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RESEARCH PAPER

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Experimental Study on Thickness-Dependent X-ray Radiation Protection of a Flexible and Lightweight Silicone Rubber–PbO Composite Apron

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ABSTRACT

The use of X-rays in medical imaging provides substantial diagnostic benefits but also poses risks associated with ionizing radiation exposure. Conventional lead-based protective aprons are effective but have major limitations, including excessive weight, rigidity, and potential toxicity. This study addresses a specific research gap by systematically evaluating the relationship between material thickness, radiation attenuation effectiveness, and the Half-Value Layer (HVL) of silicone rubber-based aprons filled with lead(II) oxide (PbO) at clinically relevant low-to-medium X-ray energies. An experimental method was employed by fabricating silicone–PbO composite apron prototypes with three thickness variations (2.5 mm, 3.0 mm, and 3.5 mm). Radiation attenuation tests were conducted at X-ray tube voltages of 60, 65, and 70 kV by measuring radiation intensity before and after transmission through the samples using a radiation detector, followed by calculating protection effectiveness and HVL values. The results demonstrate that apron thickness significantly influences radiation protection performance, with the highest attenuation of 85.11% achieved at a thickness of 3.5 mm. A moderate-to-strong positive correlation between thickness and protection effectiveness is observed at all voltage levels, with the highest coefficient of determination (R^2 = 0.916) at 65 kV. HVL values increase with thickness, indicating the need for thicker materials to achieve a 50% reduction in radiation intensity at higher attenuation levels. These findings highlight the novelty of quantitatively correlating thickness, attenuation effectiveness, and HVL within a single experimental framework and demonstrate that silicone rubber–PbO composite aprons have strong potential as a lightweight and flexible alternative to conventional lead aprons for clinical radiation protection at low-to-medium diagnostic X-ray energies.

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1. INTRODUCTION

The increasing use of X-ray–based diagnostic procedures has raised concerns regarding occupational radiation exposure among medical personnel [1], [2]. Although X-rays provide substantial clinical benefits, repeated low-dose exposure is associated with cumulative stochastic risks, including an increased probability of radiation-induced malignancies, as described by the Linear No-Threshold (LNT) model [3], [4], [5], [6]. Consequently, effective and ergonomically acceptable radiation protection remains a critical requirement in modern radiological practice.nRadiation protective aprons are the most widely used personal protective equipment to mitigate occupational exposure. Conventional aprons fabricated from pure lead exhibit excellent attenuation efficiency due to lead's high atomic number; however, their excessive weight, stiffness, and limited flexibility often lead to discomfort and musculoskeletal strain during prolonged clinical use [7], [8], [9], [10], [11]. To address these limitations, several alternative material approaches have been proposed. Polymer composites filled with bismuth oxide (Bi_2O_3) have demonstrated high attenuation efficiency at diagnostic energies while offering reduced weight; however, brittleness and material

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inhomogeneity at high filler concentrations remain significant challenges [12], [13], [14], [15]. Barium sulfate ($BaSO_4$)–based composites have also been investigated due to their non-toxicity and chemical stability, yet their lower effective atomic number often results in reduced attenuation performance compared to lead- or bismuth-based systems, particularly at higher tube voltages [16], [17]. Multilayered shielding structures combining different fillers or layered configurations have been proposed to optimize attenuation across a broader energy spectrum; however, these designs often involve complex fabrication processes and increased manufacturing costs [18], [19]. Silicone rubber composites incorporating lead oxide (PbO) fillers represent another promising approach, offering a favorable balance between radiation attenuation, flexibility, durability, and wearer comfort [20], [21], [22], [23], [24].

