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RESEARCH ARTICLE / ARAŞTIRMA MAKALESI

Development of New Radiation Shielding Materials: The Role of Rare Earth Elements

Yeni Radyasyon Zırh Malzemelerinin Geliştirilmesi: Nadir Toprak elementlerinin Rolü

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Abstract

Bismuth and Lead are commonly used for radiation shielding to mitigate risks such as radiation damage and cancer. However, these materials are costly and impractical for certain applications. This study aims to explore the attenuation properties of various elements and composites using Monte Carlo simulations to develop improved radiation shielding materials. GAMOS software was employed to simulate materials with thicknesses ranging from 0.1 to 2.0 mm and x-ray energies between 10 and 150 keV. Initial simulations focused on validating bismuth and lead by calculating their mass attenuation coefficients, which matched NIST (National Institute of Standards and Technology) values within a 2% margin of difference. After verification, the study simulated various shielding materials incorporating metals and rare earth elements. Among these, four composites with rare earth elements demonstrating the highest mass attenuation coefficients were selected. These composites exhibited superior absorption in the 50–80 keV energy range compared to bismuth and lead.

Keywords: Keywords: *Monte Carlo Method, Rare Earth Elements, Radiation Protection, GAMOS*

Öz

Bismut ve Kurşun, radyasyonun neden olduğu zarar ve kanser riskini azaltmak için yaygın olarak kullanılan koruma malzemeleridir. Ancak bu malzemeler, maliyetli ve bazı uygulamalar için pratik değildir. Bu çalışma, Monte Carlo simülasyonları kullanılarak çeşitli element ve bileşiklerin zayıflatma özelliklerini inceleyerek daha iyi radyasyon koruma malzemeleri geliştirmeyi amaçlamaktadır. GAMOS yazılımı, 0.1 ila 2.0 mm arasında değişen kalınlıklara sahip malzemeler ve 10 ila 150 keV enerji aralığındaki x-ışınları için simülasyonlar yapmak üzere kullanılmıştır. İlk simülasyonlar, bismut ve kurşunun kütle zayıflatma katsayılarını hesaplayarak bu malzemeleri doğrulamaya odaklanmış ve elde edilen değerler, NIST'in (Ulusal Standartlar ve Teknoloji Enstitüsü) verileriyle %2'lik bir fark içinde uyuşmuştur. Doğrulama sonrası, metaller ve nadir toprak elementleri içeren çeşitli koruyucu malzemeler simüle edilmiştir. Bunlar arasından, en yüksek kütle zayıflatma katsayısına sahip dört nadir toprak elementi katkılı bileşik seçilmiştir. Sonuç olarak, bu bileşiklerin 50–80 keV enerji aralığında bismut ve kurşuna kıyasla daha yüksek bir absorpsiyon sağladığı görülmüştür.

Anahtar Kelimeler: *Monte Carlo Metot, Nadir Toprak Elementleri, Radyasyondan Korunma, GAMOS*

1. Introduction

One of the most well-known methods for reducing radiation exposure to radiation workers and radiation-sensitive organ doses in patients is the use of shielding materials. Bismuth (Bi) shieldings used on patients have yielded some problems with their use even though they reduce the organ doses by up to 50% [1, 2]. In case the patient shielding is not placed correctly during the computed tomography examinations, uncertainties in Hounsfield Units (HU) values of the tissue or organ may be seen [3]. Because lead is a toxic element, the use of lead shielding to protect radiation workers has been reduced by the entry of the Restriction of Hazardous Substances Directive (RoHS) which came into force in Europe in 2003 [4]. In addition, they are not preferred for long-term applications due to their heaviness and cause limitation of movement, especially in interventional radiology [5]. Therefore, there is a need to develop new shielding materials which are alternative to bismuth and lead shielding to be used for dose reduction of radiation applications.

