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Photon Interaction Cross Section of Materials in Heterogeneous Energy Spectrum of Medical Diagnostic X-Ray Beam

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ABSTRACT

Experimental determination of mass attenuation coefficients for mono-energetic x-ray and Gamma rays has been reported by various investigators. In this study, an attempt is made to evaluate the mass attenuation coefficients (μ/ρ) and total photon interaction cross section (σ_{tot}) values of few samples in a heterogeneous x-ray beam from a medical diagnostic x-ray unit, operated at a peak voltage of 85 KVp. Sheets of aluminium, copper, brass and tissue equivalent plastic (virtual water) have been employed. By comparing the experimental values of mass attenuation coefficients (μ/ρ) with those values published in the literature, the prominent energy of interacting photons are estimated to be 36.8 KeV, 48.7 KeV, 47.8 KeV and 35.5 KeV for aluminium, copper, brass and virtual water respectively. From these experimental μ/ρ values, the total photon interaction cross section values (σ_{tot}) are calculated in the units of barn/atom. These experimental σ_{tot} values are in good agreement with the theoretical values deduced in the literature with percentage deviation of only +0.03% and +0.09% for aluminium and copper (elements) respectively at the prominent energy of interaction. The percentage deviation is -1.12% for Brass (alloy) and +5.77% for virtual water (mixture). The results are discussed.

Keywords **-** Heterogeneous x-ray energy spectrum, mass attenuation coefficient, medical diagnostic x-ray unit, mono-energetic beam, photon interaction cross section

1. Introduction

The photon interaction cross sections of various materials due to mono-energetic photons have been studied by various investigators. Hubbell[1,2,3,4] has done extensive work to deduce the photon interaction cross section values for various elements, compounds and mixtures and these values have been published in National Standard Reference Data of National Bureau of Standards, Washington. McMaster, etal[5] had compiled the x-ray properties of various materials. These values have been calculated theoretically based on Klein-Nishana equation by these investigators. R. Nowotny[6] and Akintude A Okunade, etal[7] have developed computer programs to deduce the theoretical values of mass attenuation coefficients of various materials based on the data compiled by Hubbell[8] and Boone, etal[9]. NIST[10] has published a computer program, known as XCOM, to determine the photon interaction cross section of various materials for a wide range of mono-energetic energies. Attempts have been done by Nathuram, etal[11] , Kerur, etal[12], Kaginelli, etal[13] and few other investigators to determine the mass attenuation coefficients (μ/ρ) and photon interaction cross sections of few materials experimentally with mono-energetic radiation from radioactive isotopes and characteristic x-ray radiation from variable energy x-ray source and reported that their results are in good agreement with these theoretical values. X-rays, being the most common diagnostic tool used on human population, experimental determination of the photon interaction cross sections of various materials due to the heterogeneous beam of diagnostic x-ray beams is worth to be explored. This study explores the experimental determination of mass attenuation coefficients (μ/ρ) of few samples in the medical diagnostic x-ray beam and correlation of these data with the published theoretical values. An estimation of prominent energy of the interacting beam is also done correlating the experimental mass attenuation coefficients (μ/ρ) with the theoretical values.

2. Materials & Methods

Gary D, etal[14] has described the method of calibration of x-ray units. In the present study, X-ray generators, which have undergone quality assurance tests, are employed. The sample elements used were copper, brass, aluminum and virtual water of varying thicknesses in pure form. The virtual water is composed of 77.5% of Carbon, 10%of Hydrogen, 5% of Oxygen, 3.5% of Nitrogen, 2.5%of Fluorine and 1.5% Calcium. The sample sheets were maintained at a specific distance from the focus and the incident intensity was measured using an ion chamber detector. The transmitted intensity was measured with the same exposure factors. The thicknesses were gradually increased and HVL values were measured. The results were tabulated and plots were obtained.

3. Experimental Set-up

Fig.1 Experimental set up of measurements

The experimental set up is shown in Fig.1. The measurements were done on a 500mA medical diagnostic x-ray unit (Siemens/Heliophos D). A calibrated ion chamber based detector is placed on the table top so that the detector position is around 55 cm from the focus of the x-ray tube. A stand is fabricated to place the absorbers in such a way that a distance of around 30 cm is maintained between the focus and the absorbers and a minimum of 20 cm is maintained between the absorbers and the detector to avoid scattered photons and secondary electrons reaching the detector.