From a methodological perspective, most previous studies primarily characterize shielding performance using physical attenuation parameters such as linear attenuation coefficients or the Half-Value Layer (HVL). Reported HVL values for PbO- or Bi_2O_3-filled polymer composites typically range from approximately 0.45 to 0.70 mm Pb-equivalent within the diagnostic energy range of 60–80 kV, depending on filler content and sample thickness [13], [21], [22], [25], [26], [27]. While these metrics provide valuable insight into material attenuation capability, they do not directly quantify practical radiation protection effectiveness in terms of transmitted intensity reduction. Furthermore, the influence of material thickness on protection effectiveness is often treated implicitly or evaluated at a single thickness, limiting the ability to establish clear thickness–performance relationships under clinically relevant X-ray energies [28], [29], [30]. Therefore, a clear research gap remains in the systematic evaluation of how thickness variation in flexible, polymer-based radiation protective materials affects both practical radiation protection effectiveness and HVL under diagnostic X-ray conditions. In particular, silicone rubber–based composites containing PbO fillers have not been comprehensively analyzed with respect to thickness-dependent shielding performance across commonly used clinical tube voltages.

To address this gap, the present study aims to fabricate silicone rubber radiation protective aprons filled with Lead(II) Oxide (PbO) at controlled thicknesses of 2.5 mm, 3.0 mm, and 3.5 mm and to experimentally evaluate their shielding performance at diagnostic tube voltages of 60–70 kV. By correlating material thickness with transmitted radiation intensity, protection effectiveness, and HVL, this study provides important contributions by experimentally evaluating the effect of material thickness on radiation protection effectiveness in silicone-based PbO composites. It also quantitatively analyzes the relationship between thickness, transmitted radiation intensity, and the Half-Value Layer (HVL), offering a physics-based understanding of attenuation behavior. Furthermore, this study provides practical insights into the development of lightweight, flexible, and ergonomically improved alternatives to conventional lead aprons for diagnostic radiology applications.

2. MATERIALS AND METHODS

This study employed a laboratory-based experimental design with a quantitative approach to evaluate the radiation shielding performance of silicone rubber aprons filled with lead(II) oxide (PbO). The experimental variables included apron thickness (2.5 mm, 3.0 mm, and 3.5 mm) and X-ray tube voltage (60 kV, 65 kV, and 70 kV), while the response variables were radiation protection effectiveness and the half-value layer (HVL). All other parameters, including exposure time, source-to-detector distance, and detector positioning, were maintained constant throughout the experiments. The radiation attenuation behavior of shielding materials follows the exponential attenuation law. When an X-ray beam with initial intensity I_0 passes through a shielding material of thickness x, the transmitted intensity I is expressed as [30], [31]:

$$I = I_o e^{-\mu \chi} \quad (1)$$

where μ is the linear attenuation coefficient. Based on this relationship, the radiation protection effectiveness of the apron material was calculated as the percentage reduction in transmitted radiation intensity using Eq. (2) [29], [31], [32]:

$$Effectiveness\ \ Protection\ (\%) = (\frac{I_O - I}{I}) \times 100 \quad (2)$$

The linear attenuation coefficient was obtained from Eq. (1), and $\ln(2) \approx 0.693$, the HVL defined as the thickness required to reduce the radiation intensity to 50% of its initial value, was calculated using Eq. (3) [33], [34], [35]:

$$HVL = \frac{\ln(2)}{\mu} \quad (3)$$

Apron prototypes measuring 15 × 20 cm were fabricated at the Hospital Facilities Maintenance Installation (IPSRS) of RSUD 45 Kuningan using silicone rubber as the polymer matrix, PbO as the radiation-attenuating filler, and a catalyst as the curing agent. Three thickness variations were prepared using acrylic molds. The material composition and thickness specifications of each prototype are summarized in Table 1.

Table 1. Composition of the material of the prototype apron based on the variation in thickness

Thickness (mm)	Volume (cm³)	Dough Total (g)	PbO (g)	Rubber Silicon (g)	Catalyst (g)
2.5	75.0	108.0	58.91	49.09	4.91
3.0	90.0	129.6	70.74	59.73	5.97
3.5	105.0	151.2	82.38	68.82	6.88

The fabrication process, from material preparation to radiation testing, is illustrated in Fig. 2. Radiation attenuation measurements were conducted at the

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Radiography and Computed Radiology Laboratory of the University of Muhammadiyah Purwokerto.

