

Article

Development of a Lightweight Tungsten Shielding Fiber That Can Be Used for Improving the Performance of Medical Radiation Shields

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Abstract: Radiation exposure in medical institutions is mainly due to low doses. Low-dose radiation mainly means scattered radiation, and such scattered radiation can be shielded with a lightweight shielding suit. In this study, the shielding performance of shielding fabrics woven by winding polyethylene (PE) yarn around a 30 μm tungsten wire was evaluated. To improve the shielding performance, an air pressure dispersion process of coating tungsten nanopowder on the fiber was developed. The radiation shielding effectiveness of the shielding fibers with and without dispersed tungsten nanopowder were compared by measuring the spatial dose inside the diagnostic X-ray imaging room of a medical institution. The results of the experiment confirmed that the fabric coated with tungsten nanopowder improved the shielding performance of the general tungsten fiber by approximately 15% and provided relatively effective low-dose radiation shielding at approximately 1.2 m of the X-ray imaging equipment. This study shows that tungsten fiber can be helpful in manufacturing lightweight shielding clothing for protection from scattered radiation in medical institutions.



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1. Introduction

The increasing use of artificial radiation in medical institutions has increased radiation exposure in the diagnostic area [1]. Although the dose and quality of the radiation used for the diagnosis of diseases are relatively low compared to the radiation leaked from a nuclear accident, for example, even a very small dose can have a very dangerous effect on the human body [2].

Most of the radiation exposure that is a problem in medical institutions is caused by indirect scattered rays rather than direct rays. Scattered radiation corresponds to a low dose, generally less than 100 mSv [3]. In the case of radiation exposure of less than 100 mSv, the Research Council Biological Effects of Ionizing Radiation report (BEIR VII) supports the theory of linear proportion without a threshold, thus, there is a direct potential for cancer and genetic disorders [4,5]. Therefore, the active protection of medical workers against low-dose radiation exposure is critical.

Current radiation shielding clothing in medical institutions generally uses lead as the shielding material, however, the weight of this substance hinders the physical activity of medical staff and patients. A radiation protection apron having the equivalent to 0.50 mm of lead weighs between 3.01 and 3.15 kg. Because the front part offers protection from the shoulders to the knees, these are widely used in the vicinity of X-rays in medical institutions [6].

A previous study considered that scattered rays exist within 2 m of the radiation generating site, and for this purpose, suggested a shield with a thickness of less than 0.50 mm of lead equivalent [7]. However, in order to reduce the weight of the shielding lining, it is necessary to discover a new shielding material, and this is also related to the

manufacturing process technology that is used to replace the shielding material, hence there are many complications in practical use. Recently, radiation shields have been developed using eco-friendly materials to avoid the toxicity of lead. Eco-friendly radiation shielding materials consist of tungsten, bismuth, barium sulfate, and boron, among others, mixed with a polymer material and manufactured in the form of a sheet [8,9]. Any shielding suit used in a medical institution must be lightweight and safe [10]. In order to maintain the same shielding performance for direct X-rays, it is difficult to significantly change the weight of the shield. However, since the scattered radiation generated in a certain distance and direction has a low dose, it can be shielded with lightweight shielding clothing.

Radiation shielding involves absorption using a material made of an element with a large atomic number, such as lead, or reducing the transmission of radiation through interaction with the shielding material. Therefore, lowering the amount of radiation exposure requires selecting a shielding material considering the type and energy of the radiation [11]. In the low energy region of X-rays or γ -rays with high radiation transmittance, sufficient shielding effect can be obtained with relatively thin lead, but in the high energy region, the necessary protective effect cannot be obtained unless the shield is thickened [12]. However, if the thickness of the shield is increased sufficiently, the weight of the shielding suit also increases substantially, which hinders the activity of medical personnel who must wear it for a long time during work.

In this study, PE yarn was wound around a tungsten wire to fabricate a shielding fiber that can be used as a lining for lightweight shielding clothing. The study also developed an air pressure dispersion process to disperse nanotungsten powder to eliminate pinholes in fibers. The shielding performance and weight of the fibers were evaluated to determine the potential efficiency of the fibers in low-dose shielding suits used in medical institutions. Products presented as conventional radiation shielding fibers are mainly manufactured by coating the nonwoven fabric on the shielding sheet with an inorganic mixture [13]. However, the problems of these products concern the weight and flexibility of fibers. To solve these problems, this study proposes a method to improve the shielding performance while maintaining the flexibility of the fiber.

