TVT of some shielding materials for different photon energies.

Mean free path (MFP) corresponds to an average thickness of the interacting material travelled by the photon between two successive events (scattering/absorption). The results of MFP are given in Figure 7. The minimum value of MFP was observed in case of tungsten that proved better shielding against gamma-rays. From eqs. 2–4, it can be observed that all these parameters are inversely proportional to linear attenuation coefficient with a slight change in numerator values: 0.693 for HVT, 1 for mfp and 2.303 for TVT. The probability of photon interaction decreases with the increase in energy.

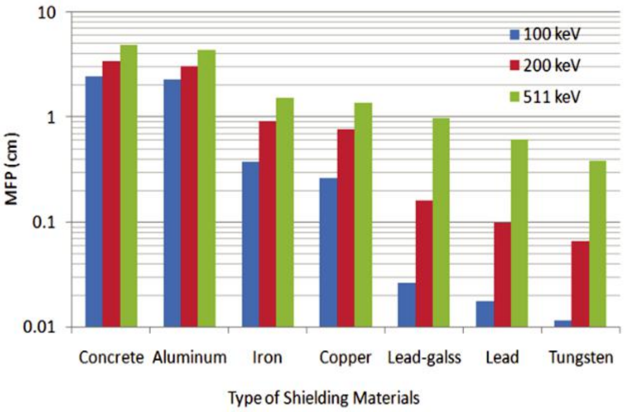

Figure 7: Mean free path (MFP) values of the select-ed shielding materials.

We compared the attenuation coefficient of the studied materials and found the Tungsten material has a higher attenuation coefficient than the other shielding materials. The Tungsten or iron material may be used as a substitute for lead because lead is a toxic shielding material (3-6). In present study economic shielding was also examined and the result of tungsten or iron absorbing material was best after lead.

CONCLUSION

The purpose of this contribution is to present a computational procedure regarding the attenuation properties of six absorbing materials for different energies used in nuclear medicine facilities. In this way it is hoped to assist those responsible for the planning and designing of nuclear medicine facilities (especially PET/CT facilities) to provide adequate and, at the same time, economical protective measures for selecting a suitable shielding material. HVT, TVT and MFP can be used for rapid shielding design by using studied shielding materials.

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