For more than 50 years, Monte Carlo (MC) calculations have become a method that can be used in assessing the potential risks of x-rays in diagnostic radiology and in almost every area of medical physics applications. The use of the MC method is rapidly increasing in different areas of medical physics such as radiation protection, diagnostic x-ray, radiotherapy physics,

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dosimetry, nuclear medicine, and microdosimetry [6] In these studies, tungsten (W), barium (Ba), tin (Sn) and antimony (Sn) elements were often used because of their lower toxicity, lower density and diversity in K-edge energies compared to lead and bismuth [7,8]. The use of high atomic numbered elements in shielding materials ensures high absorption capabilities, but it creates a disadvantage. When an electron is freed from the K layer of an element with a higher atomic number, characteristic x-rays with the higher energy are emitted. For this reason, elements with various K-edge energies should be composed together to achieve similar absorption properties with lead and bismuth. Rare earth elements, which are often used in new technologies and clean energy production are referred to as green elements [9, 10]. Their atomic numbers, densities, and toxicity are relatively low.

Unlike the literature, the absorption effects of rare earth elements have been taken into account in this study. In order to develop new shielding materials that provide as much dose reduction and less toxicity as possible, the assessment of attenuation effects of a group of metals and rare earth elements constitutes the main goal of this study. Additionally, the mass attenuation coefficients of the composites formed with the selected elements were calculated and compared with bismuth and lead.

2. Materials and Methods

MC calculations were done on a notebook computer with an i7 processor with 3.2 GHz. GAMOS v.5.0.0 was used. The simulation geometry was created in GAMOS in accordance with European Electro-Technical Standardization Committee (CENELEC) standard EN 61331-1 and in accordance with TS EN 61331-1 accepted as Turkish Standard in 2004. Narrow beam geometry was defined in GAMOS.

In the working space created in GAMOS, a linear photon emitting planar source with a surface area of (3x3) mm^2 and 1 mm thickness was used. The shielding materials (Bi, Pb) with a surface area of (10x10) mm^2 whose absorption effects are to be investigated were created in front of the source. In order to obtain an absorbed dose, a silicon (Si) detector with a volume of 10x10x10 mm^3 was created (Figure 1).

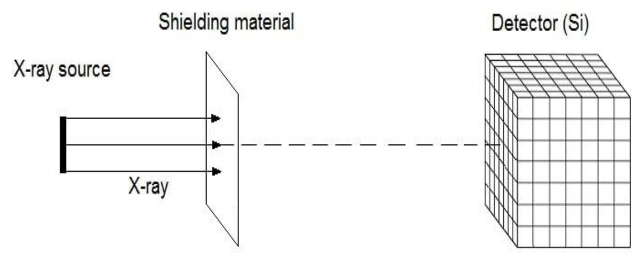


Figure 1. Narrow beam geometry created in GAMOS.

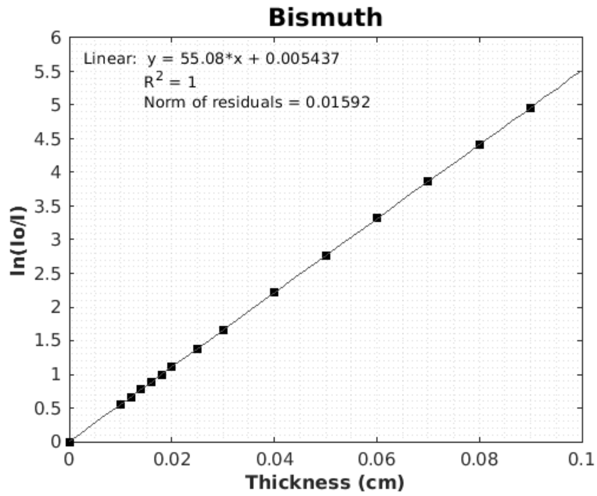
The working space was filled with air. GmEMPhysics physics package was used in all calculations. In all MC calculations, 10^7 photons were used to increase the accuracy of the calculation, and minimize the statistical error. MC calculations were conducted for each mono-energy value (10 keV - 150 keV) and different thicknesses of bismuth and lead shielding (0.1 mm - 2.0 mm). Equation (1) was used to obtain the linear and mass attenuation coefficient values.

