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# Alternative X-ray attenuation material from iodide-starch-gel-based materials

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**ABSTRACT**

**Background:** Iodine is often used as a contrast media because the k-shell binding energy (K-edge) is 33.2 keV, the average energy of a diagnostic X-ray. Thus, iodine can be utilized as a radiation attenuation material for X-rays.

**Objective:** This study aimed to produce low-energy X-ray attenuation materials used as X-ray shielding. A sodium iodide compound will be synthesized by polymerizing mung bean starch with sodium iodide.

**Materials and methods:** The iodide-starch-gel-based material (ISG) was made by mixing a mung bean starch solution (10 %w/w) with a sodium iodide (NaI) solution (100, 200, 250, and 300 mg-Iodine/gm). The linear attenuation coefficient (μ) was determined using radiation dose acquired from the DR plate system and CdTe detector. The X-rays were done at 50 - 120 kVp to study the attenuation properties.

**Results:** The results showed that the linear attenuation coefficient of t ISG was slightly higher than that of sodium iodide solution at the same concentration. The spectrum still shows an X-ray absorption characteristic at about 30.1-40.5 keV K-edge range.

**Conclusion:** Iodide-starch-gel-based components can attenuate X-ray with a K-edge range from 30-40 kVp. The attenuation coefficient of X-ray radiation varies linearly with energy level. Moreover, the concentration of the NaI solution is directly proportional to the attenuation of X-ray radiation. Thus, based on these properties and the gel-like consistency of the substance, it can be developed into a surface coating material to reduce X-ray radiation exposure.

## Introduction

X-radiation is routinely used in medical imaging to diagnose mild radiation effects; however, low-dose and low-energy X-rays may affect the cellular level change.[1-3] The k-shell binding energy of iodine and barium is similar to the average energy of a diagnostic X-ray. Therefore, those compounds are widely used as a contrast media in medical imaging and a non-particle ionizing radiation detector.[4,5] However, the iodide-containing compound induced acute kidney injury (AKI), and DNA damage.[5,6] The effects of iodine contrast agents on cellular functions of human peripheral blood mononuclear at a concentration of 50 mg-iodine/mL of iodine contrast media causes a 50% reduction in cell viability. Still, lower concentrations of 2.5, 5.0, and 10.0 mg-iodine/mL do not affect the cell cycle.[7] Previous studies have found that new lead-free shielding materials have radiation-shielding properties by using components with high-atomic-number substances[8] such as tungsten trioxide ($WO_3$), barium sulfate ($BaSO_4$), bismuth oxide ($Bi_2O_3$), and molybdenum trioxide ($MoO_3$).[9]

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Although iodide-containing compounds increase toxicity, they retain radiation attenuation properties because of the iodine in sodium iodide. So, it can be applied to utilize the radiation attenuation material.

This study aims to produce low-energy X-ray attenuation materials used as X-ray shielding by using a sodium iodide compound and the polymerization of mung bean starch.

## Material and methods

### *Agent and Solution Preparation*

Iodide-Starch-Gel Based Materials (ISG) is a mixture of mung bean starch (MBS) and sodium iodide (NaI) solution (100, 200, 250 and 300 mg-Iodine/gm). First, prepare a solution of sodium iodide. Then, MBS powder was dissolved into the sodium iodide solution to get the final concentration of MBS solution at 10 %w/w. A standard sodium iodide (NaI) solution was prepared at various concentrations of 100, 200, and 300 mg-Iodine/g. Mung bean starch (MBS 10%w/w) was dissolved with distillation water. The contrast agents as barium sulfate ($BaSO_4$) were dissolved with distillation water ($H_2O$) in a ratio of 1:1. And iodinated-base contrast omnipaque (OM) (Iohexol 300 mg-Iodine/mL, GE Healthcare) and telebrix 35 (TE) (Ioxitalamate meglumine sodium 350 mg-Iodine/mL, GUERBET France) were used. All materials were filled with 1, 2, and 3 cm thicknesses in plastic containers.

