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Evaluation of X-Ray Shielding Ability of Tungsten Rubber: A GAMOS Monte Carlo Study

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Abstract: Against the detrimental effects of ionizing radiation, time, distance, and shielding are the three most significant protective methods. Lead is the material of choice for shielding, particularly for personal protective equipment. However, lead's density, rigidity, and toxicity are significant disadvantages. In recent years, tungsten-containing rubber (TCR) and other lightweight, flexible, and non-toxic shielding materials have emerged as viable alternatives to lead. The purpose of this study is to examine the X-ray absorption capacity of TCR material, which can serve as an alternative to lead-based personal protective equipment. Using GAMOS simulation, radiation absorption characteristics for 11 different X-ray energies ranging from 30 to 1000 keV were obtained and compared with Phy-X/PSD data. While the MFP value produced from the GAMOS code for the TCR with 100 keV energy X rays was 0.0204 cm, the Phy-X/PSD value was 0.0296 cm. The HVL value of the TCR material for X-rays with an energy of 100 keV was 0.021 cm for Phy-X/PSD and 0.014 cm for GAMOS. It has been observed to provide excellent radiation protection against X-rays in the diagnostic imaging field. By providing greater flexibility than lead shielding materials, TCR can play a crucial role in decreasing radiation exposure.

Key words: GAMOS, Phy-X PSD, Shielding

1. Introduction

Numerous radiation workers and patients are exposed to the adverse consequences of ionizing radiation, particularly in interventional radiology [1]. As a result of the stochastic effects of radiation [2], radiation workers are exposed to considerable dangers such as cancer incidence and cataracts. Thanks to adequate shooting methods and the capabilities of imaging technologies, measures are taken to limit patients' exposure to radiation. Nevertheless, personal protective equipment is the most effective method for protecting radiation workers from the damaging effects of ionizing radiation [3]. Lead is the preferred material for manufacturing this equipment. In spite of the fact that lead aprons are good at shielding X-rays, they have a variety of disadvantages for everyday use. The first of these is the equipment's weight. It has been noted that regular use of heavy personal protection equipment causes back pain or disc disease [4, 5]. In addition, lead, which has very little flexibility, can cause movement restrictions during the process. The radiation absorption capability of this personal protective equipment degrades with time as a result of use-related cracking. Another drawback is that lead is toxic to the human body and has negative environmental impacts [6–8].

The Tungsten-containing rubber (TCR) produced by Hayakawa Rubber Co., Ltd. (Hiroshima, Japan) is 0.5 mm thick and includes 90% tungsten powder by mass. TCR element ratios (mol%) are as follows: 1.0% hydrogen, 6.5% carbon, 0.5% oxygen, and 90.0% tungsten [9]. As indicated in Table 1 [10], the dry mass, thickness, tensile strength, wet strength, rip strength, and air resistance of the TCR were in accordance with the Japanese Industrial Standards for paper manufacturing. The TCR was determined to be a weak material in water, with a tensile strength of 118 N/15 mm in dry conditions and 5.9 N/15 mm in wet conditions. With a thickness of 5.23 mm, the TCR was similar to 3.32 mm of lead [11].

Table 1. The physical properties of TCR: The techniques of measurement for each property are provided in the columns to the right [11].

Bone-dry basis weight (g.m^{-2})	700	JIS-P8124
Thickness (mm)	0.3	JIS-P8119
Tensile strength (N/15 mm)	118	JIS-P8113
Wet strength (N/15 mm)	5.9	JIS-P8135
Tear strength (mN)	220	JIS-P8116

The purpose of this study is to examine the TCR's ability to absorb x-rays using a GAMOS code. With the Architecture for Medicine-Oriented Simulations (GAMOS) code, the linear attenuation coefficient (μ), mass attenuation coefficient (μ_m), half value layer (HVL), tenth value layer (TVL), and mean free path (MFP) of TCR were computed. GAMOS simulation data for TCR was compared with Phy-X/PSD software data.

2. Material and Method

GAMOS v.6.2.0 software program was used for the simulations in this study. GAMOS is based on GEANT4 and is widely used for simulation studies in medical physics [12-13]. 400 cm away from the radiation source, a 50x50x2 mm^3 polyvinyltoluene (PVT) plastic scintillator was defined in the geometry file. The PMT on the top center of the PVT was assumed to be 50 mm in diameter and 100 mm tall. At the middle between the detector and the radiation source, TCR shielding material of 100 × 100 x 5 mm^3 was positioned (Figure 1).

