Fabrication of new non-hazardous tungsten carbide epoxy resin bricks for low energy gamma shielding in nuclear medicine

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Abstract

Introduction. The main aim of this study was to fabricate a lead-free tungsten carbide epoxy resin brick that has similar shielding properties to lead brick for low energy gamma shielding in nuclear medicine. The attenuation properties of bricks were characterized by using gamma transmission principle in Single-Photon Emission Computed Tomography (SPECT) scanner. Materials and methods. In this study, various percentage of tungsten carbide epoxy resin were fabricated into brick with thickness of 0.5 cm, 1.0 cm, 1.5 cm and 2.0 cm. Tungsten carbide epoxy resin and lead bricks were irradiated with gamma rays from 99mTc to evaluate the radiation attenuation properties. A detector was used to evaluate the gamma shielding performance at 140 keV. The activity of the radioactive source was measured and recorded. The radiation attenuation of tungsten carbide epoxy resin bricks was compared with lead brick of same size and thickness. The gamma transmission was evaluated by using SPECT. Results. Results showed that tungsten carbide epoxy resin brick attenuates more radiation than a lead brick of the same thickness. This study also found that tungsten carbide epoxy resin brick is an effective radiation shielding material compared to lead. The best tungsten carbide and epoxy resin combination was found with a mixture of 90%:10% by weight, respectively. The study showed that both half-value layer and mean free path are higher at thicker samples for all materials at 140 keV. This study found that tungsten carbide and tungsten carbide epoxy resin bricks have small half-value layer and mean free path compared to lead brick. The values were 0.07 cm and 0.06 cm for lead and tungsten carbide, respectively. Conclusion. This study showed that attenuation coefficient measurement can be performed using gamma transmission principle in SPECT. Tungsten carbide epoxy resin shows high potential to replace lead as radiation shielding material.

1. Introduction

Nuclear medicine uses various gamma emitting radioactive sources [1, 2]. Gamma radiation generated from nuclear facilities is harmful to human beings and surrounding. High exposure of gamma radiation can cause direct acute effects through immediate damage to cells. Low levels of exposure carry a stochastic health risk where the probability of cancer induction rises with increased exposure [3, 4]. Gamma rays had been listed as carcinogenic by the International Committee on Radiological Protection (ICRP) [5–7]. Therefore, radiation shielding is very important to weaken the carcinogenic effects as well as its genetic effects that can cause cell mutations. This has become an urgent issue in the field of radiation protection to avoid unnecessary exposure to nuclear medicine personnel and general public [8, 9].

Ionizing radiation are absorbed best by high density materials and heavy atoms [10, 11]. Radiation shielding is required to reduce the intensity of the radiation [12]. It is one of the basic three protection principles recommended by the ICRP that includes minimizing operation time and maximizing distance [13, 14].
Lead is a conventional radiation shielding material used to attenuate high radiation. It is known for its good physical and mechanical properties [15]. To date, the conventional lead has been used for radiation protection from ionizing radiation hazards. It is known that the conventional lead is the most widely used radiation shielding material due to its high atomic number and high gamma shielding capability [16]. However, the disadvantages of the conventional lead are toxic heavy metal that gives environmental problem and public health concern. Thus, lead cannot meet the requirement of lightweight and environmentally friendly product for nuclear facilities [17–19]. Recently, there is high demand for new radiation shielding materials studies to substitute shielding products made of lead with environmentally friendly, non-toxic materials [20–23]. New radiation shielding materials such as tungsten have emerged as potentially suitable materials to overcome limitation of using lead as shielding material [24–27]. In addition, novel polymer-based lightweight composite materials have been investigated to be used for radiation shielding [28]. Epoxy resin is used in many industries due to its excellent chemical corrosion resistance, high tensile, fatigue, and compressive strength [29]. Polymer materials have unique properties such as low density, lightweight, and high flexibility and are widely used in various industrial sectors [30]. The shielding capacity of epoxy resin can be improved by adding heavy metal powders with different weight percent of tungsten [31].

Figure 1. Tungsten carbide powder.

