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Development and performance evaluation of medical radiation-reducing creams using eco-friendly radiation-shielding composites

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To ensure the safety of medical personnel in healthcare organizations, radiation-shielding materials like protective clothing are used to protect against low-dose radiation, such as scattered rays. The extremities, particularly the hands, are the most exposed to radiation. New materials that can be directly coated onto the skin would be more cost-effective, efficient, and convenient than gloves. We developed protective creams using eco-friendly shielding materials, including barium sulfate, bismuth oxide, and ytterbium oxide, to avoid harmful effects of heavy metals like lead, and tested their skin-protective effects. Particularly, the radiation-shielding effect of ytterbium oxide was compared with that of the other materials. As shielding material dispersion and layer thickness greatly affect the efficacy of radiation-shielding creams, we assessed dispersion in terms of the weight percentage (wt%). The effective radiation energy was reduced by 20% with a 1.0-mm increase in cream thickness. Ytterbium oxide had a higher radiation-shielding rate than the other two materials. A 28% difference in protective effect was observed with varying wt%, and the 45 wt% cream at 63.4 keV radiation achieved a 61.3% reduction rate. Higher content led to a more stable incident energy-reducing effect. In conclusion, ytterbium oxide shows potential as a radiation-shielding material for creams.

Keywords Radiation-shielding cream, Ytterbium oxide, Shielding materials, Skin protection

X-rays, the most commonly used ionizing radiation in medical institutions, require rigorous radiation protection measures during their application. Radiation-shielding skin-protective creams that protect from medical radiation have been recently developed[1]. Skin-protective creams for use by patients during radiation cancer treatment are primarily focused on protecting and restoring healthy cells[2]. External shielding, which is used outside the patient's body, is mostly used to shield and protect patients from medical radiation. Protective agents using radiation-shielding materials are directly applied to the skin to reduce the intensity of incident radiation energy and reduce the direct-radiation response of the human body[3].

Lead is the most common external shielding material for incident radiation used industrially. However, this heavy metal is harmful to humans and therefore cannot be used as a shielding agent directly on the skin[4]. Safe and eco-friendly shielding materials incorporating non-toxic substances, such as barium sulfate, should be developed[5]. It is crucial to use environmentally friendly materials that are proven to be safe. For skin protectants designed for direct contact with the skin, non-toxic, eco-friendly substances are essential.

Healthcare workers are mainly exposed to low-dose radiation, such as natural radiation, generally corresponding to $\leq$ 100 mSv[6]. Most epidemiological studies to date suggest that radiation exposures $<$ 100 mSv, a range in which most medical radiation exposures occur, do not cause a direct increase in cancer incidence[7]. Low-dose radiation can cause radiation-induced DNA damage by breaking the bonds between atoms in genes[8,9], which is an adverse effect of radiation exposure[10]. If the amount of radiation exposure is low, such DNA damage can be repaired (copy number and DNA repair) in a relatively short period. However, in case of considerable gene damage, not all damage can be repaired or may be incorrectly repaired, depending on the level of exposure[11].

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In medical institutions, damage to skin cells primarily occurs in areas of the body exposed to high-dose radiation used for radiation therapy, leading to radiation dermatitis[12]. Radiation dermatitis is the most common side effect in patients with cancer undergoing radiation therapy and is localized to the radiation-exposed area[13]. Therefore, creams are required to protect the skin barrier. These products are not intended to provide barrier protection but rather to regenerate and restore the skin after irradiation[14]. Therefore, products are required to protect healthy skin tissue outside the radiotherapy area. Developing a radiation-shielding cream with appropriate thickness and density considering the attenuation effect through physical radiation interactions to reduce the incident energy is challenging but required to protect healthy skin tissue.

Eco-friendly materials should be prioritized for radiation-reducing creams; barium sulfate and bismuth oxide have been proposed as eco-friendly materials[15]. In the present study, we aimed to verify the radiation-reducing effect of a material, ytterbium oxide, for use as an ingredient in skin-protective creams, and to demonstrate its superiority to existing materials. The radiation-protective effect of an eco-friendly harmless shielding material can be complemented with creams with antioxidant, antibacterial, moisturizing, and skin-regenerating effects[16].

Safe substances that can shield from medical radiation and do not affect the human body are currently being used as alternatives for lead. Barium sulfate is a naturally occurring inorganic salt. The synthetic form obtained after the removal of sulfuric acid impurities is mainly used in cosmetics to retain moisture in the epidermal skin layer. It improves the skin tone by soothing the skin, reducing inflammation, and exerting antioxidant activities[17]. Barium sulfate has a density of 4.5 g/cm^3 and is used as a contrast agent in medical radiological imaging of the digestive tract[18]. As it is insoluble in water, it is not absorbed by the body, is not toxic, and absorbs radiation. Bismuth oxide, a yellow pigment with a density of 8.7 g/cm^3, is widely used as an ingredient in cosmetics. Bismuth carbonate is used to treat enteritis, stomach ulcers, and skin diseases[19]. Additionally, it is used as an electromagnetic wave-shielding element and in radiation-shielding composites. Like barium sulfate, it is an economical and eco-friendly radiation-shielding material. As it is non-toxic, it is used as a lead replacement material. Ytterbium oxide, a compound discovered in this study to serve as a new shielding material, has a density of 6.90 g/cm^3, similar to that of tungsten. It can be used as a radiation shield due to its low cost. It is mainly used as an additive in dental stainless-steel alloys. As an inexpensive material that has radiation opacity, it can be used as an eco-friendly radiation-shielding material[20]. Therefore, the materials used in this study were chosen based on previous research that investigated their toxicity profiles[21–23].

This study developed radiation attenuation creams in cosmetic cream forms using three materials—barium sulfate, bismuth oxide, and ytterbium oxide—whose radiation shielding effects have been validated in the literature. The objective was to compare and assess their shielding performance, aiming to identify the most effective material and optimal combinations through experimental investigation. These environmentally friendly shielding materials were selected for their known efficacy and incorporated into cream bases. In the field of medical radiation, we can expect an effect that reduces directly absorbed radiation.

