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Measurement of the Attenuation Properties of the Protective Materials Used as a Thyroid Guard and Apron for Personnel Protection against Diagnostic Medical X-rays

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ABSTRACT: *In the medical field, some protective materials incorporating lead or high-Z elements are used as lead-equivalent aprons or garments and thyroid guards for the protection of personnel against X-rays. However, in recent years, non-lead protective materials have become widespread in radiology because of their light weight and durability. Lead (Pb) has been replaced by non-toxic elements in conventional aprons or garments, which are generally made from Pb materials. Therefore, it is essential to experimentally demonstrate the Pb-equivalence of any protective material to determine whether it complies with nominal thicknesses of 0.25 mm, 0.35 mm, 0.5 mm or 1 mm Pb. In this study, the X-ray attenuation properties of some protective materials made from elastomers loaded by high-Z elements (such as Sb, Sn, W, Ba, etc.) were experimentally determined using both narrow and broad-beam geometry conditions. The X-ray attenuation properties have been determined in terms of the attenuation ratio (F), build-up factor (B) and lead equivalent (δ_{Pb}) for the investigated protective materials. These properties have already been stated by the manufacturers of the protective materials. From the air kerma values measured with a calibrated ionisation chamber, it was found that the mean attenuation ratios change from F = (90.7 ± 0.2)% to (20.9 ± 0.1)%, and the dose build-up factors are within the range of B = 1.90 to 2.75 at 80 kV_p. The F-ratios change from F = (41.8 ± 0.1)% to (8.5 ± 0.1)%, and those B-factors remain in the range of B = 0.85 to 1.64 at 100 kV_p. Among the attenuation properties for the x-ray protective materials, the most distinctive property is its lead equivalence. When they are compared with each other in terms of this property, e.g., for the δ_{Pb} = 0.5 mm Pb thickness stipulated by standards, it is found that some of the investigated materials did not meet this criterion when exposed to X-radiation at diagnostic beam qualities. This result clearly indicates that the quality control tests of any protective material should always be performed to verify its compliance to the attenuation requirements before it is used in medical X-ray facilities for the radiation protection of the personnel.*

Keywords: Protective material, lead-apron, lead equivalent, radiation protection, radiology

1. INTRODUCTION

Lead aprons, garments and/or thyroid guards made from some special materials are most commonly used as tools to protect medical personnel and patients against X-rays in the medical field. However, in practice, some lead apron or garment protective materials are, in general, relatively heavy because they are lead alloyed, have a surface area of 0.5 m^2 and are approximately 4.5 kg in mass. If a lead apron includes 0.5 mm of relined lead, its shielding effectiveness is the same as that of 4.5 kg of protective material, but its mass will be 2.6 kg.

It was noted by Jones and Wagner[1] that lead aprons or garments are considered to be hazardous toxic waste for disposal and are quite heavy, causing back strain and other orthopaedic problems when worn for longer periods of time. Additionally, McCaffrey et al.[2] indicated that the protective materials manufactured from the powder form of lead are poisonous and noted the decreasing lead ratio of the protective material with the use of lead alloyed or including non-lead materials. Therefore, it is a fact that the heavier lead aprons cause more ergonomic problems for medical doctors and technicians. Because of these facts, in recent years, manufacturers produced new protective materials, especially from particular plastic-based materials because of their light weights relative to lead, and they are preferred as protective materials in the diagnostic X-ray energy range. Most of these new developed protective garments are elastomeric or rubber fabric materials, which are generally manufactured by incorporating high-Z elements of about Z = 50 or higher such as In, Sn, Sb, Cs, Ba, Ce, etc. Hence, research on the production of novel protective materials incorporates the lower-Z elements rather than Pb. In newly developed protective materials, it is a fact that lead is replaced with elements having non-toxic high-Z elements such as Sn, Sb, Ba and W, whose K-edge absorption and photoelectric interactions can attenuate incoming radiation. Nevertheless, it is important to test these materials in reference to lead (Z = 82) because the K-absorption edges of such elements are always lower than the Pb K-absorption edge. It is still important to demonstrate whether the thickness of any newly developed protective material will meet the desired shielding effectiveness as well as the lead equivalent.

In this context, it is well known that various commercial protective garments or clothes manufactured from non-lead composite materials are used as protective tools or shielding materials in the medical sector. Moreover, it is generally claimed by their manufacturers that these newly developed protective materials have good radiation shielding effectiveness against X-rays in the radiologic energy range in which low energy (or superficial) X-rays are generated at tube potentials lower than or equal to 100 $kV_{p,}$ and medium energy (or orthovoltage) X-rays are generated at tube potentials higher than 100 kV_p, as classified in

AAPM's TG-61 protocol, as referenced in Ma et al.[3] However, beam qualities below 150 kV_p are commonly employed in radiology practice. This study measures the attenuation properties of some protective materials used for aprons/garments and thyroid guards that are medically used for personnel protection against diagnostic X-ray energies in the range of 60 to 120 kV_p.

