A Novel Design for Production of Efficient Flexible Lead-Free Shields against X-ray Photons in Diagnostic Energy Range

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Abstract

Background: Lead-based radiation shields are widely used in radiology departments to protect both workers and patients from any unnecessary exposure to ionizing radiation. Recently there has been a great deal of concern expressed about the toxicity of lead. Human lead toxicity is well documented. In that light, production of environmentally-friendly lead-free radiation shields with less weight compared to conventional lead-based shields is a challenging issue. The aim of this study was to design lead free flexible radiation shields for protection against X and gamma rays.

Methods: In this investigation, a wide variety of metallic compounds which potentially could be appropriate radiation shields, were studied. The Monte Carlo code, MCNP4C, was used to model the attenuation of X-ray photons in shields with different designs. Besides simulation, experimental measurements were carried out to assess the attenuation properties of each shielding design. On the other hand, major mechanical properties of this shield such as tensile strength, modulus and elongation at break were investigated.

Results: Among different metals, tungsten and tin were the two most appropriate candidates for making radiation shields in diagnostic photon energy range. A combination of tungsten (45%) and tin (55%) provided the best protection in both simulation and experiments. In the next stage, attempts were made to produce appropriate Tungsten-tin-filled polymers which could be used for production of shielding garments. The density of this tungsten-tin-filled polymer was 4.4 g/cm^3. The MCNP simulation and experimental measurements for HVL values of this shield at 100 kVp were 0.26 and 0.24 mm, respectively. On the other hand, this novel shield provides considerable mechanical properties and is highly resistant to chemicals.

Conclusions: The cost-effective lead-free flexible radiation shield produced in this study offers effective *radiation* protection in a diagnostic energy range. This environmentally-friendly shield may replace the traditional lead-based shielding garments.

Keywords

Radiation Protection, Lead-free Shields, Non-Lead Shielding Garments, Tungsten, Tin, X-rays, Diagnostic Energy

Introduction

Lead has long been used in radiology departments to protect both workers and patients from any unnecessary exposure to ionizing radiation [1-3]. Over the past years a great deal of concern has been expressed about the toxicity of lead [4]. Human lead toxicity in children as well as adults is well documented [5-11]. There are also reports on the need for corrective measures due to corrosion of lead sheets when lead is used for structural shielding [12]. Based on the above mentioned facts, production of environmentally friendly non-toxic lead-free radiation shields which provide less weight compared to conventional lead-based shields remains a challenging issue in radiation protection. On the other hand, to date, the use of non-lead shields has been associated with some unexpected problems such as being efficient only at a restricted tube-voltage range or the need for acceptance and ongoing tests [13, 14]. In that light, efforts have been made globally for finding new materials and designs for production of lead-free radiation shields [15,16]. The aim of this study was to design lead free flexible radiation shields for protection against X and gamma rays.

Materials and Methods

In the 1st phase of the study, a wide variety of metallic compounds (atomic numbers ranged 26-83) which potentially could be appropriate radiation shields, were studied. The general purpose Monte Carlo *N*-particle radiation transport computer code (MCNP4C) was used to model the attenuation of X-ray photons in shields with different designs. After finding the best combination of attenuating elements for shielding X-ray photons at 100 kVp by MCNP modeling, we used different metal powders dispersed in rubber or plastic to make *flexible* shields. Then experimental measurements were carried out to assess the attenuation properties of each shielding design. In this regard, the attenuation of poly-energetic X-rays emitted by a diagnostic CPI (CMP200 with Varian tube) X-ray machine (with 3.1 mm Al filtration at tube potential of 100 kVp) was measured under conditions of good geometry (well-collimated, narrow beam of radiation). Dose rates were measured using a Farmer type ion chamber (Wellhofer) and an electrometer (Wellhofer). On the other hand, major mechanical properties of this shield such as tensile strength, modulus and elongation at break were investigated.

Table 1: MCNP results of radiation intensity after passing from shields with different compositions

100 kVp	I	I_0	I/I_0	%metals	%metals in matrix	Density (g/cm³)
1	5.29×10^{-07}	7.71×10^{-06}	0.069	45%W 55%Sn	39.06%W 47.74%Sn	4.592
2	5.49×10^{-07}	7.71×10^{-06}	0.071	100%W	86.8%W	5.654
3	5.54×10^{-07}	7.71×10^{-06}	0.072	35%W 65%Sn	30.38%W 56.42%Sn	4.44
4	5.71×10^{-07}	7.71×10^{-06}	0.074	28.5%W 71.5%Sn	24.74%W 62.06%Sn	4.348
5	5.84×10^{-07}	7.71×10^{-06}	0.076	25%W 75%Sn	21.7%W 65.1%Sn	4.298
6	6.30×10^{-07}	7.71×10^{-06}	0.082	15%W 85%Sn	13.02%W 73.78%Sn	4.17
7	7.26×10^{-07}	7.71×10^{-06}	0.094	100%Sn	86.8%Sn	3.98
8	7.37×10^{-07}	7.71×10^{-06}	0.096	100%Pb	86.8%pb	4.795
9	7.42×10^{-07}	7.71×10^{-06}	0.096	100%Bi	86.8%Bi	4.534
10	1.10×10^{-06}	7.71×10^{-06}	0.143	100%Ba	86.8%Ba	2.636

Table 2: HVL determination by measuring the radiation intensity after passing a layer of 2mm thickness of tungsten (45%) and tin (55%) powder in grease matrix.