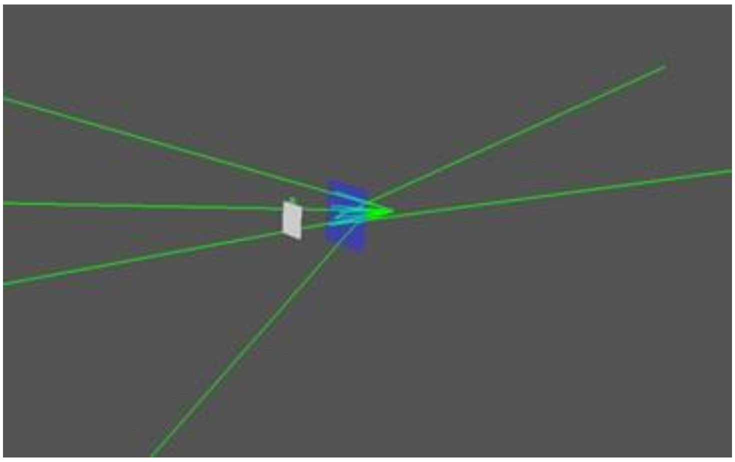

Figure 1. Simulation geometry.

In the input file, the physics, generator, and dose collection parameters were defined. In the simulation, the electromagnetic physics package was utilized. As radiation sources, gamma photons with energy of 30, 50, 60, 80, 100, 200, 300, 400, 500, 600, and 1000 keV were utilized, respectively. For scoring criteria, the amount of dose that reached the detector via "dose deposit" was tallied. Although all physics processes were included into the scoring, variance reduction techniques were not implemented. Photon intensity values obtained with and without TCR in the simulation will be obtained as transmitted (I) and primary (I_0) intensities, respectively. A history of 10^7 photons was utilized, yielding sufficient results to improve the precision of the Monte Carlo simulations and reduce statistical error.

$$I = I_0 . e^{(-\mu . x)} \tag{1}$$

μ values at different energies were calculated for TCR using Beer Lambert's law (Eq. 1). As shown in Equation 2, μ_m is derived by dividing μ by the density (ρ) of the material.

$$Mass\ Attenuation\ Coefficient\ (\mu_m) = \mu/\rho \tag{2}$$

The MFP is defined as the average distance at which a radiation can be stopped in a material and is calculated using Equation 3.

$$Mean\ Free\ Path\ (MFP) = \mu^{-1} \tag{3}$$

HVL and TVL are the shield material thicknesses corresponding to the half and tenth values of the intensity of the incoming radiation, and they are given in Equations 4 and 5, respectively.

$$Half\ Value\ Layer\ (HVL) = \frac{ln2}{\mu} \tag{4}$$

$$Tenth\ Value\ Layer\ (TVL) = \frac{ln10}{\mu} \tag{5}$$

The physical properties of the TCR used in the GAMOS code were defined in the Phy-X/PSD [14] program and the μ, μ_m, HVL, TVL and MFP values were calculated. GAMOS simulation and Phy-X/PSD data were compared with each other.

3. Results and Discussion

There are various forms of radiation, including neutrons, X-rays, gamma rays, and so on. Different lead alloys and composites are used in the commercial market as gamma radiation shielding materials. High lead content, however, prevents its widespread use [15-17]. Tungsten, on the other hand, is a great gamma-ray shield because it is non-toxic and has a large gamma-ray scattering cross-section [18-19]. There is a current market demand for gamma-ray shielding items that are flexible, have a high gamma-ray shielding ability, and have precise mechanical properties [20].

In this study, the ability of TCR to shield X-rays of different energies was investigated by GAMOS simulation. The GAMOS simulation was used to get the TCR's radiation absorption parameters (μ, μ_m, MFP, HVL, and TVL) for 11 different X-ray energies ranging from 30 to 1000 keV (Table 2).

Table 2. The μ, μ_m and, MFP values of TCR at different energies.