2. Materials and Methods

The shielding material used in this study was tungsten, which has an atomic number of 74, an atomic weight of 183.84 g/mol, and a density of 19.25 g/cm³. As its shielding performance is close to that of lead, it has been widely used recently as an eco-friendly radiation shielding material [14]. In this study, pure tungsten shielding fiber was produced from tungsten yarn made with industrial filament tungsten wire with a diameter of 30 ± 0.05 μ m. The fabric was manufactured using a weaving machine (Rapier Loom, Dornier, HTVS 8/S20, Friedrichshafen, Germany). The diameter of the tungsten wire was selected such that it was small enough to maintain the flexibility of the tungsten fabric and provide a high weaving density, but not too small that the yarn could break during the weaving process. Therefore, a diameter of 30 μ m was selected in this study [15]. In addition, the fabric was woven by the twill weave method to minimize the spacing between the yarns, which occurs in warp and weft yarns from the plain weave method traditionally used for weaving [16]. Figure 1 shows the technical difference between the twill weave method and the plain weave method. Warp and weft yarns are crossed one by one in the plain weave method, whereas two or more yarns are crossed in the twill weave method [17].

In previous studies, mesh-type connection or knit weaving methods were suggested [18]. However, maintaining a constant shape during processing and achieving reproducibility of the shielding performance requires a more effective weaving method. In addition, the fabric was intended to be stacked for shielding applications involving higher radiation intensities. Therefore, in this study, the fabric was fabricated with high density using the twill weave method. The reproducibility of the shielding performance depends on the thickness of the shield and the consistency of the process technology. Figure 2

presents a fabric woven using tungsten yarn and Figure 3 presents the fabric weaving process with a weaving machine.

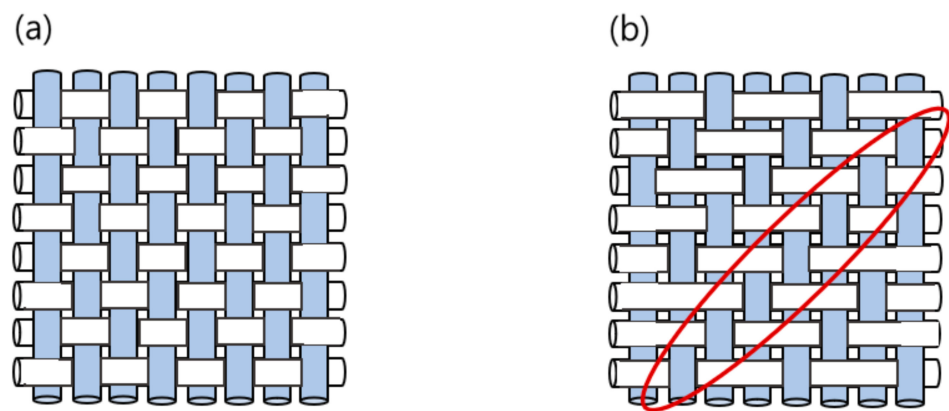


Figure 1. Fabric weaving methods. (a) Plain weave method, (b) Twill weave method.

