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A STUDY ON PERFORMANCE OF LOW-DOSE MEDICAL RADIATION SHIELDING FIBER (RSF) IN CT SCANS

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ABSTRACT
In modern medicine, a radiation scans is an very important examination tool for making a diagnosis and subsequent treatment plan. Among the range of medical examinations, Computed tomography (CT) is being performed in an increasing number of cases and a CT scan uses the most radiation of any diagnostic exam. On the other hand, radiation protection during scanning is not typical for bodily regions other than those designated for examination. Therefore, the aim of this study was to develop a lead-free fused radiation shielding fiber (RSF) and to evaluate its effectiveness with a view to reducing radiation exposure to only the effective dose or less in a CT scan by means of a multilayer structural coating. A GE High Speed Advantage Spiral CT was used to conduct measurements using a FH-40G (Eberline, USA) proportional digital counter survey meter. In a brain CT scan, abdominal CT scan, and knee CT scan, two-way ANOVA was used to analyze the changes in radiation dosage and to examine the correlation based on body parts and thickness of the RSF. In addition, when significant results were obtained, a Duncan post hoc test was used to examine the difference depending on each condition. In the brain CT scan, the highest exposure to secondary radiation was measured in the chest, which was closest in distance. The use of a 3- mm shielding fiber resulted in a shielding effect of approximately 65% shielding effect compared to the initial exposure dose. In the abdominal CT scan, no exposure dose was detected in the head area, which had been shielded with the 3-mm shielding fiber. In a knee CT scan, 1-mm shielding fiber was sufficient to demonstrate a shielding effect. The RSF developed in this study may help reduce low-dose exposure to secondary X-rays, such as scattered rays.

Keywords: Barium; Computed tomography; Lead-free; Radiation shielding fiber

1. INTRODUCTION
In modern medicine, radiation scans are important examination tools used to make diagnosis and treatment plans. Computed tomography (CT) is a major examination tool used in an increasing number of cases; yet, CT scans use the most radiation among the various diagnostic exams. On the other hand, the risk of medical radiation has been recognized recently, and radiology departments have made efforts to protect patients from unnecessary medical radiation other than diagnostic radiation. In general, radiation shielding is used mainly as protective clothing made from lead a heavy metal. This causes practical problems when lead is used in the manufacture of clothing (Kim et al., 2012; Kim et al., 2003). Although many products have been released to resolve these problems, there has been insufficient progress in the development of a shielding fiber or sheet that is light weight economical, and dependable (Kim & Park, 2010).

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The shielding capability is the most important factor when manufacturing light-weight radiation shielding fiber (RSF). Radiation equipment used for diagnosis in a typical radiology department employs radiation energy ranging from 40 to 120kVp. On the other hand, CT scans use a high level of tube voltage radiography in the range of 120kVp or higher. Therefore, CT uses a high energy flux and filter to ensure that all X-ray photons contribute to image reconstruction. Nevertheless, scattered rays are generated on the axis of the layer and its surroundings for radiography. Since direct shielding from X-rays generated from a CT scan is not meaningful for an examination of the patient, medical RSF was developed to prevent exposure to low-dose radiation of body parts other than those to be examined. In this study, materials with radiation shielding capability excluding lead were used to manufacture medical RSF. Materials, such as barium sulfate and iodine compounds, have radiation-shielding abilities; they are not harmful to the human body. Therefore, when selecting materials for use in RSF. Economic feasibility and manufacturing machinability must be emphasized. Material in the form of yarn, for example, does not offer long-term durability. As a result, a method for manufacturing a pellicle coated with barium sulfate was used in this study. Barium sulfate has a very high density of 4.5 g/cm^3 and low miscibility, causing problems in dispersion. Therefore, it is important to use special technical processing methods, such as transfer coating and direct coating (Kann, 1999; Kann, 2007). In this study, barium sulfate was used as the major material for manufacturing medical RSF. To evaluate the performance of the fiber, scanning was carried out for a brain CT, abdominal CT, and knee CT for a relatively large number of cases in the radiology clinical department. To measure the radiation dosage, five body regions were selected; head, chest, abdomen, pelvis, and knee. The experiment was conducted to examine the possibility of effectively shielding selected body regions from low-dose radiation.

