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Performance Analysis of Low-level Radiation Shielding Sheet with Diamagnetic Nanoparticles

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In this study, the authors attempted to produce a medical radiation shielding fiber that can be produced at a nanosize scale and that is, unlike lead, harmless to the human body. The performance of the proposed medical radiation shielding fiber was then evaluated. First, diamagnetic bismuth oxide, an element which, among elements that have a high atomic number and density, is harmless to the human body, was selected as the shielding material. Next, 10-100 nm sized nanoparticles in powder form were prepared by ball milling the bismuth oxide (Bi_2O_3), the average particle size of which is 1-500 μm, for approximately 10 minutes. The manufactured bismuth oxide was formed into a colloidal solution, and the radiation shielding fabric was fabricated by curing after coating the solution on one side or both sides of the fabric. The thicknesses of the shielding sheets prepared with bismuth oxide were 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 1.0 mm. An experimental method was used to measure the absorbed dose and irradiation dose by using the lead equivalent test method of X-ray protection goods presented by Korean Industrial Standards; the resultant shielding rate was then calculated. From the results of this study, the X-ray shielding effect of the shielding sheet with 0.1 mm thickness was about 55.37% against 50 keV X-ray, and the X-ray shielding effect in the case of 1.0 mm thickness showed shielding characteristics of about 99.36% against 50 keV X-ray. In conclusion, it is considered that nanosized-bismuth radiation shielding fiber developed in this research will contribute to reducing the effects of primary X-ray and secondary X-ray such as when using a scattering beam at a low level exposure.

Keywords : radiation shielding fiber, diamagnetic bismuth oxide, nanosize, shielding rate

1. Introduction

Since Professor W. C. Röntgen, the German physicist discovered the X-ray in 1985, it has been rapidly applied in the medical field, and medical breakthroughs in the diagnosis and treatment of human diseases have been possible using the object penetrability of X-ray. Exposure to radiation in the medical field is also increasing each day with its increasing frequency of use; exposure to radiation has the largest portion (approximately 13%) of artificial radiation exposure currently received by humans [1, 2]. Hence, the risk of medical radiation is newly recognized, and medical departments are trying to reduce unnecessary medical radiation and to carry out more tests for patients. In general, lead is the main material used in protective clothing worn for radiation shielding. However, lead is a harmful material to humans and the environment and induces environmental pollution. In addition, if the clothing is made of lead, the weight becomes too heavy for practical use, and many problems have been presented [3]. For this reason, studies have continued to be carried out on the development of a radiation shielding fabric that can sufficiently shield against the indirect risk of exposure while blocking the risk of direct exposure to radiation, that is comfortable to wear, has a light weight, and is harmless to the human body. The domestic K company [4] has a patented method of fabricating a radiation shielding clothing fabric, whereby the fabric is coated with a mixture of 50% lead, 20% bismuth, and 30% tin into a synthetic resin. After forming the shielding film by coating the fabric with a mixture (in which the concentration of solution of metal powder added to about 45% synthetic resin solution was 30%-70%), the coated fabric was dried for 30 minutes at about 60°C. The radiation shielding film of 0.5-1.0 mm thickness was then formed by curing the fabric for about 2 minutes at 120°C. However,

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because lead is also used with this method, environmental pollution becomes a problem.

Besides, the existing radiation shielding material has various disadvantages, including degraded mechanical properties and leaking radiation because the adhesive properties of the particles and resin are poor due to the manufacturing technique in which the shielding particles are dispersed into the polymeric resin. However, it is considered that if the nanosize particles are uniformly dispersed into the polymer resin, it will be possible to reduce the weight of the shielding material because the mechanical properties and shielding capability is improved. Accordingly, in this study, the authors attempted to produce a medical radiation shielding fiber that can be fabricated at a nanosize scale, and, unlike lead, is harmless to the human body. The performance of the medical radiation shielding fiber was then evaluated.