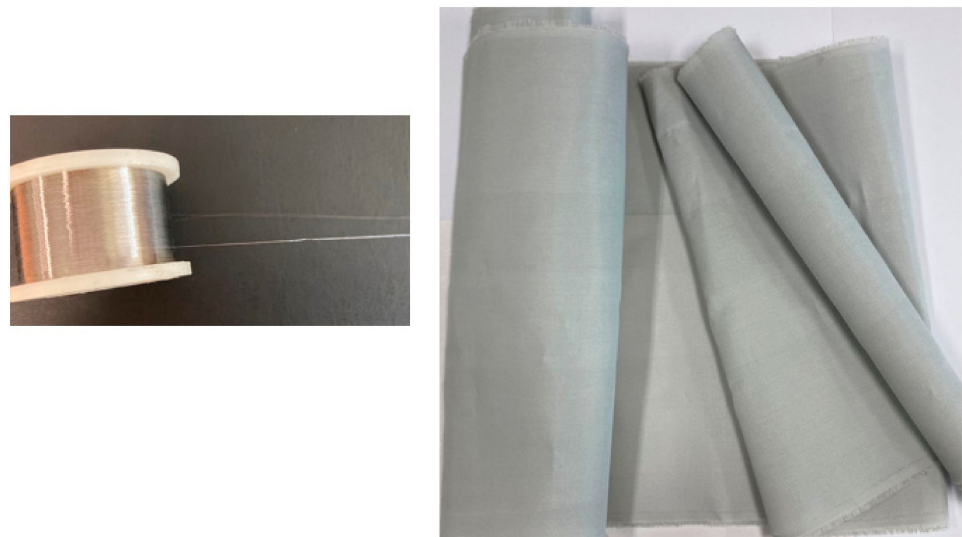


Figure 2. Tungsten yarn and fabric.



Figure 3. High-density weaving process of shielding fiber.

Methods for improving the shielding performance of the woven shielding fiber include a laminated structure, that is, using multiple layers of overlapping fabric, and a double coating method [19,20]. In general, a laminated structure of shielding fibers has the disadvantage of increased shielding thickness. Therefore, in this study, a method was developed in which a polyethylene (PE) yarn was wound around a tungsten wire and then woven into a fabric, and tungsten nanopowder was dispersed in the woven shielding fabric.

Even with high-density weaving, gaps and voids between the yarns reduce the shielding performance of the tungsten shielding fiber. Therefore, filling the voids with tungsten

nanoparticles was expected to improve the shielding performance of the fabric. The air pressure dispersion method of dispersing the tungsten nanoparticles on the shielding fiber fabric was configured as shown in Figure 4 [21].

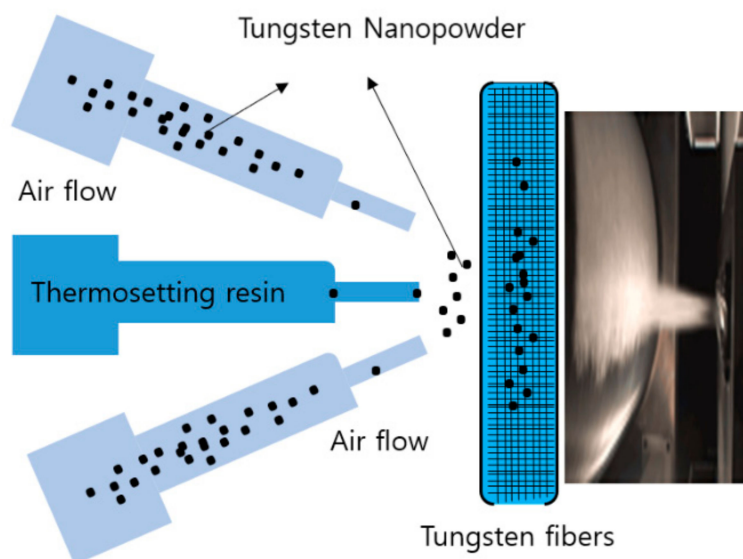


Figure 4. Tungsten nanopowder dispersion method.

The air pressure dispersion method disperses tungsten nanoparticles onto the fabric through a thin air nozzle with a diameter of 1.5 mm. In this study, a direct-dispersion form was applied. A trace amount of thermosetting phenolic resin adhesive was used for the complete fixation of tungsten powder particles on the shielding fabric, thus, fixing the particles well, increasing the affinity with the fibers, and filling the voids. The dispersed tungsten powder was applied in a small amount of less than 8 wt% of the total shielding fiber.

In this experiment, to determine the shielding area for medical radiation, the range and energy of the scattered rays inside the imaging room, which is the diagnostic area, were presented, and the shielding performance of direct radiation was evaluated. First, to evaluate the shielding performance of direct rays, the range of X-ray energy used in the diagnosis area was tested based on human body imaging. The following conditions were used in the X-ray energy shielding test—tube voltage: 60–120 kVp, tube current: 200 mA, and irradiation time: 0.1 s.

Because X-ray energy is not a single energy source, the effective energy must be determined. The effective energy of the braking radiation X-rays can be determined using the half-value layer (HVL) measurement method [22]. The HVL is the thickness of a material that attenuates the incident radiation by half. Although there is a difference between materials, the effective energy can be calculated using the following set of equations, after the material for measuring the HVL is determined [23,24].