Concerning the radiation exposure of medical personnel, attention should be paid to skin disorders due to continuous exposure to low-dose radiation, which can lead to cancer development and genetic modification, rather than acute disorders caused by high doses[24]. However, developing a shielding film with a certain thickness and bending flexibility for the hands, which are the most exposed to radiation in medical personnel, is challenging. In these sites, new radiation protection technologies are needed to reduce exposure to medical radiation during medical procedures and mitigate incident energy through regular use of protective creams. Several studies exist on materials to achieve skin regeneration and skin protection after irradiation; however, a comparative evaluation of the incident energy-reducing effect is lacking.

In this study, barium sulfate, bismuth oxide, and ytterbium oxide, three substances with demonstrated radiation-shielding effects, were added in a cream base to create a medical radiation-shielding cream. The shielding performance of the creams was compared to identify the most effective materials and combinations.

The study aim was to contribute to the protection of normal tissues of medical personnel and patients, as well as to reduce the absorbed radiation dose by normal tissues in medical settings. Specifically, we aimed to introduce a new material-based medical radiation attenuation cream that can continually mitigate low-dose exposures.

Results

First, the dispersion of barium sulfate, bismuth oxide, and ytterbium oxide in an aqueous organic carrier medium in function of the weight percentage (wt%) was evaluated. The results for barium sulfate are shown in Fig. 1. When the shielding material content reaches 45 wt%, as depicted in Fig. 1a, the concentration appears darker compared to other concentrations, discernible by the naked eye. Figure 1b illustrates 25 wt%, and Fig. 1c shows 5 wt%. The amount of shielding material mixed is represented by weight percentage, and the post-mixing concentration color is visually inspected. When manufactured in a circular shape with a diameter of 5 mm and a thickness of 1.0 mm, as shown in Fig. 2a, and imaged with X-ray, as depicted in Fig. 2b, the results can be observed accordingly.

The amount of shielding material and particle composition (distribution) of the radiation-shielding cream were confirmed using electron microscopy (Fig. 3). In Fig. 3a, “1” in the circle (A) indicates the location of barium sulfate, and “2” indicates the carrier, which is clearly separated. In Fig. 3b (circle B), the barium sulfate is evenly distributed throughout the carrier. Direct visualization is hindered due to the low amount of material and its liquid state, resulting in less clarity in electron microscope images. However, the aggregation of lipid droplets is considerably reduced. Next, we examined the particle distribution of the shielding material as a function of its weight percentage (Fig. 4). Evaluation by naked eye from 25 to 45wt% showed a feasible concentration for skin coating without burden, with a tendency for more uniform particle distribution at higher wt%.

Next, we evaluated the radiation-protective effects of the manufactured creams containing barium sulfate, bismuth oxide, or ytterbium oxide. Tables 1 and 2 show the protective effects in function of the thickness of the

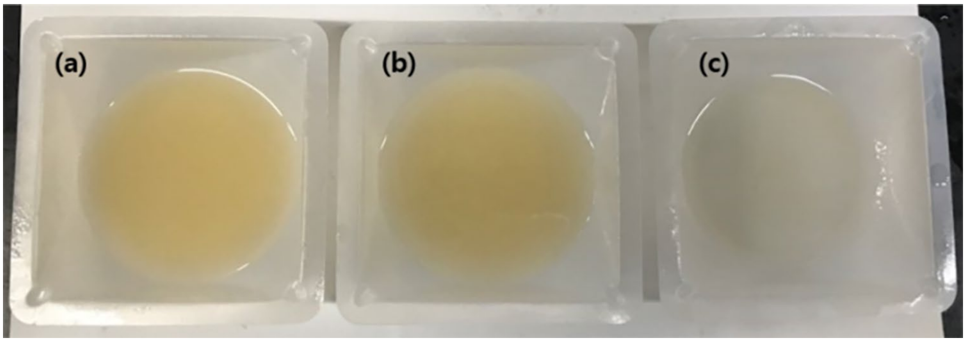

Fig. 1. Dispersion in function of the wt% of the shielding material (barium sulfate): (**a**) 45 wt%, (**b**) 25 wt%, and (**c**) 5 wt%.

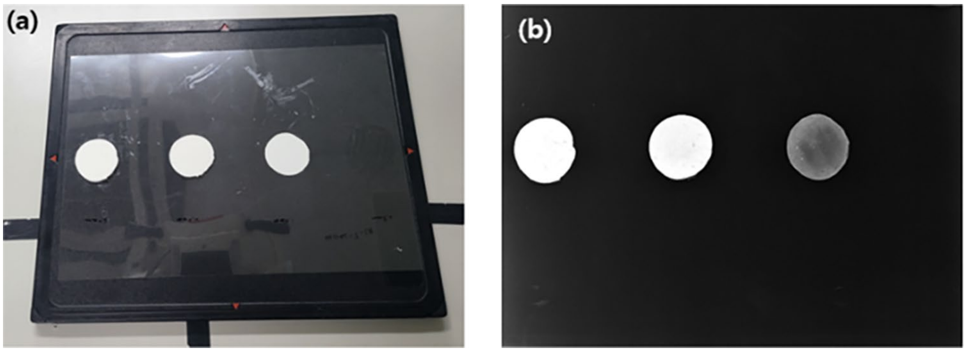

Fig. 2. X-ray imaging (80 keV, 20 mA) of dispersed barium sulfate.

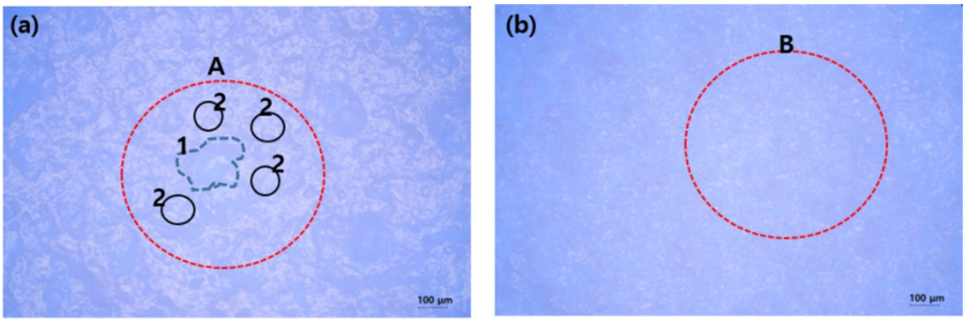

Fig. 3. Validation of the dispersion of barium sulfate in the process of abatement cream production.

cream layer (1.0 or 2.0 mm) on the skin. Overall, a 1.0-mm increase in layer thickness resulted in a 20% more effective reduction in incident energy on the skin. The increase in effectiveness was the largest for ytterbium oxide (> 32%), but barium sulfate showed a low change in defense effectiveness of around 10% due to the change in energy attenuation at the same thickness. Ytterbium oxide cream at 2.0-mm thickness attenuated incident radiation energy (63.4 keV effective energy) by 80%, indicating it has a skin-protective effect.

