Kingdom of Saudi Arabia

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Radiation Attenuation Properties of Car Window Glass at Computed Tomography X-ray Energies

A graduation project submitted to the Department of Physics in partial fulfillment of the requirements for the degree of Science in Applied Physics

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Riyadh – KSA

May-2025

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μ : linear attenuation coefficient

μ_w: the linear attenuation coefficient of water.

CT: Computed Tomography.

HU: the Hounsfield unit of CT.

ρ: *Density*.

K: is a magnification contrast (=1000) .

I_o: *initial intensity.*

I: its intensity after passing material.

ACKNOWLEDGEMENTS

The project's success and final outcome necessitate significant effort and guidance from a wide range of individuals. I am grateful for the help and guidance I received during this project, with only a small amount coming from Allah. Additionally, I would like to express my gratitude to my supervisor and guide, Dr. Mohammad Wassef Marashdeh, who was instrumental in initiating and supervising the project. I diligently work on every step of the project, and Dr. Marashdeh guides me to gather the necessary information to achieve the best possible outcome for the advertisement. He also extends his sincere thanks for the encouraging support and guidance from all faculty members in the Physics Department, especially Dr. Ahmad Al-Qaoud, the head of the department. I would like to thank my parents, siblings, and friends for their encouragement and support beyond measure. I also want to thank the Radiology Department, especially Dr. Mazen Al-Majali at the private medical center at Imam Muhammad bin Saud Hospital, for helping us with the project.

Thank you all

ABSTRACT

This study focused on evaluating the radiation shielding properties of five different car window glass samples (S1 to S5) using CT scan-based techniques. The goal was to determine which samples are most suitable for use in environments exposed to X-ray radiation, such as in medical imaging or mobile CT scan units. The density of each sample was measured, with S3 having the highest value (2.859 g/cm^3), followed by S1 (2.826 g/cm^3), indicating they may offer stronger radiation protection. CT number analysis showed that S1 had the highest average CT number (985.6 HU), but samples S3 and S5 were more consistent, with slightly lower averages (960.7 HU and 962.9 HU) and lower standard deviations, making them more reliable for shielding purposes. Linear attenuation coefficients confirmed that S1 had the highest value (0.559 cm^{-1}), while S5 and S3 followed closely. In terms of mass attenuation, S2 showed the highest value (0.250 cm^2/g) due to its lower density, while S4 and S5 showed the smallest difference from the standard material polyvinyl butyral (PVB), with only 1.0% and 1.2% variation, respectively. These results suggest that S3 and S5 are the most balanced and effective choices for radiation protection, offering both strong shielding ability and material consistency. This makes them good candidates for practical applications in medical environments where protection from X-ray exposure is required.

الملخص

ركزت هذه الدراسة على تقييم خصائص التغطية الإشعاعية لخمسة نماذج مختلفة من زجاج نوافذ السيارات S1 إلى S5 باستخدام تقنيات مستندة إلى التصوير المقطعي المحوسب .(CT) وكان الهدف هو تحديد النماذج الأكثر ملاءمة للاستخدام في البيئات المعرضة لأشعة إكس، مثل وحدات التصوير الطبي أو وحدات الأشعة المتنقلة. تم قياس كثافة كل عينة، حيث سجلت العينة S3 أعلى كثافة (2.859 جم/سم^3)، تليها العينة S1 (2.826 جم/سم^3)، مما يشير إلى أنها قد توفر حماية إشعاعية أقوى. أظهرت نتائج رقم CT أن العينة S1 سجلت أعلى متوسط (985.6 HU) ، ولكن العينتين S3 و S5 أظهرتا ثباتاً أكبر، مع متوسطات أقل قليلاً 960.7 HU) و 962.9 (HU وانحرافات معيارية منخفضة، مما يجعلهما أكثر موثوقية للاستخدام في الحماية من الأشعة. وأكدت معاملات التوهين الخطية أن العينة S1 كانت الأعلى (0.559 سم$^{-1}$)، تليها S5 و .S3 أما بالنسبة لمعاملات التوهين الكتلية، فقد سجلت العينة S2 أعلى قيمة (0.250 سم^2/جم) بسبب كثافتها المنخفضة، في حين أظهرت العينتان S4 و S5 أقل فرق مقارنة بالمادة القياسية بولي فينيل بيوتيرال (PVB) ، بنسبة فرق بلغت 1.0٪ و 1.2٪ على التوالي. وتشير هذه النتائج إلى أن العينتين S3 و S5 هما الأكثر توازناً وفعالية من حيث الحماية من الإشعاع، حيث تجمعان بين قدرة التوهين العالية وثبات المادة، مما يجعلهما خياراً مناسباً للتطبيقات العملية في البيئات الطبية التي تتطلب الحماية من التعرض لأشعة إكس.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The rapid advancement of imaging technologies, especially computed tomography (CT), has led to a significant increase in diagnostic imaging procedures globally. CT imaging, due to its superior spatial resolution and speed, is widely used to diagnose a range of organ systems including the lungs, liver, and cardiovascular structures. However, this increase in utilization has raised concerns about patient radiation exposure and necessitated the evaluation of materials used in radiological environments for safety and shielding efficiency [1,2].