When the incident radiation intensity I_0 interacts with the shielding material while passing through the shield, the intensity I of the transmitted radiation can be expressed by Equation (1):

$$I = I_0 e^{(-\mu t)} \quad (1)$$

Here, μ is the linear attenuation coefficient and t is the thickness of the shield. The HVL is the thickness of the material at which the intensity of the incident radiation is halved ($\frac{I_0}{2}$). Thus, after the expression $I = \frac{I_0}{2}$ is substituted in Equation (1) with $t = \text{HVL}$, it becomes $\frac{I_0}{2} = I_0 e^{-\mu \text{HVL}}$:

$$\mu = \frac{\ln 2}{\text{HVL}} \quad (2)$$

Therefore, the effective energy of the incident X-rays can be determined using the linear attenuation coefficient μ calculated from Equation (2) and Hubbell's mass attenuation coefficient [25].

The medical radiation-shielding performance was evaluated for each calculated effective energy. For the experimental method for testing the shielding performance of the two shielding fibers presented in this study, the geometric conditions were set as shown in Figure 5. The shielding rate calculation of the shielding sheet was $\left(1 - \frac{W}{W_0}\right) \times 100$ [26]. Here, W is the irradiation dose measured when there is a shielding fiber between the X-ray tube (E7239, 150 kV-500 mA, Toshiba, Tokyo, Japan) and the dosimeter (Dosimax plus 1, IBA Dosimetry Corp., Schwarzenbruck, Germany) W_0 is the irradiation dose measured when there is no shielding fiber between the X-ray tube and the dosimeter.

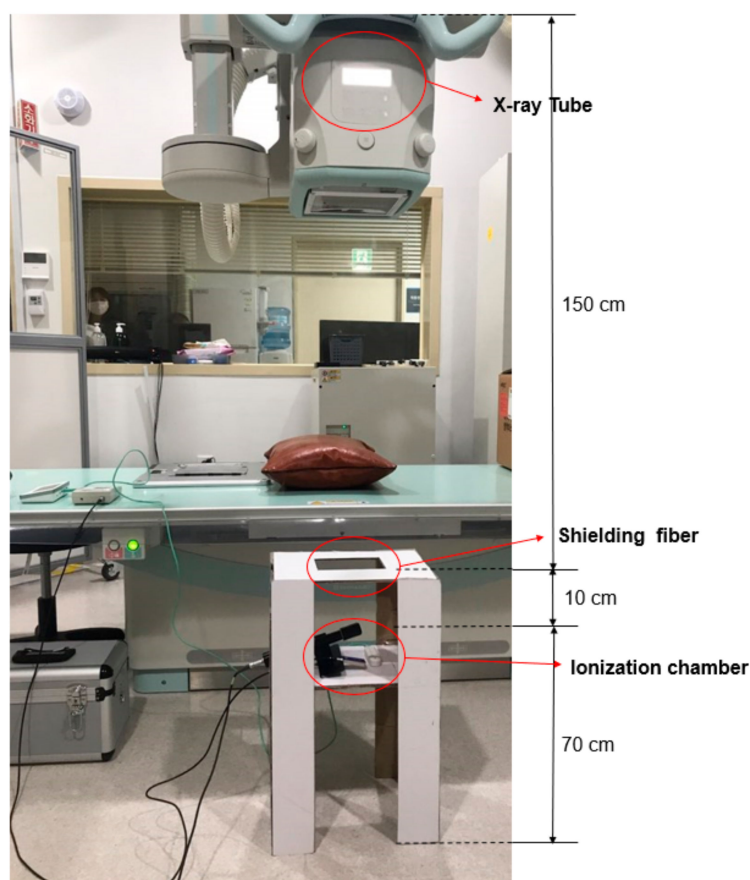


Figure 5. Method for evaluating the shielding performance of shielding fibers.

In this study, in order to verify the effectiveness of low-dose radiation shielding in a general imaging room of a medical institution using the fabricated shielding fiber, the irradiation dose was measured from the X-ray generator referenced to the horizontal plane of the patient examination table [27]. The measuring points were set 360° from the radiation generator position and at distances up to 200 cm in 50 cm increments. The spatial dose was measured using a spatial dosimeter (Raysafe 452, Billdal, Sweden).