2 mm	39.06%W, 47.74%Sn,13.2% Grease		
100 kVp	**I**	**I_0**	**I/I_0**
1	0.018	2.84	0.006
2	0.012	2.84	0.004
3	0.02	2.84	0.007
4	0.026	2.84	0.009
5	0.021	2.84	0.007
6	0.011	2.84	0.004
7	0.013	2.84	0.005
8	0.016	2.84	0.006
9	0.015	2.84	0.005
Average	0.016889	2.84	0.006

Table 3: HVL determination by measuring the radiation intensity after passing a layer of 2mm thickness of lead powder in grease matrix.

2 mm	86.8% Pb,13.2% Grease		
100 kVp	**I**	**I_0**	**I/I_0**
1	0.048	2.81	0.017
2	0.048	2.81	0.017
3	0.048	2.81	0.017
4	0.048	2.81	0.017
5	0.053	2.81	0.019
6	0.051	2.81	0.018
7	0.039	2.81	0.014
8	0.045	2.81	0.016
9	0.044	2.81	0.016
Average	0.047111	2.81	0.017

Results

In the screening phase of the study, tungsten and tin were found to be the two most appropriate candidates for radiation shielding in a diagnostic photon energy range. A combination of tungsten (45%) and tin (55%) provided the best protection in both simulation and experiments. In Table 1 radiation intensities after passing from shields with different compositions using MCNP modeling is shown. As indicated in this table, the highest attenuation comes from a specific combination of two non-lead metals (45% tungsten and 55% tin). The attenuation of lead shields was much lower than that of the non-lead shield. The densities of lead and tungsten-tin shields were 4.80 and 4.59 g/cm^3, respectively. Table 2 shows the results of HVL determination by measuring the radiation intensity after passing a layer of 2mm thickness of tungsten (45%) and tin (55%) powder in grease matrix. On the other hand, in Table 3, the results of HVL measure-

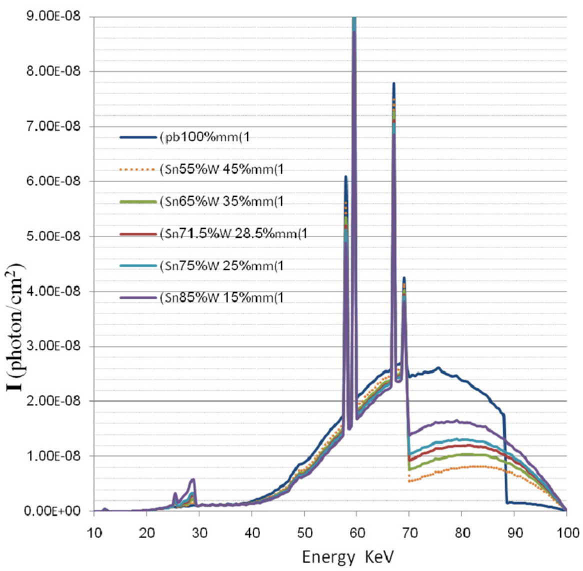

Figure 1: Comparison of the attenuation of grease based tungsten, tin and lead shields using MCNP modeling

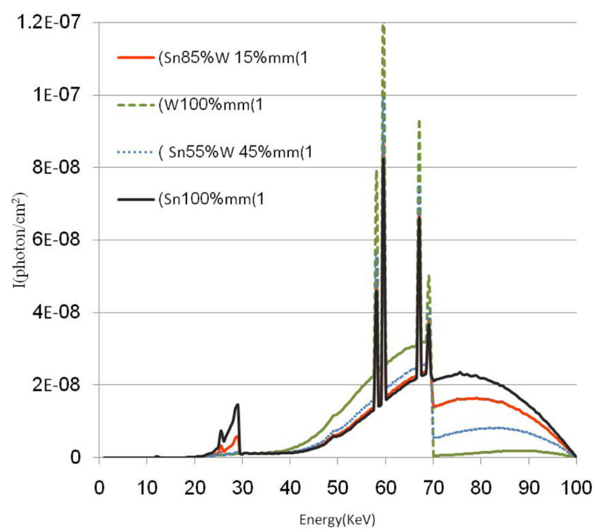

Figure 2: Comparison of the attenuation of grease based tungsten and tin shields using MCNP modeling

ment by measuring the radiation intensity after passing a layer of 2mm thickness of lead powder in grease matrix is presented.