It is important to measure the radiation attenuation properties of any protective materials and demonstrate the conformity of the radiation shielding effectiveness to the requirements stipulated by the EN 61331-1 international standard.[4] This can be achieved by implementing an appropriate verification procedure in which the testing of any protective material or device is based on the evaluation of the measured quantities, for example, in terms of the lead equivalent, build-up factor and attenuation ratio.

In the literature, the shielding effectiveness of lead aprons was determined by performing simple transmission experiments. For this purpose, a polymethyl methacrylate (PMMA) body phantom was used and placed at the back of lead aprons having nominal 0.25 mm and 0.50 mm lead equivalent. Next, the transmission tests were performed to determine the attenuation ratio of the lead apron with an ionisation chamber interposed between the lead apron and phantom, as explained by Christodoulou et al.[5] Aside from the lead apron, the attenuation ratio and lead equivalent values were calculated for four different non-lead protective materials, and it was shown how the radiation shielding changed with increasing X-ray tube voltage, as described by Vaiciunaite et al.[6] Additionally, in the diagnostic energy range, the conformity to standard requirements was tested on the thyroid guard and lead apron materials that are manufactured from the lead alloyed (Hx-Pb) and non-lead materials (e.g., tungsten, rubber, elastomers and Greenalite), i.e., its structural formula: Fe^{+2} + $_{4.5}Fe^{+3}$ + $_{1.0}(Si_4O_{10})(OH)_8$) given by Steadman and Youell. [7]

In this work, a radiometric bench with a suitable X-ray device having an energy range between 40–150 kV_p was used to provide broad-beam geometry (BBG) and narrow beam geometry (NBG) conditions in order to validate a full procedure. In addition, inverse broad-beam geometry (IBG) can also be discretely used for testing a protective material, as suggested by Büermann.[8] It is worth noting that the IBG condition is only an alternative method to the BBG condition, but it is not a compulsory method to measure the attenuation ratio, F_B, of the BBG. In fact, IBG measurements can be conducted in the beam qualities of the same X-ray facility, but a flat ionisation chamber needs to be used. However, the present work does not cover the IBG condition because a flat ionisation chamber with a wide area is not available in the laboratory for this purpose.

The main purpose of this work is to determine the radiation attenuation properties of some protective materials used as thyroid guard and lead apron/garments against an X-ray beam in the diagnostic energy range (40–150 kV_p) by employing an appropriate procedure.

2. EXPERIMENTAL

2.1 X-ray Irradiation and Measurement System

The irradiations were made by a Varian Rad 21 X-ray tube with an Italray High Voltage Generator (Scandicci, Florence, Italy) located in the X-Ray Calibration Laboratory, Ankara University Institute of Nuclear Sciences. The X-ray calibration system's frequency is 50/60 kHz, the kV range in radiography mode is 40–150 kV and 40–125 kV in fluoroscopy mode, and the mA range in radiography mode is 25–600 mA and 0.5–6 mA in fluoroscopy mode. The anode material of the X-ray tube is tungsten, and the anode angle is 12°. A voltage divider is used to measure the applied voltage to the X-ray tube by the GiCi-PM generator, which has a kV range of 0–150 kV.

The air kerma (dose) measurements were carried out using a calibrated PTW type (TM 32005) ion chamber (Freiburg, Germany). The main technical specifications of the ion chamber are given in Table 1. The PTW UNIDOS Webline model (S/N: T10021-0049) electrometer was used together with the ion chamber. Additionally, different thicknesses of copper filters (0.15 mm and 0.25 mm) were used to obtain beam qualities (energies) specified within the requirements of the EN 61331-1 standard. A photograph showing an X-ray tube and a radiometric bench used for the attenuation measurements of the thyroid guards and lead aprons is shown in Figure 1. In this setup, the necessary fixing items were used for a suitable alignment of the measurement geometry.

Table 1: Technical specifications of a calibrated ion chamber.

Detector	Type	Operating voltage (V)	Dose range		Dose rate range		Energy dependence
			Min (μGy)	Ma (mGy)	Min (μGy/min)	Max (Gy/min)	
PTW, 28 cm^3 Spherical ion chamber*	TM 32005	+400	2.2	23.8	12.96	65	Between 48 keV–1.25MeV (^{60}Co) ≤ ± %5

Note: *Ionisation chamber and electrometer used for the measurements were calibrated by Secondary Standard Dosimetry Laboratory (SSDL), Physikalisch-Technische Werkstatten (PTW), Freiburg, Germany.*

Figure 1: A photograph of a radiometric bench used for measurement of attenuation properties of X-ray protective materials.