2. Materials and Methods

2.1. Manufacturing of Fiber

Bismuth oxide, an element which, among elements that have a high atomic number and density, is harmless to the human body, was selected as the shielding material for reducing the dose of radiation exposed to patients or radiation workers when using medical radiation. Because the atomic number of bismuth is 83 and the probability of photoelectric effect for diagnostic X-ray is higher, bismuth was selected by estimating that the shielding efficiency will be higher. In classical physics, attempts have been made to explain the photoelectric effect by justifying the electron emission from a light-irradiated metal target by the thermal emission which occurs when a piece of metal is heated to a high temperature. In practice, the thermal emission of electrons requires temperatures above 1500°C for most metals, when electrons as well as the crystal lattice are heated, resulting in target melting. In classical physics, it was acknowledged that a minimum energy E0 is needed to free an electron from a metal. E0 is called work function. The maximum kinetic energy of a photoelectron is given by: [5]

$$K_{\max} = E_{elec} - E_0 \tag{1}$$

In (1), Eelec is the electron energy inside the metal. The stopping potential corresponds to zero current. Therefore: [5]

$$V_{stop} = \frac{K_{\max}}{e} \tag{2}$$

Albert Einstein postulated the quantization of electromagnetic radiation energy: each quantum of light has energy,

$$E = hf \tag{3}$$

In (3), $h = 6.63 \times 10{-}34$ J·s is Planck's constant; f is frequency of light.

An electron can escape from a metal, becoming a photoelectron, if $E_{elec} = hf \geq E_0$ Combining (1), (2), and (3), we obtain Einstein's equation for the photoelectric effect: [5]

$$eV_{stop} = hf - E_0 \tag{4}$$

According to (4), the stopping potential is a linearly increasing function of f: [5]

$$V_{stop} = \frac{f}{e}(f - f_0) \tag{5}$$

Because bismuth oxide is a chemically very stable material, it has no effect on the human body, and can thus be used as the fiber. Nanoparticles of 10-100 nm size in powder form were prepared by ball milling the bismuth oxide (Bi_2O_3) with an average particle size of 1-500 μm for approximately 10 minutes. The colloid solution of a minimum of 50,000 ppm was manufactured by mixing and dispersing the manufactured bismuth with a particular polymeric resin. The composition for forming the radiation shielding coating layer was then prepared by mixing 20% silicone-based rubber and 80% colloidal solution by weight ratio. The radiation shielding fabric was fabricated by curing after coating the manufactured radiation shielding coating composition on one side or both sides of the fabric.

In order to determine the internal structure of a particle, the particle magnified at 500 magnification was observed under 15 kV accelerated voltage using S-4800 (Hitachi, Japan), a scanning electron microscope (FE-SEM). A photograph was then taken, using the mode whereby the secondary electron image and the backscattered electron image were mixed, to determine the morphological difference according to the material (Fig. 1).

The thicknesses of the shielding sheets that were manufactured using the bismuth oxide were 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 1.0 mm (Fig. 2).

2.2. Experimental Method

The lead equivalent test method for X-ray protection goods as presented by the Korea Industrial Standards (KIS) was used as the experimental method in this study [6]. First, the test was performed using an X-ray generator (LISTEM Co, IEX-650R, Korea). Then, the distance between the X-ray tube given by KIS and the shielding material was constantly maintained. The distance given