One area of interest is the radiation attenuation capability of materials found in everyday environments, such as car window glass. Vehicles, especially during patient transport or mobile radiological services, may expose individuals to scattered or direct X-ray radiation from nearby CT scan equipment. Understanding the shielding properties of car window glass at diagnostic photon energy ranges, particularly those relevant to CT scans (typically 80–140 keV), is critical for improving radiation protection protocols [3].

Car window glass, commonly composed of laminated or tempered silica-based composites, presents a unique structure that may influence its interaction with X-rays. Investigating its ability to attenuate ionizing radiation can help assess whether such glass provides adequate passive shielding or requires enhancement for safer medical transport or imaging setups. While previous studies have focused on dedicated shielding materials like lead or specific polymers, minimal research has explored everyday materials like automotive glass in medical radiation contexts [4].

This study aims to fill that gap by evaluating the linear and mass attenuation coefficients of car window glass using both experimental CT scan imaging and theoretical calculations from the XCOM database. CT numbers (Hounsfield Units) and material densities are also analyzed to determine the glass's compatibility and effectiveness in attenuating X-rays at diagnostic energy levels.

1.2 Objectives of the Present Study

The overall objective of this study is to evaluate the radiation shielding properties of car window glass at CT scan energy levels.

The specific objectives are:

- To prepare and determine the density of car window glass samples.
- To calculate the CT numbers (Hounsfield Units) of the samples.
- To determine the linear and mass attenuation coefficients using both CT scan measurements and theoretical XCOM simulations in the CT scan energy range.

1.3 Structure of the Report

Chapter One introduces the importance of radiation shielding in CT imaging and outlines the study objectives. Chapter Two provides a theoretical background on X-ray interactions, radiation attenuation, and CT imaging physics. Chapter Three describes the materials and methods used, including CT scanning protocols and density/attenuation measurements. Chapter Four presents the results of the attenuation coefficient and CT number analyses of the car window glass samples. Finally, Chapter Five offers the conclusion and potential applications of the study findings.

CHAPTER 2

THEORY AND LITERATURE REVIEW

2.1 Production of X-ray Beam

2.1.1 Characteristic Radiation

Characteristic radiation is generated when high-energy electrons collide with a target material, such as a metal anode. This interaction dislodges electrons from the inner shells of atoms in the target, creating electron vacancies. Electrons from higher energy levels then drop into these lower energy levels, releasing energy in the form of X-ray photons. The energy of these emitted photons is characteristic of the target material's atomic structure [5].

2.1.2 Bremsstrahlung Radiation

Bremsstrahlung, or 'braking' radiation, occurs when electrons are decelerated by the electric field of atomic nuclei. As the electrons slow down, they emit photons with a continuous energy spectrum. This type of radiation is common in X-ray tubes and contributes significantly to the X-ray spectrum used in medical imaging [6].

2.2 Interaction of Photons with Matter

X-ray photons interact with matter primarily through three mechanisms: the photoelectric effect, Compton scattering, and pair production. These interactions are responsible for energy deposition in tissues during diagnostic imaging [7].