### *Measurements of the X-ray linear attenuation coefficient*

The attenuated photons absorbed or scattered per unit thickness of the absorber are expressed as the linear attenuation coefficient (μ). The Beer-Lambert Rule describes the linear attenuation coefficient of X-ray as the following equation.

$$I = I_0 e^{-\mu X}$$

Where:

I: the intensity of photons transmitted across some distance X

$I_0$: the initial intensity of photons

μ: the linear attenuation coefficient ($cm^{-1}$)

X: distance traveled (cm)

The diagnostic X-ray machine (Shimadzu RADspeed Pro) with a filter of 0.5 mm aluminum was used to perform the initialized radiation. To determine the linear attenuation coefficient, all materials were exposed at a source-to-image distance (SID) of 180 cm at various energy settings at 50, 60, 70, 80, 90, and 100 kVp with 4 and 5 milliampere-seconds (mAs). A digital radiography plate (DR) of 14x17 square inches (FUJIFILM FDR D-EVO plus C35i) was applied to record the initial intensity ($I_0$) and the transmitted intensity (I) of radiation through all materials. To estimate the initial radiation intensity, an aluminum 11-step wedge with a step of 3 mm rise was exposed parallel with all materials. (Figure 1)


***Figure 1**. Arrangement of equipment for measuring the initial and transmitted radiation of all materials on the DR plate.*

### *X-ray spectrum measurement*

The X-ray spectrum was recorded using a CdTe detector (Amp-Tek XR-100T-CdTe Detector) at the setting energy of 60, 70, 80, 90, 100, and 120 kVp.[10] The detector was previously calibrated using a Ba-133 source with a gain of 3.197 and the number of multichannel analyzers (MCA) at 2048 channels. The detector was set at SID 40 cm to measure the number of X-ray photons as a function of energy (keV) in the condition with and without iodide-starch-gel-based 1 cm.

## Results

The physicochemical properties of Iodide-starch-gel-based materials (ISG) were investigated during preparation. The exothermic reaction between mung bean starch (MBS) colloid solution and sodium iodide solution (NaI) causes a gel-like texture of ISG with a pH value range of 5-6. (Figure 2) The homogeneity of ISG, as shown in Table 1, is indicated by a consistent density level of each sample with a CV (coefficient of variation) of less than 10.

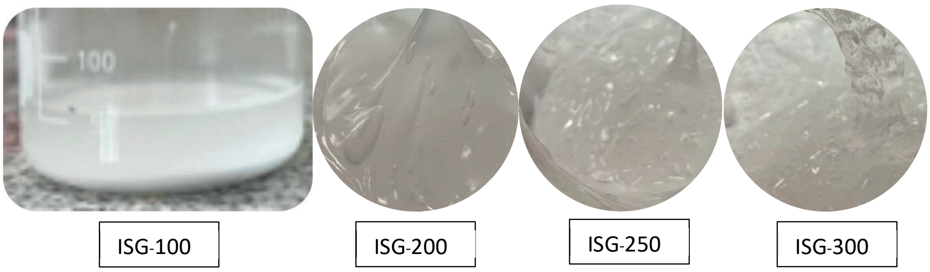



***Figure 2****. The physical appearance of iodide-starch-gel based material at different concentrations of iodide at 100 (ISG-100), 200 (ISG-200), 250 (ISG-250), and 300 (ISG-300) mg-Iodine/gm.*

### *System validation*

This study measured the radiation doses (I and $I_0$) by applying the DR image recording system as a radiation detector that provides a gray-scale image dependable to radiation dose. The radiation dose rate, the uniformity of the DR plate, and the effect produced by the plastic container were verified. The radiation dose of the X-ray was displayed from the X-ray machine in mGy. The radiation property showed a linear proportion of mGy/mAs manner of kVp ($r^2$=1) as shown in Figure 3-left. To check the background and the effect of a clear plastic container on image intensity, the DR plate was irradiated at various energy settings at 50, 60, 70, 80, 90, and 100 kVp. The radiation dose response on the DR plate was shown as background image intensity. The dose-response curve from the DR plate detector is illustrated in a logistic curve. And the plastic containers showed a slightly reduced image intensity. (Figure 3) The uniformity of the DR plate was investigated from 3 acquired images at 50kVp 2 mAs. The intensity (O.D.) of the region of interest in 6 areas (4 corner locations, 1 middle location, and the whole area) were measured. The mean intensity of the DR plate with the standard deviation (S.D.) equal to 2368+101, And the %CV was 4.3 (Figure 4)