Energy (keV)	μ (cm^{-1})		μ_m (cm^2/g)		MFP (cm)	
	Phy-X/PSD	**GAMOS**	**Phy-X/PSD**	**GAMOS**	**Phy-X/PSD**	**GAMOS**
30	172.976	169.830	22.611	22.346	0.0058	0.0059
50	81.198	77.316	5.920	5.918	0.0221	0.0358
60	28.260	27.897	3.694	3.671	0.0354	0.0222
80	59.432	64.008	7.769	8.685	0.0168	0.0151
100	33.771	40.951	4.414	5.441	0.0296	0.0204
200	5.975	9.270	0.781	1.220	0.1674	0.1079
300	2.469	3.212	0.323	0.423	0.4051	0.3113
400	1.469	1.247	0.192	0.164	0.6809	0.8019
500	1.052	0.790	0.138	0.104	0.9504	1.0659
600	0.835	0.559	0.109	0.074	1.1976	1.3882
1000	0.506	0.042	0.066	0.005	1.9756	2.0964

These parameters were then compared with the data from the Phy-X/PSD program. The geometry presented in Figure 1 was used to calculate the radiation absorption properties of the materials.

It is seen in Figure 2 that the μ value decreases as the photon energy increases. A peak between 80 and 90 keV was observed for the μ value. The μ value for 60 keV X-rays was 28.260 and 27.897 cm^{-1} for Phy-X/PSD, and GAMOS, respectively.

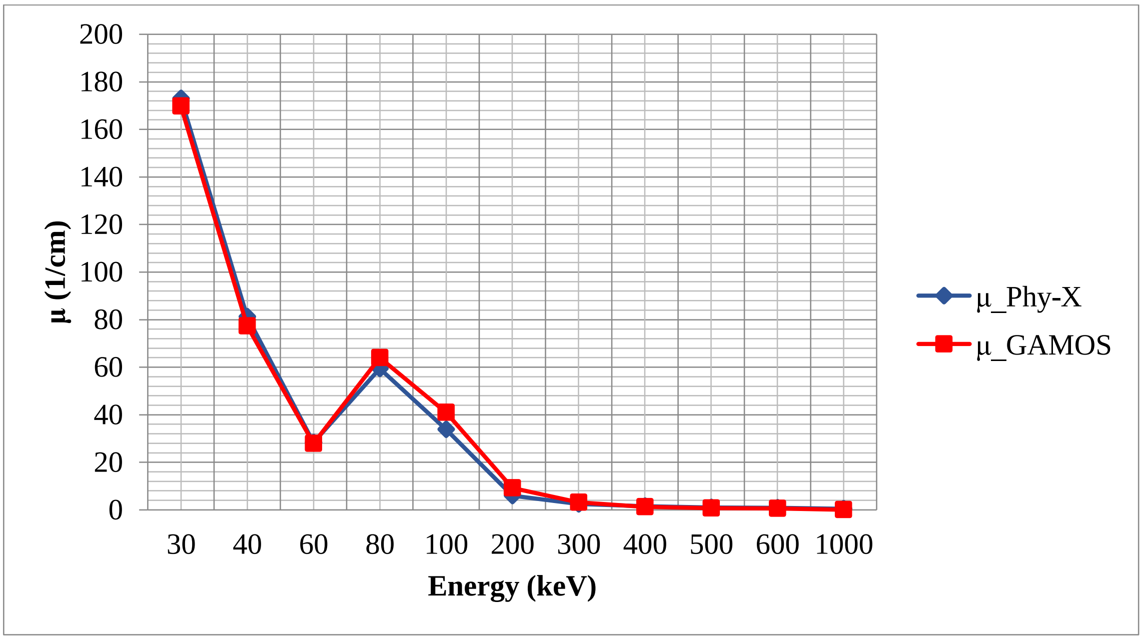

Figure 2. The μ values of TCR at different energies

The μ_m value decreased as the photon energy increased (Figure 3). The μ_m value for X-rays with 400 keV energy was 0.192 and 0.164 g/cm^2 for Phy-X/PSD, and GAMOS, respectively. As expected, maximum μ and μ_m values were observed at lower photon energies due to photoelectric interactions between photons and TCR atoms with high atomic numbers. Later, as the probability of photon penetration increased with the increased photon energy, these values rapidly decreased. On the other hand, the more photon energy increased, the Compton scattering effect was overwhelmed, and the weakening of TCR atoms was more dependent on the electron density than the atomic number. Therefore, TCR's mass attenuation coefficients have decreased with increased gamma-ray energies.

