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THE ABSORPTION PROPERTIES OF LEAD-FREE GARMENTS FOR USE IN RADIATION PROTECTION

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In this study, the absorption capability and the weight of various radiation-shielding materials were evaluated, for applications as alternatives to lead garments. Toxicity, atomic number, density, K-edge absorption energy and availability of elements that can serve as an alternative to lead, including tin, antimony, bismuth and tungsten, were considered. The attenuation coefficients of these elements were determined using the XCOM software package, and these metals were mixed with polymers at 50, 70, 80 and 85 % mass ratios. It can be concluded that all of the new shielding materials used in the study can be used for a diagnostic range of X-rays. However, they were compared with the commercial lead garments in terms of weight and attenuation coefficient; the 85 % samples were lighter than a 0.5-mm lead garment and provided superior radiation protection, which demonstrates its potential for commercial applications.

INTRODUCTION

Lead-based protective garments has been widely utilised in radiation protection[1] to protect staff as well as patients in the health centres against therapeutic and diagnostic X-ray exposures. The main reasons for the use of lead can be summarised as follows: lead is easy to process, has a large absorption coefficient and can provide effective protection over a wide range of photon energies[2, 3]. However, lead garments are naturally heavy and wearing them for long runs of new radiological procedures such as interventional radiology makes it uncomfortable for radiation workers. In addition, lead is a toxic element, and hence the fabrication and disposal of lead has been restricted and also prohibited in some cases[4].

The problem of heavy weight of lead-based shielding garments has been addressed by replacing a fraction of lead with moderate atomic number elements such as tin, antimony, yttrium, copper and barium. To provide the attenuation like lead, these new shielding garments utilise K-edge photoelectric interactions and high photon absorption occurs for photons with the energy of equal or slightly higher than K-shell binding energy. On the other hand, radiation protection properties of lead-free garments are strongly influenced by beam quality and the specification of attenuation characteristics at various beam qualities is required. Additionally, in the medical guidelines document (Medical Guidance, 2002) published by the Institute of Physics and Engineering in Medicine (IPEM), it is recommended that 'body garments should be available with a protective equivalent of not less than 0.25 mm lead for x-rays up 100 kVp and not less than 0.35 mm lead for x-rays over 100 kVp'. On the other hand, the quantity of lead used in protective garments may be reduced through the use of composite materials, which can reduce the toxic effects of lead as well as the weight of the garment[5]. Lead-free garments have also been manufactured, and some of these products have been commercialised and have been introduced into imaging departments of hospitals.

Several studies have reported the performance of new lead-composite, and lead-free shielding materials both in primary and scattered X-ray beams[6–15]. Hubbert *et al*. studied the attenuation properties of lead-composite garments against scattered radiation of a fluoroscopy beam at 110 kVp. They found that lead-composite garments are capable of providing protection comparable with lead garments[16]. Jones and Wagner measured the penetration of primary and scattered radiation through lead sheets and three protective garments of nominal 0.5 mmPb equivalence, one lead and two lead-free.

The objective of this study was to investigate the potential for production of new generation lighter garments that can provide radiation protection equivalent to that of lead garments.

MATERIALS AND METHODS

Determination of the samples and production

Tin, antimony, bismuth and tungsten were selected as alternatives to lead and were purchased from MHC Industrial Co., China, in powder form, with diameters in the range of 20–50 μm. The mass attenuation coefficients of metal powder mixtures of these four elements were determined using the XCOM software package (XCOM, version 3.1, M.J. Berger and J.H. Hubbell, 23 June 1999) (Figure 1). In accordance with the data obtained using XCOM, four samples were produced with the following mass ratios: 50 % metal powder and

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50 % polymer (first sample), 70 % metal powder and 30 % polymer (second sample), 80 % metal powder and 20 % polymer (third sample) and 85 % metal powder and 15 % polymer (fourth sample).

During mixing and vulcanisation, a homogenous distribution of the metal powder within the polymer matrix was achieved. The Mooney viscosity was measured according to ISO 289-1 standards; the vulcanisation curve was determined using a rheometer according to ISO 3417 standards; the tensile properties were evaluated according to ASTM D412 standards; the hardness was evaluated according to ASTM D2240 standards; and the density was determined using Archimedes' principle. Samples that did not pass one of these tests (which were carried out in the Plastics and Rubber Technology Laboratory) were not used for further study. This study observed that a mass fraction of the metals of 85 % was the saturation point for the polymer material used, and samples with a metal mass fraction of 90 % or greater were not produced. However, it was found that all the samples produced had elasticity property.