$$\mu = \frac{1}{x} ln\left(\frac{I}{I_0}\right) \quad (1)$$

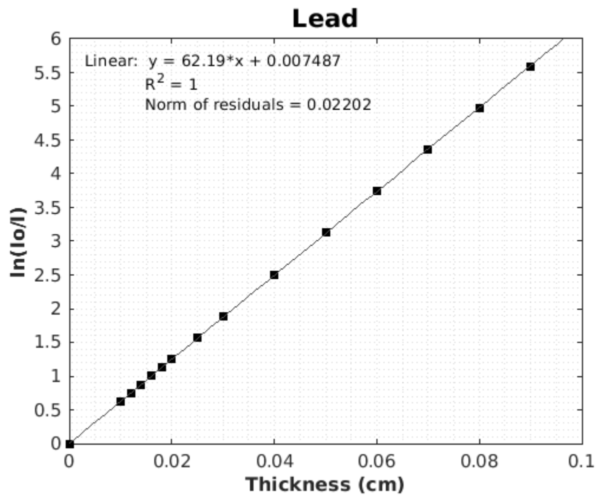
Linear attenuation coefficients (μ) were calculated from the slope of the dose graphs depending on the thickness, and the mass attenuation coefficients (μ/ρ) were calculated by dividing these linear attenuation coefficients by the density. The same process was conducted for the lead shielding.

3. Results and Discussion

The calculated mass attenuation coefficients were compared with the mass attenuation coefficients of the monoenergetic values presented in the National Institute of Standards and Technology (NIST) database. The (μ) values of bismuth and lead, obtained from the slope of the absorption graphs depending on the thickness of shielding for 100 keV mono-energy are shown in Figure 2(a) and (b). Figure 3(a) and (b) show the energy dependence graphs of the calculated mass attenuation coefficients of the bismuth and lead shielding, respectively.



(a)



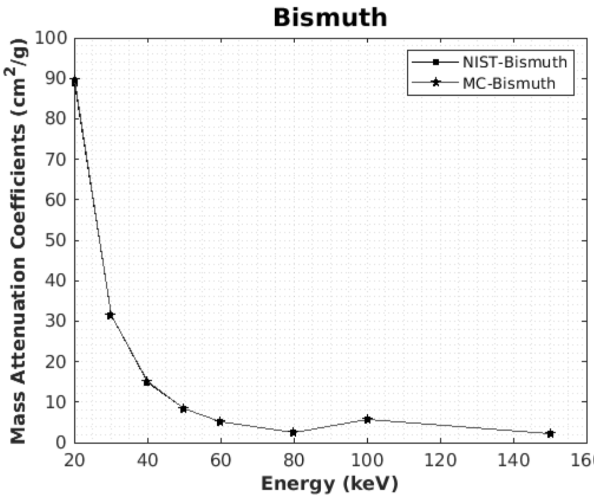
(b)

Figure 2. Dose changing, dependent on the thickness of simulated (a) bismuth, (b) lead shielding.

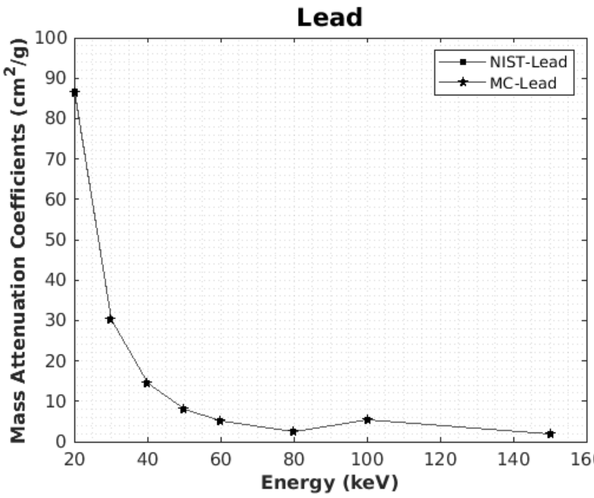
After validation with Bi and Pb, only by the change of the shielding material in the GAMOS geometry file, MC calculations have been carried out for the other elements given in Table 1. For the comparison of the attenuation coefficients of the selected elements, especially for energies between 40 keV and 90 keV, which included the most commonly used average energy values in the diagnostic examinations, was considered (Figure 4). The composites were simulated using some of the metal group elements (Barium, Antimony, Bismuth, Tungsten, etc.) and some of the rare earth elements (Erbium, Gadolinium, etc.). The elements that have higher attenuation effects at different energies, were combined with different percentages to form the composites in GAMOS.