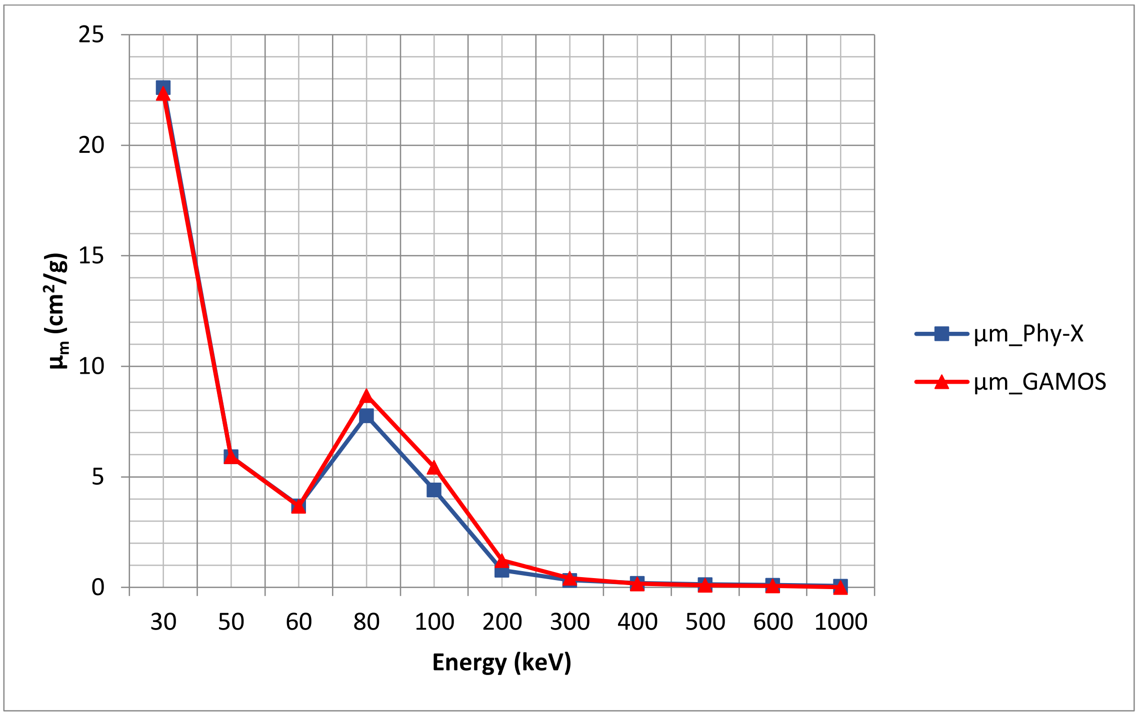

Figure 3. The μ_m values of TCR at different energies

MFP values obtained using both GAMOS and Phy-X/PSD were directly proportional to energy (Figure 4). The MFP value obtained from the GAMOS code for TCR with 100 keV energy X-rays was 0.0204 cm, while this value was 0.0296 cm for Phy-X/PSD.