2.2 Description of the Measurement Configurations

In this work, the standard method defined in the EN 61331-1 standard was chosen to determine the attenuation properties of protective materials. This method involves the testing of materials used as protective clothes against X-ray radiation qualities up to 400 kV and a total filtration of up to 3.5 mm Cu. The method can also be applied to measure the shielding effectiveness of X-ray absorber equipment besides radiation protective materials or devices. The following conditions are provided to implement the method in accordance with the EN 61331-1 standard: a) in NBG, the X-ray beam width consists of a diameter of 20 mm ± 1 mm radiation beam at the distal side of the test object; b) in NBG, the test object has dimensions of at least 100 mm × 100 mm; and c) in BBG, the test object has dimensions of at least 500 mm × 500 mm. In these measurements, the ionisation chamber has a sensitive volume of 28 cm^3, its diameter is no more than 50 mm, and the energy dependence of this detector is less than ±5%, as given in Table 1.

The NBG conditions are shown in Figure 2. The first condition is related to the geometric configuration, that is, $a \geq 10 \cdot \max(D, t)$, where D is the detector diameter and t is the diaphragm aperture. The second condition is related to the signal to noise ratio, that is, $\dot{K}_1 \geq 10 \cdot \dot{K}_B$, where $\dot{K}_1$ is the air kerma rate with the test object in the radiation beam, and $\dot{K}_B$ is the air kerma rate with the test object in the beam replaced by a sheet of material of the same shape with an attenuation ratio greater than 10^5. A lead sheet of 1.5 mm was used in this work, thus reducing the background radiation to almost zero. This choice always leads to a better factor than the expected factor of 10^5.

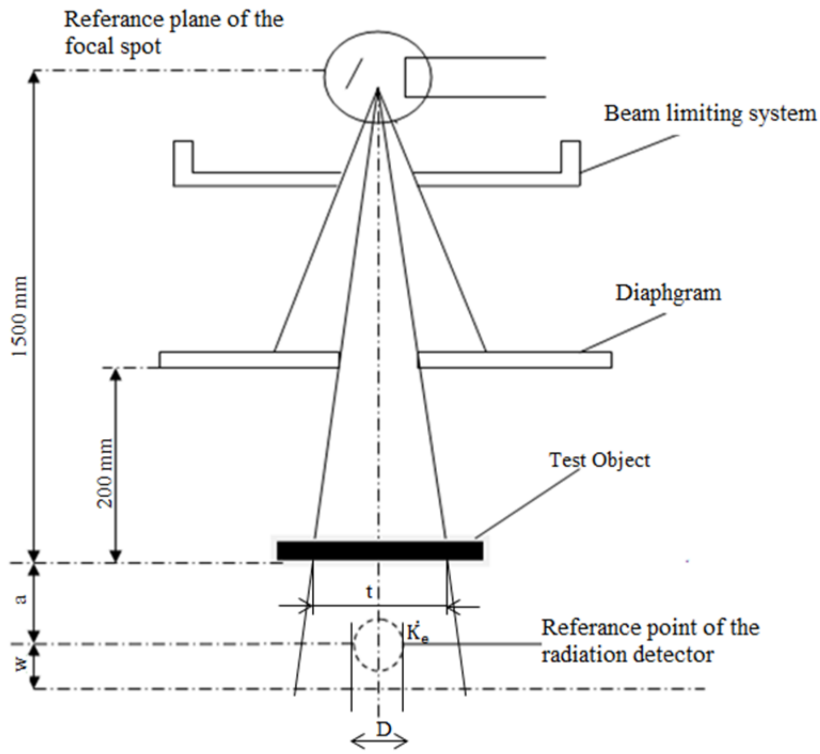

Figure 2: Narrow beam geometry, NBG.[4]