The x-ray unit was initially subjected to a set of quality assurance test procedures before being employed for the present study. RADCHECK PLUS [Fluke/model 06-526], which is capable of integrating the x-ray output, is used for the purpose of measuring the integrated exposure.

Exposure factors of 85 KVp and 16 mAs were chosen using a collimator field size which covers the detector area sufficiently. Exposure was given without any absorber placed above the detector. The reading shown by the detector was noted as incident intensity (I'). An absorber of known thickness was placed on the stand and the exposure reading was noted again as transmitted intensity (I). The thicknesses of the absorbers were varied and the readings were noted.

The above procedure was repeated for other absorbers as well. The sample sheets of Aluminium, Copper and Brass of thicknesses varying from 0.5mm to 3.5mm at the increment of 0.5mm and virtual water of thicknesses varying from 0.5cm to 3.5cm with the increment of 0.5cm were used in this study.

Plots of intensity (exposure) Vs thickness are obtained for each sample material and Half value Layer (HVL) for each one, which is the thickness required to reduce the transmitted intensity of radiation to half of its original intensity was obtained from these plots. These plots for all the absorbers used are depicted in Fig (2) and Fig (3). The mass attenuation coefficients (μ/ρ) of each material were calculated by the following equations,

$I = I' e^{-(\mu/\rho)(\rho x)}$ ---------- (1) and
$\mu = 0.693/HVL$ ----------- (2) where

μ - Linear attenuation coefficient in cm^{-1}
μ/ρ - Mass attenuation coefficient in cm^2/gm
ρx - Thickness of the absorber in gm/cm^2

The total photon interaction cross section has been calculated as

$\sigma_{tot} = (\mu/\rho)A/N_A$ -----------(3) where
A - relative atomic mass of the target element
N_A- Avagadro's number

4. Results & Discussion

Fig. 2 and fig. 3 shows the variation of transmitted intensity/exposure with increase in absorber thickness. The experimental μ/ρ values of the materials due to the heterogeneous energy spectrum from the diagnostic x-ray beam were evaluated using (2) after obtaining HVL thicknesses from these plots for all samples. The average energy of the unfiltered x-ray beam is empirically considered as one-third of the KVp applied and this average energy is expressed in KeV[15,16,17]. Since 85 KVp was the kilovoltage applied to the x-ray tube in this study, the empirical average energy of the unfiltered x-ray beam is approximately 28 KeV. However, due to the elimination of low energy components of the x-ray beam by the inherent and additional filtration provided by the x-ray tube, the practical average energy would be much higher.