Table 1. Elements used in simulated composite shielding.

Elements	Atomic Number	K Absorption Edge (keV)	Density (g/cm^3)
Antimony	51	30.5	6.69
Barium	56	37.4	3.62
Europium	63	48.5	5.24
Gadolinium	64	50.2	7.90
Dysprosium	66	53.8	8.55
Erbium	68	57.5	9.07
Ytterbium	70	59.3	6.90
Tungsten	74	69.5	19.30
Bismuth	83	90.5	9.77



(a)



(b)

Figure 3. Energy-dependent change of calculated mass attenuation coefficients for (a) bismuth, (b) lead shielding.

After validation with Bi and Pb, only by the change of the shielding material in the GAMOS geometry file, MC calculations have been carried out for the other elements given in Table 1. For the comparison of the attenuation coefficients of the selected elements, especially for energies between 40 keV and 90 keV, which included the most commonly used average energy values in the diagnostic examinations, was considered (Figure 4). The composites were simulated using some of the metal group elements (Barium, Antimony, Bismuth, Tungsten, etc.) and some of the rare earth elements (Erbium, Gadolinium, etc.).

The elements that have higher attenuation effects at different energies were combined with different percentages to form the composites in GAMOS. The percentages of the elements to be used in the composites were determined by taking into account the graphs of the energy attenuation coefficients and the absorption graphs depending on the thickness. The linear and mass attenuation coefficients of these simulated composite shielding materials were calculated for energies between 10 keV and 150 keV, and various material thicknesses between 0.1 mm and 2.0 mm. In this study, four composite shielding, which could provide protection of radiosensitive organs by decreasing the radiation dose are presented in Table 2. The mass attenuation effects of these theoretically formed composites were compared with the mass attenuation effects of bismuth and lead shielding. This study was conducted in accordance with ethical standards under the responsibility of institutional review board that has approved the study. (Decision No: 2015/05-20)

Table 2. Simulated composite shielding.

	Composites	Density (g/cm^3)
1	Gadolinium, Barium, Tungsten, Bismuth	8.29
2	Europium, Dysprosium, Barium, Bismuth	6.34
3	Ytterbium, Erbium, Europium, Bismuth, Tungsten	8.58
4	Ytterbium, Erbium, Antimony, Bismuth	7.78

The relationship between the absorption and thickness of bismuth and lead has led to the determination of linear attenuation coefficients, which are represented by the slope of the linear fitting models illustrated in Figure 2. Mass attenuation coefficients for 100 keV have been found 5.64 cm^2/g and 5.48 cm^2/g for bismuth and lead, respectively. The results were observed to be in close agreement with the NIST database considering the maximum percentage differences of 2.0% for bismuth and 1.2% for lead. The comparison of linear and mass attenuation coefficients at 100 keV, and the other energies, obtained from the MC calculations and from the NIST database has been given in Table 3.

The concordant results between the mass attenuation coefficients obtained from the simulation and the NIST database are also shown in Figure 3 for different energy levels. In order to determine the percentage of the elements to be used in the composites to be formed by simulation, it is necessary to obtain the energy-dependent absorption coefficients of the selected elements. For this reason, the processes for bismuth and lead shielding were repeated for the metal and lanthanide group elements shown in Figure 4.

The changes in the energy-dependent absorption coefficients of dysprosium, europium, erbium, gadolinium, ytterbium, barium, antimony, tungsten and bismuth were compared with each other. Antimony, barium and europium elements exhibited higher absorption rates than bismuth for 50 keV. Erbium, dysprosium, and gadolinium exhibited higher absorption rates than bismuth for 60 keV. When the energy range of 70-90 keV is evaluated, it is seen that bismuth has the least absorption effect compared to other elements. In accordance with this information, after calculating the mass attenuation coefficients of the composite shielding presented in Table 2, they were compared with bismuth and lead shielding.