3. Results

Table 1 shows the characteristics of the yarns and fabrics used to determine the shielding effectiveness of the radiation-shielding fibers. The manufactured yarn was made by winding PE thread on a 30 μ m tungsten wire with 98% purity. The reason why the PE thread was wound around the tungsten wire was to ensure the flexibility of the fiber when woven with a shielding fiber and to allow the dispersed tungsten nanopowder to be well settled. The woven fiber was 0.2 mm thick and weighed 954.3 g/m². Therefore, a shielded

suit of less than 1 kg can be produced when used as the apron. Additionally, because the strength of the yarn was 1.45 g/d, weaving with it posed no problem.

Table 1. Characteristics of medical radiation shielding yarn and fabric.

PE-Tungsten Wire Composite Yarn			Shielding Fiber			
Fineness	Tensile Strength (g/d)	Elongation at Break (%)	Thread Count (Thread/Inch)		Weight (g/m ²)	Thickness (mm)
			Warp	Weft		
501.1	1.45	4.2	80	60	112–121	0.20–0.21

The properties of the fibers dispersed with tungsten powder and fibers without dispersion were compared. Figure 6 shows electron micrographs of fabrics with and without tungsten powder dispersed in the fabricated shielding fiber. Figure 7 shows enlarged electron microscope images of the fabrics. Figure 7a shows the voids between the yarns, and Figure 7b shows the tungsten powder particles filling the voids and distributed evenly on the yarn.

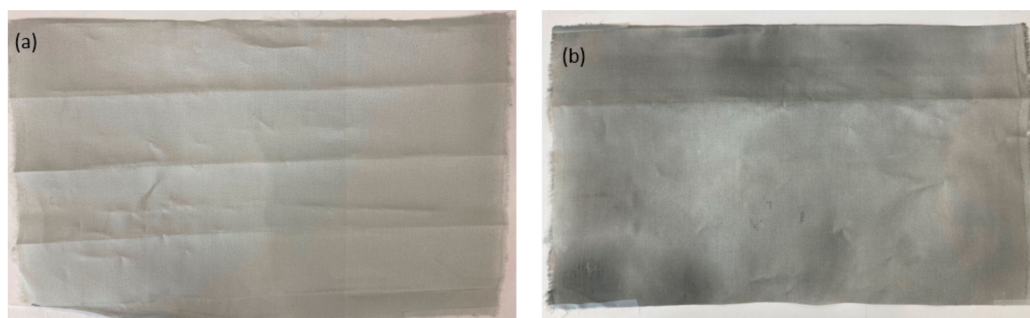


Figure 6. Electron micrographs of the fabricated shielding fabrics. (a) Fabric without dispersed tungsten powder, (b) Fabric with dispersed tungsten powder.

Table 2 shows the shielding performance for the two fabricated shielding fibers. Dispersing tungsten powder in the fiber improves the shielding performance by approximately 15%, making it more effective in low-dose areas. Therefore, the dispersion of tungsten powder in the fiber protects against secondary scattering rays.

Table 2. Comparison of shielding rate of the two shielding fibers.

Radiation Type	Effective X-ray Energy (keV)	Mean of Exposure (μR)			Shielding Rate (%)	
		Nothing	Tungsten Fiber	Tungsten Powder Fiber	Tungsten Fiber	Tungsten Powder Fiber
X-ray	24.6	106.90	72.01	55.49	32.64	48.09
	28.7	381.83	284.2	231.27	25.53	39.40
	32.5	799.70	632.82	545.80	20.87	31.75
	48.5	1318.33	1082.01	984.00	17.96	25.36
	54.9	1648.33	1407.70	1312.67	14.60	20.36

The low doses encountered in medical institutions are mainly generated in general imaging rooms and the diagnostic areas [28]. In this study, the dose in the space inside the imaging room was measured horizontally within 2 m of the equipment, based on abdominal imaging, which uses the highest dose in the diagnostic area (80 kVp, 30 mAs). The results are shown in Figure 8. Therefore, this shielding fiber fabric is expected to provide shielding at a distance of 1.2 m or more. The experimental results indicated that the spatial dose was 1400 μR within 1 m (Figure 8), and it can be said that ~30% of the spatial

dose can be shielded. Therefore, when the distance is greater than 1.2 m, it is expected that the shielding fiber manufactured in this study can be used to protect against scattered radiation, which is indirect radiation.