2.2.1 Photoelectric Effect

In this interaction, a photon transfers all its energy to an inner-shell electron, ejecting it from the atom. This results in a vacancy filled by an outer-shell electron, emitting characteristic radiation. The photoelectric effect is more probable at lower photon energies and in materials with higher atomic numbers [7].

2.2.2 Compton Scattering

Compton scattering occurs when a photon interacts with an outer-shell or free electron. Part of the photon's energy is transferred to the electron, which is ejected, and the photon is scattered at a reduced energy. This effect is significant in soft tissues and becomes more dominant at higher photon energies [7].

2.2.3 Pair Production

When a photon with energy exceeding 1.02 MeV passes near a nucleus, it can transform into an electron-positron pair. This process is relevant at very high energies and is accompanied by the emission of annihilation photons when the positron interacts with an electron [7].

2.3 Attenuation Coefficients

The linear attenuation coefficient (μ) quantifies the likelihood of photon interactions per unit distance in a material. It depends on both the photon energy and the material's composition. The mass attenuation coefficient (μ/ρ) normalizes μ by the material's density (Figure 2.1). Photon attenuation in matter follows an exponential decay model, governed by the equation:

$$I = I_o e^{-\mu x} \qquad (2.1)$$

where ***I*** is the intensity at depth x, ***I₀*** is the initial intensity, and ***μ*** is the linear attenuation coefficient. This relationship shows how photon intensity decreases with depth. The total attenuation includes contributions from the photoelectric effect (τ), Compton scattering (σ), and pair production (κ):

$$\mu = \tau + \sigma + \kappa \qquad (2.2)$$

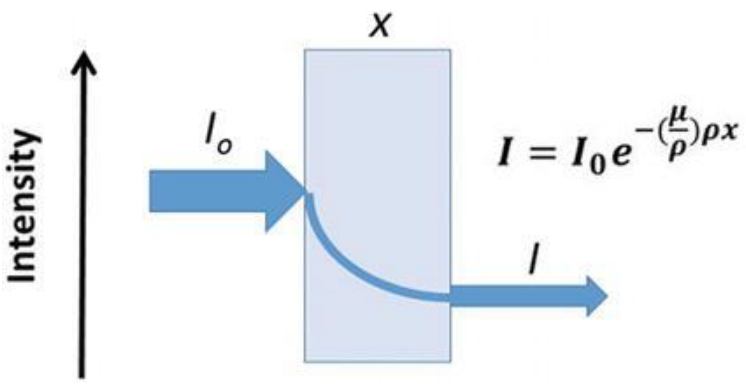

Figure 2.1 Linear Attenuation Coefficient [8].

CHAPTER 3

MATERIALS AND METHODS

3.1 Density Measurement

The density of the car window glass samples was calculated using their mass and external dimensions. According to the International System of Units (SI), density is expressed in grams per cubic centimeter (g/cm^3). Each sample's length, width, and thickness were measured using a ruler, while the mass was measured using an electronic scale. To ensure accuracy, three readings were taken for each car window glass sample, and the average values were used. The volume of each sample was calculated using the formula:

Volume = length × width × thickness (in cm^3).

Density was then calculated by dividing the mass by the volume:

Density = mass / volume (g/cm^3).

All samples were prepared with the same dimensions for length and width (10×10 cm^2), as illustrated in Figure 3.1.