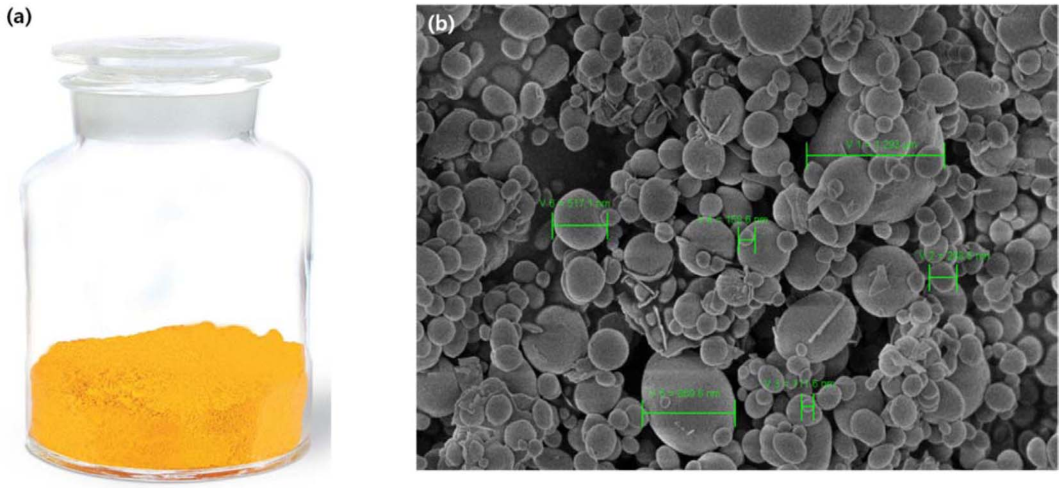

Fig. 1. (Color online) Nano-particles of 10-100 nm size were manufactured in powder form (a). In addition, in order to determine the internal structure of the particles, they were observed by using a scanning electron microscope of 500 magnification (b).

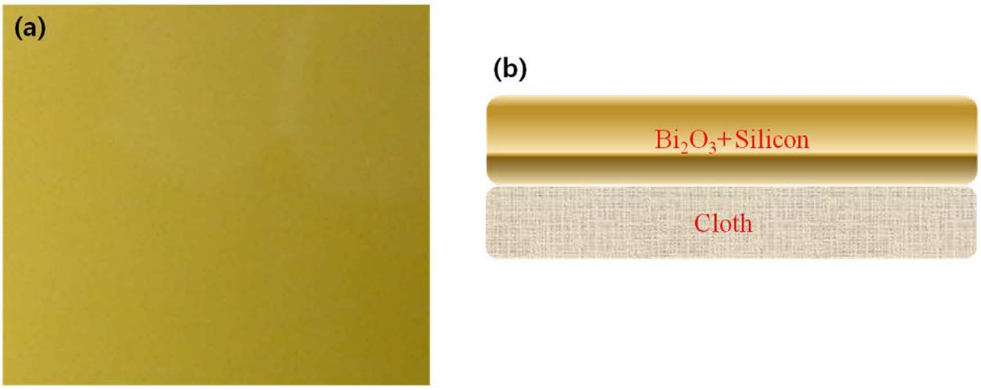

Fig. 2. (Color online) The colloid solution was manufactured using the manufactured bismuth oxide (a), and the composition for forming the radiation shielding coating layer was prepared by mixing 20% silicone-based rubber and 80% colloidal solution by weight ratio (b). The thicknesses of the shielding sheets that were manufactured using the bismuth oxide were 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 1.0 mm.

by KIS is as follows:

If a narrow beam was used, the distance between the X-ray tube and the sample was 1500 mm, between the sample and the instrument, 32 mm or more, between the instrument and the floor surface, 700 mm or more, and between the fixed aperture and the sample, 200 mm. In this study, the phantom made of acryl was used in this experiment in order to maintain the constant distance between the X-ray tube proposed by KIS and the shielding material (Fig. 3). The ionization chamber (Piranha, RTI Electronics AB, Sweden) was used in the dosimetry of this experiment. The X-ray was irradiated on the sample under the condition that the tube current and the time used in this experiment were 200 Ma and 0.1 sec, respectively, and the tube voltage was used alternating between voltages of 50, 80, 100, and 120 kVp. First, the measuring methods were used to measure the irradiation and the absorbed dose by irradiating four times under each X-ray condition in the absence of the shielding material. Next, the X-ray was irradiated onto the manufactured shielding sheets according to the thickness (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 1.0 mm) under the above condition. The irradiation and absorbed dose were measured and consequently, the shielding ratios were obtained. The independent sample test method that compares each average of the absorbed dose, the irradiation dose, and the shielding ratio was used as the analysis method.