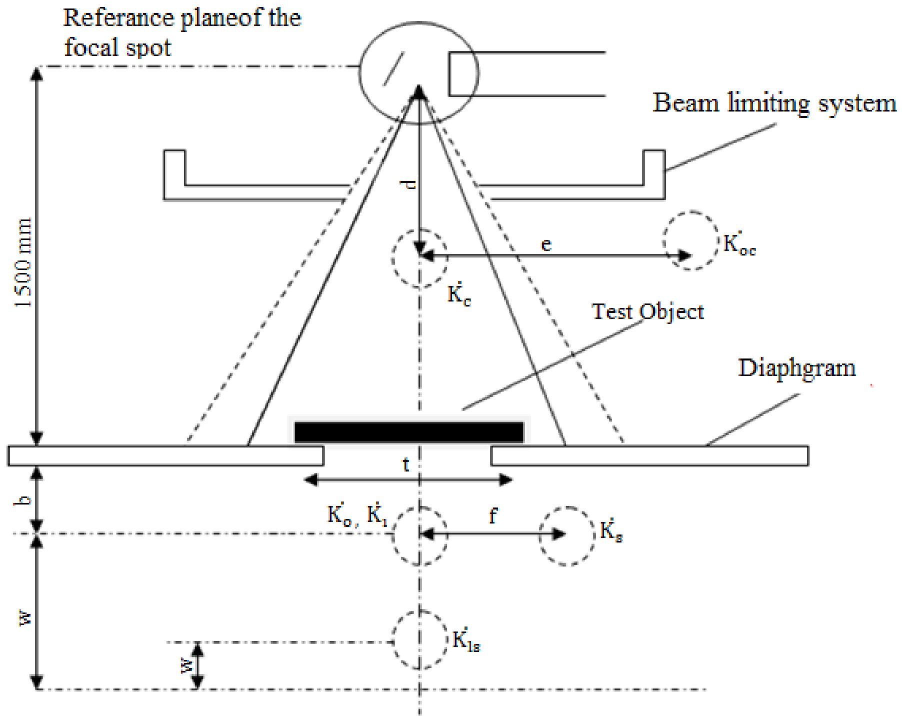

Figure 3: Broad-beam geometry (BBG).[4]

The BBG conditions are shown in Figure 3. The first condition is related to the geometric configuration, that is, $a \geq 3 \cdot t$ and $t \geq 10 \cdot b$, where b is the distance between the detector centreline and the test object, and t is diaphragm aperture. The second condition is related to the signal to noise ratio, i.e., $\dot{K}_1 \geq 10 \cdot \dot{K}_B$. Several additional dose measurement points are indicated in Figure 2 to determine the scattered radiation arising from the environment structure.

The a (mm) and b (mm) parameters shown in Figure 2 and Figure 3 are the distance (mm) from the distal side of the test object to the reference point of the radiation detector. The difference [W-w] is the distance between the dose measurement point of K_{ls} and the dose measurement points of K_o, K_i and K_s. As seen in Figure 3, d is the distance between the focal spot of the X-ray tube and the measurement point of K_c. The distance between the measurement points of K_c and K_{oc} is defined as the e (mm) parameter. The distance between the measurement points of K_o and K_s is defined as the f (mm) parameter. The distance between the focal spot of the X-ray tube and the test object is 1500 mm, and the distance between the focal spot of the X-ray tube and the detector is 1550 mm.

The air kerma values (**K**) measured by the ionisation chamber are defined using different subscripts, as follows:

K_i = Air kerma rate in the attenuated broad beam,
K_0 = Air kerma rate in the unattenuated broad beam,
K_e = Air kerma rate in the attenuated narrow beam,
K_c = Air kerma rate in the centre of the broad beam measured between the radiation source and the test object and at the same distance from the radiation source as K_{oc},
K_{oc} = Air kerma rate outside the broad beam emerging from the beam limiting system of the radiation source, which is measured at the same distance from the radiation source as K_c,
K_s = Air kerma rate inside the projection of the initial broad beam but outside the radiation beam limited by the diaphragm,
K_{ls} = Air kerma rate in the attenuated broad beam but measured at the same distance from the radiation source as K_s.

The attenuation properties are defined in terms of three parameters. These are: 1) the attenuation ratio; 2) the build-up factor; and 3) the lead equivalent.

1) The attenuation ratio, F_N or F_B, can be evaluated as follows:

$$F_N \ or \ F_B = \frac{\dot{K}_0 - \dot{K}_B}{\dot{K}_1 - \dot{K}_B} \tag{1}$$

where F_N denotes the attenuation ratio measured with a narrow beam condition, whereas F_B denotes the attenuation ratio measured under broad-beam conditions.

2) The build-up factor, B, defines the air kerma rate in an attenuated broad beam and the build-up effect on the material while attenuating air kerma rates in a narrow beam. It is simply expressed as:

$$B = \frac{F_N}{F_B} \tag{2}$$

This factor can also be calculated as $B = K_i / c \cdot K_e$ if the measurements of K_e are carried out for the material being tested and compared with the thickness of a layer of the reference material, resulting in the same value of K_e. The factor $c = [(a + 1500)/1550]^2$ is dimensionless and used for correcting the differences of the measuring point distances from the radiation source.

3) The lead equivalent, δ_{Pb}, is determined by the measurements of K_e for the material being tested and by comparison with the thickness of a layer of the reference material (one lead layer or extra lead layers), resulting in the same value of K_e. In this work, the thyroid guard and lead apron are used as the test material or test object.

2.3 The Tests for X-ray Protective Materials

The attenuation properties can be measured with different X-ray beam qualities, as shown in Table 2, and they are defined in terms of their total filtration and first half-value layers (HVLs). From these, the most representative beam energies are 80 kV_p and 100 kV_p beam qualities in radiology practice. It was determined that these kV_p values are enough to determine the attenuation parameters in the diagnostic energy range. However, other X-ray tube voltages up to 400 kVp can be employed on demand for protective material testing.