Figures 1 and 2 compare the attenuation of grease based tungsten, tin and lead shields in different energies (up to 100 keV) using MCNP modeling. In the next stage, attempts were made to produce appropriate Tungsten-tin-filled polymers which could be used for production of shielding garments. The density of this tungsten-tin-filled polymer was 4.4 g/cm^3. The MCNP simulation calculations for HVL of this shield at 100 kVp was 0.26 mm. On the other hand, narrow beam absorption measurements indicated a HVL of 0.24 mm. Besides having considerable attenuation properties, this novel radiation shield provided considerable mechanical properties and was highly resistant to chemicals.

Discussion

In this study a specific combination of tungsten (45%) and Tin (55%) provided the best radiation shielding property in both simulation and experiments. On the other, results obtained in this study help us improve the manufacturing of the appropriate polymers as the matrix and different metal powders as the attenuating elements. The cost-effective lead-free flexible radiation shield produced in this study offers effective radiation protection in a diagnostic energy range. Due to its main physical properties such as high density, ease of casting and fabrication, and malleability, lead has been introduced as a popular radiation shield. However, according to US Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) which provides a Federal Superfund to clean up uncontrolled or abandoned hazardous wastes, lead is ranked number two in top 20 hazardous substances priority list. In that light lead as a highly toxic chemical needs very restrictive threshold limits. Besides environmental impact, very high weight of the lead shields limits its use as personal protective clothing. Results obtained in this study help scientists find substitute materials for radiation shielding in the common energy range of diagnostic X-ray tubes (voltages up to 100 kVp).

Conclusion

A specific combination of tungsten (45%) and Tin (55%) in a polymer matrix can be considered as an elastic, environmentally-friendly, lightweight substitute for conventional lead shields in the energies of X-rays produced by voltages up to 100kVp.

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Conflict of interest: None Declared

References

1. Scuderi GJ, Brusovanik GV, Campbell DR, Henry RP, Kwon B, Vaccaro AR. Evaluation of non-lead-based protective radiological material in spinal surgery. *Spine J*. 2006;6(5):577-82.
2. Ngaile JE, Uiso CB, Msaki P, Kazema R. Use of lead shields for radiation protection of superficial organs in patients undergoing head CT examinations. *Radiat Prot Dosimetry*. 2008;130(4):490-8.
3. McGinley PH, Miner MS. A history of radiation shielding of x-ray therapy rooms. *Health Phys*. 1995;69(5):759-65.
4. Hulbert SM, Carlson KA. Is lead dust within nuclear medicine departments a hazard to pediatric patients? *J Nucl Med Technol*. 2009;37(3):170-2.
5. Verstraeten SV, Aimo L, Oteiza PI. Aluminium and lead: molecular mechanisms of brain toxicity. *Arch Toxicol*. 2008;82(11):789-802.
6. Coon T, Miller M, Shirazi F, Sullivan J. Lead toxicity in a 14-year-old female with retained bullet fragments. *Pediatrics*. 2006;117(1):227-30.
7. Healey N. Lead toxicity, vulnerable subpopulations and emergency preparedness. *Radiat Prot Dosimetry*. 2009;134(3-4):143-51.
8. Heath LM, Soole KL, McLaughlin ML, McEwan GT, Edwards JW. Toxicity of environmental lead and the influence of intestinal absorption in children. *Rev*

Environ Health. 2003;18(4):231-50.

9. Millstone E, Russell J. Lead toxicity and public health policy. *J R Soc Health*. 1995;115(6):347-50.
10. Murata K, Iwata T, Dakeishi M, Karita K. Lead toxicity: does the critical level of lead resulting in adverse effects differ between adults and children? *J Occup Health.* 2009;51(1):1-12.
11. Vig EK, Hu H. Lead toxicity in older adults. *J Am Geriatr Soc*. 2000;48(11):1501-6.
12. Schick DK, Casey RN, Sim LH, Siddle KJ. Corrosion of lead shielding in a radiology department. *Australas Radio*l. 1999;43(1):47-51.
13. Eder H, Schlattl H, Hoeschen C. X-Ray protective clothing: does DIN 6857-1 allow an objective comparison between lead-free and lead-composite materials? *Rofo*. 2010;182(5):422-8.
14. Finnerty M, Brennan PC. Protective aprons in imaging departments: manufacturer stated lead equivalence values require validation. *Eur Radiol.* 2005;15(7):1477-84.
15. Simons GR, Orrison WW, Jr. Use of a sterile, disposable, radiation-absorbing shield reduces occupational exposure to scatter radiation during pectoral device implantation. *Pacing Clin Electrophysiol.* 2004;27(6 Pt 1):726-9.
16. Katoh Y, Fukushi M, Abe S, *et al.* Evaluation of non-lead board as X-ray protective material. *Nippon Hoshasen Gijutsu Gakkai Zasshi*. 2007 20;63(4):428-35.