2. METHODOLOGY/ EXPERIMENTAL

The radiation dose in a scan conducted in a radiology department plays an important role in obtaining an accurate image. On the other hand, it is impossible to ignore the potential risk that patients and radiation workers face during scanning. The radiation dose in a CT scan can vary according to scanner geometry, degree of filtering, and shape of dose profile (Mettler et al., 2000). The X-ray flux in a CT dose rotates around the patient for 360 degrees, which is unlike the case with conventional X-ray scanning. Therefore, the exposure dose means that the absorbed energy per unit mass in a very small volume within a local region of human tissue is exposed to X-rays during scanning (Brenner et al., 2007). The exposure dose can differ between the area that is perpendicular to the section under examination and the location designated for imaging because of the major flux and the secondary radiation that leaks from scattered rays and the X-ray tube, In this study, the measurements were conducted to determine the incident radiation exposure to the skin area of the body region located a certain distance from the section designated for imaging to verify the shielding effect from secondary radiation, (e.g., scattered rays), rather than to examine the shielding capability of the major flux in a CT scan. Regarding radiation exposure, dosage and energy generally decrease as radiation penetrates the human body and reacts with its tissues. When a CT scan is conducted, the degree of radiation shielding can be confirmed based on the ratio of the radiation intensity that is measured before and after penetration at a certain distance. The radiation intensity, I(r), at point, (Ro), of the major flux where radiation is generated in CT equipment, can be expressed as Equation 1.

$$I_{(r)} = \frac{R_o}{4\pi r^2} \qquad (1)$$

If radiation intensity is I_1 and I_2 at a distance of r_1 and r_2 from the radiation, Flux (R_o), I_2/I_1, can be expressed as Equation 2.

$$\frac{I_2}{I_1} = \frac{\left(\frac{R_O}{4\pi r_2^2}\right)}{\left(\frac{R_O}{4\pi r_1^2}\right)} = \frac{r_1^2}{r_2^2} \tag{2}$$

If the detection count of the radiation detector is C, the measured radiation intensity (S) can be expressed as Equation 3.

$$S = C \times I \tag{3}$$

The ratio of radiation intensity, $I(t_1)$ and $I(t_2)$, measured at the time intervals (t_1, t_2), to the actual radiation intensity $S(t_1)$ and $S(t_2)$ can be expressed as Equation 4.

$$\frac{I(t_1)}{I(t_2)} = \frac{S(t_1)}{S(t_2)} \tag{4}$$

Because the dose measurement of the detector used in this experiment was not dependent on the detection count, the transmission dose on the incident surface was measured using a proportional counter detector, by which the radiation dose could be measured readily. We noted that when the detector was placed between the shielding fibers to conduct scanning, the radiation intensity was $I(r)$ at a certain distance of r, whereas the intensity of the radiation flux point was I, which led to $I \geq I(r)$. This is a case for which the shielding effect of the shielding fiber should be considered. Because $I/I(r)$ should be less than 1, the measurement was conducted based on Equation 4.

Imaging from medical radiation adheres to the basic principle that the transition of an orbital electron occurs when it absorbs energy corresponding to the specific orbital energy of the matter. In the range of radiation used for the human body, energy change is mainly due to interactions with the innermost orbital electron.

If the energy of the innermost orbital electron is E_b, the energy of the excited electron equals $E_e=E_p-E_b$, when E_p is the energy of the external collision energy. During this process, the photoelectric effect occurs as external radiation loses its energy and characteristic X-ray emits. The photoelectric effect is proportional to the cube of an atomic number and inversely proportional to the cube of the energy; thus, it is a very important criterion for selecting radiation shielding material.