Tables 3, 4 and 5 show the protective effects of the barium sulfate, bismuth oxide, and ytterbium oxide creams tested at 0.5-mm thickness. The effect of the barium sulfate cream increased with increasing wt% of the shielding material, and the cream was protective when the content was > 35 wt% (Table 3). The variation in the protective effect in function of the incident energy was lower than the variation in function of wt%, with 56% at 28.9 keV and 44.1% at 63.4 keV. The effect in function of the wt% of bismuth oxide was higher than that of barium sulfate (Table 4); however, at a difference of < 5%, the effects were nearly similar. Table 5 shows that the effect in function of the wt% of ytterbium oxide was higher than that of barium sulfate and bismuth oxide. Additionally, the difference in the wt% of the material was associated with a 28% difference in protection, and at 63.4 keV, the 45 wt% ytterbium oxide of cream reduced radiation by 61.3%. These findings indicated that, the higher the shielding material content, the higher and more stable the energy-reducing effect, and that ytterbium oxide demonstrated superior efficacy over barium sulfate and bismuth oxide.

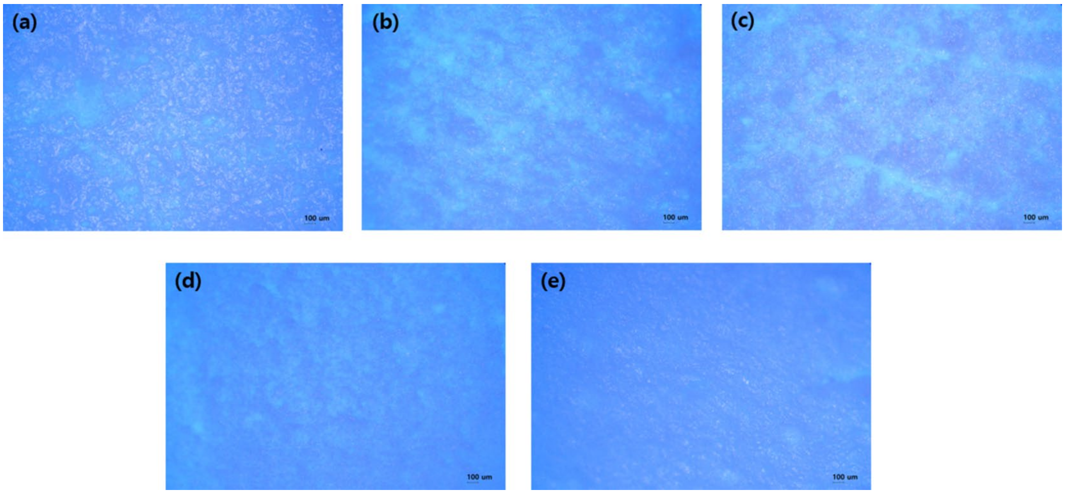

Fig. 4. Electron micrographs of barium sulfate in function of the wt%. (**a**) 25 wt%, (**b**) 30 wt%, (**c**) 35 wt% (**d**) 40 wt%, (**e**) 45 wt%.

Material (35 wt%)	Effective energy	28.9 keV		36.5 keV		54.8 keV		63.4 keV	
		Non	Shield	Non	Shield	Non	Shield	Non	Shield
Barium sulfate	Absorbed dose (mR)	19.10	9.58	44.86	24.80	76.66	43.53	112.83	68.43
	Shielding rate (%)	49.84		44.72		43.22		39.35	
Bismuth oxide	Absorbed dose (mR)	19.10	9.24	44.86	23.37	76.66	42.50	112.83	65.64
	Shielding rate (%)	51.62		47.90		44.56		41.82	
Ytterbium oxide	Absorbed dose (mR)	19.10	7.86	44.86	19.81	76.66	38.25	112.83	59.51
	Shielding rate (%)	58.85		55.84		50.10		47.26	

Table 1. Medical radiation-reducing effect of a 1.0-mm-thick protective cream layer.

Material (35 wt%)	Effective energy	28.9 keV		36.5 keV		54.8 keV		63.4 keV	
		Non	Shield	Non	Shield	Non	Shield	Non	Shield
Barium sulfate	Absorbed dose (mR)	19.10	5.63	44.86	15.03	76.66	27.52	112.83	44.46
	Shielding rate (%)	70.52		66.5		64.1		60.6	
Bismuth oxide	Absorbed dose (mR)	19.10	4.73	44.86	12.51	76.66	23.34	112.83	39.03
	Shielding rate (%)	75.24		72.11		69.56		65.41	
Ytterbium oxide	Absorbed dose (mR)	19.10	2.27	44.86	6.71	76.66	13.71	112.83	22.67
	Shielding rate (%)	88.12		85.04		82.11		79.91	

Table 2. Medical radiation-reducing effect of a 2.0-mm-thick protective cream layer.

The energy attenuation effects of combinations of barium sulfate, bismuth oxide, and ytterbium oxide were evaluated in this study. For comparative analysis, each material was uniformly blended at a concentration of 35 wt%, with film thicknesses set at 1.0 mm and 2.0 mm. According to the experimental results in Tables 6 and 7, the combination of 50% bismuth oxide and 50% ytterbium oxide exhibited the highest incident energy attenuation effect. The results revealed that the 1:1 mixture of bismuth oxide and ytterbium oxide had the highest incident energy-reducing effect of 80% when applied at 2.0-mm thickness, demonstrating its effectiveness. At 1.0-mm thickness and under 63.4 keV effective energy, the mixture of barium sulfate and bismuth oxide achieved a 38.4% reduction effect; however, the bismuth oxide and ytterbium oxide combination achieved a 54.2% reduction effect, representing a 15.7% increase. Although film thickness has an effect on efficacy, these findings indicated that the combination of materials also has an effect. At 2.0-mm thickness, the bismuth oxide and ytterbium oxide combination was 16.8% more efficacious than the barium sulfate and bismuth oxide combination. Particularly, the trend of change can be compared as shown in Fig. 5. The shielding performance of Ytterbium oxide in Fig. 5c exhibited greater differences in relation to weight percentage (wt%) than that of Barium sulfate in Fig. 5a or Bismuth oxide in Fig. 5b.