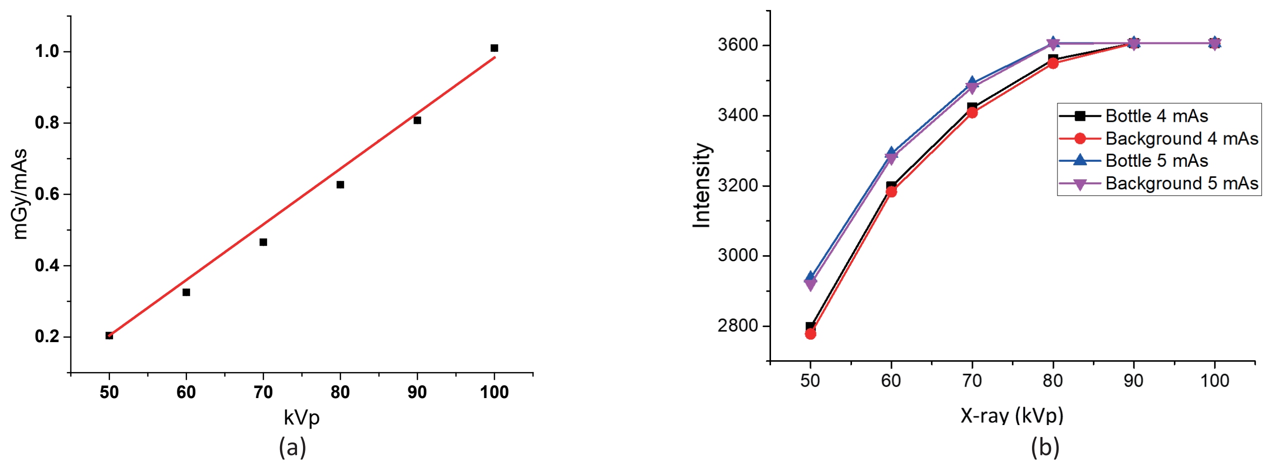
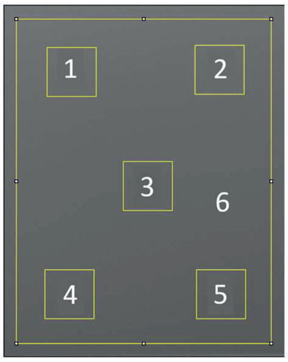



***Figure 3****. The radiation dose per mAs (mGy/mAs) as a function of kVp, SID 180 cm, 0.5 mm aluminum filter (a), and intensity of plastic container (bottle) and background intensity (b) presented as mean±SD (N=2).*




6 Regions of interest on the DR plate

| ROI | Intensity |
|---|---|
| 1 | 2235.5 |
| 2 | 2269.2 |
| 3 | 2388.5 |
| 4 | 2456.4 |
| 5 | 2494.0 |
| 6 | 2366.4 |
| **Mean** | **2368.3** |
| **SD** | **101.4** |
| **%CV** | **4.3** |

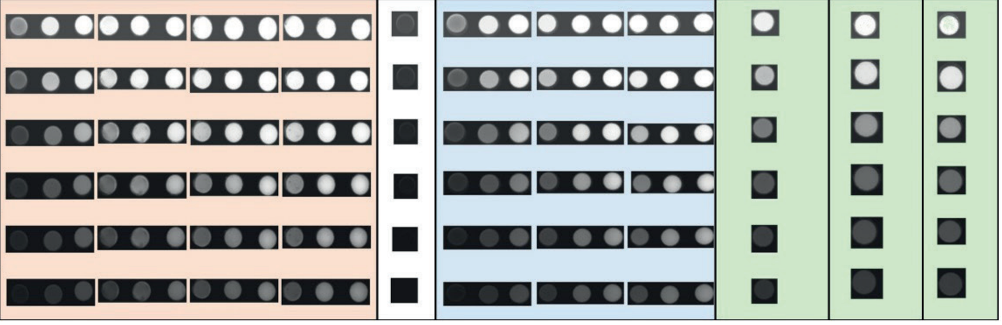
***Figure 4**. Region of interest (ROI 1, 2, 3, 4, 5, and 6) and intensity value for uniformity evaluation of DR plate.*