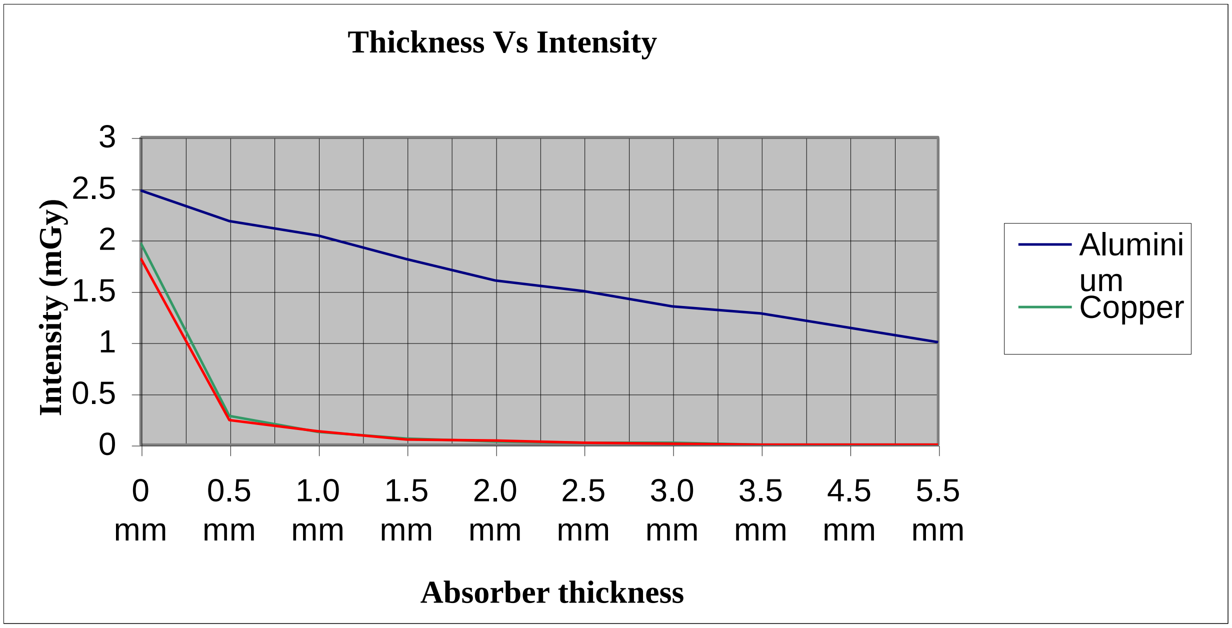

fig 2. Thickness Vs intensity plot for Aluminium, Copper and Brass

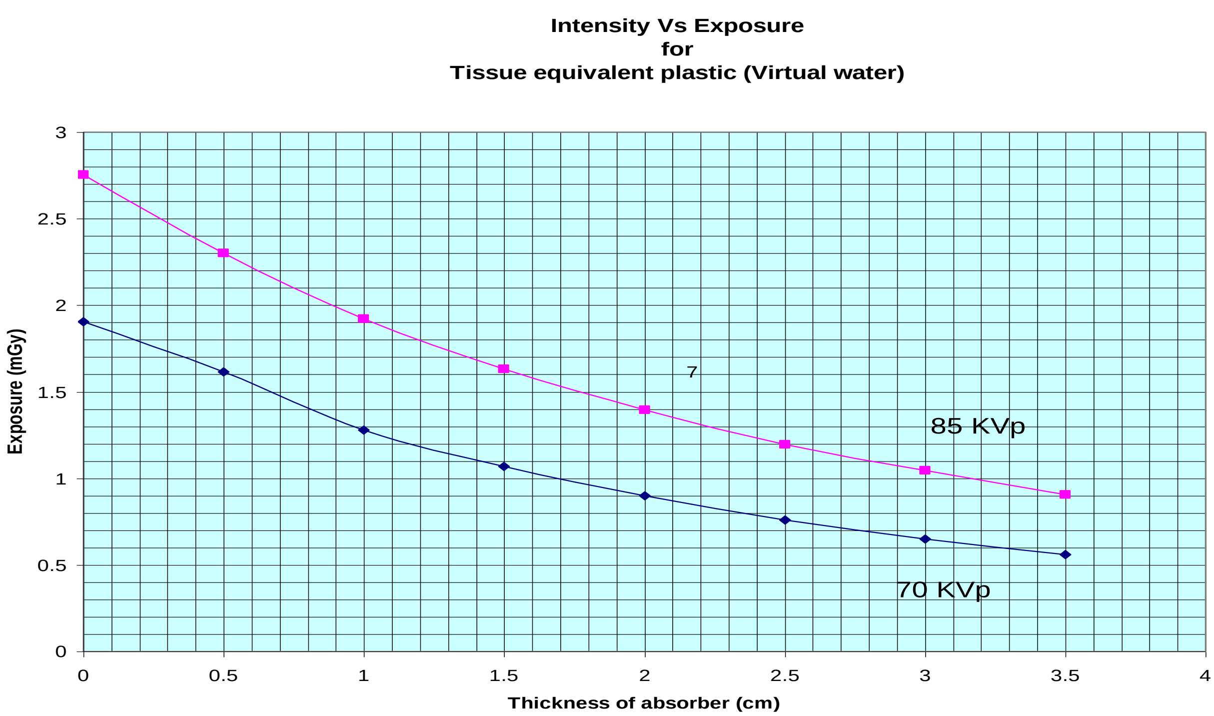

fig 3. Thickness Vs intensity plot for virtual water

The theoretical mass attenuation coefficient (μ/ρ) values of the samples used were determined using the XMudat computer program[6] developed by R. Nowotny based on the data published by Hubbell[8] and Boone[9]. The variation of μ/ρ for a wide range of energy ranging from 1 KeV to 10 MeV for mono-energetic photons for these absorbers as derived from this XMudat program is shown in Fig (4). These values were compared with the experimental mass attenuation coefficient (μ/ρ) values. The results indicate that the prominent energy of the interacting x-ray photons reaching the detector after suffering attenuation is different for different materials. This prominent energy predictably depends largely on the atomic number of the materials because of the predominance of photo electric effect in the diagnostic x-ray energy range and the photo electric effect is directly proportional to Z^{3}[17] . In the case of