In this study, T(%), the transmittance of the absorbing material was obtained using barium (Z=56) instead of lead(Pb) as the radiation shielding material; the spectrum was 50 kVp and 100 kVp (X-123, Spectrometer, supplied by APPTEK), Relevant calculation are shown in Equation 5 below (Redus, 2008).

$$T(\%) = \frac{\int_{\Delta E}^{E_{max}} \psi(E) i exp^{-[(\mu\times t)a+(\mu\times t)b]} dE}{\int_{\Delta E}^{E_{max}} \psi(E) i dE} \times 100 \tag{5}$$

To reduce energy, ΔE was set to 10 keV. Additionally, a and b refer to the quality of material, and t is the thickness of absorbing material. The linear absorption coefficient μ, a function of energy, used the data of the mass absorption coefficient, the mass absorption coefficients of each Pb and Barium (Ba) are compared and shown in Figure 1 (Choi et al., 2010).

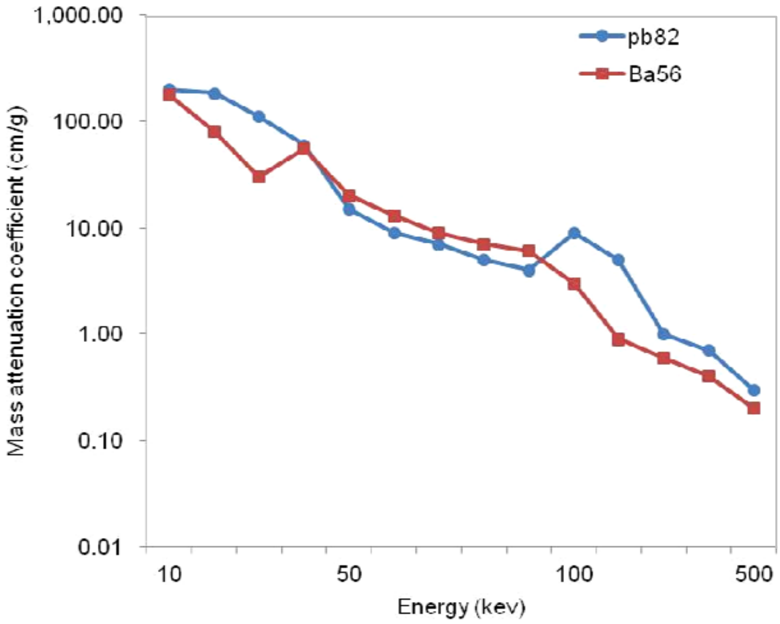

Figure 1 The linear attenuation coefficients as a function 56(Ba) and 82(Pb) of radiation energy in keV

Medical RSF consists of an exocuticle and the dermis. The exocuticle is composed of cotton fabrics, whereas the dermis has spread layers composed of polyester fibers and polyurethane resin. For this study, the spread layer was coated with barium sulfate, whereas some compounds that could affect the porosity were added to increase the spread density. In addition, the mean particle size was set to 10 µm or less to ensure that Ba had been dispersed evenly. Porosity was maintained approximately 30%. The coating was manufactured with a multilayer, rather than a single layer, structure, as shown in Figure 2, to improve the shielding capability.

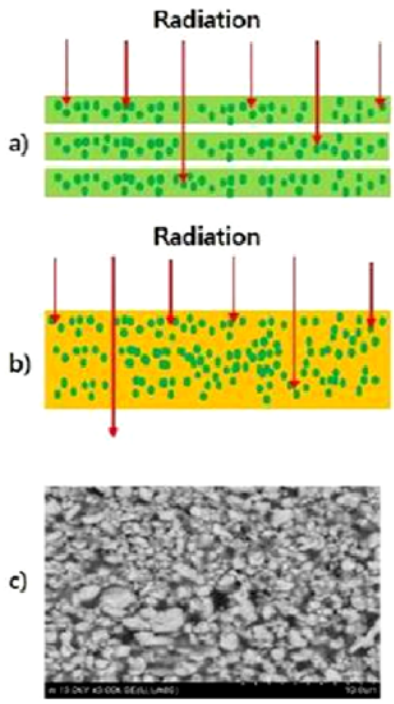

Figure 2 Coating structure of RSF: a) RSF light-weight multilayer structure coating method; b) RSF light-weight single layer structure coating method; c) RSF Scanning electron micrograph of silicon in the radiation shielding sheet