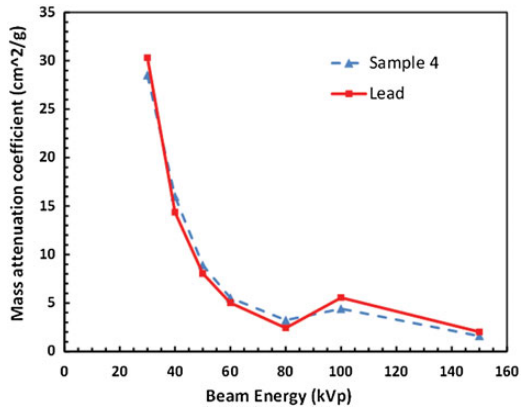

Figure 1. Mass attenuation coefficient as a function of the photon energy for metal mixtures and lead. These data were calculated using XCOM.

Determination of the shielding effect for primary and secondary X rays

The radiation absorption properties of the samples were measured for primary and secondary (scattered and leakage) X rays. For primary radiation measurements, the X-ray exposure at the distance of 100 cm was measured in μGy for a field size of 14 × 14 cm using a solid-state Unfors Xi detector (Unfors Instruments, Billdal, Sweden).

The air kerma values were measured in air for tube voltages in the range of 50–125 kVp at 5 kVp intervals. Tube current of 100 mA and the exposure time of 0.1 s were maintained constant, and five measurements were made for each tube voltage. The air kerma was read in μGy, and the results were recorded as the mean, with the error given by the standard deviation of these data. For the attenuation measurements, the samples were placed on the detector as shown in Figure 2.

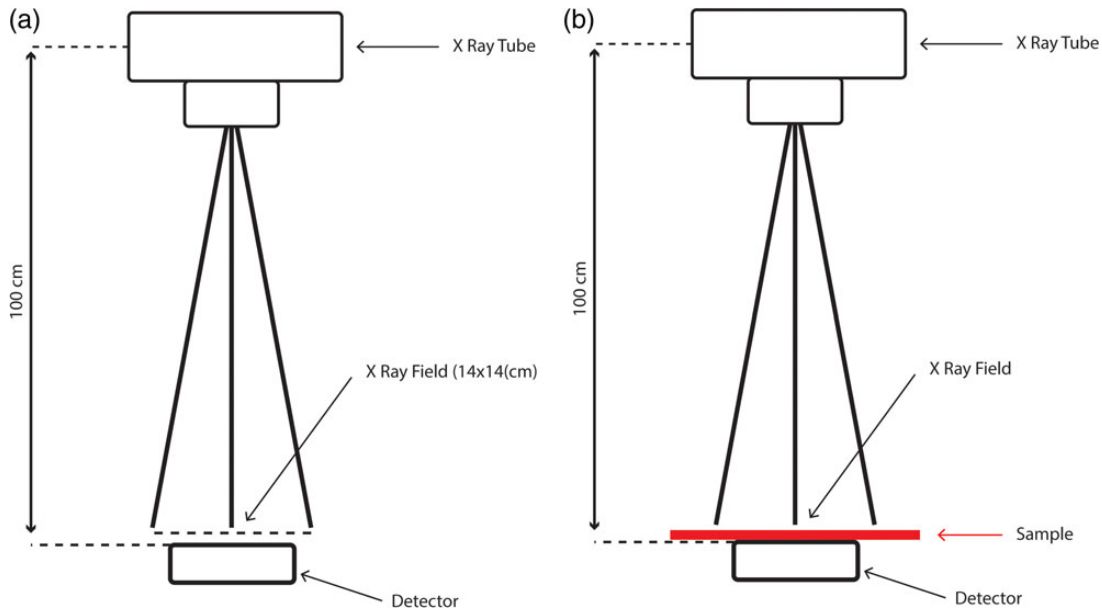

Figure 2. (**a**) Measurement of the air kerma in the primary radiation field. (**b**) Measurement of the radiation attenuation of the samples in the primary radiation field.