***Linear Attenuation Coefficient***

The linear attenuation coefficient of the sample composition consisting of ISG-100, ISG-200, ISG-250, and ISG-300 mg-Iodine/gm was calculated from image intensity on the DR plate produced by the transmitted radiation (I) (Table 1). Each energy's initiation radiation ($I_0$) was estimated using the intensity passed each step of the step-wedge. The sigmoid curve fit extrapolated the initiation radiation value ($I_0$) as the intensity where step equal to 0 as plotted in Figure 5. Each energy's global linear attenuation coefficient (kVp setting) was calculated using the Beer-Lambert equation. (Figure 6) The results showed the linear attenuation coefficient of each material was decreased, whereas the exposure technique (kVp) increased. When compared to other substances, the ISG-300 mg-Iodine/gm is higher than NaI (300 mg-Iodine/gm), $BaSO_4$ (1:1), omnipaque (300 mg-Iodine/mL), and telebrix (350 mg-Iodine/mL) at exposure technique 50-100 kVp. (Figure 6)

**Table 1**. The images relate to various thicknesses (1, 2, and 3 cm) of materials.

| Exposure technique setting (4 mAs) | ISG (mg-Iodine/gm) | | | | MBS | NaI (mg-Iodine/gm) | | | Contrast media | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100 | 200 | 250 | 300 | | 100 | 200 | 300 | $BaSO_4$ | OM | TE |
| Thickness (cm) | 1 2 3 | 1 2 3 | 1 2 3 | 1 2 3 | 1 | 1 2 3 | 1 2 3 | 1 2 3 | 1 | 1 | 1 |
| 50 kVp | | | | | | | | | | | |
| 60 kVp | | | | | | | | | | | |
| 70 kVp | | | | | | | | | | | |
| 80 kVp | | | | | | | | | | | |
| 90 kVp | | | | | | | | | | | |
| 100 kVp | | | | | | | | | | | |



*Note: ISG: iodide-starch-gel based, MBS: mung bean starch, NaI: sodium iodide solution, $BaSO_4$: barium sulfate, OM: omnipaque, TE: telebrix.*