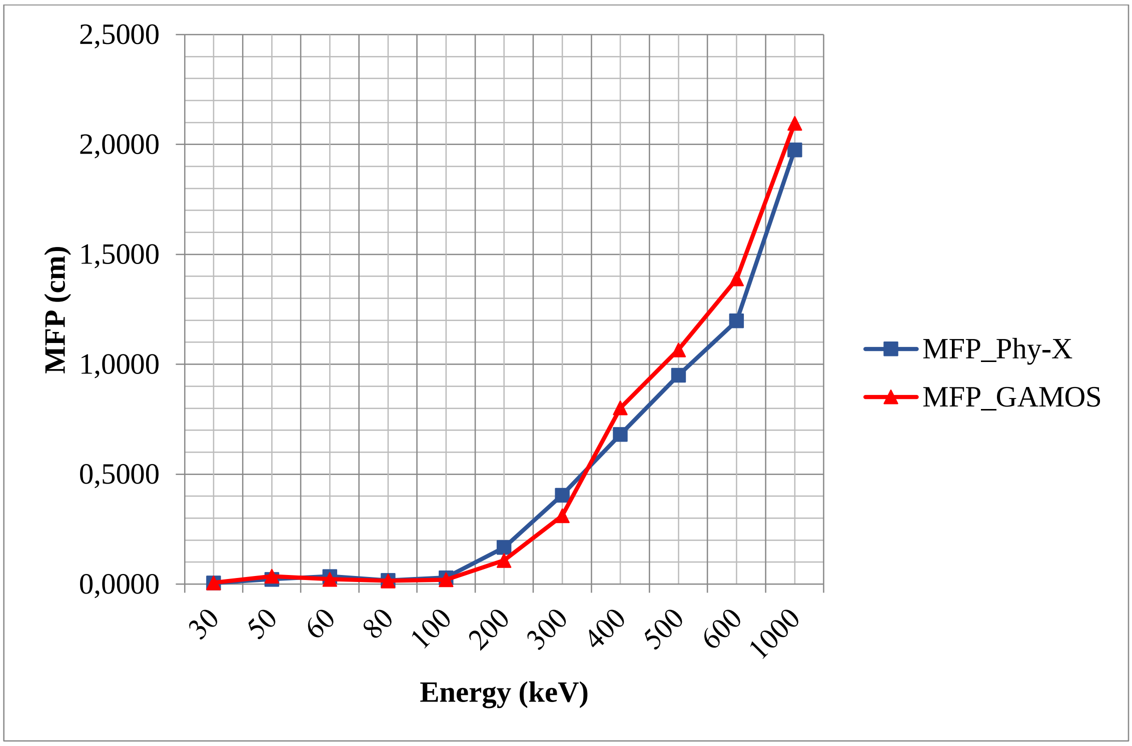

Figure 4. The MFP values of TCR at different energies

Xu et al. [21] found that the radiation absorption rates of tungsten-doped rubber composites of 5 and 6 mm thickness at 0.667 MeV gamma-ray energy were 20.6% and 25%, respectively. The gamma ray shielding rate of tungsten-doped rubber composites with a thickness of 10 mm is around 45.2%, demonstrating excellent gamma ray shielding performance [10].

The μ values of hybrid elastomers doped with tungsten in various proportions ranges from 0.078 cm^{-1} for pure polymer (0% tungsten) to 0.688 cm^{-1} for 88.1% tungsten. Gamma rays with a wavelength of 0.662 MeV can be attenuated by 49.74% by a 1 cm thick shielding material containing 88.1% tungsten by weight. In the same study, the μ_m increases from 0.0789 cm^2/g at 0% wt to 0.1035 cm^2/g at 88.1% wt [20]. Despite the fact that the mass attenuation coefficient of pure tungsten is 0.0933 cm^2/g [22], the TCR has a greater value due to the lower density. In addition to possessing outstanding shielding qualities, TCR also possesses elastomer-like properties. In our study, μ values obtained from GAMOS simulation for TCR ranged from 0.042 to 169.830 cm^{-1}. μ values were between 0.506 and 172.976 cm^{-1} in the Phy-X/PSD program. The μ_m values ranged between 0.005 and 22.346 cm^2/g according to the GAMOS code. The μ_m values obtained for TCR from the Phy-X/PSD program were between 0.066 and 22.611 cm^2/g and were consistent with the GAMOS results (Figure 2). As expected, the values of μ and μ_m decreased with the increase in incident photon energies. At lower energies, where photoelectric absorption predominates, the μ_m values have maximum values [24]. However, it has been demonstrated that TCR effectively absorbs photons and reduces transmitted radiation. At medium and higher energies, however, the contribution of Compton scattering is not negligible relative to photoelectric absorption. Therefore, different ratios of the same material by weight cause a change in the mass attenuation coefficient.

For the TCR, the HVL values calculated with the data obtained from GAMOS in the energy range of 30–1000 keV varied between 0.004–1.470 cm (Figure 5). The HVL value of the TCR material for X-rays with 100 keV energy was 0.021 and 0.014 cm for Phy-X/PSD, and GAMOS, respectively (Table 3). In the 30-1000 keV energy range, the TVL values calculated from the GAMOS code varied between 0.014 and 5.048 cm (Figure 5) (Table 3).