3. Results

The absorbed dose was 0.141 ± 0.001 mGy, and the

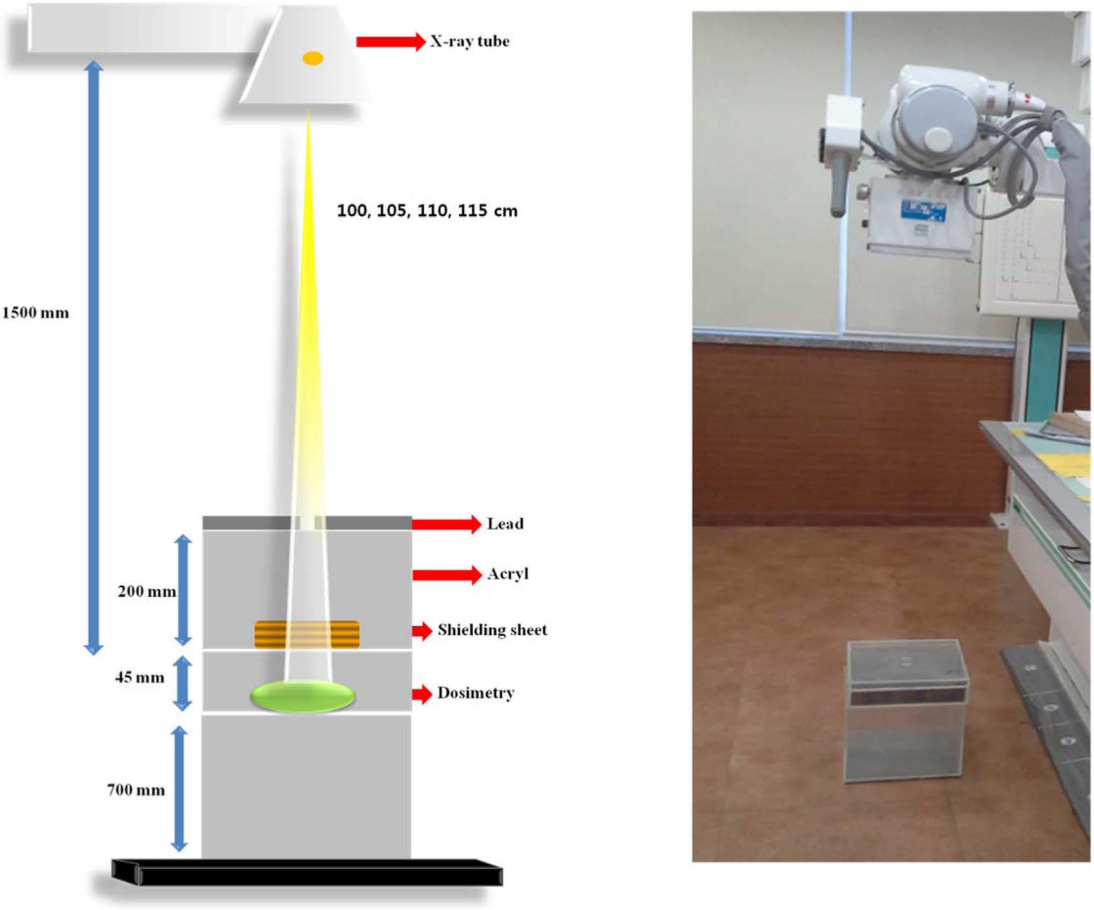

Fig. 3. (Color online) The phantom made of acryl was used in this experiment so that a constant distance can be maintained between the X-ray tube proposed by KIS and the shielding material.