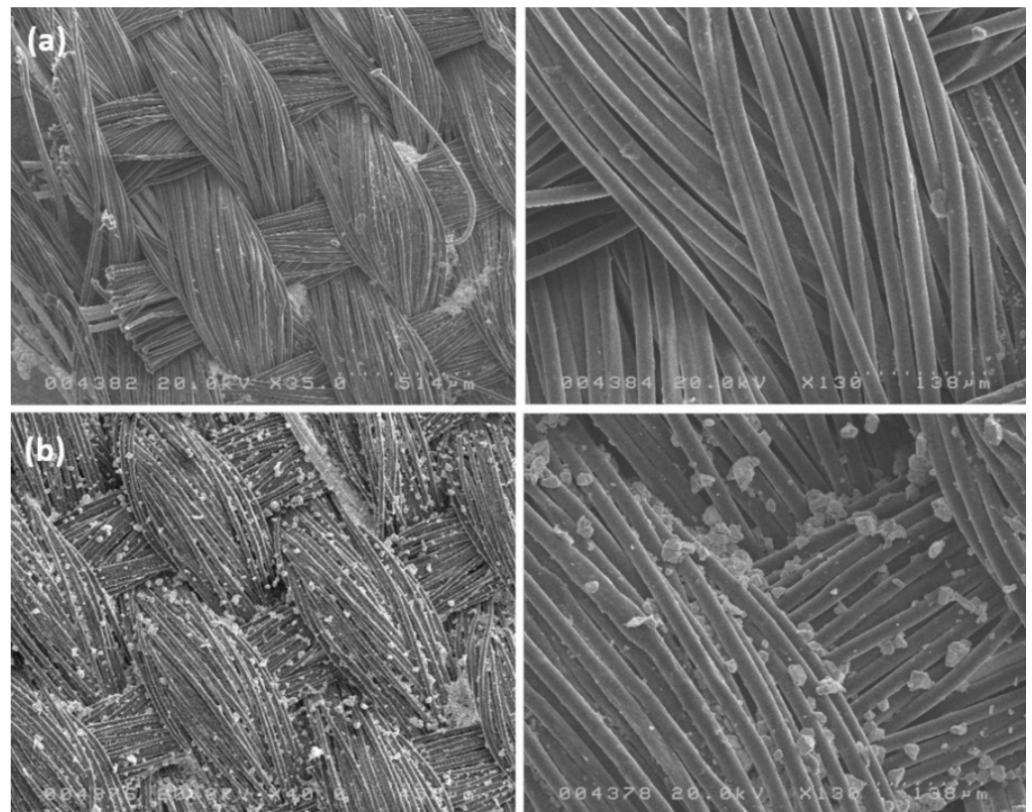


Figure 7. Enlarged electron microscope images of the fabrics. (a) Tungsten powder is not dispersed in the fabric, (b) Tungsten powder is dispersed.

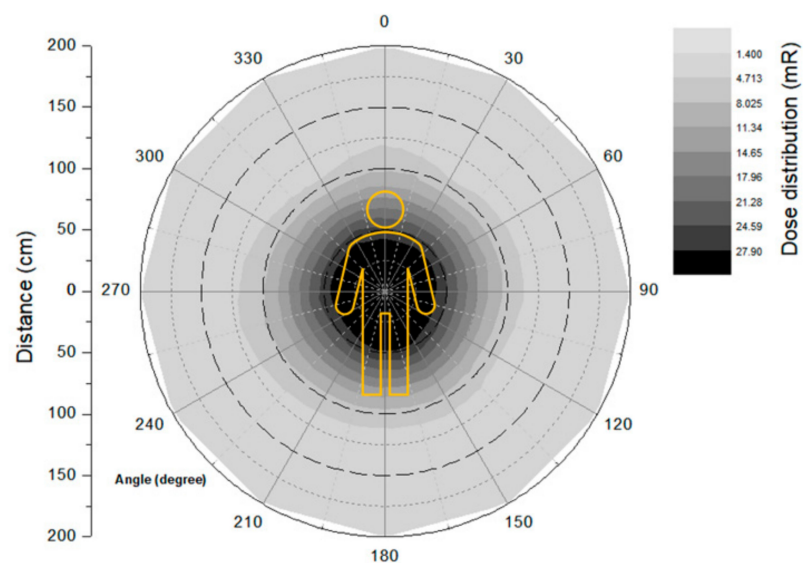


Figure 8. Spatial dose distribution inside the imaging room of a medical institution.