aluminium (Z=13) and virtual water (Z=7.4), the prominent energy of interaction was found to be 36.8 KeV and 35.5 KeV respectively which indicate that the average energy of the filtered x-ray beam is not much affected by the attenuation due to these two samples. However, for copper (Z=29) and brass (Z=30), the prominent energy of interaction turned out to be 48.7 KeV and 47.8 KeV respectively indicating the removal of some more low energy components of the incident x-ray beam. These results are shown in the Table (1). This table also shows the percentage of deviation of experimental mass attenuation coefficient (μ/ρ) values from the theoretical values had we considered the average energy of the unfiltered x-ray beam, ie, 28 KeV for all these interactions. The percentage of deviation ranges from 17% for aluminium to 37.4% for copper and 34.46% for brass while for virtual water the percentage of deviation is 24.47%.

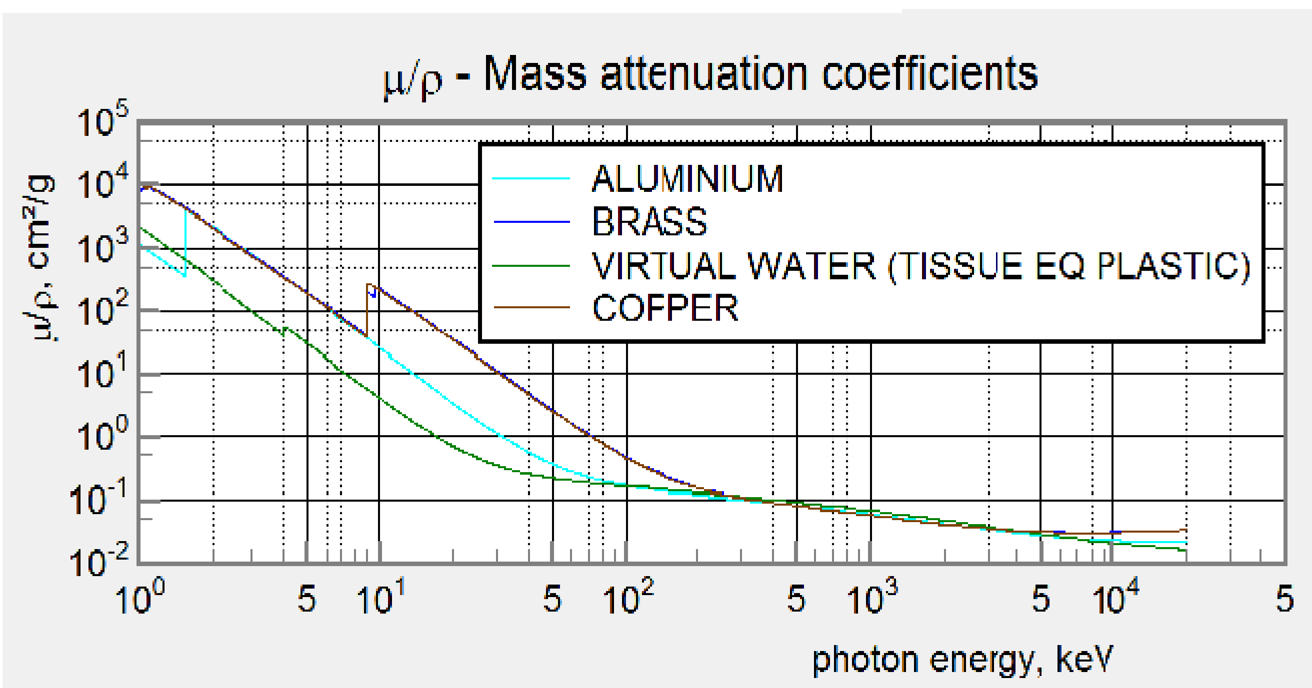

fig. 4 Theoretical variation of Photon Mass attenuation coefficient with energy from 1 Kev to 10 MeV (Ref: Xmudat program based on Hubbell & Boone)