Table 2: Standardised X-ray beam qualities.[4]

X-ray tube voltage (kV_p)	Total filtration* (mm Cu) nominal	First HVL (mm Al) nominal
30	0.05	0.99
50	0.05	1.81
80	0.15	2.77
100	0.25	3.44
150	0.7	5.17
200	1.2	14.16
250	1.8	16.8
300	2.5	18.6
400	3.5	20.8

*Note: *These are also equal to 2.5 mm Al for beam qualites up to 150kV_p.*

In this work, high purity (99%) lead sheets were used as reference materials to compare the attenuation properties of the investigated protective materials. First, transmission measurements were made at NBG and BBG conditions using 0.5, 1 mm and 1.5 mm thick lead sheets. Then, a nominal thickness of δ_{Pb} = 0.5 mm lead equivalent thyroid guard, a nominal thickness of δ_{Pb} = 0.5 mm lead equivalent thyroid guard and lead aprons belonging to manufacturers, which are labelled here as letters A and B, were tested. A nominal thickness of δ_{Pb} = 0.5 mm lead equivalent lead apron is called here C for the relevant manufacturer.

3. RESULTS AND DISCUSSION

3.1 Dose Measurements at NBG Conditions

NBG and BBG conditions, shown in Figure 2 and Figure 3, were set up to determine the attenuation properties of the protective materials. The measured distances in Table 3 were chosen at these geometries to meet the standard requirements. While choosing the distances and tube currents, the X-ray exposure rates were adjusted to give at least between 0.6 to 0.9 mGy s^{-1} 1 m from the source. The distances given in Table 3 were fixed to measure accurate doses in the nominal dose range of the ionisation chamber.

Table 3: The fixed distances for the dose measurements.

Parameters	Length (mm)
a	100 ± 1
b	100 ± 1
d	940 ± 9.5
e	400 ± 4
f	300 ± 3
W–w	50 ± 0.5

As given in Table 4, the X-ray tube voltages were measured by means of a voltage divider, as mentioned in Section 2.2, after a suitable total filtration value was chosen. Air kerma value K_e measurements in NBG conditions were taken at least three times using 0.5 mm, 1.0 mm, 1.5 mm lead layers. These dose measurements were then used to calculate the lead equivalent, δ_{Pb}, of the investigated thyroid guard materials compared to that of the known nominal lead equivalent.

Table 4: X-ray beam qualities used for measurement of the samples.

Beam quality		Total filtration	
Nominal kV_p	Measured* kV_p	Nominal total filtration (mm Cu)	Obtained total filtration** (mm Cu)
80	79.2	0.15	0.14
100	99.2	0.25	0.24

Notes:

* *It was measured by using voltage divider.*

** *Inherent filtration of X-ray tube is 1.2 mm Al. Copper equivalent of this value was calculated as 0.04 mm Cu with using Xcomp5r spectrum software.*

As given in Table 5, the weighted mean values calculated from at least three measurements of the air kerma K_e values were given. The air kerma (dose) uncertainties varied between 2.66%–3.70%. The measurement sensitivity of the ion chamber decreased with increasing lead thickness as a result of decreasing the dose values, and hence, the dose uncertainties increased at low dose values.

Table 5: Measured Ke air kerma values when reference lead materials are interposed between X-ray tube and detector.

Thickness (mm Pb)	X-ray tube voltage (kV_p)	Total filtration (mm Cu)	Weighted air kerma values at NBG conditions* K_e (μGy)
0.5	80	0.15	30 ± 0.3
0.5	100	0.25	129 ± 4
1.0	80	0.15	3.17 ± 0.01
1.0	100	0.25	25 ± 0.2
1.5	80	0.15	0.53 ± 0.01
1.5	100	0.25	6.58 ± 0.01

*Note: *These are the weighted mean values calculated from at least 3 measurements.*

Reference lead materials were replaced by thyroid guard materials that interposed between the detector and the X-ray tube in a predefined location. Then, the measurements were performed in NBG conditions, and the measured air kerma values, K_e, are given in Table 6.

Table 6: Measured K_e air kerma values and calculated lead equivalents when reference thyroid guard material interposed between X-ray tube and detector.

X-Ray tube voltage (kV_p)	Total filtration (mm Cu)	Narrow beam air kerma value, K_e (μGy)	Nominal thickness (mm Pb)	Lead equivalent, δ_{Pb} (mm Pb)
80	0.15	26.64 ± 0.74	0.50	0.53 ± 0.02
100	0.25	119 ± 3	0.50	0.53 ± 0.02

Lead thickness versus dose graphs were plotted with obtained dose (air kerma) values in reference to lead material measurements, as shown in Figure 4 and Figure 5 for 80 and 100 kV_p beam qualities, respectively. The measured dose values approximately decrease exponentially with increasing lead thickness, as expected. The regression coefficients were found to be $R^2 \cong 0.992–0.993$.