Table 3. Differences between mass attenuation coefficients obtained by MC calculations and presented at NIST.

Bismuth				
Energy (keV)	MC (μ)	MC (μ/ρ)	NIST (μ/ρ)	Difference (%)
10	1316.71	134.77	136.00	0.91
20	868.10	88.85	89.52	0.75
30	307.31	31.42	31.52	0.32
40	144.80	14.91	14.95	0.27
50	81.15	8.31	8.37	0.72
60	50.60	5.18	5.23	0.96
70	33.82	3.46	-	-
80	24.09	2.47	2.52	2.00
90	17.95	1.84	-	-
100	55.08	5.64	5.73	1.58
120	35.03	3.59	-	-
150	20.04	2.05	2.08	1.45
10	1316.71	134.77	136.00	0.91
20	868.10	88.85	89.52	0.75

Lead				
Energy (keV)	MC (μ)	MC (μ/ρ)	NIST (μ/ρ)	Difference (%)
10	1467.12	129.38	130.60	0.94
20	984.67	86.83	86.36	0.54
30	343.71	30.31	30.32	0.03
40	162.87	14.36	14.36	0.00
50	90.83	8.01	8.04	0.37
60	56.45	4.98	5.02	0.80
70	33.82	2.98	-	-
80	27.08	2.39	2.41	0.83
90	79.25	6.99	-	-
100	62.19	5.48	5.55	1.27

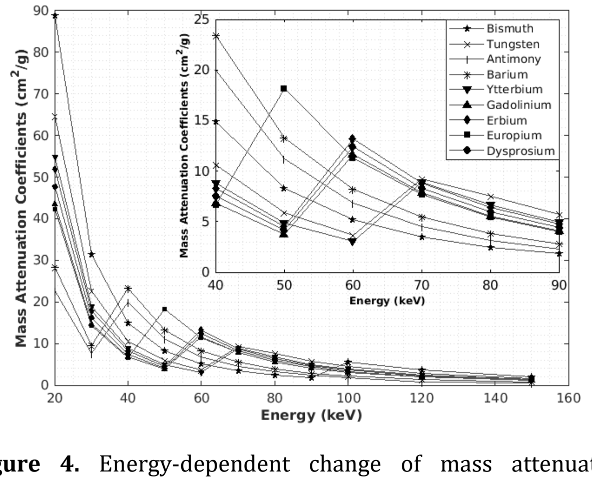
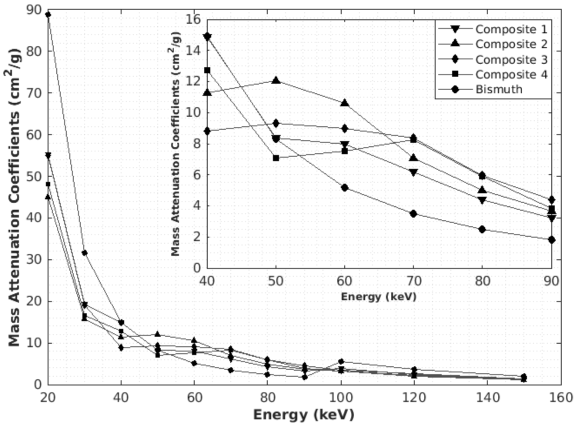


Figure 4. Energy-dependent change of mass attenuation coefficients of the elements used in composites

Figure 5 shows the comparison of mass attenuation coefficients of four composite shielding and bismuth shielding. For 50 keV energy, other composite shielding except composite 4, appear to have a higher absorption effect than bismuth. At the energies of 100 keV and above, bismuth was found to have a higher mass attenuation coefficient than composites. When the percent difference graph of the mass attenuation coefficients of bismuth and composites is examined, it is seen that the highest difference values are in the range of 70-90 keV. In the evaluation of the mass attenuation coefficients of lead and composites given in Fig. 6, it was observed that all composite specimens except composite 4 had higher absorption coefficients than lead. It is clear in Figure 6 that composites up to 90 keV energy have higher mass attenuation coefficients than lead. It is seen that the highest differences between the mass attenuation coefficients of lead and composites are in the energy range of about 70-80 keV.