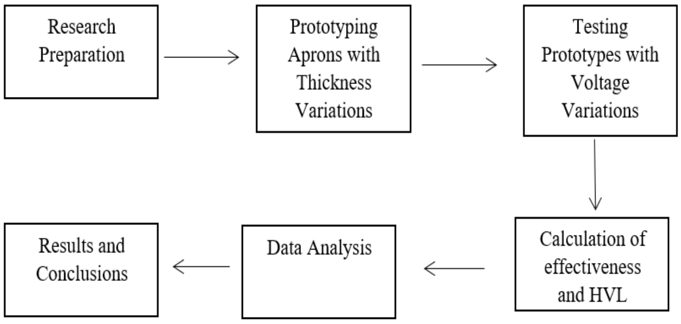

Fig. 2 Research Flow Diagram

Each apron prototype was positioned perpendicular to the X-ray beam between the radiation source and the detector, as shown in Fig. 3.

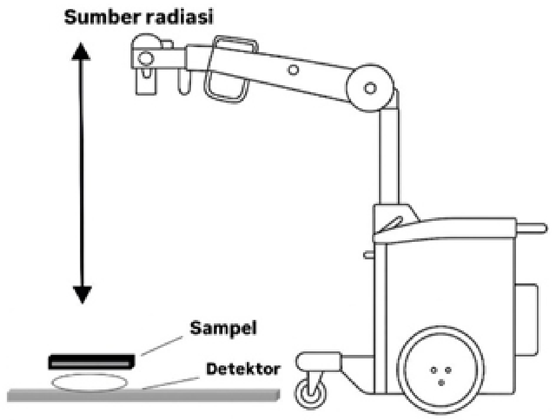

Fig. 3 Testing of Apron Prototypes Toward x-rays

Measurements were performed under two conditions: without shielding (I_0) and with shielding (I). For each thickness and tube voltage combination, ten repeated exposures were performed to improve measurement reliability. All experimental data were analyzed using descriptive and inferential statistical methods. Mean values and standard deviations were calculated for radiation protection effectiveness and HVL. The relationship between apron thickness and radiation protection effectiveness at each tube voltage was evaluated using simple linear regression analysis. The regression models were assessed using the coefficient of determination (R^2), and statistical significance was determined using p-values, with a significance threshold of $p < 0.05$.

3. RESULTS

The creation of the apron prototype was carried out as an initial stage to provide test samples in accordance with the study design. Three prototypes made of silicone rubber with Lead (II) Oxide (PbO) filler were produced using 15 × 20 cm molds with thickness variations of 2.5 mm, 3.0 mm, and 3.5 mm. Prototype documentation is shown in Fig. 1. which presents the top and side views as verification of the final shape before radiation testing was carried out.

Radiation protection material testing was conducted at three X-ray tube voltages: 60 kV, 65 kV, and 70 kV. This variation was chosen because it is suitable for clinical use in various radiological procedures. Adult thorax examinations generally use a voltage of 60–70 kV, which results in a balance between image contrast and radiation dose [36]. The 60 kV voltage provides high contrast for bone structures, while the 65 kV and 70 kV voltages provide more optimal penetration for patients with larger body habitus or when soft tissue details need to be highlighted [37].

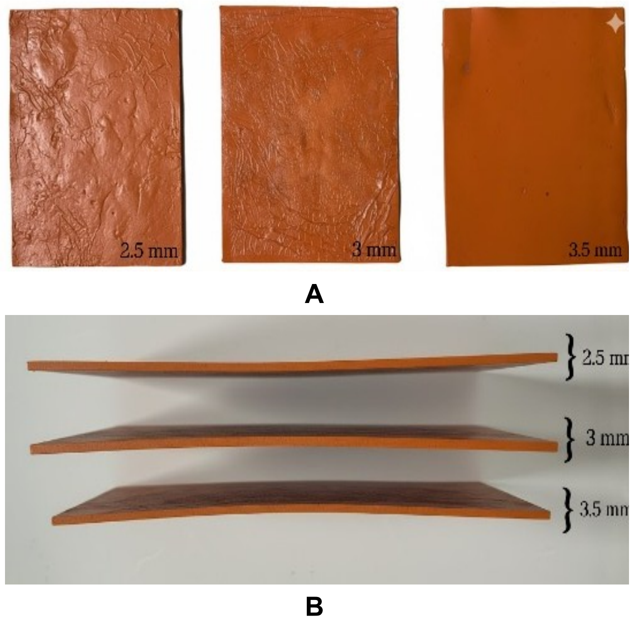

Fig. 1 Apron prototype results: (a) top view; (b) side view with thickness variations of 2.5 mm, 3.0 mm, and 3.5 mm