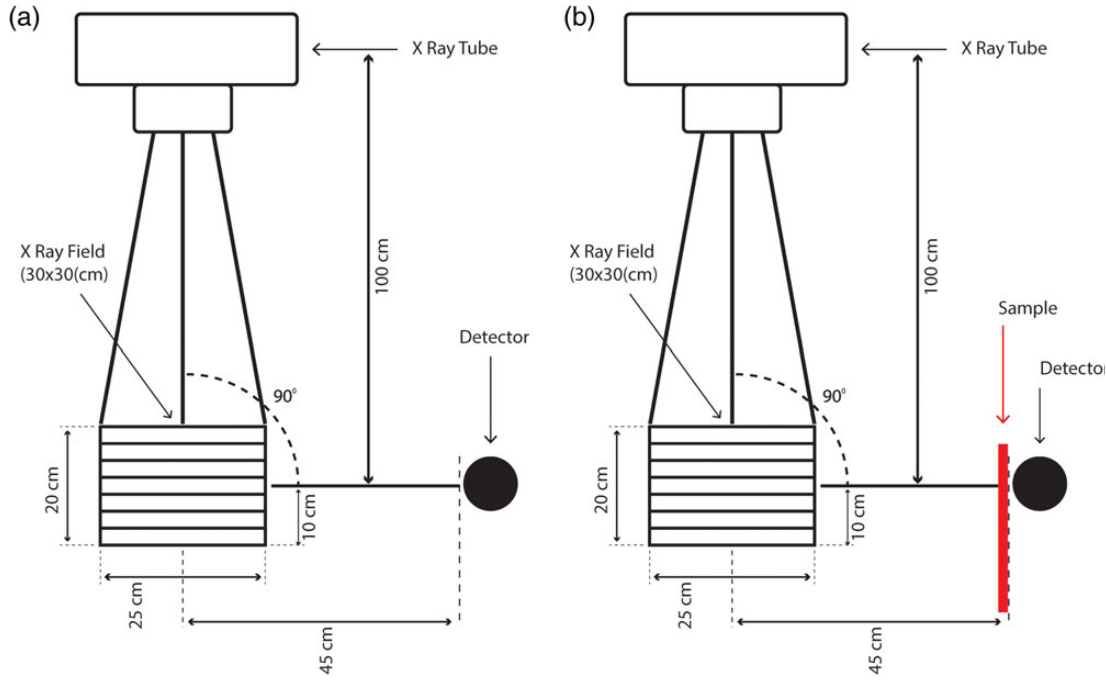

Figure 3. The system used to measure the air kerma of scattered radiation. (**a**) Measurement without shield and (**b**) measurement with the presence of shields.

For scattered radiation measurements, the scattered radiation from a 20-cm-thick polymethyl methacrylate (PMMA) phantom was utilised. To evaluate the absorption of scattered X radiation, the measurement set-up illustrated in Figure 3 was used.

For scattered radiation measurements, the distance between the focal spot and the centre of the phantom was 100 cm and the distance between the centre of the phantom and the detector was 45 cm. The experimental set-up was consistent with the Jones and Wagner study[11]. The PMMA phantom with thickness of 20 cm, the field size of 30 × 30 cm, the tube current of 100 mA and the exposure time of 0.1 s was used. The samples were placed in front of the detector and all the parameters were kept the same throughout the scattered radiation experiments except for the tube voltage. For the all measurements described in this paper, the broad beam geometry was used as illustrated in Figures 2 and 3.

To determine the absorption capability of the garments, the percentage shielding effect[3] was calculated as follows:

$$\text{Shielding effect} = \frac{M_{\text{no}} - M_{\text{with}}}{M_{\text{no}}} \times 100 \qquad (1)$$

where M_{no} and M_{with} are the air kerma measurements without and with the presence of the garments, respectively.

The percentage shielding effect was calculated for each tube voltage using the air kerma values obtained with the primary X-ray beam and secondary (scattered) X-ray radiation. The same process was implemented for commercially available lead garments with 0.25 and 0.50 mm.

Lead-equivalent thickness of the samples

The Archer equation was used to calculate the lead-equivalent thickness of the samples, i.e.

$$x = \frac{1}{\alpha\gamma} \ln\left(\frac{B^{-\gamma} + (\beta/\alpha)}{1 + (\beta/\alpha)}\right), \qquad (2)$$

where the coefficients at a tube voltage of 100 kVp are $\alpha = 2.5$, $\beta = 15.28$ and $\gamma = 0.7557$, and B is the transmission coefficient, which is determined for each sample as the ratio of the radiation dose measured with an attenuating sample to that measured without (i.e. where the radiation passes only through air)[5, 6].

RESULTS

Sample thicknesses

The samples were obtained around 1 mm thick. The measured thicknesses are listed in Table 1, with an accuracy of ± 0.001 mm.

Table 1. The thickness of the samples.