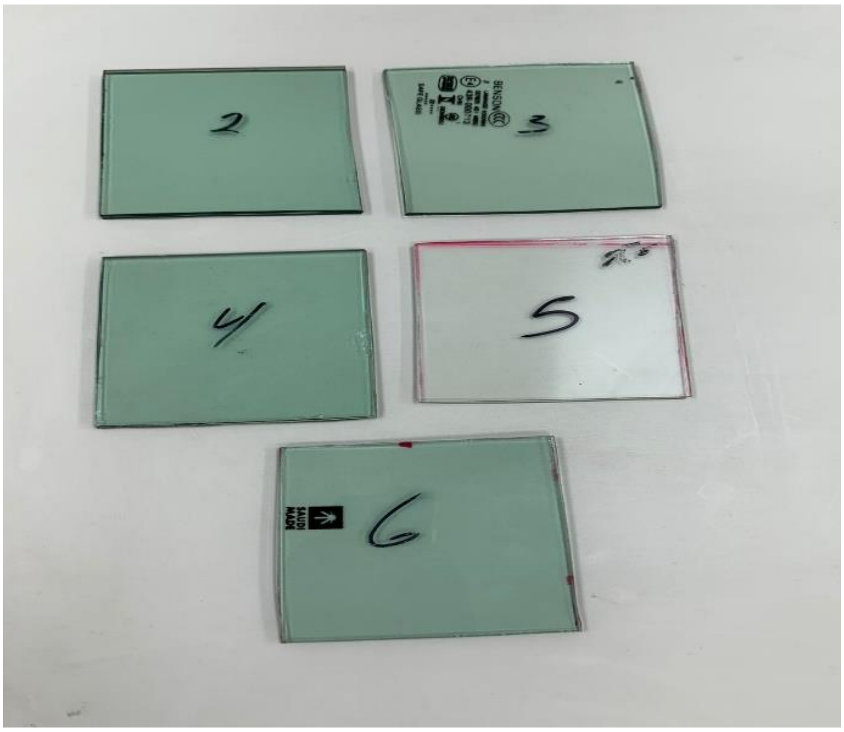

Figure 3.1: Car window glass samples used in this study

Table 3.1 Type of car window glass samples and source of these samples

Sample	Type of sample	Source of the samples
S1	Glass	France
S2	Glass	Saudi Arabia
S3	Glass	Saudi Arabia
S4	Glass	China
S5	Glass	China

3.2 X-Ray Computed Tomography (CT) Scanner

The CT number values inside car window glass samples were examined using an X-ray computed tomography scanner (SOMATOM-SIEMENS CT scan, German). Tungsten acted as the X-ray target. A CT number, or image pixel value, is provided by X-ray CT scans. The CT number is defined as

$$\text{CT number} = \mathrm{K}\ \frac{\mu - \mu_w}{\mu_w} \qquad (3.1)$$

where μ, μ_w is the linear attenuation coefficient of the sample and linear attenuation coefficient of water, respectively. In addition, K is a magnification contrast (=1000) [9]. The Hounsfield unit (HU), a number associated with density, is used to express the CT number. Air and water have HU values of -1000 and 0, respectively. As seen in Figure 3.2, the five samples (S1, S2, S3, S4 and S5) with various car window glass types were examined in this investigation. Using a 120 KV X-ray with roughly 110 rays that are 5 mm thick, the samples were scanned. To minimize pixel averaging at the edges, as illustrated in Figure 3.3, we selected an area of interest that measures 147 mm^2 and occupies nearly 50% of the cross-sectional area of the rectangular square cross-section. The average CT number for the interest areas was noted. To reduce pixel averaging at the car window glass -air interface on the edge, CT number values were not captured at the start and end of the scans. It was calculated to get the 15 average CT number values.