wt%	Effective energy	28.9 keV		36.5 keV		54.8 keV		63.4 keV	
		Non	**Shield**	**Non**	**Shield**	**Non**	**Shield**	**Non**	**Shield**
25	Absorbed dose (mR)	18.47	13.30	44.07	32.74	74.73	57.77	109.73	86.58
	Shielding rate (%)	28.0		25.71		22.7		21.1	
30	Absorbed dose (mR)	19.17	13.5	45.39	33.36	76.99	57.97	113.87	88.25
	Shielding rate (%)	29.6		26.5		24.7		22.5	
35	Absorbed dose (mR)	19.10	11.82	44.86	30.06	76.66	52.51	112.83	78.87
	Shielding rate (%)	38.1		33.0		31.5		30.1	
40	Absorbed dose (mR)	19.05	10.5	44.92	27.18	74.54	47.41	111.95	73.10
	Shielding rate (%)	44.9		39.49		36.4		34.7	
45	Absorbed dose (mR)	18.94	8.33	45.23	21.98	75.24	39.50	112.54	62.91
	Shielding rate (%)	56.0		51.4		47.5		44.1	

Table 3. Medical radiation-reducing effect in function of the wt% of barium sulfate in the cream (thickness: 0.5 mm).

wt%	Effective energy	28.9 keV		36.5 keV		54.8 keV		63.4 keV	
		Non	**Shield**	**Non**	**Shield**	**Non**	**Shield**	**Non**	**Shield**
25	Absorbed dose (mR)	18.47	12.65	44.07	31.51	74.73	55.52	109.73	83.07
	Shielding rate (%)	31.5		28.5		25.7		24.3	
30	Absorbed dose (mR)	19.17	12.96	45.39	31.68	76.99	55.89	113.87	85.29
	Shielding rate (%)	32.39		30.2		27.41		25.1	
35	Absorbed dose (mR)	19.10	10.60	44.86	26.29	76.66	48.68	112.83	75.14
	Shielding rate (%)	44.5		41.4		36.5		33.4	
40	Absorbed dose (mR)	19.05	9.66	44.92	24.44	74.54	43.61	111.95	70.42
	Shielding rate (%)	49.29		45.59		41.49		37.1	
45	Absorbed dose (mR)	18.94	7.88	45.23	19.95	75.24	36.19	112.54	58.07
	Shielding rate (%)	58.39		55.89		51.9		48.4	

Table 4. Medical radiation-reducing effect in function of the wt% of bismuth oxide in the cream (thickness: 0.5 mm).

wt%	Effective energy	28.9 keV		36.5 keV		54.8 keV		63.4 keV	
		Non	**Shield**	**Non**	**Shield**	**Non**	**Shield**	**Non**	**Shield**
25	Absorbed dose (mR)	18.47	10.14	44.07	25.78	74.73	45.96	109.73	69.90
	Shielding rate (%)	45.1		41.5		38.5		36.3	
30	Absorbed dose (mR)	19.17	9.68	45.39	24.42	76.99	46.12	113.87	70.14
	Shielding rate (%)	49.5		46.2		40.1		38.4	
35	Absorbed dose (mR)	19.10	8.32	44.86	20.99	76.66	39.48	112.83	63.52
	Shielding rate (%)	56.44		53.21		48.5		43.7	
40	Absorbed dose (mR)	19.05	6.59	44.92	16.89	74.54	29.96	111.95	51.27
	Shielding rate (%)	65.41		62.4		59.81		54.2	
45	Absorbed dose (mR)	18.94	5.07	45.23	13.93	75.24	25.51	112.54	43.55
	Shielding rate (%)	73.23		69.2		66.1		61.3	

Table 5. Medical radiation-reducing effect in function of the wt% of ytterbium oxide in the cream (thickness: 0.5 mm).

Therefore, the wt% and shielding material combination influence the effectiveness of radiation-reducing creams. A comparison of the skin application experience in function of the wt% (25, 35, and 45 wt%) of the shielding material is shown in The wt% content affected the texture of the skin (Fig. 6). Although a difference of 10wt% was observed, a realistic problem is that the higher the wt%, the more difficult it is to maintain the same distribution and thickness when the coating is performed directly with fingers without any tools. Therefore, the lower the wt%, the better the accessibility and usability in the case of skin applications, which is not conducive for the reduction effect.

Material (35 wt%)	Effective energy	28.9 keV		36.5 keV		54.8 keV		63.4 keV	
		Non	Shield	Non	Shield	Non	Shield	Non	Shield
A + B	Absorbed dose (mR)	19.23	9.32	45.32	24.38	76.78	43.61	112.52	69.31
	Shielding rate (%)	51.53		46.2		43.2		38.4	
A + C	Absorbed dose (mR)	19.23	8.81	45.32	22.12	76.78	39.54	112.52	63.35
	Shielding rate (%)	54.19		51.2		48.5		43.7	
B + C	Absorbed dose (mR)	19.23	6.65	45.32	17.04	76.78	30.86	112.52	51.53
	Shielding rate (%)	65.42		62.4		59.81		54.2	

Table 6. Medical radiation-reducing effect of creams containing different combinations of the shielding materials (1.0-mm-thick layer). A: barium sulfate, B: bismuth oxide, C: ytterbium oxide.

Material (35 wt%)	Effective energy	28.9 keV		36.5 keV		54.8 keV		63.4 keV	
		Non	Shield	Non	Shield	Non	Shield	Non	Shield
A + B	Absorbed dose (mR)	19.23	5.17	45.32	13.50	76.78	24.26	112.52	40.06
	Shielding rate (%)	73.1		70.21		68.4		64.4	
A + C	Absorbed dose (mR)	19.23	4.46	45.32	11.69	76.78	21.96	112.52	35.67
	Shielding rate (%)	76.81		74.21		71.4		68.3	
B + C	Absorbed dose (mR)	19.23	2.03	45.32	5.80	76.78	12.13	112.52	21.15
	Shielding rate (%)	89.44		87.2		84.2		81.2	

Table 7. Medical radiation-reducing effect of creams containing different combinations of the shielding materials (2.0-mm-thick layer). A: barium sulfate, B: bismuth oxide, C: ytterbium oxide.