irradiation dose was 16.12 ± 0.18 mR. In addition, the shielding ratio was 55.37% under the experimental condition in which the thickness of the shielding film was 0.1 mm and the tube voltage was 50 kVp. In the case of the shielding film with 0.5 mm thickness, the absorbed dose was 0.015 ± 0.002 mGy, the irradiation dose was 1.664 ± 0.10 mR, and the shielding ratio was 95.25%. In the case of the shielding film with 1.0 mm thickness, the absorbed dose was 0.002 ± 0.002 mGy, the irradiation dose was 0.213 ± 0.17 mR, and the shielding ratio was 99.36%. As a result, the difference of the absorption ratio between 0.1 mm thickness and 1.0 mm thickness was about 44% ($p < 0.05$). The absorbed dose was 0.467 ± 0.002 mGy, the irradiation dose was 53.29 ± 0.21 mR, and the shielding ratio was 42.76% under the experimental condition in which the thickness of the shielding film was 0.1 mm and the tube voltage was 80 kVp. In the case of the shielding film with 0.5 mm thickness, the absorbed dose was 0.122 ± 0.002 mGy, the irradiation dose was 13.89 ± 0.21 mR, and the shielding ratio was 85.04%. In the case of the shielding film with 1.0 mm thickness, the absorbed dose was 0.042 ± 0.002 mGy, the irradiation dose was 4.830 ± 0.21 mR, and the shielding ratio was 94.85%. As a result, the difference of the absorption ratio between 0.1 mm thickness and 1.0 mm thickness was about 52.09% ($p < 0.05$). The absorbed dose was 0.753 ± 0.002 mGy, the irradiation dose was 85.97 ± 0.18 mR, and the shielding ratio was 37.33% under the experimental condition in which the thickness of shielding film was 0.1 mm and the tube voltage was 100 kVp. In the case of the shielding film with 0.5 mm thickness, the absorbed dose was 0.258 ± 0.002 mGy, the irradiation dose was 29.43 ± 0.21 mR, and the shielding ratio was 78.55%. In the case of the shielding film with 1.0 mm thickness, the absorbed dose was 0.122 ± 0.002 mGy, the irradiation dose was 12.84 ± 0.21 mR, and the shielding ratio was 89.85%. As a result, the difference of the absorption ratio between 0.1 mm thickness and 1.0 mm thickness was about 52.52% ($p < 0.05$). The absorbed dose was 1.028 ± 0.002 mGy, the irradiation dose was

Table 1. Absorbed dose, irradiation dose, and shielding ratio of Bismuth oxide shielding sheet according to thickness.