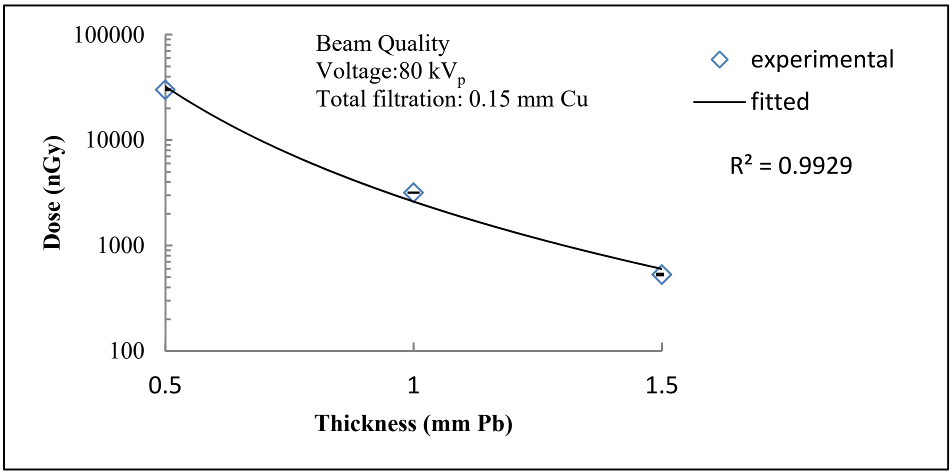

Figure 4: Relationship between reference lead thickness and measured dose at X-ray tube voltage of 80 kV_p.

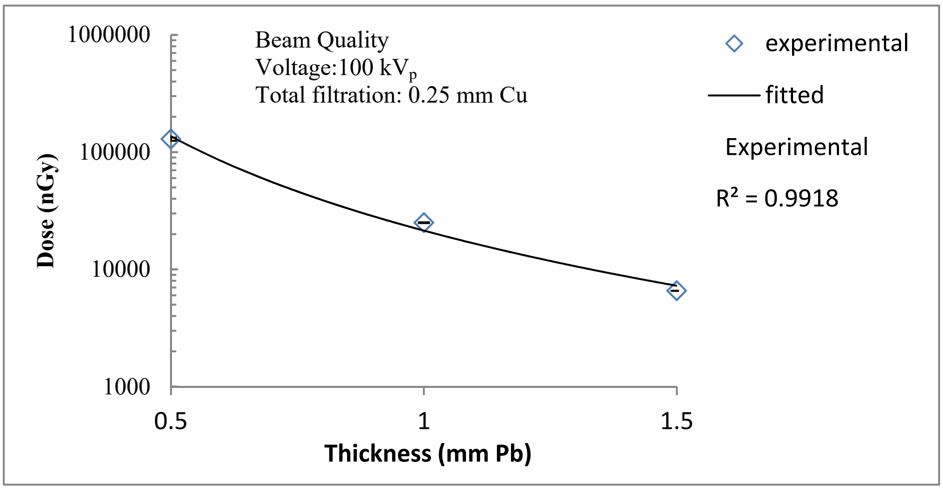

Figure 5: Relationship between reference lead thickness and measured dose at X-ray tube voltage of 100 kV_p.

The lead equivalent of the reference thyroid guard material at 80 kV_p was calculated as $\delta_{Pb} = 0.53 \pm 0.02$ mm. Similarly, the lead equivalent of the reference thyroid guard material at 100 kV_p was calculated as $\delta_{Pb} = 0.53 \pm 0.02$ mm.

The uncertainty sources of these measurements are due to the distance between the X-ray tube focal spot and the test object (±%1), the distance between the test object and the ion chamber (±%1), the X-ray tube voltage (≤%1), the sensitivity of using the ion chamber and the electrometer (<%2), and systematic uncertainties (<%2).

3.2 Dose Measurements at BBG Conditions

The attenuation ratio and build-up factors of the reference thyroid guard material were calculated according to Equation (1) and Equation (2) by measuring the K_0 and K_i air kerma values at BBG conditions, as shown in Figure 2. The measured results are given in Table 7 together with the calculated attenuation ratios and build-up factors at two different beam qualities. The attenuation ratios of the thyroid guards are found to be 24.5 and 10.6 material at 80 kV_p and 100 kV_p beam qualities, respectively. It was observed that the thyroid guard material prevented the X-radiation at approximately 96% at 80 kV_p beam quality and 91% at 100 kV_p beam quality. This protection level of the present thyroid guard material seems to be reasonable, but it can still be enhanced by approximately 8%–9%.