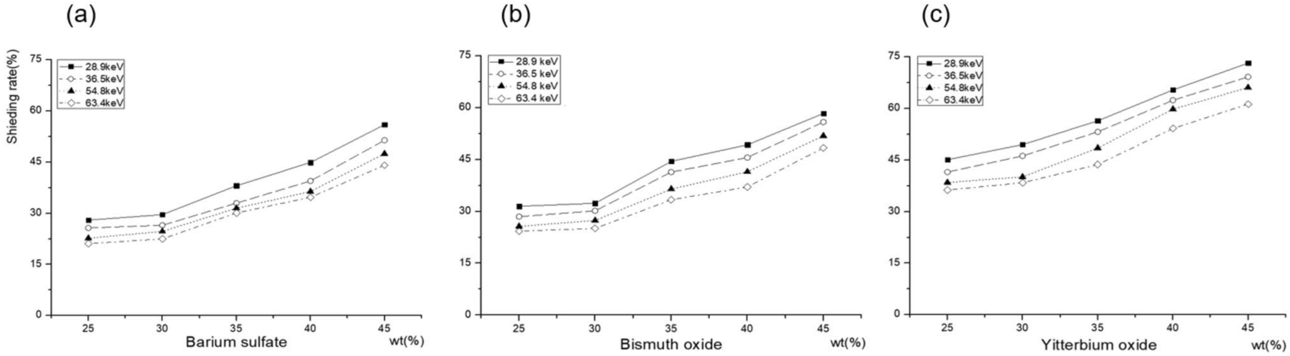

Fig. 5. Trends in medical radiation reduction according to the weight percentage (wt%) of the shielding materials: (**a**) Barium sulfate, (**b**) Bismuth oxide, (**c**) Ytterbium oxide.

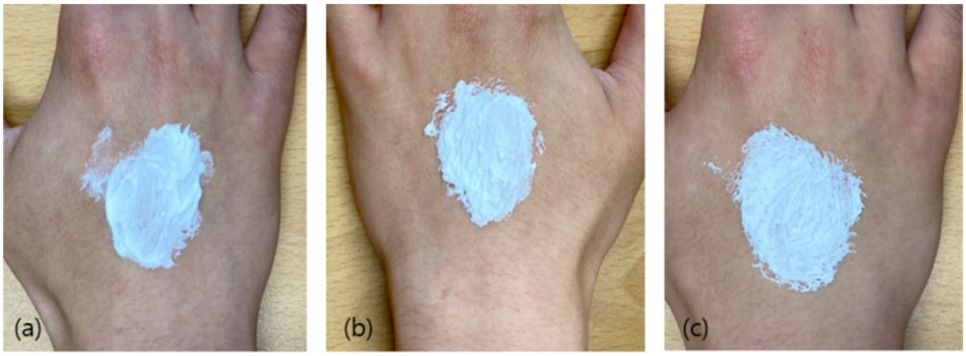

Fig. 6. Comparison of skin application experience based on WT% of shielding material. (**a**) 25wt%, (**b**) 35wt%, (**c**) 45wt%. The images were acquired by the author after coating the creams directly on the skin.

X-ray imaging was used to directly observe the radiation-protective effect of the bismuth oxide plus ytterbium oxide cream. The cream was coated on the back of a mannequin hand at a 1.0-mm thickness (Fig. 7a) to obtain the image shown in Fig. 7b. We tested 25, 35, and 45 wt% creams (Fig. 7c) to obtain the image shown in Fig. 7d. The images confirmed that the cream had a radiation-protective effect and that the protective effect depended on the shielding material content.

Discussion

We manufactured various radiation-protective creams and verified their effectiveness in reducing incident medical radiation on the skin. We assessed the radiation-reducing effect of ytterbium oxide alone and in combination with other shielding materials, including bismuth oxide and barium sulfate, which are well-known eco-friendly shielding materials. Radiation-reducing skin creams are developed to protect the skin from radiation. Creams are expected to provide better continuous adhesion and usability than gels, solutions, and suspensions, to protect human skin from damage caused by incident radiation[25].

Applying the radiation-reducing cream to the skin at an even and consistent thickness is vital. The skin coating appears different depending on degree of coating or lack of consistency in thickness (Fig. 8). Figure 8a–c show images of 10 wt% (which is the wt% generally used in cosmetics) cream coatings on a mannequin for the three materials. The lower the concentration (wt%) of the shielding material, the more challenging it is to coat,

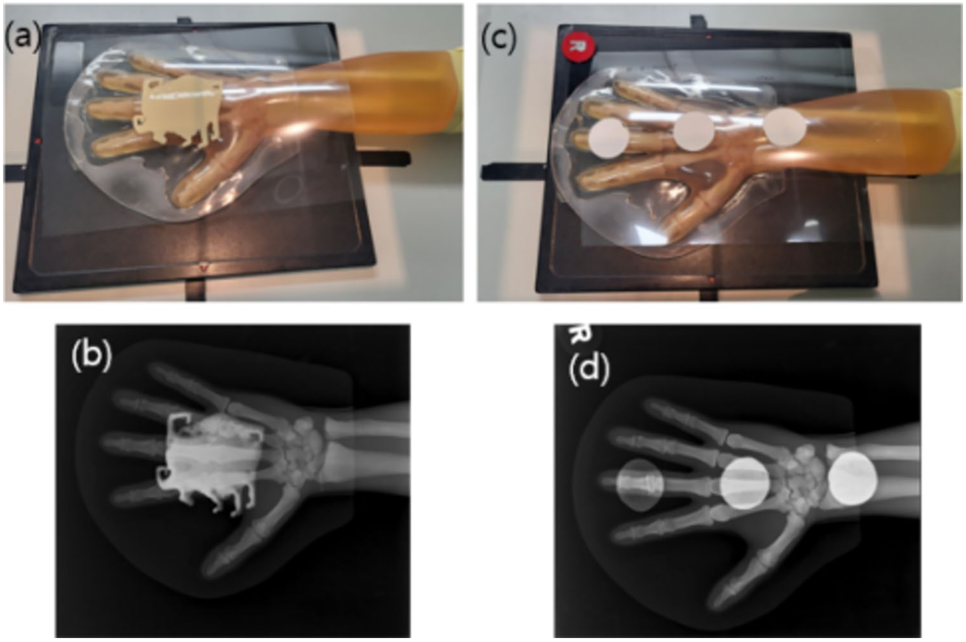

Fig. 7. X-ray imaging (40 kVp, 5 mAs) of the radiation-reducing material at 25, 35, and 45 wt% and 1.0 mm thickness.