Table 2. Average transmitted radiation intensity (mean ± SD) at X-ray thickness and voltage variations

Thick (mm)	Average Transmitted Radiation Intensity		
	60 kV (mGy)	65 kV (mGy)	70 kV (cmGy)
2.5	0,0108±0,0008	0,0234±0,0008	0,0583±0,0023
3.0	0,0081±0,0008	0,0184±0,0013	0,0546±0,0051
3.5	0,0079±0,0008	0,0162±0,0028	0,0409±0,0015

The WHO recommendation sets 70 kV as the standard for AP and lateral cranial projections, whereas 65 kV is used when finer contrast is needed for thin skull structures. Extremity examinations generally use low voltage, although it can be increased to 60 kV for thicker objects. The voltage selection in this study reflects common clinical variation, so the test data can characterize the performance of the protective apron under real-world conditions. The purpose of the study was to evaluate the effectiveness of radiation protection provided by silicone rubber aprons formulated with lead(II) oxide (PbO) filler. The test involved three apron prototype thicknesses, namely 2.5 mm, 3.0 mm, and 3.5 mm. The initial radiation

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intensity without an apron was 0.047 mGy at 60 kV, 0.065 mGy at 65 kV, and 0.109 mGy at 70 kV. The average radiation intensity transmitted through each apron thickness at the specified voltage levels is presented in Table 2, which also reports the mean values and standard deviations for each test.

The variability analysis indicates that the intensity of transmitted radiation decreases with increasing apron thickness. This trend indicates that silicone rubber materials with PbO fillers exhibit effective attenuation and that increasing thickness significantly reduces radiation transmission. A relatively small standard deviation (<3%) indicates stable and reproducible measurement results.

Table 3. Radiation protection effectiveness (mean ± SD) at X-ray thickness and voltage variations

Thick (mm)	Average Effectiveness Passed on		
	60 kV (%)	65 kV (%)	70 kV (%)
2.5	77,02 ± 1,68	69,32 ± 1,25	70,92 ± 2,93
3.0	82,77 ± 1,87	74,58 ± 1,96	71,56 ± 1,43
3.5	83,19 ± 1,87	84,92 ± 1,48	74,86 ± 2,25

The effectiveness of radiation protection shown in The variability analysis indicates that the intensity of transmitted radiation decreases with increasing apron thickness. This trend indicates that silicone rubber materials with PbO fillers exhibit effective attenuation and that increasing thickness significantly reduces radiation transmission. A relatively small standard deviation (<3%) indicates stable and reproducible measurement results. Table 3 indicates that protection effectiveness increases as apron thickness increases. Across all voltages, the observed pattern indicates a positive relationship between material thickness and radiation reduction capability. The highest protection effectiveness is achieved at a thickness of 3.5 mm, particularly at a voltage of 65 kV, with a value of 84.92 ± 1.48%. This value indicates optimal conditions because, in the medium energy range (60–70 kV), photoelectric interactions are still dominant; thus, the increase in material density due to PbO fillers plays a significant role in absorbing X-ray photons.