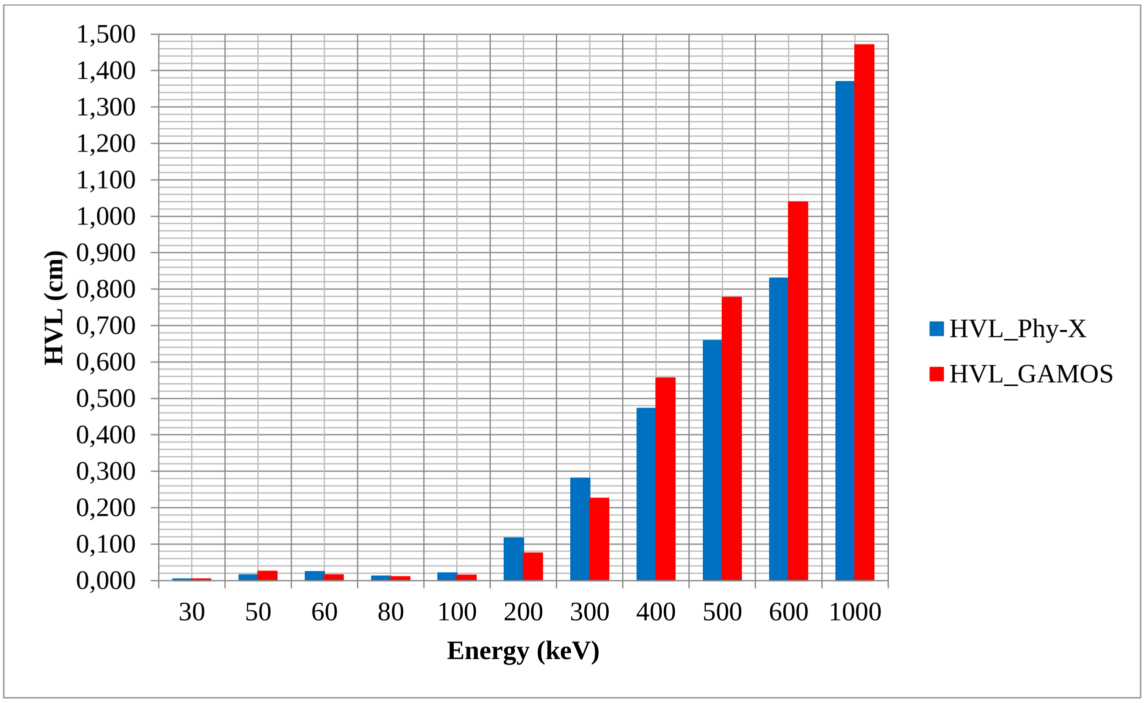

Figure 5. HVL values of TCR at different energies.

Table 3. HVL and TVL values of TCR at different energies.

Energy (keV)	HVL (cm)		TVL (cm)	
	Phy-X/PSD	GAMOS	Phy-X/PSD	GAMOS
30	0.004	0.004	0.013	0.014
50	0.015	0.025	0.051	0.051
60	0.025	0.015	0.081	0.083
80	0.012	0.011	0.039	0.035
100	0.021	0.014	0.068	0.047
200	0.116	0.075	0.385	0.248
300	0.281	0.226	0.933	0.717
400	0.472	0.556	1.568	1.846
500	0.659	0.777	2.188	2.515
600	0.830	1.040	2.757	2.518
1000	1.369	1.470	4.549	5.048

Other parameters to compare the shielding efficiency of a material are its HVL and TVL. HVL decreases from 8.88 to 1.01 cm with a change in weight percent of tungsten from 0% to 88.1%. At 662 keV energy, the HVL of 88.1 wt% tungsten-loaded composites is 1.01 cm [20]. Tungsten-lead wool blankets (T-Flex® W, 88% W by mass) suspended in polymer are another material used for radiation shielding. At 662 keV, the HVL for T-Flex® W is 2.2 cm [24]. In our study, the TCR's $HVL_{Phy\text{-}X}$ and HVL_{GAMOS} values for X-rays with 600 keV energies were found to be 0.830 and 1.040 cm, respectively. At higher photon energies, HVL and TVL values increased. The exchange of HVL and TVL at different photon energies can be confirmed based on the dominance of various photon interactions in different energy regions. In addition, the HVL values increased at higher photon energies, and the HVL variation with the photon energy in these samples could be justified based on the dominance of various photon interaction processes in different energy regions, as discussed above in the mass attenuation coefficients. Notably, lower HVL values were required for a better gamma-ray shielding material as it provided a higher probability of photon interactions with the material.

4. Conclusion

TCR is a new flexible protective material that contains a metal with a high atomic number in rubber and has a shielding ability equivalent to or higher than lead. It has been observed to provide excellent radiation protection against X-rays in the diagnostic imaging field. It can help reduce radiation exposure in a big way because it is more flexible than lead shielding materials.

Authorship contribution statement

M. C. Şahin: Conceptualization, Methodology, Data Curation, Original Draft Writing; **K. Manisa**: Conceptualization, Methodology, Visualization, Supervision/Advice.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics Committee Approval and/or Informed Consent Information

As the authors of this study, we declare that we do not have any ethics committee approval and/or informed consent statement.

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