(Online First) Mass attenuation coefficients of several water equivalent phantom materials by using Compton scattering technique in comparison to the theoretical XCOM values

Mohd Fahmi Mohd Yusof¹, Puteri Nor Khatijah Abd Hamid², Abd Aziz Tajuddin², Rokiah Hashim³, Norriza Mohd Isa⁴

¹ School of Health Sciences, Universiti Sains Malaysia, 16150 Kelantan, Malaysia, ² School of Physics, Universiti Sains Malaysia, 11800 Penang, Malaysia, ³ School of Industrial Technology, Universiti Sains Malaysia, 11800 Penang, Malaysia, ⁴ Medical Physics and Secondary Standard Dosimetry Laboratory, Malaysian Nuclear Agency, 43000 Bangi, Selangor, Malaysia

ABSTRACT

The mass attenuation coefficients of several water equivalent phantom materials and fabricated Rhizophora spp. particleboards were measured using Compton scattering technique of Ludlum configuration. The scattered gamma energies were calculated at 30, 45, 60 and 75°. The measured mass attenuation coefficients of the samples were compared to their theoretical values using XCOM calculation soft ware and the XCOM values of water as standard phantom material for high energy photons. The results showed that the measured mass attenuation coefficients of solid water and fabricated Rhizophora spp. particleboards were in good agreement to their respective theoretical values with p-value of 0.2411 and 0.934. A comparison to the XCOM value of water also showed that all experimented values of the water equivalent phantom were in good agreement to water with p-values between 0.055 and 1. The results had indicated the suitability of the Ludlum configuration to be used for the measurement of mass attenuation coefficients using Compton scattering technique.

Keywords: mass attenuation coefficients; Compton scattering technique; phantoms

1. Introduction

1.1 Overview of Phantom Materials

Phantom is the material that simulates the absorption and scattering characteristics of human soft tissues towards ionizing radiations[1]. Phantom becomes an important tool for quality control and dosimetry works involving ionizing radiations in medical physics works. Water has been recommended as phantom material for high energy photons and electrons by many available dosimetric protocols due to its density and effective atomic number close to the human soft tissue. The use of water as phantom however is not always possible due to its liquidity and compatibility of many radiation dosimeters to be used in water. Several solid type phantom such as Perspex® and solid water phantoms are introduced to substitute water such as Perspex® and solid water phantoms. Several studies had been conducted to determine the similarities of the water equivalent phantom materials to water. A previous study indicated the similarities of dosimetric characteristics of solid water phantoms to water shown by the beam output calibration of high energy photons[2]. A study on the Monte Carlo simulation also indicated an agreement of gamma transmission between solid water and water[3].

1.2 Mass Attenuation Coefficient of Phantom Materials

The mass attenuation coefficient is a main parameter to determine the absorption and scattering properties of a material towards ionizing radiations[4]. The knowledge of mass attenuation coefficient of a material can be used to un-
derstand the attenuation properties of a material in comparison to known materials. The mass attenuation coefficient of a material can be measured experimentally based on the transmission of known photon energy through the material based on the Beer-Lambert law. A previous study suggested that the measurement of mass attenuation coefficient at high energy photons can be measured using the Compton scattering method by using $^{137}$Cs gamma energy\textsuperscript{[5]}. This method provided better accuracy of experimented gamma energy range as the scattering of incident gamma to the attenuator is commonly inelastic at specific angles and scattered gamma energies. Therefore this study focused on the measurement of mass attenuation coefficient of several phantom materials by using the Compton scattering technique.

The measurement of mass attenuation coefficient of materials with known elemental compositions can be determined theoretically by using computer program of photon cross-section database named XCOM\textsuperscript{[6]}. The program is later transformed into computer platform and named as WinXCOM. This program enables the calculation of mass attenuation coefficient at various ranges of photon energies and has been used by many researchers. The mass attenuation coefficient of substances that consists of more than one element can also be calculated by inserting the percentage of the respective elements into the calculation program. Therefore, this study compared the measured mass attenuation coefficient of several phantom materials using experimental set up to their theoretical values using XCOM.

2. Materials and Methods

2.1 Preparation of Phantom Material

The mass attenuation coefficients of solid water and Perspex\textsuperscript{®} phantoms were measured in the present study. Solid water phantom is an epoxy resin-based water substitute phantom material commonly used for quality control and dosimetric studies in radiotherapy. Perspex\textsuperscript{®} on the other hand is the most common phantom material for diagnostic imaging. Another type of phantom was also experimented in this study. The mass attenuation coefficient of fabricated particleboards made of Rhizophora spp. with target density similar to water (1.0 g/cm$^3$) based on the previous study by Mohd Fahmi \textit{et al}\textsuperscript{[7]} was also evaluated. A previous work had suggested the similarity of mass attenuation coefficients of the particleboards and Rhizophora spp. wood to the values of water at X-ray Fluorescence (XRF) between 16.59 and 25.26 keV\textsuperscript{[8-15]}. The detail of the phantom materials used in the experiment is presented in Table 1.