Figure 2. The tungsten carbide/epoxy mixture placed on a magnetic stirrer.
Previous study showed that the radiation shielding and mechanical characteristics of tungsten and epoxy composites were evaluated by using a $^{60}$Co gamma radiation source. It is also showed that with the increment of tungsten loading, shielding property of composites increases [26]. A composite shield is made up of a base material mixed with additives. This can improve the radiation shielding capability of the material [32].

Improvement and development of non-toxic, environmentally friendly radiation shielding materials are rapidly growing. In this study, radiation attenuation of new lead-free radiation shielding material consisting of tungsten carbide powder and epoxy resin with different weight percentages was investigated for low energy gamma shielding in nuclear medicine.

### 2. Materials and methods

#### 2.1. Tungsten carbide epoxy resin bricks preparation

In this study, four different thicknesses of tungsten carbide epoxy mixture were fabricated with thickness of 0.5 cm, 1.0 cm, 1.5 cm and 2.0 cm. The tungsten carbide powder used in this study was purchased from Mayinglong Pharmaceutical Group Ltd. The purity of tungsten carbide was 99.9% and aerodynamic particle size was within the range 40–50 μm.
The epoxy resin and hardener type (E-110I/H-9) was purchased from Pan Asel Chemicals Company. The fabricated samples were weighed by an analytical balance before mixing process (figure 1). Tungsten carbide powder and epoxy resin were mixed to get homogenous mixture. Then, the mixture was added to a magnetic stirrer at 1400 rpm for 20 min (figure 2). The tungsten carbide epoxy mixture was poured into a small mould (figure 3) and left for 24 h to dry. The weight percentage of different tungsten carbide epoxy resin samples are listed in table 1.

The density of the fabricated tungsten carbide epoxy resin is shown by equation (1) [33].

$$\rho_m = \frac{\rho_t}{\rho_w} \cdot \frac{100}{100 - \epsilon_w}$$

where, $\rho_m$ is the density of the mixture, $\epsilon_w$ is the concentration by weight in percent, $\rho_t$ is the density of epoxy resin, and $\rho_w$ is the density of tungsten carbide powder. The measured densities of the fabricated materials are listed in table 2.

2.2. SPECT scanning

The general concept of photon attenuation incorporates two types of interactions: absorption and scattering. The total attenuation coefficient for an interaction is given by the sum of the possible photon interaction mechanisms [34]. The attenuation of gamma radiation can be calculated using equation (2).
\[ I = I_0 e^{-\mu x} \]  

(2)

where \( I_0 \) denotes the initial photon intensity and \( I \) is the photon intensity transmitted through the sample with thickness \( x \). Determination of mass attenuation coefficient of the materials was performed by dividing the linear attenuation coefficient of the material by the density \( (\rho) \) of the material (equation 3).

\[ \frac{\mu}{\rho} = x^{-1} \ln \left( \frac{I_0}{I} \right) \]  

(3)

Attenuation coefficient measurements can be calculated quantitatively in SPECT. The radioactive source emits gamma radiation [35]. A gamma camera measured counts from the radioactive source based on the gamma energy, and signals are converted into a display image by a computer [36].

Following the same principle, this study used a radioactive source, \(^{99m}\)Tc, to evaluate the radiation shielding efficiency of different materials by placing the sample between a shielded vial contained radioactive source (only the top part covered by the sample was unshielded) and a detector. Count rates were recorded in this study with and without placing shielding material on the radioactive vial. The reduction in the counts rate showed the attenuation of gamma photons by the sample. The radionuclide used in this study is shown in table 3.

The activity of the \(^{99m}\)Tc was measured and recorded using Dose Calibrator from BIODEX—ATOMLAB 500 as shown in figure 4. The radioactive source was placed on a shielded vial with an unshielded top to place the sample, as shown in figure 5.