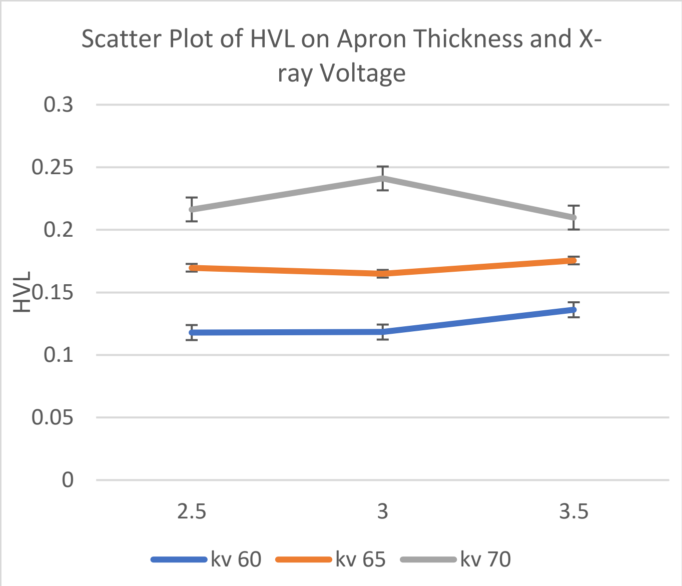
Fig. displays the results of a simple linear regression analysis using the full measurement dataset (not the average values). The scatter plot shows the distribution of protection effectiveness across each apron thickness, with a linear regression line indicating a positive correlation between thickness and protection effectiveness. The analysis showed that at 65 kV the relationship was very strong (R^2 = 0.916), at 60 kV it was moderate (R^2 = 0.5851), and at 70 kV it was relatively weak (R^2 = 0.3363). These findings indicate that increases in apron thickness significantly affect protection effectiveness, particularly at medium energy (65 kV), when photoelectric interactions remain dominant. HVL was calculated to assess the attenuation characteristics of the material. The average values ± standard deviations are presented in Table 4. At 60 kV, the HVL ranges from 0.1178 ± 0.0008 to 0.1361 ± 0.0009 cm. At 65 kV, HVL is in the range of 0.1649 ± 0.0013 to 0.1755 ± 0.0028 cm. Meanwhile, at 70 kV, HVL increases to a range of 0.2098 ± 0.0015 to 0.2411 ± 0.0051 cm. In general, HVL values tend to increase with increasing X-ray voltage, which indicates increased radiation penetration at higher energies.

Table 4. HVL (mean ± SD) at apron thickness and X-ray voltage variations (kV)

Thick (mm)	Average Half Value Layer passed		
	60 kV (cm)	65 kV (cm)	70 kV (cm)
2.5	0,1178±0,0008	0,1697±0,0008	0,2163±0,003
3.0	0,1182± 0,0023	0,1649±0,0023	0,2411±0,001
3.5	0,1361± 0,0009	0,1755±0,0028	0,2098±0,005

Fig. 5 shows the relationship between the thickness of the synthetic apron and the HVL value at different X-ray voltages. At 60 kV, the HVL value is relatively low, with a range of 0.1179–0.1361 cm, suggesting that at low energies the apron can attenuate most of the radiation with relatively thin thickness. At 65 kV, the HVL value increases to the range of 0.1649–0.1755 cm. Meanwhile, at 70 kV, the HVL is higher, ranging from 0.2098 to 0.2411 cm, indicating greater radiation penetration at higher voltages; thus greater material thickness is required to reduce radiation intensity by 50%.

Fig. 5 Scatter plot of HVL values versus thickness at X-ray voltage variations



The radiation shielding performance obtained in this study was compared with previously reported protective materials used in diagnostic radiology. Hayre et al. in 2020 [3] reported that conventional lead-based aprons with lead equivalence of 0.25–0.5 mm Pb provide substantial dose reduction and effective shielding at diagnostic X-ray energies; however, their effectiveness is associated with high material density, significant weight, and reduced ergonomic comfort. In contrast, the silicone

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rubber–PbO composite developed in the present study achieved a maximum protection effectiveness of 84.92 ± 1.48% at 65 kV with a relatively thin structure (3.5 mm), indicating competitive shielding performance while offering improved flexibility and potential ergonomic advantages [26], [27].

Quantitatively, the HVL values obtained in this study (0.117–0.176 cm at 60–65 kV) are comparable to or lower than those reported for silicone-based composites containing heavy metal oxide fillers. In 2022, El-Khatib et al. [16] reported HVL values in the range of 0.18–0.25 cm for silicone rubber composites filled with PbO at comparable diagnostic energy levels, while in 2024, Divband et al.[27] observed HVL values exceeding 0.20 cm for silicone-based matrices reinforced with PbO and Bi_2O_3 nanoparticles. The lower HVL values observed in the present study, particularly at 60–65 kV, indicate more efficient attenuation capability per unit thickness. Studies on alternative fillers such as Bi_2O_3 and WO_3 have demonstrated enhanced attenuation performance due to their high atomic numbers; however, they often require higher filler loading or increased thickness to achieve clinically relevant shielding levels [12], [38], [39], [40]. In comparison, the silicone–PbO composite investigated in this study demonstrates effective attenuation within a moderate thickness range, making it suitable for wearable radiation protection applications.