Table 7: Measured K_0, K_i, K_e air kerma values and calculated attenuation ratio and build up factors for reference thyroid guard material.

X-ray tube voltage (kV_p)	Total filtration (mm Cu)	Air kerma values (µGy)			F	c^*	B
		K_0	K_i	K_e			
80	0.15	1895 ± 53	77.47 ± 2.16	26.64 ± 0.74	24.5 ± 0.1	1.07	2.72 ± 0.23
100	0.25	2140 ± 58	202.13 ± 5.50	119 ± 3	10.6 ± 0.1	1.07	1.59 ± 0.12

Notes:
F = Attenuation Ratio, c = Correction Factor, B = Build up Factor
* *Here, c coefficient was calculated from Equation (3) for the distance of a=100 mm*

The K_c, K_{oc}, K_{ls} and K_s values measured the protective material's other radiation attenuation parameters at BBG in accordance with the EN 61331-1 standard, and the results are given in Table 8. $K_{oc} \leq 0.05 \cdot K_c$ was met by the boundary condition of the K_{oc} air kerma value. In a similar way, $K_s \leq 0.01 \cdot K_{ls}$ was met by the boundary condition of the K_s air kerma value. If these conditions can be met at BBG, it means that the scattered radiation arising from the environmental structure and walls around the X-ray setup is unimportant at the BBG measurement condition. Therefore, both the NBG and BBG conditions specified in the described method used in this work were entirely met.

Table 8: Measured K_c, K_{oc}, K_{ls} ve K_e air kerma values.

X-ray tube voltage (kV_p)	Total filtration (mm Cu)	Air kerma values (μGy)				Boundary condition	Boundary condition
		K_c	K_{oc}	K_{ls}	K_s	$K_{oc} \leq 0.05 \cdot K_c$	$K_s \leq 0.01 \cdot$
80	0.15	5397 ± 150	38 ± 1	68 ± 2	0.51 ± 0.01	≤ 270	≤ 0.68
100	0.25	6140 ± 167	51 ± 1	156 ± 4	0.87 ± 0.02	≤ 307	≤ 1.56

3.3 Measurements for the Shielding Effectiveness of the Thyroid Guard and Lead Apron

The shielding effectiveness parameters (attenuation ratio, build-up factor and lead equivalent) of the thyroid guards and lead aprons manufactured by various manufacturers were calculated at NBG and BBG measurement conditions, as explained in Section 3.1 and 3.2. For this purpose, the products of the various manufacturers were coded as A, B and C. To conform to standard tests of protective materials manufactured by various manufacturers and calculate their lead equivalent values of the thyroid guard and lead apron materials, the K_e values belonging to the reference lead materials (0.5 mm, 1 mm and 1.5 mm Pb), given in Table 5, were used. The measured air kerma values and calculated lead equivalent values at NBG conditions are given in Table 9 for thyroid guard and lead apron materials.

Table 9: Measured K_e air kerma values and calculated lead equivalents for the investigated protective materials.

Investigated Sample		Beam quality		Narrow beam air kerma K_e (μGy)	Equivalent thickness	
Manufacturer	Intended use	X-ray tube voltage (kV_p)	Total filtration (mm Cu)		Nominal thickness (mm Pb)	Lead equivalent, δ_{Pb} (mm Pb)
A	Thyroid guard	80	0.15	30.2 ± 0.8	0.5	0.50 ± 0.02
		100	0.25	131.8 ± 3.6		
	Lead apron	80	0.15	35.3 ± 1.0	0.5	0.48 ± 0.02
		100	0.25	147.7 ± 4.0		
B	Thyroid guard	80	0.15	28.3 ± 0.8	0.5	0.51 ± 0.02
		100	0.25	125.6 ± 3.4		
	Lead apron	80	0.15	32.7 ± 0.9	0.5	0.49 ± 0.02
		100	0.25	139.8 ± 3.8		
C	Lead apron	80	0.15	10.6 ± 0.3	0.5	0.69 ± 0.03
		100	0.25	57.9 ± 1.6		

Note: In this work, A, B, C letters are arbitrarily assigned to indicate different manufacturer's products.

The K_0 and K_i air kerma values at the BBG and the K_e air kerma values at the NBG of the investigated thyroid guard and lead apron materials are given in Table 10. For the samples, the attenuation ratio from Equation (1) and the build-up factor from Equation (2) are calculated. The results show that the lead equivalent values of the thyroid guard and lead apron materials of the A and B coded manufacturers are close to the nominal value of δ_{Pb} = 0.5 mm Pb. However, only the lead equivalent value of δ_{Pb} = 0.69 ± 0.03 mm Pb of the lead apron material of the C coded manufacturer is higher than nominal value of δ_{Pb} = 0.5 mm Pb.