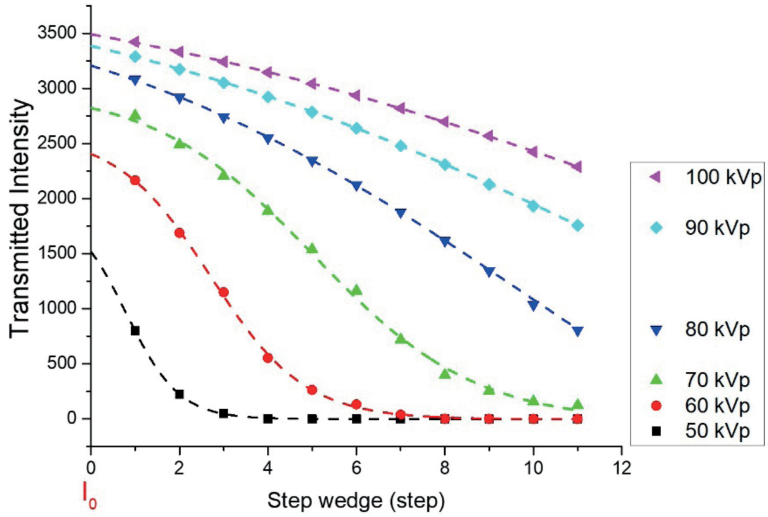



***Figure 5**. Initiation radiation ($I_0$) estimation using transmitted intensity from a step wedge.*

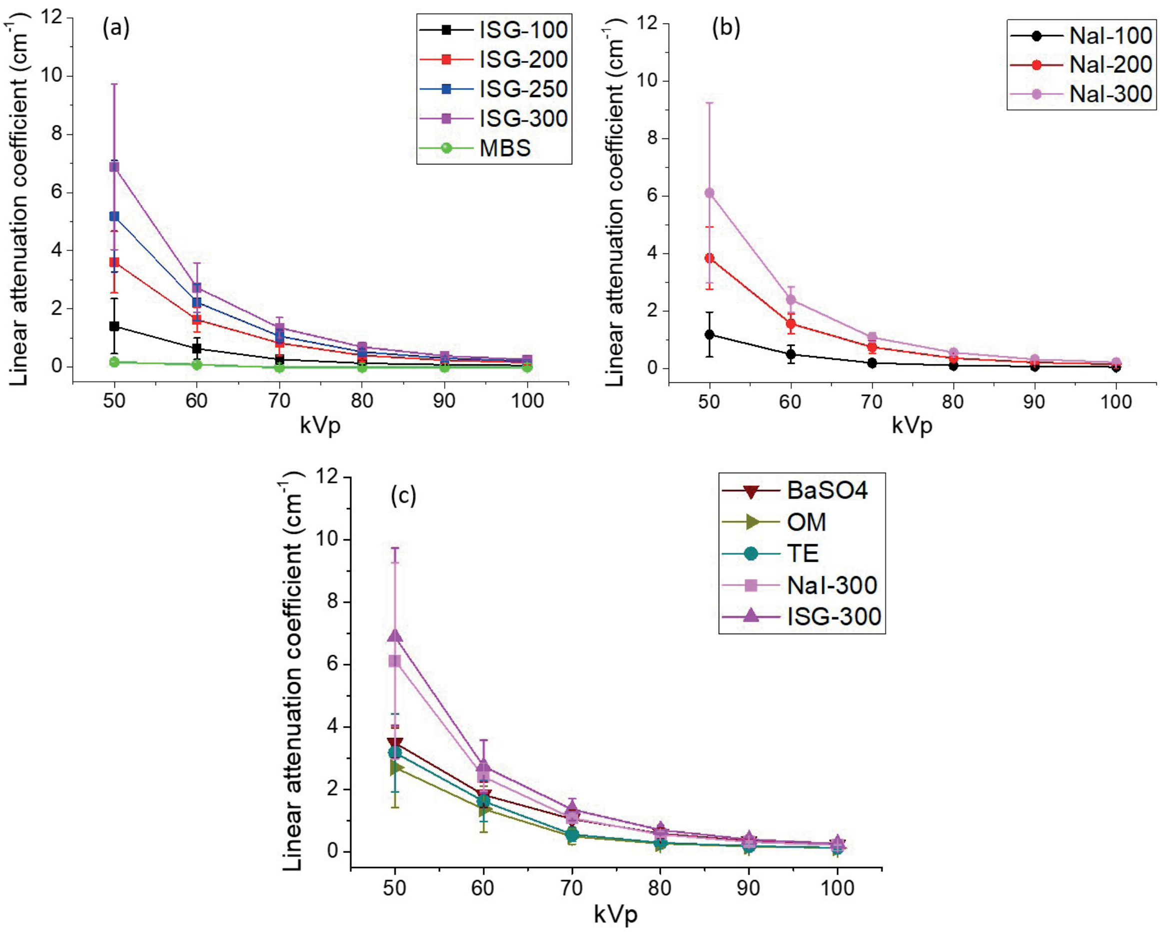



***Figure 6**. X-ray linear attenuation coefficient (mean±SD) of various materials.*

***X-ray spectrum***

The radiation property of X-ray was investigated by recording the photon spectrum that presents photon profiling as a function of energy (keV). The X-ray spectrum illustrated the photon profiling of each setting energy (kVp) of initiation radiation ($I_0$) and transmitted radiation penetrating through ISG-300. The result showed that ISG-300 efficiently attenuates the X-ray radiation compared with the initiation radiation. The linear attenuation coefficient profile of each energy setting (kVp) calculated from the X-ray spectrum allowed us to identify the K-edge of ISG, which covers a broad-spectrum range of 30.1-40.5 keV. (Figure 7) Iodine appears to be the main element responsible for this K-edge value. The half-value layer (HVL) and ten-value layer (TVL) were calculated from the mean value of the linear attenuation coefficient and presented in Table 2.