Figure 3.2: CT scan and samples during the experiment

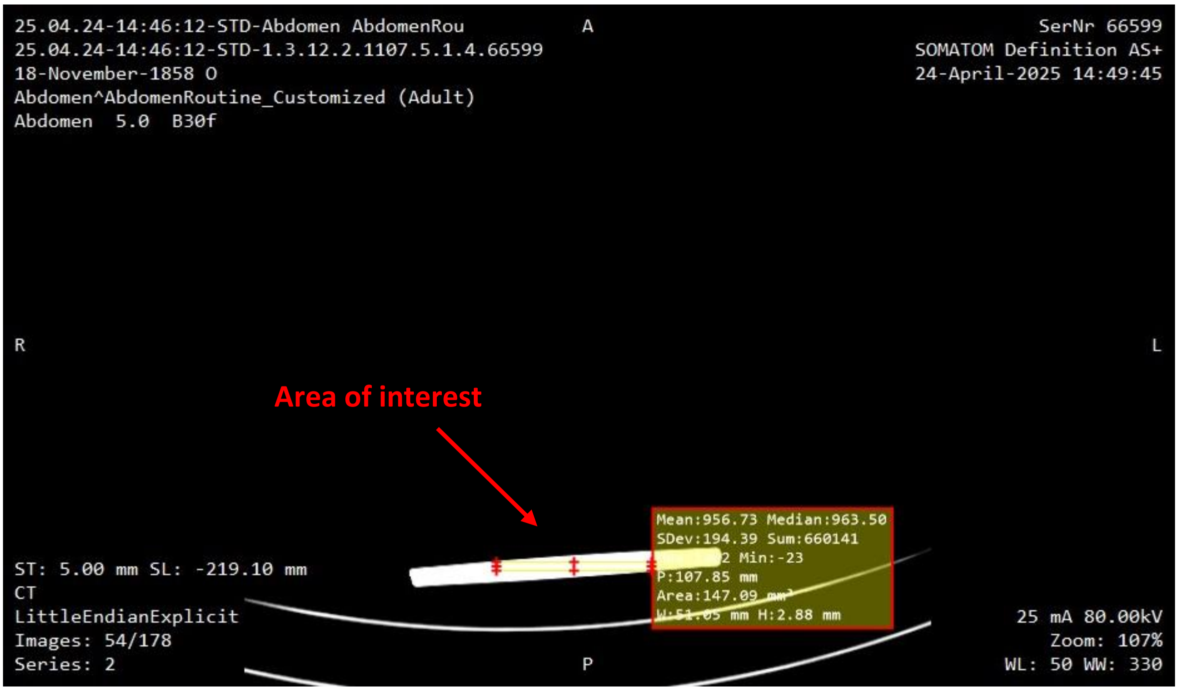

Figure 3.3: Illustration of a cross-sectional CT image containing an area of interest.

3.3 Linear and Mass Attenuation Coefficients Determination

To compare their results, the XCOM program calculated the mass attenuation coefficients for the car window glass samples and the standard lung phantom materials. Equation 3.1 will be used in the experimental determination of the mass attenuation coefficients (μ/ρ) of car window glass samples. For X-ray CT, the water's linear attenuation coefficient, μ, was theoretically computed at an effective energy of 38 keV. Each sample's linear attenuation coefficient values were averaged and then divided by the sample density. The theoretical values of water were compared with the obtained (μ/ρ) values. The XCOM computer program will be used to theoretically calculate mass attenuation coefficients at photon energy of 38 keV. The National Institute of Standards and Technology (NIST) has released a computer code called the XCOM: Photon Cross Sections Database [10]. After choosing to use total attenuation with coherent scattering, run the XCOM application.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Density measurements of car window glass sample

The densities of the five selected car window glass samples were calculated by dividing the samples masses (g) by their volumes (cm^3). Table 4.1 shows the calculated densities of the car window glass samples.

Table 4.1: Measured densities of car window glass samples

Sample	Length (cm)				Width (cm)				Thicknesses (cm)	Mass	Density
	L1	L2	L3	L_{avg}	W1	W2	W3	W_{avg}	T_{Avg}	(g)	(g/cm^3)
S_1	10.1	10.1	10.1	10.1	10	10	10.2	10.06	0.50	143.6	2.826
S_2	10.4	10.5	10.4	10.4	10.5	10.5	10.3	10.4	0.50	114.7	2.120
S_3	10.2	10.2	10.3	10.2	10.1	10.1	10.2	10.1	0.50	147.3	2.859
S_4	10	10	10.1	10	10.1	10.1	10.2	10.1	0.50	112.7	2.231
S_5	10.1	10.2	10.2	10.1	10.1	10.2	10.1	10.1	0.50	115.7	2.268

The density measurements of five different car window glass samples were conducted to evaluate their structural consistency and potential influence on radiation attenuation performance. As shown in Table 3.1, the density values ranged from 2.120 g/cm³ to 2.859 g/cm³, depending on the origin and type of glass. The lowest density was recorded for sample S2 (2.120 g/cm³), sourced from Saudi Arabia, whereas the highest density was found in sample S3 (2.859 g/cm³), also sourced from Saudi Arabia. Notably, the French sample S1 exhibited a high density of 2.826 g/cm³, comparable to S3. On the other hand, the Chinese samples S4 and S5 displayed densities of 2.231 g/cm³ and 2.268 g/cm³, respectively, indicating moderate consistency in manufacturing.