<table>
<thead>
<tr>
<th>Phantom material</th>
<th>Chemical composition</th>
<th>Density (g/cm$^3$)</th>
<th>Effective atomic number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid water</td>
<td>(C$_3$O$_2$H$_8$)$_n$</td>
<td>1.16\textsuperscript{1}</td>
<td>6.48\textsuperscript{1}</td>
</tr>
<tr>
<td>Perspex</td>
<td>Epoxy resin\textsuperscript{1}</td>
<td>1.00\textsuperscript{1}</td>
<td>7.35\textsuperscript{1}</td>
</tr>
<tr>
<td>Rhizophora spp. particleboards</td>
<td>C$<em>{3}$O$</em>{12}$F\textsuperscript{2}</td>
<td>1.03\textsuperscript{2}</td>
<td>7.22\textsuperscript{2}</td>
</tr>
</tbody>
</table>

\textsuperscript{1}Khan, (2010), \textsuperscript{2}Mohd Fahmi \textit{et al}, (2017)

\textbf{Table 1}. The chemical compositions, density and effective atomic number of phantoms used in the study.

2.2. Experimental Set Up

The measured mass attenuation coefficient of the phantoms was determined by using Compton scattering techniques and Ludlum configuration as shown in Figure 1. The Ludlum configuration was used in conjunction with $^{137}$Cs sealed source that produced gamma peak energy of 0.662 MeV. The $^{137}$Cs source was encapsulated within a lead container with collimation of 1.0 mm to simulate a line source. An Al plate with 1.0 mm thickness was used as attenuator to provide scattered photon energies. The Ludlum detector was placed at 30, 45, 60 and 75\degree angles from the Al attenuator and the phantom materials were placed between the attenuator and the Ludlum detector. The energies of scattered gamma was calculated based on the relationship between the incident and scattered gamma energies given by the equation

$$E_\gamma' = \frac{E_\gamma}{1 + (1 - \cos \theta) E_\gamma/m c^2} \tag{1}$$

with $E_\gamma$ and $E_\gamma'$ is the incident and scattered gamma energy respectively, $\theta$ is the angle of scattered gamma and m is the electron rest mass\textsuperscript{[16,17]}. This formula is derived with the assumption that the relativistic collision between the gamma ray and electron is initially at rest\textsuperscript{[5]}. Appropriate identification of research participants is critical to the science and practice of psychology, particularly for generalizing the findings, making comparisons across replications, and
using the evidence in research syntheses and secondary data analyses. If humans participated in the study, report the eligibility and exclusion criteria, including any restrictions based on demographic characteristics.

**Figure 1.** The experimental set up to determine the mass attenuation coefficients of materials using Ludlum configuration and Compton scattering technique.

2.3. Measurement of Mass Attenuation Coefficient

The linear attenuation coefficient of the phantom samples was measured based on the transmission of photon through the samples based on the Beer-Lambert equation of

\[ I = I_0 e^{-\mu x} \]  

(2)

with \( I_0 \) and \( I \) is the initial and transmitted photon respectively, \( \mu \) is the linear attenuation coefficient of the sample medium and \( x \) is the thickness of the sample medium. The linear attenuation coefficient can be calculated by rearranging Equation 2 into the equation

\[ \mu = \frac{\ln(I/I_0)}{x} \]  

(3)

The mass attenuation coefficient, \( \mu/\rho \) of the phantom materials can be calculated by dividing the value of linear attenuation coefficient with the density of the phantom material.

The theoretical value of mass attenuation coefficients can be calculated by using the XCOM software. The percentage of elemental compositions of the phantom materials and the range of photon energies were inserted into the calculation software and the tabulated data on the mass attenuation coefficients of the phantom materials will be obtained. The theoretical values of mass attenuation coefficients of the phantom materials were compared to their measured values from the Ludlum configuration measurement.

3. Results and Discussion

3.1 Analysis of Scattered Gamma Energies

The calculated scattered gamma energies of \(^{137}\text{Cs}\) gamma are presented in Table 2. The results showed that the scattered gamma energies were lower at larger scattering angle. The results were in good agreement to the previous study on the measurement of scattered gamma from \(^{137}\text{Cs}\) by Limkitjaroenporn et al\(^{[5]}\).

<table>
<thead>
<tr>
<th>Scattering angle, ( \theta )</th>
<th>Incident gamma energy, ( E_\gamma ) (MeV)</th>
<th>Scattered gamma energy, ( E_{\gamma'} ) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>662</td>
<td>564.09</td>
</tr>
<tr>
<td>45</td>
<td></td>
<td>479.90</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td>401.76</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td>337.72</td>
</tr>
</tbody>
</table>

Table 2. The calculated scattered gamma energies from \(^{137}\text{Cs}\) at different scattering angles.