The half value layer was evaluated in this study to analyse the penetrating ability of radiation through materials. It represents the thickness of an absorber that will reduce the gamma radiation to half. The HVL was evaluated by dividing \( \ln 2 \) with linear attenuation coefficient at specific gamma-ray energy as shown in equation (4).

\[ HVL = \frac{\ln 2}{\mu} \]  

(4)

The mean free path is the average distance a photon travels between collisions with atoms of the target material. The mean free path of material was computed from equation (5).

\[ MFP = \frac{1}{\mu} \]  

(5)
Table 6. Mass attenuation coefficient of lead, tungsten carbide and tungsten carbide epoxy resin composites at 140 keV.

| Thickness (cm) | Lead | WCE1 | WCE2 | WCE3 | WCE4 | WCE5 | WCE6 | WCE7 | WCE8 |
|---------------|------|------|------|------|------|------|------|------|------|
| 0.5           | 1.23 | 1.17 | 1.17 | 1.42 | 1.37 | 1.24 | 1.18 | 1.26 | 1.25 |
| 1.0           | 1.11 | 1.12 | 1.02 | 1.27 | 1.29 | 1.12 | 1.05 | 1.05 | 0.9  |
| 1.5           | 0.98 | 0.98 | 0.8  | 0.87 | 0.78 | 0.67 | 0.66 | 0.76 | 0.8  |
| 2.0           | 0.88 | 0.89 | 0.6  | 0.75 | 0.7  | 0.6  | 0.5  | 0.5  | 0.49 |

Table 7. The half value layer of all samples at 140 keV.

| Thickness (cm) | Lead | WCE1 | WCE2 | WCE3 | WCE4 | WCE5 | WCE6 | WCE7 | WCE8 |
|---------------|------|------|------|------|------|------|------|------|------|
| 0.5           | 0.07 | 0.06 | 0.07 | 0.09 | 0.09 | 0.11 | 0.15 | 0.16 | 0.17 |
| 1.0           | 0.08 | 0.08 | 0.08 | 0.08 | 0.09 | 0.11 | 0.17 | 0.19 | 0.24 |
| 1.5           | 0.11 | 0.10 | 0.11 | 0.11 | 0.12 | 0.12 | 0.17 | 0.20 | 0.21 |
| 2.0           | 0.15 | 0.14 | 0.15 | 0.15 | 0.15 | 0.15 | 0.17 | 0.21 | 0.21 |

Table 8. Mean free path (cm) value of all samples at 140 keV.

| Thickness (cm) | Lead | WCE1 | WCE2 | WCE3 | WCE4 | WCE5 | WCE6 | WCE7 | WCE8 |
|---------------|------|------|------|------|------|------|------|------|------|
| 0.5           | 0.10 | 0.09 | 0.11 | 0.11 | 0.14 | 0.16 | 0.22 | 0.23 | 0.25 |
| 1             | 0.12 | 0.12 | 0.12 | 0.12 | 0.14 | 0.16 | 0.25 | 0.27 | 0.35 |
| 1.5           | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.17 | 0.25 | 0.29 | 0.30 |
| 2             | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.25 | 0.30 | 0.31 |
3. Results and discussion

Table 4 summarizes the properties of the epoxy resin and hardener used in this study. E-110I/H-9 is two-component non-volatile, non-toxic, and colorless material. It exhibits outstanding features, making it the best combining material, as shown in table 4.

3.1. Tungsten carbide epoxy resin composites measurements

Results of linear attenuation coefficients, mass attenuation coefficient, half value layer and mean free path of lead, tungsten carbide, and tungsten carbide epoxy resin composites of 0.5 cm, 1.0 cm and 1.5 cm, and 2 cm thickness at 140 keV are summarised in tables 5–8, respectively. Table 6 shows the mass attenuation coefficient of one layered shield composed of tungsten carbide and epoxy resin relative to lead in comparing to a study performed on three layered shield composed of tungsten, bismuth and gadolinium [37].

Thin layers of lead, WCE2, and WCE3 samples with 1.0 cm and 1.5 cm thickness have approximately same attenuation ability at 140 keV. The WCE2 sample with thickness of 2.0 cm thickness is the best attenuator at the same energy. On the other hand, WCE7 and WCE8 samples are the least effective attenuators, as shown in figure 6.

In this study, WCE1 sample recorded slightly higher attenuation coefficient than lesser thickness of lead and WCE2 sample energy of 140 keV (figure 7). On the other hand, WCE1 sample and lead had same attenuation coefficient at thicker sample. WCE5 and WCE6 samples had the same attenuation coefficient at 1.5 cm thickness, while WCE6 and WCE7 samples had same attenuation coefficient at 2.0 cm thickness.