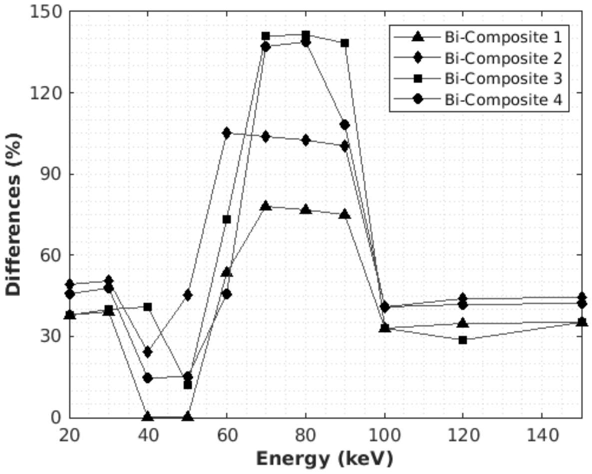


Figure 5. Comparison of the mass attenuation coefficients of simulated composites and bismuth, percentage differences.

The rare earth elements have relatively lower atomic numbers, mass densities and toxic effects compared to bismuth and lead. In addition, they are often used in new technologies and in the production of renewable energy [9]. In this study, these elements have been evaluated by means of their mass attenuation coefficients. Several composite materials, as alternatives to bismuth and lead, were formed with higher abilities to absorb radiation at diagnostic energy levels.

With the use of such shielding materials which have higher absorption, during radiologic examinations, higher protection can be achieved in the radiosensitive organs of patients. In radiologic examinations in which ionizing radiation is used, particularly in pediatric cases where high-energy x-rays are not used and the patient tissues are more radiosensitive than adult patients, radiation protection is important to diminish cancer risk. For this reason, it is of significant advantage of use shielding materials with a higher ability to absorb radiation at energy levels most commonly used in the clinic. Alternatively, replacing lead with a material with less toxicity is another point of superiority.

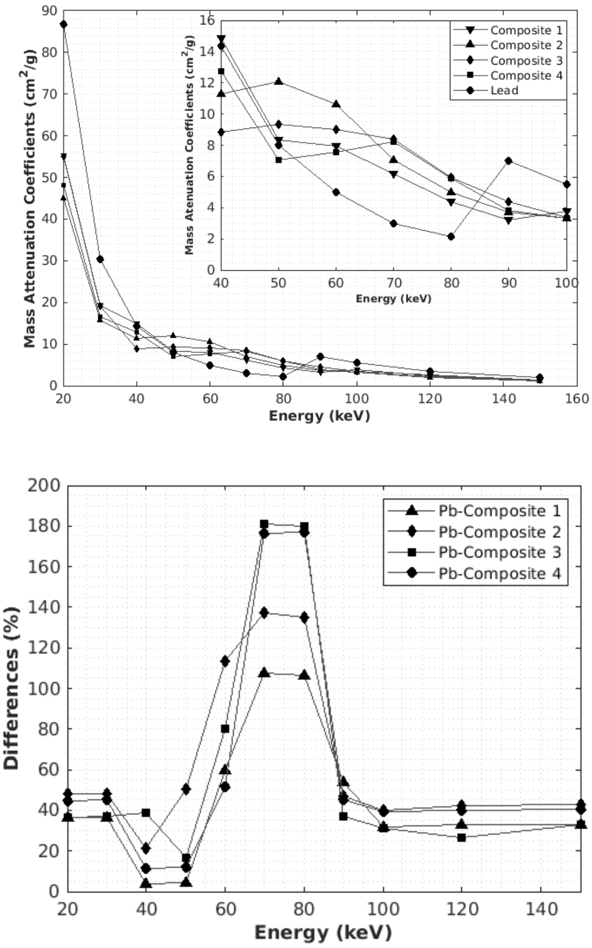


Figure 6. Comparison of the mass attenuation coefficients of simulated composites and lead, percentage differences.