Table 1: Mass Attenuation coefficients (Experimental & theoretical):

Absorber material	μ/ρ (experimental) (cm^2/gm)	* Energy of the x-ray spectrum close to the μ/ρ (experimental) values	μ/ρ (theoretical) (cm^2/gm) for empirical average energy (28 KeV)	% Deviation of μ/ρ values at empirical average energy (28 KeV)
Aluminium	0.685	36.8 KeV	0.568	17.00
Copper	2.813	48.7 KeV	4.490	37.40
Brass	3.066	47.8 KeV	4.678	34.46
Tissue equivalent Plastic (virtual water)	0.286	35.5 KeV	0.378	24.47

- Xmudat program based on Hubbell & Boone

The total photon interaction cross-sections (σ_{tot}) of these samples were calculated using eq (3) from the experimental μ/ρ values. The photoelectric effect is the predominant interaction mode in the diagnostic x-ray energy range used in the study. σ_{tot} values thus calculated were compared against the theoretical σ_{tot} values which were estimated through the XCOM computer program developed by the National Institute of Standards and Technology (NIST) [10], United States. The σ_{tot} values including a small cross section of Rayleigh scattering obtained through this program agree closely with the experimental σ_{tot} values in the case of aluminium and copper (elements) with a percentage deviation of only +0.03% and +0.09%. The percentage deviation is -1.12% for brass (alloy) and it is +5.77% for virtual water (mixture). These results are shown in the Table (2).

Table 2: Total photon interaction cross-section values (Experimemtal & theoretical):

Absorber material	σ_{tot} (experimental) (barns/atom)	σ_{tot} (theoretical) (barns/atom)	% Deviation at prominent energy	σ_{tot} (theoretical) (barns/atom) at empirical average energy of x-ray (28 KeV)	% Deviation at empirical average energy (28 KeV)
Aluminium	30.68	30.67	+0.03	25.43	20.70
Copper	296.78	296.50	+0.09	473.80	37.40
Brass	323.50	327.17	-1.12	493.63	34.46
Tissue equivalent Plastic (virtual water)	5.60	5.29	+5.77	7.40	24.46

* XCOM program developed by NIST based Hubbell & Sieltzer S M)

However, σ_{tot} values estimated based on the theoretical μ/ρ values at the empirical unfiltered average x-ray energy of 28 KeV deviates from 20.7% for aluminium to 37.4% for copper. For virtual water, the percentage of deviation is 24.46% and for brass it is 34.46%. These deviations demonstrate that the practical average energy of the x-ray beam is much more than 28 KeV due to the inherent and additional filtration of the x-ray tube. The prominent energy of interaction for each set of samples is still higher than this filtered average energy for the reasons described earlier.

5. Conclusion

The comparison of experimental values of mass attenuation coefficients (μ/ρ) and total photon interaction cross section (σ_{tot}) due to diagnostic x-ray energy spectrum of heterogeneous nature reveals that the experimental and theoretical values for the empirical average x-ray energy do not agree accurately with each other. This is due to the fact that the actual average energy of the filtered x-ray beam is more than the empirical average energy. The prominent energy of the photons which interacted with these absorbers could be deduced from the experimental mass attenuation coefficients (μ/ρ) which is higher than the predicted average energy of the heterogeneous beam of x-ray. Therefore the radiation shielding requirements for radiation safety considerations and the estimated absorbed dose by various anatomical structures during diagnostic procedures based on the empirical average energy of a heterogeneous beam of x-ray spectrum will not be accurate and knowledge of the prominent energy of interaction among the entire spectrum of the beam will give more accurate estimation.

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