Sample no.	Mass ratio	Thickness (mm)
1	%50 metal powder, %50 polymer	1.028 ± 0.030
2	%70 metal powder, %30 polymer	1.498 ± 0.045
3	%80 metal powder, %20 polymer	1.016 ± 0.059
4	%85 metal powder, %15 polymer	0.961 ± 0.011

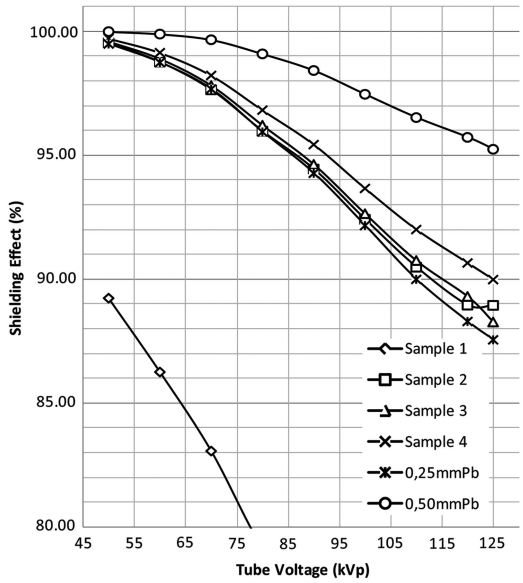

Figure 4. The percentage shielding effect of the samples and commercial garments as a function of the tube voltage for primary X-ray radiation.

Primary X-ray measurements

The calculated percentage shielding effect for primary X rays as a function of the tube voltage is shown in Figure 4. As it can be seen that with tube voltage increase the absorption capability of the samples decreased for all studied samples. It was also found that with increasing the content of metal in the samples, the absorption coefficient is also increased. The second, third and fourth samples exhibited similar absorption properties to the 0.25-mm lead-equivalent garment; however, the absorption coefficient of the first sample (with 50 % metal powder by mass) was significantly lower compared with other samples. None of the lead-free samples provided the same absorption as the 0.50-mm lead garment.

Scattered X-ray measurements

Figure 5 shows the percentage shielding effect as a function of the tube voltage for scattered X-ray radiation. The absorption coefficient decreased as the photon energy of the radiation increased, and the absorption coefficient increased as the mass fraction of metal in the composite samples increased.

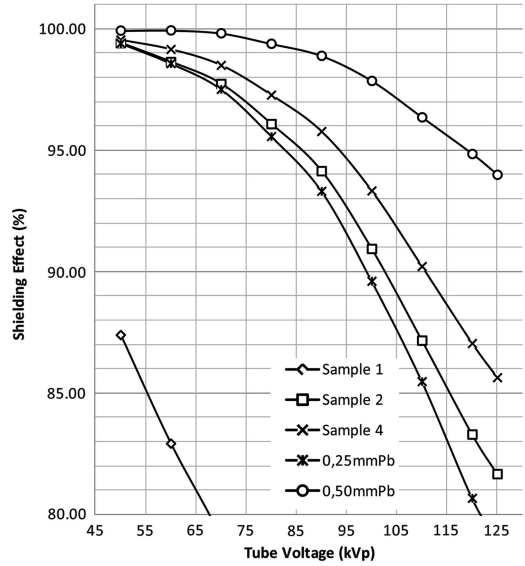

Figure 5. The percentage shielding effect of the samples and commercial garments as a function of the tube voltage for scattered x-ray radiation.

The second, third and fourth samples exhibited larger absorption coefficients than the first sample. The study also found that these three samples exhibited superior absorption to the 0.25-mm lead garment. As with the primary radiation absorption, all lead-free garments provided lower absorption than the 0.50-mm lead garment.

Lead-equivalent thicknesses and weight of the samples

Using the measured radiation doses a tube voltage of 100 kV for these four samples, the lead-equivalent thicknesses were calculated using the Archer equation (equation 2), and the masses were measured using a precision balance. Table 2 lists the radiation attenuation coefficient, and the mass and the thickness of the samples.

Pure Pb shielding would weigh 0.568 g cm^{-2}; therefore, a garment with an area of 1.0 m^2 and 0.5 mmPb equivalent material would weigh at least 5.7 kg. The average mass of a typical commercial one-piece 0.50-mmPb equivalent radiation-shielding garment is ~8 kg. 0.25-mmPb equivalent garment weighs half of the 0.5 mmPb equivalent garment[12]. As seen from the data listed in Table 2, samples used in this study were lighter than 0.5 mmPb.

DISCUSSION

Lead shields are mostly used against ionising radiation used during diagnosis and therapy and they are

considerably heavy. Therefore, a series of successful theoretical and experimental studies has increased the production of new shielding materials that have better protection and lightweight compared with lead shields.