Therefore, GE High Speed Advantage Spiral CT was used to verify the protective effect of the shielding fiber that was manufactured in this experiment. A FH-40G (Eberline, USA) proportional counter digital survey meter (energy measurement range of 30 keV-1.3 MeV and dose measurement range of 100 nSv/h-100 mSv/h) was used as a detector to measure the high radiation count rate. A phantom (CT Whole Body Phantom PBU-60, USA) was used to conduct the brain CT scan (120 kVp and 250 mA), abdominal CT scan (135 kVp and 250 mA) and knee CT (120 kVp and 100 mA) in the same way as performed for a common CT scan. In this case, five body regions were selected; head, chest, abdomen, pelvis, and knee. The meter was placed at a certain distance between each region for scanning before performing the measurement 10 times under the same conditions. Shielding was focused on the chest, reproductive organs, and abdomen because the priority for shielding was placed on the body regions exposed to radiation at relatively high levels. Under identical conditions, the experiment was conducted using RSF in thickness of 1 mm, 2 mm, and 3 mm, for the same and targeted the same body regions as those cited in Figure 3.

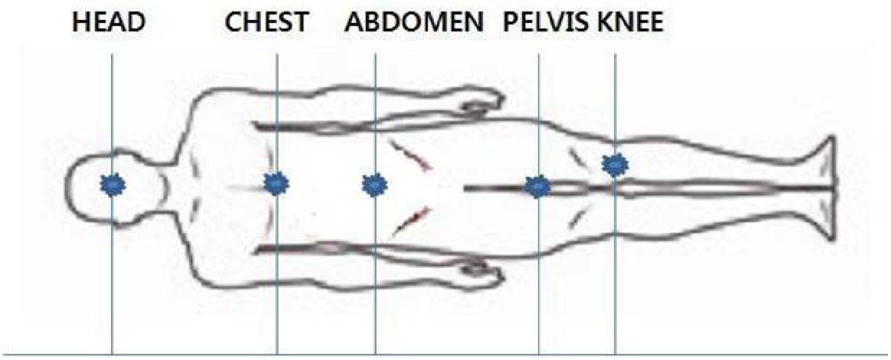

Figure 3 Location of the radiation dosimeter

SPSS 12.0 for Windows was used for statistical analysis. Two-way ANOVA was conducted to analyze changes in radiation dosage and to examine the correlation depending on each part and thickness of the RSF. In addition, when significant results were obtained, a Duncan post-hoc test was used to examine the difference depending on each condition. The significance level (α) was set at 0.05.

3. RESULTS

Experimental results were obtained based on exposure doses measured at certain distances under the common conditions for CT scans. Dose intensity was weakened as distance from the scanned body part increased. On the other hand, the effectiveness of medical RSF was confirmed and analyzed, as shown in Tables 1 and 2, to reduce low-dose exposure.

In a brain CT scan, the highest exposure dose was measured in the chest. Secondary exposure was reduced by 70% when 3-mm shielding fiber was used. Each body region in the order of the chest, abdomen, pelvis, and knee showed different results with statistical significance. In addition, the secondary exposure dose decreased significantly with increasing thickness of the RSF. Post-hoc analysis showed different results according to thickness.