4. Discussion

The ability to shield X-rays and γ -rays used in the diagnostic area of medical institutions depends on the type and thickness of the shielding material [29,30]. When lead

is used as the main material, the X-ray protective clothing used for shielding by medical personnel or patients generally uses 0.25 and 0.50 mm lead thickness. The reported shielding performance of these thicknesses are more than 93.8% at 0.25 mm and 98.9% at 0.5 mm [31]. However, for low-dose radiation shielding, economic, environmental, and personnel activity issues arise because of the excessive protection provided by these lead thicknesses [32].

In this study, a tungsten-based shielding fiber for the efficient shielding of low-dose radiation generated in medical institutions was proposed. In addition, it was attempted to improve the shielding performance by dispersing tungsten nanopowder to remove pinholes between yarns, which are a problem when manufacturing with fibers. Using a large amount of powder increases the shielding effect, but reduces the fiber's flexibility. To retain fiber flexibility, tungsten powder usage was maintained at approximately 8 wt% of the total weight. As a result, the shielding performance was improved by 15% in the low-dose region.

The woven shielding fiber can also be used as a lining for special shielding suits such as partial shielding clothing for flight crews and firefighting suits; furthermore, it can be used in medical institutions for protection against scattered rays, rather than direct rays [33]. In the diagnosis area, as shown by the experimental results, shielding using a shielding fiber fabric is possible at a distance of 1.2 m or greater from the X-ray generator in the imaging room. Therefore, although it is insufficient for direct radiation shielding, it could be possible to manufacture a light-weight shielding suit for shielding against scattered rays. In particular, in places where low-dose radiation is used, such as dentistry or veterinary hospitals, the fabric can reduce the hindering effects of heavy shielding clothing on the users' activities [34].

A typical conventional method consists of mixing a resin-based polymer substance and a shielding substance and applying a thin coating on a non-woven fabric. This method increases the strength of the shield more than when it is manufactured in the form of a sheet, but the thin coating results in inconsistent shielding reproducibility, which makes mass production difficult. In addition, continuous use incurs problems such as the separation of the coating from the nonwoven fabric and cracks in the coating, resulting in poor durability of the product [35].

Effective shielding of low-dose radiation generated in medical institutions is closely related to distance, and the micro-design of shielding clothing considering distance is possible. Micro-shielding design can be classified according to the radiation sensitivity of major organs of the human body, and an effective radiation defense plan can be realized through customized shielding for each part [36]. In addition, a safe shielding range should be established to minimize the risk to the human body. Because the use of artificial radiation in medical institutions can control the intensity of energy, it can be used to resolve this risk [37–40].

Therefore, based on the range of scattered radiation and the amount of scattered radiation presented in the results of this study, the extent of low-dose shielding possible with a 1 kg lightweight shielding suit was determined. In particular, a new process technology for filling pinholes in fibers with nanopowders was also presented.

In medical institutions radiation shielding suits are worn by medical staff and patients and must satisfy the conditions of safety and light weight [41–43]. In this study, fibers using tungsten wire were woven to preferentially satisfy the light weight condition, and an effective coating method was proposed through the air pressure dispersion method. In addition, the possibility of improving the shielding performance of the shielding fiber manufactured in this way was verified, and basic data for the development of composite shielding bodies by this verification was provided.

5. Conclusions

To develop a light-weight shielding fiber for use in medical institutions, PE yarn was wound around a 30 μm tungsten wire and woven into a shielding fiber. In addition, to

improve the shielding performance, tungsten nanopowder was coated on the shielding fiber by using an air pressure dispersion method. This method ensured the flexibility of the shielding fiber and also improved the shielding performance by ~15%. The developed shielding fiber weighs at 954.3 g/m², which satisfies the condition of light weight. Furthermore, it could be possible to shield against scattered rays at a distance of 1.2 m or greater with reference to the imaging table with a shielding fiber manufactured by examining the spatial dose distribution inside the imaging room.

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