Overall, compared to previous studies that primarily report attenuation coefficients or HVL values, the present study provides direct quantitative protection effectiveness (%) together with HVL analysis under clinically relevant diagnostic voltages (60–70 kV). This combined evaluation enables a more practical assessment of shielding performance and highlights the importance of thickness optimization, particularly at medium diagnostic energy (65 kV), where the strongest correlation between thickness and protection effectiveness is observed.

4. DISCUSSION

This study was conducted to evaluate the effect of thickness variation on radiation protection effectiveness and the Half-Value Layer (HVL) of synthetic aprons fabricated from a silicone rubber matrix filled with Lead (II) Oxide (PbO) under clinically relevant diagnostic X-ray energies (60–70 kV). The experimental results demonstrate that increasing apron thickness consistently reduces transmitted radiation intensity and improves radiation protection effectiveness across all tested tube voltages, as shown in Table 2 and Table 3. For example, at 65 kV, increasing the thickness from 2.5 mm to 3.5 mm reduced the transmitted dose from 0.0234 ± 0.0008 mGy to 0.0162 ± 0.0028 mGy, corresponding to an increase in protection effectiveness from 69.32 ± 1.25% to 84.92 ± 1.48%. This trend confirms that the silicone rubber–PbO composite exhibits effective attenuation behavior and that thickness plays a critical role in shielding performance.

The strongest thickness–effectiveness relationship is observed at 65 kV, where simple linear regression analysis yielded a very strong correlation ($R^2 = 0.916$), as illustrated in Fig. 4. At 60 kV, the correlation is moderate ($R^2 = 0.5851$), while at 70 kV the correlation weakens considerably ($R^2 = 0.3363$). These findings indicate that thickness variation is the dominant factor controlling dose reduction at medium diagnostic energies, whereas at higher energies the contribution of additional interaction mechanisms becomes more significant.

From a radiation physics perspective, this behavior can be explained by the changing balance between photoelectric absorption and Compton scattering. In the 60–65 kV range, photoelectric interactions remain dominant, particularly in materials containing high atomic number fillers such as PbO. As a result, increases in material thickness and effective atomic number significantly enhance photon absorption. At 70 kV, however, Compton scattering becomes increasingly dominant, reducing the sensitivity of attenuation efficiency to thickness variation and leading to diminishing returns in protection effectiveness despite further increases in thickness [41], [42]. The HVL results further support these observations. As shown in Table 4 and Fig. , HVL values increase with tube voltage, ranging from 0.1178–0.1361 cm at 60 kV to 0.2098–0.2411 cm at 70 kV. Lower HVL