In the abdominal CT scan, the shielding effect was approximately 60% in the vicinity of the reproductive organs. Exposure to secondary radiation in each body region in the order of the chest, pelvis, head, and knee resulted in similar exposure rates the chest and pelvis. On the other hand, the exposure dose in each body region was significantly different ($p<0.001$), as confirmed by post-hoc analysis. Differences were dependent on the thickness of the RSF. In particular, when 2-mm RSF was used, the dose was reduced significantly compared to the case in which 1-

mm RSF was used, as confirmed by post-hoc analysis ($p<0.001$). In a CT scan of the knee, radioactive exposure was detected in the chest when 3-mm RSF was used. For all body regions, the exposure dose decreased significantly according to an increase in RSF thickness. In particular, no measurable exposure dose was recorded in the head and chest areas when 2-mm RSF was used. These findings demonstrate that RSF has an apparent low-dose shielding effect. In addition, the decreases in doses differed according to each body region selected for CT imaging. The effectiveness of the 3-mm thick RSF increased with decreasing distance. In fact, when the distance was increased, it was possible to obtain a sufficient effect of the RSF, even at a thickness of 2 mm. (Figure 4, Figure 5, Figure 6).

Table 1 Variation of dose depending on the thickness of the RSF in a CT scans of each body regions

CT Scan	RSF	Chest	Abdomen	Pelvis	Knee
Brain	No	0.214	0.121	0.041	0.012
	1 mm	0.190	0.082	0.021	0.006
	2 mm	0.102	0.041	0.009	0.000
	3 mm	0.074	0.021	0.000	0.000
Abdomen	No	0.311	0.150	0.301	0.071
	1 mm	0.251	0.095	0.245	0.035
	2 mm	0.113	0.025	0.102	0.017
	3 mm	0.052	0.000	0.041	0.008
Knee	No	0.005	0.003	0.062	0.022
	1 mm	0.002	0.000	0.031	0.012
	2 mm	0.000	0.000	0.015	0.005
	3 mm	0.000	0.000	0.008	0.000

Note: Units are expressed as the number of mSv

Table 2 Correlation of the dose depending on the thickness of the RSF in CT scans of designated body regions

CT Scan	RSF	Type III SS	MS	F	p
Brain	Parts of the body (P)	0.485	0.162	1067344.95	0.000^{***}
	RSF Thickness (T)	0.135	0.045	297389.83	0.000^{***}
	P * T	0.102	0.008	297389.83	0.000^{***}
Abdomen	Parts of the body (P)	0.670	0.223	1701544.81	0.000^{***}
	RSF Thickness (T)	0.842	0.281	2137631.43	0.000^{***}
	P * T	0.192	0.021	162470.52	0.000^{***}
Knee	Parts of the body (P)	0.021	0.007	154575.00	0.000^{***}
	RSF Thickness (T)	0.010	0.003	82935.00	0.000^{***}
	P * T	0.010	0.001	26388.33	0.000^{***}

SS: Sum of squares, MS: Mean squares. Interaction effect using two-way ANOVA model and post-hoc test of Duncan test*** $p<0.001$

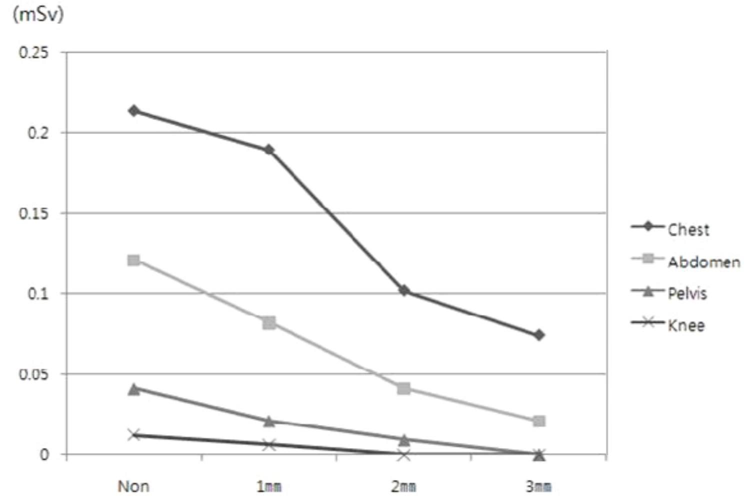

Figure 4 Low-dose shielding effect of the RSF for each body part in the brain CT scan