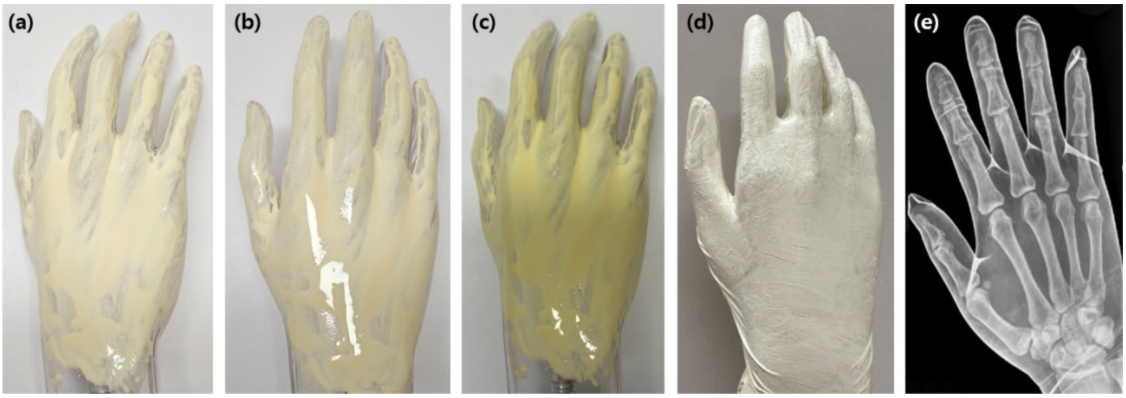

Fig. 8. Verification of the dispersion effect in the process of radiation-reducing cream production. (**a**) 10 wt% barium sulfate, (**b**) 10 wt% bismuth oxide, (**c**) 10 wt% ytterbium oxide, (**d**) 25 wt% barium sulfate on a surgical glove, (**e**) X-ray image (40 kVp, 5 mAs) of (**d**).

from the user's perspective. Figure 8d shows the coating of a 25 wt% barium sulfate cream on a surgical glove, and Fig. 8e shows an X-ray image of the coating on the glove shown in Fig. 8d.

Therefore, cream thickness and wt% directly affect the incident radiation-reducing effect, and the effectiveness varies depending on the use, making it challenging to achieve reproducibility. Therefore, in future, cream-type radiation-reducing creams should be formulated that are free of gel and moisture and closely adhere to the skin. Additionally, as shown by the experiments, it is preferable to apply the cream on the skin on the back of the hand (rather than the hand palm) before applying gloves rather than applying it on the gloves[26].

The development of radiation-reducing creams that protect the skin from radiation using eco-friendly materials that are non-toxic to the skin and can be applied to the skin at even thickness is challenging[27]. We attempted to address this issue by using a novel eco-friendly material, ytterbium oxide, and aimed to achieve a reproducible shielding effect by determining an optimal wt% for a given film thickness.

The use of a single cream material is associated with limitations, which can be addressed using composite materials. Furthermore, various materials and fabrication methods can be used to achieve a constant film thickness on the skin. Thin-film media used in protective creams must be acceptable to the user, and reproducible protective performance should be ensured. In the present study, a radiation-reducing cream was developed to protect the skin from scattered radiation in medical institutions, while ensuring user-friendliness and avoiding interference with the user's medical activity[28].

The radiation-reducing cream presented in this study was designed for use on the flexible human skin, unlike the inflexible films and sheets generally used as shielding materials. The cream can be directly applied by the user, ensuring user-friendliness. As achieving good dispersal of radiation-protective materials during manufacturing is challenging, we investigated the protective effect in function of the wt% of the materials, using a mixing method so as to fix the particles at a specific position in the base material. In future, we plan to expand the scope of medical radiation-shielding materials to include direct and scattered rays.

In conclusion, the shielding material content and film thickness influence the effectiveness of radiation-shielding creams. An excellent radiation reduction of 5–8% was achieved when ytterbium oxide was used instead of barium sulfate and bismuth oxide. A mixture of ytterbium oxide and bismuth oxide achieved 15–17% better radiation reduction than the other material combinations. Therefore, ytterbium oxide alone or in combination with other materials has application potential as an eco-friendly radiation-reducing material to protect the skin from medical radiation.

Methods

The net effect of the interaction of medical radiation with matter is the absorption or scattering of incident photons. The thickness of the material where a single event occurs, $\Delta\chi$, and the attenuation factor, μ, which corresponds to the intrinsic modulus of the material, determine the number of attenuated photons, ΔB(Eq. 1)[29].

$$\Delta \mathrm{B} = \mu \mathrm{B} \Delta \chi. \tag{1}$$

Therefore, the attenuation of incident radiation is directly dependent on the thickness of the material through which the radiation passes, χ, and the attenuation factor μ (Eq. 2)[30].

$$\mathrm{B} = \mathrm{B}_0 \mathrm{e}^{-\mu \chi}. \tag{2}$$

Particularly, the attenuation factor depends on the interaction probability per atom; therefore, the larger the atomic cross-sectional area σ_a, the greater the attenuation (Eq. 3; A is the mass number and $\mathrm{N_A}$ is Avogadro's number). Therefore, the interaction with atoms is probabilistic, and the radiation-attenuating effect increases with increasing thickness, atomic number, and mass (Eq. 4)[31].

The probability of interaction with matter $(\tau, \sigma, \mathrm{k})$ as it passes through a material with a thickness of χ is dependent on the incident energy, with absorption and scattering occurring through photoelectric absorption, Compton scattering, and pair production[32].

$$\sigma_a = \frac{\mu \mathrm{A}}{\mathrm{N_A}}, \tag{3}$$

$$\mu = \tau + \sigma + \mathrm{k}, \tag{4}$$

$$\tau\left(\mathrm{cm}^{-1}\right) = \mathrm{aN}\left(\frac{\mathrm{Z}^{\mathrm{n}}}{\mathrm{E}_{\gamma}{}^{\mathrm{m}}}\right)[1 - \mathrm{f(Z)}], \sigma\left(\mathrm{cm}^{-1}\right) = \mathrm{NZf}\left(\mathrm{E}_{\gamma}\right),\ \mathrm{k}\left(\mathrm{cm}^{-1}\right) = \mathrm{NZ}^2\mathrm{f}(\mathrm{E}_{\lambda}, \mathrm{Z}),$$

where a is a general constant; m, n are parameters; N is the atomic density, Z is the atomic number, $\mathrm{E}_{\lambda} \mathit{and} \mathrm{E}_{\gamma}$ signify the incident energy, and σ is the cross-sectional area.