3.2 Mass Attenuation Coefficients of the Phantom Samples

The measured mass attenuation coefficients of solid water phantoms, Perspex® and fabricated Rhizophora spp. particleboards in comparison to their theoretical values by XCOM is presented in Table 3. The comparison of mass attenuation coefficients between the measured and theoretical values for solid water phantoms, Perspex® and fabricated Rhizophora spp. particleboards are illustrated in **Figure 2**, 3 and 4 respectively. The results showed that the mass attenuation coefficients of the phantom samples were decreased at higher scattered gamma energies similar to the study by Limkitjaroenporn et al\(^{[5]}\). The results also showed that the measured mass attenuation coefficients of the phantom materials were in agreement to their respective theoretical values measured using XCOM calculations. The paired sample t-test was calculated between measured and theoretical values of mass attenuation coefficients and presented in Table 3. The results showed that there was no significant different between the theoretical values to the measured values of mass attenuation coefficients of the phantom samples. This indicated the consistency between the experimental values of the mass attenuation coefficients to the theoretical values.
<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Water (XCOM)</th>
<th>Solid water</th>
<th>Perspex®</th>
<th>Rhizophora particleboards</th>
<th>spp.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu/\rho_{\text{meas}}$</td>
<td>$\mu/\rho_{\text{theo}}$</td>
<td>$\mu/\rho_{\text{meas}}$</td>
<td>$\mu/\rho_{\text{theo}}$</td>
<td>$\mu/\rho_{\text{meas}}$</td>
</tr>
<tr>
<td>337.72</td>
<td>0.120</td>
<td>0.115</td>
<td>0.107</td>
<td>0.114</td>
<td>0.118</td>
</tr>
<tr>
<td>401.76</td>
<td>0.106</td>
<td>0.105</td>
<td>0.103</td>
<td>0.11</td>
<td>0.115</td>
</tr>
<tr>
<td>479.90</td>
<td>0.105</td>
<td>0.096</td>
<td>0.094</td>
<td>0.105</td>
<td>0.109</td>
</tr>
<tr>
<td>564.09</td>
<td>0.097</td>
<td>0.085</td>
<td>0.086</td>
<td>0.099</td>
<td>0.103</td>
</tr>
</tbody>
</table>

Table 3. The measured and theoretical (XCOM) values of mass attenuation coefficients of water, solid water, Perspex® and fabricated Rhizophora spp. particleboards at scattered gamma energies.

Figure 2. The measured and theoretical (XCOM) values of mass attenuation coefficients of solid water phantoms at different scattered gamma energies.

Figure 3. The measured and theoretical (XCOM) values of mass attenuation coefficients of Perspex® at different scattered gamma energies.
Figure 4. The measured and theoretical (XCOM) values of mass attenuation coefficients of fabricated Rhizophora spp. particleboards at different scattered gamma energies.

3.3. Comparison of Mass Attenuation Coefficients to Water

The measured mass attenuation coefficients of the phantom samples in comparison to the theoretical values of water using XCOM are illustrated in Figure 5. The results showed good agreement between the experimental values of mass attenuation coefficients in the phantom samples to the values of water. The values of mass attenuation coefficients of the phantom samples were closer to the values of water at lower gamma energies compared to that in higher gamma energies. Water had been recommended as standard phantom material for high energy photons by many available dosimetry standards. Therefore the comparison of mass attenuation coefficients to water can be used to determine the water equivalent property of the phantom samples.

The paired sample t-test was also calculated between the values of water to that in the phantom samples as shown in Table 4. The results showed that there were no significant different of mass attenuation coefficients between the water and the phantom samples indicating the similarities of attenuation properties of the phantoms to water.

<table>
<thead>
<tr>
<th>Paired samples</th>
<th>Mean</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid water_{meas}Solid water_{theo}</td>
<td>0.096</td>
<td>1.457</td>
<td>3</td>
<td>0.2411</td>
</tr>
<tr>
<td>Perspex_{meas}Perspex_{theo}</td>
<td>0.111</td>
<td>17</td>
<td>3</td>
<td>0.0004</td>
</tr>
<tr>
<td>Rhizophora_{meas}Rhizophora_{theo}</td>
<td>0.097</td>
<td>2.422</td>
<td>3</td>
<td>0.0934</td>
</tr>
</tbody>
</table>

Figure 5. The mass attenuation coefficients of the phantom materials in comparison to the theoretical values of water (XCOM).
Table 4. The paired sample t-test between the theoretical and measured values of mass attenuation coefficients of the phantom samples.

The overall results indicated the consistency of mass attenuation coefficients between the experimental values to the theoretical values using XCOM. The results also indicated the suitability of Ludlum configuration for the measurements of mass attenuation coefficient using Compton scattering technique.

4. Conclusion

The energy of scattered gamma decreased at larger scattering angles. The measured mass attenuation coefficients of the experimented water equivalent phantom materials and fabricated Rhizophora spp. particleboards decreased at higher gamma energies. A comparison to the theoretical values of mass attenuation coefficients using XCOM showed good agreement between the experimental values and theoretical values at all gamma energies. The experimental values of mass attenuation coefficients of the phantom samples also showed good agreement to the theoretical values of water using XCOM at all gamma energies. The close values of mass attenuation coefficients of the fabricated Rhizophora spp. particleboards to water in this study is in good agreement to the previous works on the fabrication of Rhizophora spp. particleboards as phantoms. The overall results also indicated the suitability of Ludlum configuration for measurement of mass attenuation coefficient using Compton scattering technique.

References