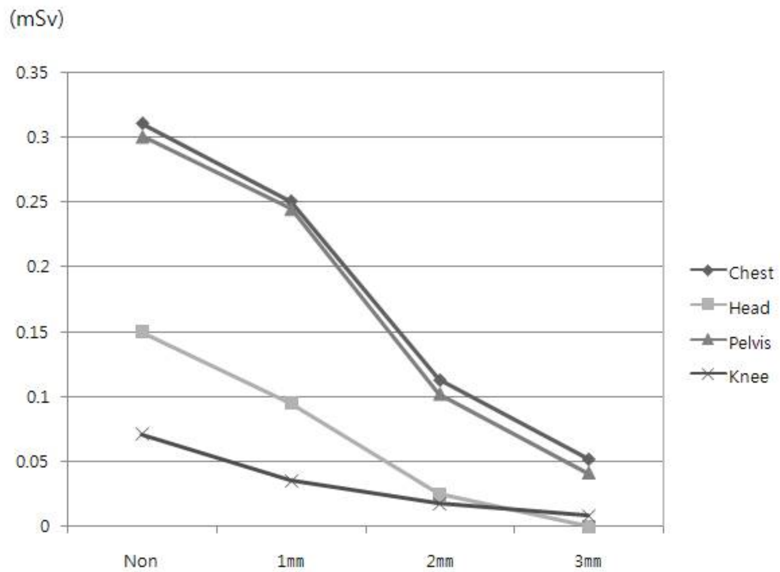

Figure 5 Low-dose shielding effect of the RSF for each body part in the abdomen CT scan

4. DISCUSSION

This study measured the secondary exposure dose of radiation released in body regions other than those targeted for imaging with a CT scan. In addition, the effectiveness of low-dose radiation shielding during a CT scan was assessed based on an evaluation of the shielding capability of the RSF that was developed using eco-friendly materials instead of Pb. In a common CT scan, the radiation level to which a patient is exposed should as low as possible. On the other hand, radiation exposure increases in proportion to the image quality; it is programmed into the equipment according to the diagnostic value of the image therefore, it is technically difficult technically to protect against radiation exposure. Furthermore, since a multi-detector CT (MDCT) has become commonplace since 2000, the number of CT scans has increased rapidly. In the US, the number has increased by approximately 10% annually (United Nations Scientific Committee on the Effects of Atomic Radiation, 2010). Table 3 lists effective doses for CT scans and radiography.

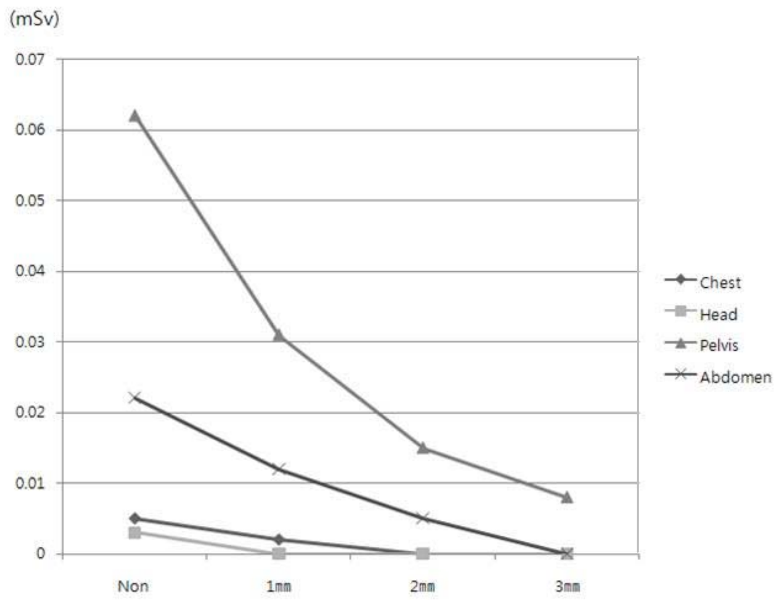

Figure 6 Low-dose shielding effect of the RSF for each body part in the knee CT scan