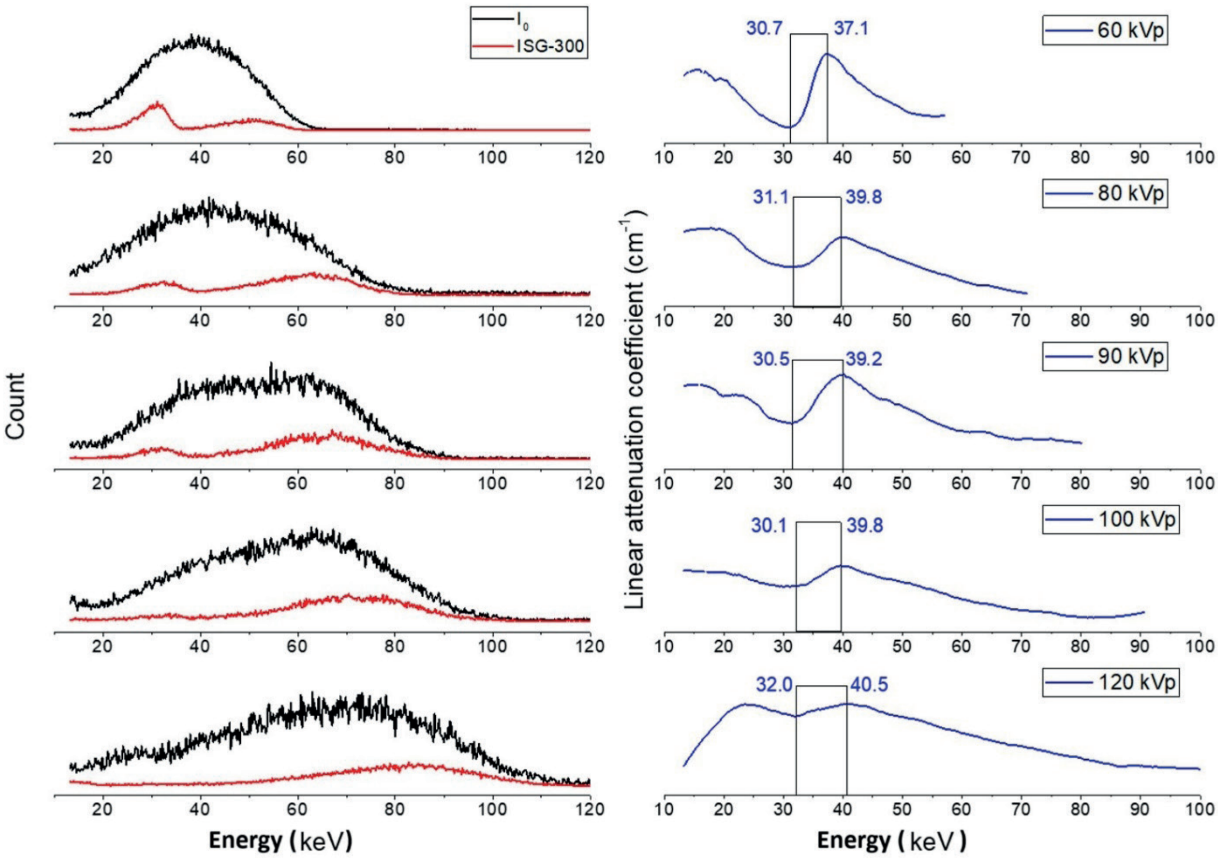



***Figure 7**. The spectrum of X-ray photon profiling of initiation radiation (black line) and transmitted radion through iodide-starch-based material (red line) (left), and the linear attenuation coefficient values at setting energy (right).*

**Table 2**. Half value layer (HVL) and ten value layers (TVL) of iodide-starch-gel based (ISG), $BaSO_4$, omipaque (OM), and telebrix (TE).