These density differences reflect variations in raw materials and manufacturing methods. Since higher density generally improves X-ray attenuation, samples S1 and S3 are expected to offer better shielding performance. This makes them more suitable for use in CT-related environments where radiation protection is important.

4.2 CT Number Measurement

Table 4.2 shows the CT numbers of five car window glass samples (S1–S5) and water across various thicknesses (5–75 mm). Sample S1 had the highest average CT number at **985.6 HU**, indicating high density, though with moderate variability. S5 and S3 followed, showing both high CT values (**962.9 HU** and **960.7 HU**, respectively) and low standard deviations, reflecting strong and consistent attenuation. S2 had the lowest average CT number (**881.0 HU**), while S4 showed the highest variability despite a moderate mean (**890.2 HU**). Water values stayed close to 0 HU, as expected.

Table 4.2: Mean, maximum, minimum and standard deviation of the CT number of each car window glass sample.

Thickness (mm)	Water	S1	S2	S3	S4	S5
5	10.7	1041.0	881.8	946.7	849.7	992.7
10	9.2	1004.0	873.7	957.2	786.7	956.7
15	-1.3	1002.7	862.9	974.2	887.5	960.8
20	0.1	1017.8	893.4	955.1	868.2	969.9
25	-1.5	980.4	870.1	984.6	878.6	958.5
30	-0.9	992.0	873.4	964.5	877.9	951.4
35	-0.7	993.7	881.2	952.4	884.9	970.9
40	-1.4	995.0	875.5	964.3	889.7	954.3
45	-2.0	996.1	891.4	944.3	882.6	970.0
50	-1.5	973.8	864.5	955.4	898.4	947.6
55	0.6	899.0	896.4	951.6	902.7	960.7
60	-0.7	968.8	875.4	970.0	913.6	972.3
65	-1.3	992.2	892.5	958.6	924.0	966.2
70	-2.4	963.0	893.8	971.0	940.0	960.5
75	20.9	964.6	888.6	960.4	968.3	950.6
Average	1.8	985.6	881.0	960.7	890.2	962.9
Max.	20.9	1041.0	896.4	984.6	968.3	992.7
Min.	-2.4	899.0	862.9	944.3	786.7	947.6
Standard deviation	6.6	31.6	11.2	10.9	41.2	11.4

The CT number shows how well each glass sample can block X-rays, which is important for radiation shielding. Sample **S1** had the highest average CT number at **985.6 HU**, meaning it offers strong shielding, but its variation (**±31.6**) suggests the material may not be very consistent. Samples **S3** and **S5** had slightly lower average CT numbers (**960.7 HU** and **962.9 HU**, respectively), but with much smaller variations (**±10.9** and **±11.4**), making them both effective and reliable for CT shielding use. **S2** showed the lowest average CT number at **881.0 HU**, which means it provides the least protection. **S4** had a moderate average (**890.2 HU**) but the highest variation (**±41.2**), indicating inconsistency in material quality. These results suggest that **S3 and S5** are the best candidates among the tested car window glass samples for use in environments where CT radiation protection is needed.

4.3 Linear and Mass Attenuation Coefficient Measurements

Table 4.3 presents the linear attenuation coefficients (μ) of five different car window glass samples (S1 to S5) measured using CT scan imaging at thicknesses ranging from 5 mm to 75 mm. Among the samples, **S1** exhibited the highest average linear attenuation coefficient (**0.559 cm^{-1}**), followed closely by **S5** (**0.553 cm^{-1}**) and **S3** (**0.552 cm^{-1}**). **S2** recorded the lowest average coefficient (**0.530 cm^{-1}**), indicating the weakest performance in terms of X-ray attenuation. **S4** also showed a relatively low average of **0.532 cm^{-1}**.