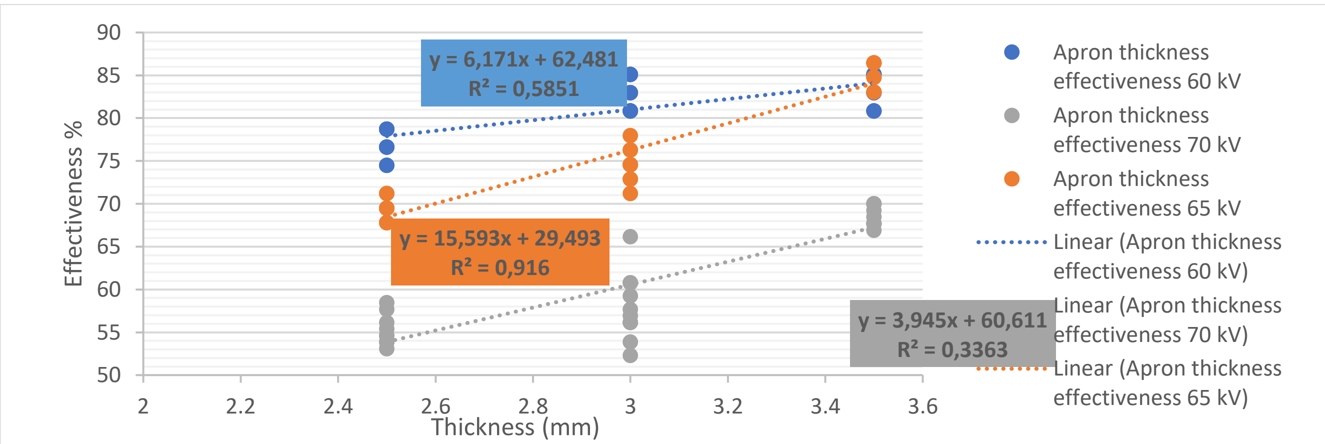

Fig. 4 The Relationship Between The Thickness Of Synthetic Aprons And The Effectiveness Of X-Ray Radiation Protection

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values at lower energies indicate more efficient attenuation, meaning that thinner material layers are sufficient to reduce the incident radiation intensity by half. Conversely, higher HVL values at 70 kV reflect increased photon penetration and beam hardening effects, explaining the weaker correlation between thickness and protection effectiveness at higher energies. These results confirm that HVL and radiation protection effectiveness are physically interconnected parameters, with HVL providing insight into energy-dependent attenuation behavior rather than acting as an independent performance metric.

The attenuation performance observed in this study is consistent with previously reported findings. In 2020, Hayre et al. [3] demonstrated that rubber–silicone-based shielding materials containing PbO fillers can achieve substantial dose reduction at diagnostic X-ray energies, with effectiveness strongly influenced by thickness and tube voltage. Similarly, in 2022, El-Khatib et al. [16] reported HVL values of approximately 0.18–0.25 cm for silicone rubber composites filled with PbO, which are comparable to or higher than those obtained in the present study, particularly at 60–65 kV. In 2024, Divband et al. [27] also reported increased HVL values at higher energies for silicone-based composites reinforced with heavy metal oxide fillers, indicating reduced attenuation efficiency per unit thickness at elevated tube voltages.

Compared with alternative fillers such as Bi_2O_3 or WO_3, which often require higher filler loading or greater thickness to achieve clinically relevant attenuation, the silicone rubber–PbO composite evaluated in this study demonstrates effective shielding performance within a moderate thickness range. The maximum protection effectiveness of 84.92 ± 1.48% achieved at 65 kV with a thickness of 3.5 mm suggests a favorable balance between attenuation efficiency and material thickness, which is important for wearable radiation protection applications. Nevertheless, practical considerations must be acknowledged. Increasing apron thickness may adversely affect weight, flexibility, and user comfort, which are critical factors for prolonged clinical use. In this context, the optimal performance observed at 65 kV and 3.5 mm thickness represents a compromise between radiation protection effectiveness and ergonomic feasibility rather than an absolute maximization of attenuation.

5. CONCLUSION

This study evaluated the effect of thickness variation on radiation protection effectiveness and the Half-Value Layer (HVL) of synthetic aprons fabricated from silicone rubber with Lead (II) Oxide (PbO) filler at diagnostic X-ray energies (60–70 kV). The results indicate that increasing material thickness significantly reduces transmitted radiation intensity and enhances radiation protection effectiveness. The highest protection effectiveness of 84.92% was achieved at a thickness of 3.5 mm at 65 kV, demonstrating optimal attenuation performance within the investigated range. A strong positive correlation between thickness and radiation protection effectiveness is observed, particularly at 65 kV (R^2 = 0.916), confirming that thickness plays a dominant role in attenuation behavior at moderate diagnostic energies. In addition, HVL values increase with higher tube voltage, indicating greater photon penetration and reduced attenuation efficiency at higher energies, which is consistent with fundamental X-ray interaction principles. These findings demonstrate that silicone rubber–PbO composite materials have strong potential as flexible, lightweight, and effective radiation shielding alternatives to conventional lead-based aprons. Future study is recommended to explore higher tube voltage ranges, optimize PbO filler concentration, and evaluate mechanical properties, durability, and ergonomic performance to support broader clinical implementation.

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