Compared to the mass attenuation coefficients of bismuth and lead, it was observed that the mass attenuation coefficients of the composite material were higher up to 80 keV, whereas it was lower around 90 keV. This can be due to the lower K shell-binding energies in composite materials. Composite 3 and composite 4 can act as better materials of attenuation, especially around 80 keV, since they have mass attenuation coefficients at better levels compared to other materials in the study. Alternatively, all composites showed superior attenuation at 90 keV compared to bismuth, while lower attenuation compared to lead. At energies between 100-120 keV and above, bismuth and lead have been observed to have better protection. All radiation-based applications are governed by the ALARA (As Low As Reasonably Achievable) principle, which indicates the use of the lowest possible radiation exposure to accomplish a certain goal. The main precautions applied based on these principles include distance from the radiation source, time of exposure and the shielding between the source and the person exposed to radiation. With the increasing usage of ionizing radiation for diagnostic purposes, the increase in the dose increases the risk of cancer in later periods by creating a stochastic effect that threatens the health. For this reason, personal shielding plays a significant role in the radiation protection of patients and workers being exposed to direct or scattered radiation in the medical field, to decrease the absorbed dose to radiation sensitive tissues [10]. One of the most common methods used for radiation protection of both patients and radiation workers is the practice of radiation shielding materials (lead apron, thyroid and lens shieldings, etc.), as highlighted in the literature. Studies in the literature show that a reduction of up to 50% of the radiation dose to organs has been achieved by bismuth (Bi) shielding materials [1, 11]. Other studies investigating the use of lead-containing or lead-free materials to protect radiation-sensitive tissues of patients and workers are also present, which in conclusion emphasized the convenience of lead-free shields referring to their lower toxicity and weight (20%) with similar attenuation properties compared to lead-containing materials, parallel to the main point of this study [12, 13] In this study, where only MC calculations are made, the reason why GEANT4 based GAMOS is preferred; GAMOS is a software for medical physicists and has an easy to understand command language [14]. In a study conducted on the attenuation properties of different biological samples, experimental data have been compared to GEANT4, MCNP, and XCOM data. Calculated results on mass attenuation coefficients have been found similar to experimental results, indicating that MCNP and GEANT4 simulation tools can act as successful tools to estimate mass attenuation coefficients for several absorbing mediums at different energies [15]. As a result, different composite materials have been suggested in this study, which have a higher ability to absorb radiation at some energy levels when compared to bismuth and lead. Results from GAMOS have shown that these materials exhibit superior attenuation properties compared to bismuth and lead between 50-90 keV and 50-80 keV, respectively.

4. Conclusion

This study has focused on the calculation of mass attenuation coefficients of some metals and lanthanides, which can be used in the production of alternative radiation shielding materials to bismuth and lead. Most of the composite samples put into simulation have been observed to exhibit superior attenuation properties compared to bismuth and lead for 50-90 keV and 50-80 keV energy ranges, respectively. In other words, alternative shielding materials have been composed to achieve similar or better attenuation with respect to bismuth and lead within the x-ray energy range commonly used for diagnostic imaging purposes in the clinic. Alternatively, similar attenuation properties have been observed between all materials at less commonly used energies between 100-120 keV. When their less toxicity and lighter structure are considered, the use of lead-free shielding materials will provide significant advantages, especially for the radiation workers in the clinic dealing with x-rays under 100 keV and being exposed to the scattered radiation.

Author Contribution Statement

Concept , Gizem Şişman, Hakan Epik. Data collection Gizem Şişman. Data analysis, Gizem Şişman, Hakan Epik, Kadir Akgüngör, Recep Kandemir, Ayşegül Yurt. Literature search Gizem Şişman. Writing, Gizem Şişman. Critical review, Hakan Epik, Kadir Akgüngör, Ayşegül Yurt.

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