Table 4.3: Linear attenuation coefficients (μ) value of car window glass samples calculated from CT scan measurement.

Thickness (mm)	S1	S2	S3	S4	S5
5	0.575	0.530	0.548	0.521	0.561
10	0.565	0.528	0.551	0.503	0.551
15	0.564	0.525	0.556	0.532	0.552
20	0.568	0.533	0.551	0.526	0.555
25	0.558	0.527	0.559	0.529	0.552
30	0.561	0.528	0.553	0.529	0.550
35	0.562	0.530	0.550	0.531	0.555
40	0.562	0.528	0.553	0.532	0.551
45	0.562	0.533	0.548	0.530	0.555
50	0.556	0.525	0.551	0.535	0.549
55	0.535	0.534	0.550	0.536	0.552
60	0.555	0.528	0.555	0.539	0.556
65	0.561	0.533	0.552	0.542	0.554
70	0.553	0.533	0.555	0.547	0.552
75	0.553	0.532	0.552	0.554	0.549
Average	**0.559**	**0.530**	**0.552**	**0.532**	**0.553**

These results suggest that glass samples with higher average linear attenuation coefficients, like S1, S3, and S5, are more effective in reducing X-ray transmission and are thus more suitable for shielding applications, especially in environments where CT-level photon energies are used. The stability of the coefficients across increasing thicknesses also reflects material uniformity, with only minor fluctuations observed across all samples.

Table 4.4: Linear and mass attenuation coefficient of car window glass samples at CT scan energy 38 keV.

Sample	Density (g/cm^3)	μ (cm^{-1})	μ/ρ (cm^2/g)
S_1	2.826	0.559	0.198
S_2	2.120	0.530	0.250
S_3	2.859	0.552	0.193
S_4	2.231	0.532	0.239
S_5	2.268	0.553	0.244

Table 4.4 summarizes both linear and mass attenuation coefficients (μ/ρ) at a photon energy of 38 keV. When considering the material density, sample **S2** had the highest mass attenuation coefficient (**0.250 cm^2/g**), despite its lower linear attenuation, due to its lower density (**2.120 g/cm^3**). Conversely, **S3** showed the lowest μ/ρ value (**0.193 cm^2/g**), even though it had one of the highest linear attenuation coefficients and the highest density (**2.859 g/cm^3**). This reflects the inverse relationship between mass attenuation and density, where a denser material can exhibit a lower μ/ρ despite strong shielding ability.

Figure 4.1 illustrates the mass attenuation coefficients of the glass samples compared to polyvinyl butyral (PVB) across the 10–50 keV energy range using the XCOM database. All glass samples showed higher attenuation at lower photon energies, consistent with the known behavior of photon-matter interactions where lower energy photons are more easily attenuated. The attenuation performance of the glass samples was generally higher than that of PVB, confirming their superior shielding characteristics in the diagnostic energy range.