Thickness (mm)	Dose	50 kvp		80 kvp		100 kvp		120 kvp		P
		Non	Protect fabric	Non	Protect fabric	Non	Protect fabric	Non	Protect fabric	
0.1	Absorbed dose (mGy)	0.316±0.002	0.141±0.001	0.816±0.002	0.467±0.002	1.203±0.001	0.753±0.002	1.525±0.001	1.028±0.002	0.025
	Exposure dose (mR)	35.81±0.12	16.12±0.18	93.06±0.19	53.29±0.21	137.2±0.22	85.97±0.18	174.1±0.20	117.3±0.20	
	Shield rate (%)	55.37		42.76		37.33		32.62		
0.2	Absorbed dose (mGy)	0.316±0.002	0.055±0.001	0.816±0.001	0.257±0.001	1.203±0.003	0.466±0.001	1.525±0.002	0.6367±0.003	
	Exposure dose (mR)	35.81±0.21	6.263±0.235	93.06±0.20	29.30±0.22	137.2±0.23	53.17±0.19	174.1±0.19	76.05±0.21	
	Shield rate (%)	82.51		68.51		61.24		58.22		
0.3	Absorbed dose (mGy)	0.316±0.002	0.033±0.001	0.816±0.001	0.192±0.001	1.203±0.001	0.370±0.001	1.525±0.001	0.547±0.002	
	Exposure dose (mR)	35.81±0.21	3.815±0.21	93.06±0.21	21.86±0.20	137.2±0.21	42.20±0.19	174.1±0.18	62.47±0.20	
	Shield rate (%)	89.55		76.47		69.24		64.13		
0.4	Absorbed dose (mGy)	0.316±0.003	0.030±0.002	0.816±0.001	0.181±0.001	1.203±0.002	0.351±0.003	1.525±0.002	0.529±0.002	
	Exposure dose (mR)	35.81±0.21	3.427±0.13	93.06±0.16	20.63±0.20	137.2±0.20	40.10±0.23	174.1±0.18	59.98±0.20	
	Shield rate (%)	90.5		77.81		70.82		65.31		
0.5	Absorbed dose (mGy)	0.316±0.003	0.015±0.002	0.816±0.002	0.122±0.002	1.203±0.001	0.258±0.002	1.525±0.002	0.402±0.001	
	Exposure dose (mR)	35.81±0.21	1.664±0.10	93.06±0.19	13.89±0.21	137.2±0.20	29.43±0.21	174.1±0.20	45.83±0.20	
	Shield rate (%)	95.25		85.04		78.55		73.63		
0.7	Absorbed dose (mGy)	0.316±0.003	0.004±0.002	0.816±0.002	0.064±0.002	1.203±0.001	0.157±0.002	1.525±0.002	0.254±0.001	
	Exposure dose (mR)	35.81±0.21	0.489±0.12	93.06±0.23	7.31±0.20	137.2±0.18	17.96±0.17	174.1±0.21	28.83±0.20	
	Shield rate (%)	98.73		92.15		86.94		83.34		
1	Absorbed dose (mGy)	0.316±0.003	0.002±0.002	0.816±0.002	0.042±0.002	1.203±0.001	0.122±0.002	1.525±0.002	0.186±0.001	
	Exposure dose (mR)	35.81±0.21	0.213±0.17	93.06±0.19	4.830±0.21	137.2±0.20	12.84±0.21	174.1±0.20	21.27±0.20	
	Shield rate (%)	99.36		94.85		89.85		87.8		

117.3 ± 0.20 mR, and the shielding ratio was 32.62% under the experimental condition in which the thickness of shielding film was 0.1 mm and the tube voltage was 120 kVp. In the case of the shielding film with 0.5 mm thickness, the absorbed dose was 0.402 ± 0.001 mGy, the irradiation dose was 45.83 ± 0.20 mR, and the shielding ratio was 73.63%. In the case of the shielding film with 1.0 mm thickness, the absorbed dose was 0.186 ± 0.001 mGy, the irradiation dose was 21.27 ± 0.20 mR, and the shielding ratio was 87.80%. As a result, the difference of the absorption ratio between 0.1 mm thickness and 1.0 mm thickness was about 55.18% ($p < 0.05$) (Table 1). As a result, the shielding effect for each tube voltage of X-ray was higher, as the thickness of the shielding film was increased. When the thickness of the shielding fiber inside and outside the cloth was 0.1 mm, the X-ray shielding effect was about 55.37% against 50 keV X-ray, and if the thickness was 1.0 mm, the X-ray shielding effect showed shielding characteristics of about 99.36% against 50 keV X-ray.