Radiation-reducing creams reduce the absorption of incident radiation by forming an integral protective barrier on the skin. Therefore, protons must be attenuated through absorption and scattering in the protective cream with a thickness χ before they penetrate the skin to prevent them from reaching the deeper layers (Fig. 9). There are limits to unilaterally increasing the thickness; therefore, materials with higher atomic numbers or densities have to be used to improve smearability[33]. Therefore, the density and material composition influence the protective effects of a shielding cream.

The three shielding materials used in this study were bismuth oxide (Bismuth(III) oxide 99% 500 g EP, Junsei Chemical CO., Ltd., JAPAN), barium sulfate (Barium Sulfate 97% 500 g CP, Daejung Reagents, KOREA), and ytterbium oxide (Ytterbium(III) oxide 99.9% 25 g, Wako, JAPAN). The base was an aqueous organic carrier, which

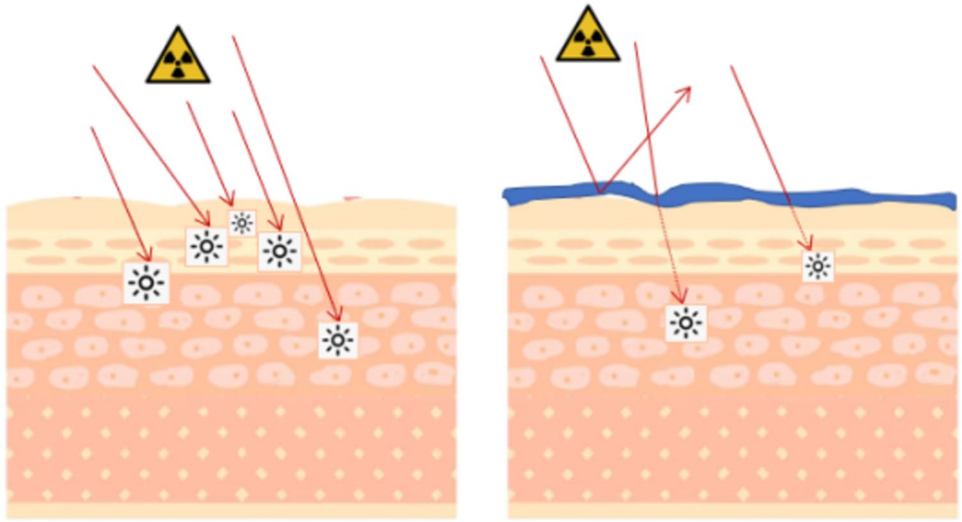

Fig. 9. Radiation incidence on the skin before and after application of a radiation-protective cream.

is the raw material of hand creams, containing lubricants (Zelec® UN lubricant, Sigma-Aldrich, KOREA), wetting agents (Hyaluronic Acid(HD), Naturesouce Co.Ltd., KOREA), and surfactants (Glycerin 99.9%, SamHyun Pharm, KOREA), including glycerin, and emulsifiers (410–4405 Glyceryl Monostearate Extra Pure 31566-31-1 500G, Daejung Chemicals, KOREA), such as glyceryl stearate, to achieve a similar texture as conventional hand creams when applied to the skin[34]. As texture is a qualitative property perceived by the user, we tested a wt% reference concentration of the shielding material.

In the manufacturing of radiation-reducing creams, emulsification, which increases the interaction among mixed substances, and dispersion of the shielding substances are crucial. Emulsification involves the artificial mixing of water and oil-immiscible substances using a device and an emulsifier to form a cream[35]. Dispersion, which is the step before mixing the solid shielding material, involves evenly dispersing the shielding materials (i.e., barium sulfate, bismuth oxide, and ytterbium oxide) in the carrier medium. The dispersion and emulsification processes influence the shielding performance and uniform contact with the skin, respectively.

The dispersion of the emulsion mixture was achieved using high-speed rotation (3000 rpm) under vacuum (Fig. 10). The texture of the cream on the skin was evaluated in function of the material input amount. Additionally, the incident radiation-reducing effectiveness was determined. The weight percentage was increased in 5 wt% increments from 25 to 45 wt%. This experimental test range was determined based on how easily the product could be washed from the skin; creams with concentrations > 45 wt% were excluded because they were challenging to wash off. The shielding materials and carrier were mixed using a homo mixer (T.Kprimix, Japan) at 3000 rpm, 70 °C for 5 min. A vacuum defoamer (HYUP SHIM vacuum deaerator, low-noise-type) was used to remove air bubbles. The particle size and dispersion of the shielding material were observed using a field emission scanning electron microscope (S-4800; Hitachi), using shielding cream sections.

To evaluate the shielding performance of medical radiation, a 5 mm diameter hole was drilled into a 0.5 mm thick polycarbonate plate (Fig. 10), and experiments were conducted by filling the holes with samples of identical size and thickness. The thickness of the cream is crucial for achieving radiation attenuation effects. Two criteria were established: the maximum thickness that can be applied to the skin and a thickness that allows

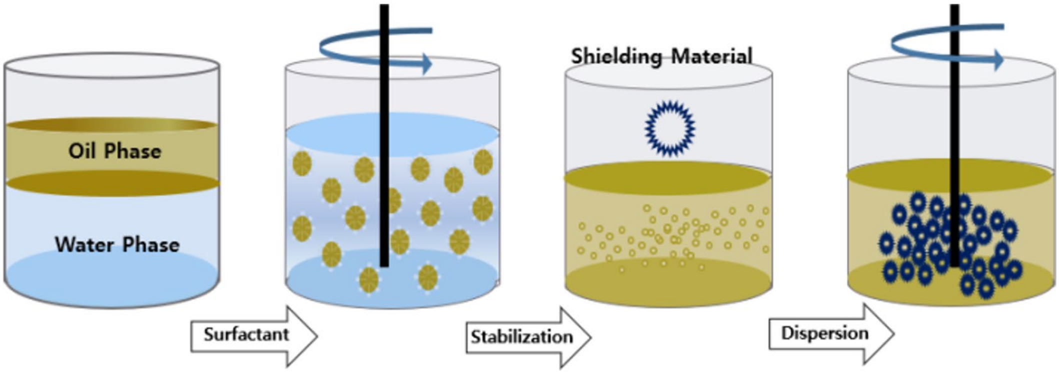

Fig. 10. Emulsification and dispersion of the shielding materials.

unrestricted movement after application on the dorsal hand. The selected thicknesses for the shielding cream were implemented as minimum of 1 mm and a maximum of 2 mm.