It is obvious that the mass attenuation coefficient (MAC) improves with increased weight percentage of tungsten carbide powder at 140 keV. However, there was no improvement of the mass attenuation coefficient with the increase of the loading of particles as shown in WCE2 and WCE3 samples. This is due to partial inhomogeneity occurs during the fabrication process of the samples. Thus, there was poor contact between the tungsten carbide particles and epoxy resin matrix. The homogeneity of the mixture can be improved in future study by applying advanced proper stirring technique rather than the manual and magnetic stirring.

In addition, tables 7 and 8 showed the half value layer and the mean free path value of all samples at 140 keV. The study showed that both half value layer and mean free path are higher at thicker samples at 140 keV for all samples. The half value layer values of the tungsten carbide epoxy samples under study have been calculated using the obtained μ values as explained in equation (4). The range of HVL of the studied samples is observed to be (0.06–0.17 cm), (0.08–0.24 cm), (0.10–0.21 cm), and (0.14–0.21 cm) for tungsten carbide epoxy samples at 0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm thickness respectively. The lower half value layer is found at 0.5 cm thickness of WCE1 sample that has the highest density among all tungsten carbide epoxy samples. It is followed by lead, WCE2 and WCE3 samples with half value layer of 0.07 cm.

Samples with higher densities have higher potential for gamma photons to strike the atoms, which increases the probability of photon interactions resulting in only a few photons being passed through the shielding material. The average distance a photon can travel before interaction with the atoms of the target material.
known as mean free path. As shown in table 8, the highest mean free path values are obtained with the sample WCE8 that has the least weight percentage of tungsten carbide content, while the lowest mean free path value obtained with the samples WCE1 and WCE2 together with lead sample.

Results also showed that WCE2 sample is the best mixture combination of tungsten carbide and epoxy resin mixture among all samples for effective radiation shielding material. Effective shielding material should decrease radiation energy in a small depth of penetration without emitting other type of radiation. Furthermore, the half value layer and mean free path indicate the performance of the radiation shielding material. Materials with low half value layer and mean free path exhibit superior radiation shielding performance [28]. In other words, the lower the half value layer, the better the material under consideration for radiation shielding purposes. As the half value layer is inversely proportional to the linear attenuation coefficient, it means that materials with high linear attenuation coefficient should have a low half value layer.

This study also found that tungsten carbide and tungsten carbide epoxy resin bricks show better radiation shielding performance compared to lead at same energy. The development of materials with high radiation shielding capability is vitally needed due to the safety regulations for gamma utilization in various applications and activities. Small thickness of tungsten carbide is required for radiation shielding compared to lead at the same energy. The radiation shielding performance of tungsten carbide epoxy resin in terms of half value layer and mean free path analysis show that tungsten carbide epoxy composites performance is consistent.

Furthermore, tungsten carbide also has superior physical properties such as hardness and strength compared to lead and pure tungsten [38]. Tungsten carbide epoxy resin are easily fabricated, known as light weighted and non-toxic composites as well as their gamma ray shielding effectiveness, make them a choice for commercial utilization [39]. Therefore, the tungsten carbide epoxy resin shows promising lead-free radiation shielding material for radiation protection in nuclear medicine.

4. Conclusion

In conclusion, this study has successfully fabricated a lead-free tungsten carbide epoxy resin brick that has similar shielding properties to conventional lead brick for low energy gamma shielding in nuclear medicine. This study also found that pure tungsten carbide and tungsten carbide epoxy composite can be used as a radiation shielding material to stop gamma radiation. Tungsten carbide samples attenuate more radiation than lead samples which indicates it as an effective shielding material. The best tungsten carbide epoxy resin combination was found at a mixture of 90%:10% by weight, respectively. The study showed that both half value layer and mean free path are higher at thicker samples at the same energy for all tested samples. Hence, pure tungsten carbide has high potential to replace lead as a new lead-free radiation shielding material in diagnostic imaging and therapy. The study suggests that the use of polymer composites as a substitute for the harmful lead currently in radiation shielding compartments is feasible.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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