4. Discussion

For radiation in the current diagnostic medical area, because the generated radiation dose is relatively small and the physical damage caused by the radiation is not usually immediately apparent, ordinary persons as well as medical experts underestimate or overestimate the risk without a clear understanding. However, the real issue is that radioactive testing carried out in medical practice is increasing and the risk of a cumulative radiation dose is increasing. According to the report 160 of the National Council on Radiation Protection & Measurements (NCRP) published in 2009, most of the ionizing radiation exposure (83%) in the early 1980s was due to natural radiation, but the ratio of medical radiation was about 15%. However, it is now approaching almost 50%, while the ratio of medical radiation in the survey in 2006 had significantly increased [7, 8]. Hence, the risk of medical radiation has been newly recognized, and image medical department personnel are trying to defend themselves and their patients against unnecessary medical radiation. In general, for radiation shielding, protective garments such as aprons, in which the main ingredient is lead, are largely used. Because these products are made with a mixture of lead powder and rubber, they have the risk of being made of heavy metal as well as being very heavy. Hence, oxide powders of rare-earth elements such as Tungsten and Antimon, which are costly materials, have also been used. However, this involves the issues of economic feasibility and safety. In recent years, shielding materials using bismuth have been developed [12-15]. Gwon *et al.* [16] evaluated the dose of the eye lens of a dummy phantom by using a glass dosimeter in order to evaluate the reduction of eye lens dose and the shielding effect using bismuth for shielding in a CT scan of the eye and head. They reported that because the results were measured using a glass dosimeter, the mean dose before using bismuth was 21.54 mGy and the mean dose after using bismuth was 10.46 mGy; the dose was thus reduced by 51.3%. As mentioned above, while it has been reported that bismuth has an excellent shielding effect, because its real weight is heavy, it involves great inconvenience. It is considered that if the bismuth particles are fabricated at a nanosize scale, not only do the mechanical properties improve, but the shielding is also improved, and the weight reduction of the shielding material will also be possible. Therefore, in this study, the authors researched the shielding performance of nanosized bismuth.

From the research results, in the shielding characteristics according to each tube voltage of X-ray, as the thickness of the shielding film was increased, the shielding effect of radiation also increased. If the thickness of the shielding fiber inside and outside the cloth is 0.1 mm, the X-ray shielding effect was about 55.37% with 50 keV X-ray, and if the thickness is 1.0 mm, the X-ray shielding effect showed shielding characteristics of about 99.36% with 50 keV X-ray. In general, as the particle size is reduced, the porosity itself also reduces, and the shielding effect is increased. Accordingly, it is considered that unlike conventional bismuth material, the shielding effect of nanosized-bismuth is improved, and its actual weight can be reduced. In relevant studies published on bismuth, measurements using secondary scattering beam have typically been performed. In the Compton scattering, which is the secondary scattering beam, the scattering X-ray is generated in the direction independent of the generation direction of the primary X-ray. The Compton scattering has a different scattering direction and energy according to the collision angle, because of the phenomenon whereby the incident X-ray loses some energy after collision with the orbital electron and is scattered in a different direction. In other words, the energy of the incident X-ray is reduced in Compton scattering, but in the case of single collision, not all of the X-ray is absorbed and only the direction is changed while only some energy is absorbed. Thus, the energy of the secondary beam will be greatly reduced in comparison with that of the primary beam. The energy of scattering X-ray is as follows [17]:

$$E_{scatt} = E_0 \frac{1}{1 + \dfrac{E_0}{m_e c^2 (1 - \cos\theta)}} \tag{6}$$

where E_o is the energy of the incident X-ray, E_{scatt} is the energy of X-ray, m_e is the remaining mass of an electron (9.1×10^{-3} 1 kg), c is the light beam, and θ is the scattering angle. In this study, the shielding ratio for a primary X-ray was measured, and the research results of the shielding effect of radiation showed a shielding ratio of about 55.37% with 50 keV X-ray. In addition, the shielding ratio of an actual secondary scattering beam was measured, and it is considered that this will be increased.

In conclusion, when using the nanosized-bismuth as a shielding material, because the shielding ratio is increased and the weight of shielding is reduced, it is considered that if manufacturing an actual radiation shielding fabric, the comfort and ease of use of the fabric will be excellent.

5. Conclusions

It is considered that the nanosized-bismuth, which is a radiation shielding fiber developed in this research, will contribute to reducing the primary X-ray and secondary X-ray effects, such as when using a scattering beam at a low level exposure. In addition, it is considered that if the nanosized-bismuth is used, except for the case where lead is used as an environmental material, it will contribute to reducing the weight of the shielding material and the development of radiation shielding products.

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