The mixing method used for the creams combining the three selected materials was the same as that used for the single-component creams. The materials were used at 35wt%, and the medical radiation-shielding performance of the creams was analyzed using X-ray imaging (Fig. 11). The medical radiation used in the experiment was converted to the effective energy, the slope was calculated from the attenuation coefficient law ($I = I_0e^{-\mu x}$) to measure the half-value layer, and the value of the linear absorption coefficient μ was obtained from the slope and half-value layer (=0.693/μ)[36]. The effective energy was determined using Hubbell's mass absorption coefficient table to calculate the energy having a half-value layer corresponding to single energy[37]. The radiation generated by the X-ray generator (E7239; 150 kV, 500 mA; Toshiba, Japan) was measured 10 times, and the average value was calculated, as shown in Fig. 12. The dose detector was a DosiMax Plus 1 (IBA Dosimetry), which was calibrated before use. To evaluate the performance of the fabricated creams, the X-ray-shielding rate was calculated using Eq. (5)[38].

$$\text{X-ray-shielding rate (\%)} = (1 - \frac{k}{k_0}) \times 100, \tag{5}$$

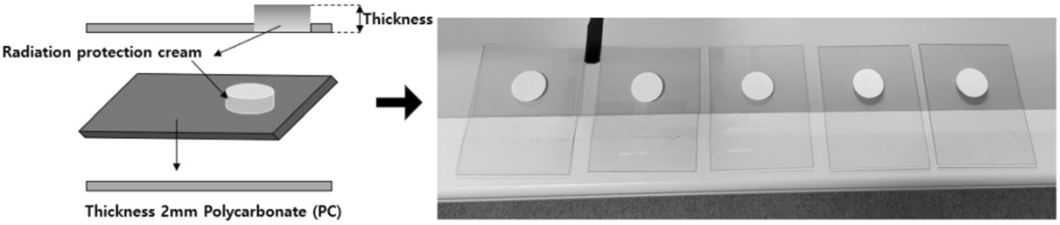

Fig. 11. Experimental methods based on the shielding material content and abatement cream thickness.

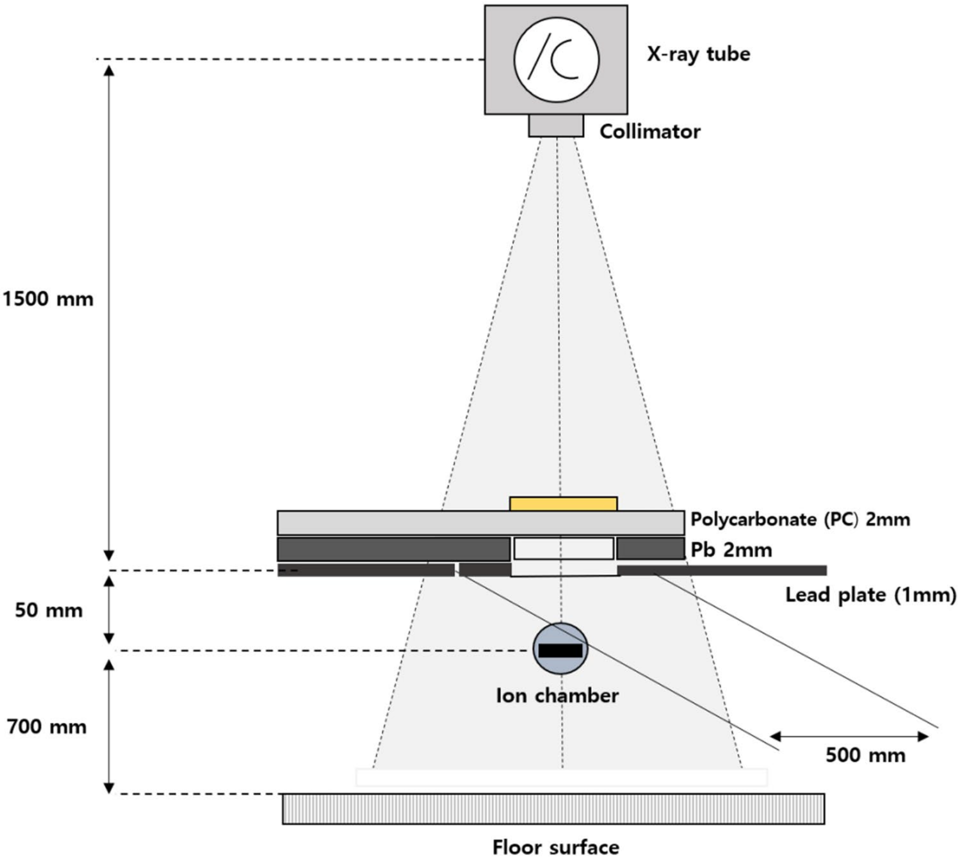

Fig. 12. Setup of the medical radiation-shielding experiment to assess the shielding creams.

where k_0 = incident dose (radiation dose measured in the presence of the cream between the X-ray beam and detector; mR); k = transmitted dose (the radiation dose measured in the absence of the cream between the X-ray beam and detector; mR).

Conclusion

The radiation attenuation cream, demonstrating effectiveness in reducing medical radiation is influenced by the concentration of shielding materials (wt%) and the coating thickness. When using ytterbium oxide, an eco-friendly dental material, it showed a superior radiation reduction effect of approximately 5–8% compared to barium sulfate and bismuth oxide. Combining these materials in radiation shielding creams, the combination of eco-friendly ytterbium oxide and bismuth oxide exhibited a 15–17% higher medical radiation attenuation effect. Therefore, ytterbium oxide, both alone and in combination, holds promising potential as a shielding material to protect the skin from medical radiation in the future.

Data availability

All data generated during this study are included in this manuscript.

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Author contributions

S.C.K. conceived the study, conducted the experiments, and wrote the paper.

Competing interests

The author declares no competing interests.

Additional information

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