Table 10: Measured K_0, K_i, K_e air kerma values and calculated attenuation ratio and build up factors for investigated protective materials.

Inspected sample		Beam quality		Measured air kerma values (μGy)			Calculated factors		
Manufacturer code	Intended use	X-ray tube voltage (kV_p)	Total filtration (mm Cu)	K_0	K_i	K_e	Attenuation ratio, F	Correction factor, c	Build up factor, B
A	Thyroid guard	80	0.15	1909 ± 53	84.1 ± 2.3	30.2 ± 0.8	22.7 ± 0.1	1.05	2.65 ± 0.21
		100	0.25	2158 ± 59	224.8 ± 6.1	131.8 ± 3.6	9.6 ± 0.1		1.62 ± 0.11
	Lead apron	80	0.15	1909 ± 53	91.3 ± 2.5	35.3 ± 1.0	20.9 ± 0.1	1.05	2.46 ± 0.19
		100	0.25	2158 ± 59	253.9 ± 6.9	147.7 ± 4.0	8.5 ± 0.1		1.64 ± 0.10
B	Thyroid guard	80	0.15	1909 ± 53	81.6 ± 2.3	28.3 ± 0.8	23.4 ± 0.1	1.05	2.75 ± 0.21
		100	0.25	2158 ± 59	205.5 ± 5.6	125.6 ± 3.4	10.5 ± 0.1		1.56 ± 0.11
	Lead apron	80	0.15	1909 ± 53	90.1 ± 2.5	32.7 ± 0.9	21.2 ± 0.1	1.05	2.62 ± 0.20
		100	0.25	2158 ± 59	229.6 ± 6.2	139.8 ± 3.8	9.4 ± 0.1		1.56 ± 0.11
C	Lead apron	80	0.15	1916 ± 53	21.1 ± 0.6	10.6 ± 0.3	90.7 ± 0.2	1.05	1.90 ± 0.37
		100	0.25	2169 ± 59	51.9 ± 1.4	57.9 ± 1.6	41.8 ± 0.1		0.85 ± 0.19

The results show that the obtained attenuation ratio and build-up factor values of the protective materials (Table 10) increase with increasing attenuation ratio values (Table 9). For example, the attenuation ratio of the lead apron manufactured by the C coded manufacturer is F = 41.8 ± 0.1 at 100 kV_p. The shielding effectiveness (i.e., protection level) of this material was calculated to be 97.6% from the measured data given in Table 10. Similarly, the attenuation ratio of this material is F = 8.5 ± 0.1 at 100 kV_p for the lead apron manufactured by the A coded manufacturer. The shielding effectiveness of this lead apron against X-rays was calculated to be 88.2% from the measured data given in Table 10.

The lead equivalent values, δ_{Pb}, of the thyroid guard and lead apron materials obtained from Table 9 and Table 10 are generally close to the conventionally accepted nominal value of δ_{Pb} = 0.5 mm Pb. Concordantly, the attenuation ratio values of the investigated guard and apron materials at 80 kV_p and 100 kV_p are compatible with each other. However, the lead equivalent value of the lead apron provided by the C coded manufacturer was determined to be δ_{Pb} = 0.69 ± 0.03 mm Pb, which is relatively higher than the nominal value of δ_{Pb} = 0.5 mm Pb by 38%, which means that this value is the best one.

4. CONCLUSION

The results indicate that there are significant differences relating to the shielding effectiveness of commercial protective materials. The essential point is that the shielding effectiveness of such protective material complies with at least one of the measured parameters, such as "lead equivalence." However, a complete procedure should always be completed whether the material being tested "passes" or "fails" in regard to the radiation protection criteria according to the requirements stipulated by the standard. Hence, after performing X-ray transmission tests on the protective materials, the complete analysis of the obtained results regarding the key parameters, such as the build-up factor, attenuation ratio and shielding effectiveness percentage, for any protective material is essential for the acceptance of the pre-usage of these types of materials in X-ray working places such as hospitals. Moreover, periodically performing quality control (QC) tests of the lead apron and thyroid guard materials is suggested. In these tests, it is also important to observe the laceration, buckling, puncture and fracture of the protective materials with fluoroscopic examination and also to observe the size of the puncture and fracture of the lead equivalent materials. It is necessary to protect medical personnel and to decide whether the materials are acceptable or not. These tests strongly suggest performing radiation transmission tests of protective materials for their acceptance, especially considering the radiation protection of personnel or workers.

It is worth noting that these types of materials are being increasingly used for personnel protection during diagnostic imaging in medical centres. In addition, their usage has also increased significantly for the protection of personnel working in other harsh radiation environments, such as in handling and transportation and industrial X-ray or gamma-ray applications.

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