| kVp | ISG-100 | ISG-200 | ISG-250 | ISG-300 | $BaSO_4$ | OM | TE |
|---|---|---|---|---|---|---|---|
| | Half value layer, HVL (cm) | | | | | | |
| 50 | 0.49 | 0.19 | 0.13 | 0.10 | 0.20 | 0.26 | 0.22 |
| 60 | 1.09 | 0.43 | 0.31 | 0.25 | 0.38 | 0.51 | 0.43 |
| 70 | 2.63 | 0.84 | 0.65 | 0.51 | 0.66 | 1.44 | 1.26 |
| 80 | 5.13 | 1.73 | 1.33 | 1.00 | 1.20 | 2.70 | 2.45 |
| 90 | 8.26 | 2.94 | 2.29 | 1.80 | 2.04 | 4.19 | 3.86 |
| 100 | 12.05 | 4.34 | 3.39 | 2.71 | 3.06 | 5.95 | 5.52 |
| | Ten value layer, TVL (cm) | | | | | | |
| 50 | 1.64 | 0.64 | 0.44 | 0.33 | 0.66 | 0.85 | 0.73 |
| 60 | 3.63 | 1.41 | 1.03 | 0.84 | 1.26 | 1.69 | 1.43 |
| 70 | 8.73 | 2.79 | 2.16 | 1.71 | 2.21 | 4.77 | 4.18 |
| 80 | 17.03 | 5.75 | 4.40 | 3.33 | 4.00 | 8.98 | 8.14 |
| 90 | 27.45 | 9.76 | 7.61 | 5.96 | 6.78 | 13.92 | 12.81 |
| 100 | 40.03 | 14.41 | 11.27 | 9.01 | 10.17 | 19.78 | 18.33 |

## Discussion

Although the study of low-energy X-ray used in mammography on biological effects showed non-significant cellular damage, the increase of double-strand DNA breaks was observed as related to the rise in mutational damage than higher energy X-ray.[3,11] The iodide-based material is generally used as a contrast agent for diagnostic X-rays. Because of its properties of the K-edge value (33.2 keV) that covers the X-ray spectrum in diagnostic radiation, we herein provide it as a low-energy radiation protection material. Using iodide-based compounds such as NaI with high concentrations causes high toxicity to the body and affects the condition of nausea, vomiting, and peptic ulcer.[12,13] Therefore, it was developed as an X-ray protection material.

In this study, we invented a radioprotective, iodide-starch-gel-based material that can reduce low-energy X-rays significantly. Moreover, this study simplified a radiation detection system using a DR plate that can be applied to radiation dose detectors in clinical use. Therefore, verifying the X-ray source dose rate and homogeneity of the DR plate is necessary. To apply this detection system, the homogeneity of the DR plate must be verified. The findings indicate that the variability in the homogeneity of the used DR plate (%CV=4.3) was less than 10%, which is within acceptable limits for use as a detector.

This research determined the Linear attenuation coefficient (μ) using 2 methods: 1) a DR plate detection system and 2) a CdTe detector. The radiation dose was determined from the full-energy X-ray spectrum using the DR plate detection system. The resulting μ value reflects the material's attenuation capacity across the entire energy range. The μ value obtained from this method showed that ISG-300 mg-Iodine/gm has more efficiency than the others. The X-ray spectrum acquired by the CdTe detector represents the number of X-ray photons at each energy level (keV) the tungsten target produces. This spectrum enabled the determination of the μ value as a function of energy (keV). The results revealed a reduction in photon intensity, particularly in the 30-40 keV range, when the X-rays passed through the iodide-starch-gel-based material, effectively attenuating low-energy X-rays. Moreover, the linear attenuation coefficient calculated from the X-ray spectrum at each energy (keV) revealed that the μ profile of the ISG-polymer exhibited a broader K-edge spectrum compared to that of the iodine atom alone.

Based on these results, the ISG material is potentially used as X-ray shielding. The critical advantage of iodide-starch-gel-based materials is their ability to self-polymerize through an exothermic reaction, simplifying the preparation process. Additionally, their semi-solid, gel-like nature allows for various functional modifications. These properties suggest that ISG materials can be developed as coatings to attenuate X-rays in diagnostic radiology.[9, 14]

## Conclusion

The iodide-starch-gel-based components, derived from mung bean starch combined with a sodium iodide solution, effectively attenuate X-ray radiation in the 30-40 kV range used in diagnostic radiology. With these properties and gel-like consistency, the material shows potential for development as a protective material to reduce X-ray exposure.

## Conflict of interest

The authors claim no conflict of interest.

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