Table 3 Effective dose in a CT Scan and radiography

Classifications	Parts of the body	Effective Dose (mSv)
X-ray	Skull	0.03
	Chest	0.02
	Abdomen	0.70
	Pelvis	0.70
CT	Head	2
	Chest	8
	Abdomen	10
	Pelvis	10

Note: IMPACT 2002 (Image performance assessment of CT)

Regarding protection from medical radiation, radiologists generally do not apply partial shielding to patients in most of the examination rooms in a CT scan because they remain out of the rooms. Furthermore, as the protection tool is made mostly of Pb, there are difficulties in management and operation due to the weight. Therefore, a medical radiation protection system that helps resolve these problems needs to be developed, with a focus on the patient (Kim, 2009; Kim, 2008; Lee, 2001; Korean Intellectual Property Office Patent Gazette (A), 2000). This study has focused on shielding of low-dose radiation generated from a CT scan to develop RSF without Pb. In regard to a common X-ray scan, many studies have been performed on safe methods of medical radiation shielding. Recently, considerable efforts have been made to develop eco-friendly materials instead of Pb for radiation shielding. Barium was selected as an alternative material for RSF because it has an absorption edge in the lower region than lead that has high atomic number with the energy of the photoelectric effect area. Barium is relatively harmless to the human body, and it is economical. From a technical stand point, it is believed that Ba would not present any problems in mass production. In particular, Ba is used as a compound, as in barium sulfate. In addition, it can be mixed with other materials, such as tungsten, bismuth, and antimony; these mixtures show strong potential for being used in the desired manner. On the other hand, it is important to secure sufficient technology for coating fabric (Dong et al., 2011; Dong et al., 2009). Dispersion is the most important technology. The process requires repeated coatings and a stable maturity of the endocuticle to ensure the same shielding capability while maintaining a certain thickness. In this study, coating with a light weight multilayer structure was used to help improve the shielding capability against thickness. As shown in the study results, when 2- and 3-mm RSF was used, it was possible to ensure shielding so that only the effective dose or less was released. The RSF is believed to be convenient for use because of light weight structure (Korean Standards Association, 2005; Korean Industrial Safety Association, 1995). The ultimate goal of this study was to produce light weight and perfect shielding material. The RSF currently manufactured showed a shielding effect equivalent to 0.15-0.3mmPb. To produce a more effective shielding fiber, further study regarding reduction in thickness and volume is required. Additionally, research associated with improving the filling factor of shielding materials is needed.

5. CONCLUSION

In this study, we compared the conventional shielding material Pb, and Ba, which showed the same mass absorption coefficient with Pb in the energy range of 50keV~100keV (required for producing medical radiation images). Our findings indicated that a multi-coating shielding material using Ba was as effective as Pb in shielding patients from low levels of radiation.

In a medical examination that uses radiation, it is important to remove unnecessary exposure, particularly low-dose exposure. In the present study, the RSF that was developed showed a maximum reduction effect of 85%. Prior to use of RSF, a brain CT scan released a high dose of radiation to the chest, which was at a close distance. When a 3-mm shielding fiber was used, however, the shielding effect was approximately 65% compared to the initial dose. In the abdominal CT scan, no radiation exposure was detected in the head area that had been shielded with 3-mm shielding fiber. In the CT scan of the knee, a 1-mm shielding fiber showed a sufficient shielding effect. Since human organs are sensitive to radiation from CT scans, it is important to make every effort to reduce unnecessary exposure. Finding from this study support the use of the RSF developed in reducing low-dose exposure to secondary X-rays, such as scattered rays. The RSF was manufactured using eco-friendly materials (e.g. Ba) instead of Pb; its benefits include reducing the weight of the shielding material and assisting in the development of various radiation protection products groups in the future.

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