There have been many papers regarding the lead-free garments used for radiation shielding in the literature. In these studies, the radiation absorption properties of high-density metals have been increased by using metal powders and polymer materials.

In Figures 4 and 5, compared with the lead sheet with thickness of 0.25 mm, all samples used in this study, except Sample 1, showed higher shielding effect in all studied ranges of beam energies, from 50 to 125 kVp. Maximum shielding effect was seen for Sample 4 for all energy ranges and the least shielding was observed for Sample 1. It is because the metal content of Sample 4 is 85 % and is the highest one among the study samples. Moreover, it is evident that the shielding effect of Samples 2, 3 and 4 is comparable and very close to lead sheet of 0.5 mm for the energy range of 50 to 80 kVp. The results were consistent with the results of Eder *et al.*[1, 2].

In the study of Eder *et al.* using the polymer material as a substrate, different fractions of tin, bismuth and tungsten were used to fabricate new shielding sheets. Then they evaluated the radiation attenuation characteristics of their samples against beam energies of between 60 and 150 kVp of X-ray tube. The shielding effect of 95 % for 60 kVp, 89 % for 80 kVp, 80.8 % for 100kVp, 74.4 % for 125 kVp and 69.7 % for 150 kVp was seen in their results[1]. The results are in close agreement with their study and the shielding effect of Sample 4 was better than their results. In another study by the same group, new materials were designed and their absorption properties were measured for 100 kVp. They reported that their samples lead-equivalent thickness were 0.60 mm Pb, 0.65 mm Pb, 0.66 Pbmm and 0.63 mm Pb[17]. Their lead-equivalent thickness was better than our results because of differences in used materials and their fractions.

In several studies, the shielding effect of various commercial lead and lead-free garments were evaluated and lead-equivalent thickness was determined. The results indicated that commercial garments equivalent thickness was not consistent with the measured values in these studies[5, 18]. As stated by Muir *et al.* the commercial garment/vest, labelled 0.5-mm lead at 85 kVp, provides the equivalent protection between 0.3 and 0.39 mm lead depending on the energy used[18].

In another study by Jones and Wagner, the similar results were reported and they recommended that lead-equivalent thickness determination should be based on primary radiation measurements not on scattered radiations[11], because there are many influencing factors to the shielding effect measurement of scattered radiations.

The results are consistent with above-mentioned study and as it can be seen in Table 2 it was found 1.02, 3.84, 3.73 and 4.01 kg m^{-2} of the mass of the samples for 0.11, 0.32, 0.33 and 0.36 mmPb of the lead-equivalent thickness, respectively. Furthermore, comparison the weighs of the commercial lead garments and the samples, it was obtained 5.67 kg for the weight of a pure lead garment with thickness of 0.5 mm and area of 1 m^2 while for Sample 4 weight is 4.008 kg which is 30 % lighter. Sample 3 is lighter than Sample 4 because of the content of the metal 80 %, 0.33 mmPb of the lead-equivalent thickness and 3.73 kg m^{-2} of mass.

Taking into account all of these results, the lead-equivalent thickness of Sample 4 is preferable to the medical guidelines document of IPEM which states, 'Body garments should be not less than 0.35 mm lead for x-rays over 100 kVp'.

CONCLUSION

Conventional personal protection garments containing lead are widely used for protection from ionising radiation. Although inexpensive and easy to process, lead is toxic and heavy. For this reason, a new generation of protective garments, which can provide lead-equivalent protection, is of interest.

Protective garments must be sufficiently lightweight to enable long-term use by physicians, technicians and nurses. Except for the 50 % metal sample, all samples provided better protection than 0.25 mmPb equivalent. If the thickness of the samples was increased, it would be possible to achieve 0.50-mmPb equivalent. In

Table 2. The transmission coefficient and lead-equivalent thicknesses at a tube voltage of 100 kV, as well as the mass of the samples and commercial garments.

Sample no	Transmission coefficient (B), %	Lead-equivalent thickness (mmPb)	Mass (kg m^{-2})
1	27	0.11	1.0190 ± 0.0002
2	8	0.32	3.8415 ± 0.0001
3	7	0.33	3.7302 ± 0.0001
4	6	0.36	4.0081 ± 0.0001
0.25 mmPb	8	0.25	2.8
0.5 mmPb	3	0.5	5.7

particular, the 85 % metal sample, which was lighter than the 0.5 mmPb, provided 0.36 mmPb at a tube voltage of 100 kV and had a mass per unit area of 4.0081 kg m^{-2}.

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