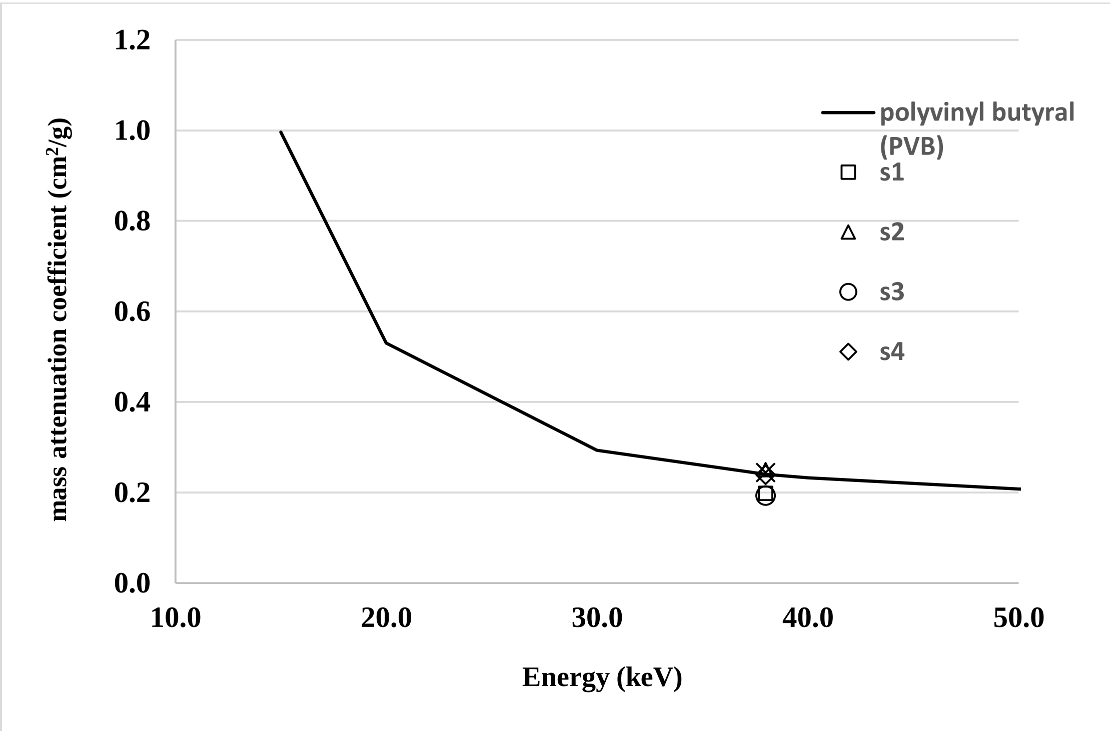

Figure 4.1 Mass attenuation coefficients at range of photon energies (10-50 keV) of the car window glass samples and polyvinyl butyral (PVB) material using XCOM program.

Table 4.5 provides the percentage difference between the mass attenuation coefficients of each glass sample and that of PVB (used as a reference with $\mu/\rho = 0.241$ cm²/g). Samples **S4** and **S5** showed the smallest differences (**1.0%** and **1.2%**, respectively), suggesting they are closest in performance to PVB. **S2** also showed a small difference (**3.7%**), while **S1** and **S3** deviated more significantly (**17.9%** and **19.8%**, respectively), likely due to their higher density and different elemental compositions.

Table 4.5: The percentage difference of mass attenuation coefficient results between car window glass samples and polyvinyl butyral (PVB) .

Sample	polyvinyl butyral (PVB) **μ/ρ = 0.241 cm^2/g**
S1	17.9 %
S2	3.7 %
S3	19.8 %
S4	1.0 %
S5	1.2 %

In conclusion, **S1**, **S3**, and **S5** demonstrate strong linear attenuation characteristics, making them promising for radiation shielding, while **S4** and **S2** align closely with standard materials like PVB in terms of mass attenuation, indicating their suitability for applications requiring a balance between performance and compatibility with established standards.

CHAPTER 5
CONCLUSION

In this study, five different car window glass samples (S1 to S5) were tested to see how well they could block X-rays, especially in environments where CT scans are used. The results showed that sample S3 had the highest density (2.859 g/cm^3), followed by S1 (2.826 g/cm^3), which means they are likely stronger and better at stopping radiation. On the other hand, S2 had the lowest density (2.120 g/cm^3), so it may not perform as well. These differences are likely due to how the glass was made and the materials used.

When looking at the CT numbers, which tell us how well a material can block X-rays, S1 had the highest average value (985.6 HU), showing strong shielding ability. However, it also had some variation. S3 and S5 had slightly lower CT numbers (960.7 HU and 962.9 HU) but were more consistent, meaning they worked well and reliably. That makes S3 and S5 good options for use in CT rooms or medical transport vehicles. S2 and S4 had lower CT values or more variation, so they may not be as dependable for radiation protection.

The linear and mass attenuation results showed that S1 had the highest ability to stop X-rays overall, but S2 had the best performance when considering its lower density. When comparing to a standard material like PVB (polyvinyl butyral), S4 and S5 were the closest in performance, with only a small difference of around 1%. This means they could be good substitutes for standard shielding materials. In general, samples S3 and S5 showed the best mix of strong and consistent radiation protection, making them the most promising choices for real-world use.

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