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A Comparative Analysis of Metal Shielding for Mammography Using Monte Carlo Simulation

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As the incidence of breast cancer increases, concerns about unnecessary exposure to radiation during mammography are increasing. This study quantitatively evaluated the thickness and weight showing 95 % shielding ability of silicon, lead, bismuth, and tungsten with a tube voltage of 30 kVp and a distance between the X-ray tube and shield of 100 cm using Geant4 Application for Tomographic Emission (GATE). The absorbed dose to the breast was derived when the optimal shield derived from GATE was used using Monte Carlo N-Particle code. The optimal thickness was in the order of tungsten, lead, bismuth, and silicon, and the total weight was found in the order of bismuth, lead, tungsten, and silicon. There was no difference in the absorbed dose to the breast depending on the material. When considering the thickness and weight of the shield, lead appears to be the best material. Lead can be an optimal shield with reduced thickness and weight if it is wrapped with a minimum amount of silicon.

Keywords : mammography, Monte Carlo simulation, shielding rate, lead, bismuth, tungsten

1. Introduction

Breast cancer is the third most common cancer worldwide [1]. Breast cancer accounts for 11.6 % of all cancer-related deaths, with a reported mortality rate of 30.7 %. Typically, women have an average 12.8 % risk of breast cancer in their lifetime across all age groups [2]. In addition, the incidence of breast cancer is up to four times higher in developed countries than in developing countries [3]. The incidence of breast cancer is affected by lifestyle-related factors such as obesity, smoking, alcohol consumption, and carcinogenic factors such as electromagnetic waves and charged-particle radiation exposure [4].

Currently, many imaging techniques are used to accurately diagnose breast diseases, including mammography, ultrasonography, optical imaging, magnetic resonance imaging, and scintigraphy. The selection of a specific technique, usually based on clinical requirements, includes an assessment of the benefits and risks of the procedure, the purpose of imaging (diagnosing or screening), and breast density [5]. Radiation exposure by single or repeated mammography has been reported to increase the risk of breast cancer.

The frequent use of electromagnetic waves in medical institutions is at odds with the need to protect humans from radiation. Therefore, the importance of using a shield for mammography has emerged. Lead has been used for a long time as the most used shielding material despite its toxic properties. Recently, medical institutions have used a breast shield made of silicon, but there are concerns about its shielding ability and weight. Accordingly, research on the development of a lead-free shield has

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been actively conducted, but one has not been commercialized because of various problems such as the cost and homogeneity of the material [6, 7].

This study attempted to evaluate the single-element shielding ability of a Si-X-Si system using lead, which is most often used for radiation shielding, and bismuth and tungsten, which are known as eco-friendly shielding materials. Therefore, the optimal thickness for shielding a single material was derived using Monte Carlo simulation, and the absorbed dose to the breast was evaluated.

2. Materials and Methods

2.1. GATE code modeling

GATE (Geant4 Application for Tomographic Emission) is a radiation simulation code commonly used in the medical field [8]. In this study, the shield of a Si-X-Si system composed of a single element (X) that can reduce the radiation exposure dose was modeled using GATE 8.0, a Monte Carlo simulation tool based on Geant4. Silicon was modeled to prevent the leakage of harmful components of lead to the outside by setting the minimum thickness (0.3 mm) to not tear. Material X was assigned as lead, bismuth, or tungsten, and the materials and thicknesses were optimized (Table 1).

The distance between the X-ray tube and the shield was set to 100 cm with a tube voltage of 30 kVp, which is the average voltage used in mammography. The size of the shield was set to 100 × 100 mm^2, and the geometry of the GATE simulation used to evaluate the penetration ratio is shown in Fig. 1.

The continuous energy spectrum for 30 kV utilized in the simulation was obtained using a tungsten anode spectral model using interpolating polynomials [9]. The inherent filtration was set to 0.9 mmAl, and the number of photons (1×10^6) was converted into an energy ratio [10].

Table 1. Characteristics of elements for shielding sheet composition.

Materials	Silicon	Lead	Bismuth	Tungsten
Atomic Number	14	82	83	74
Density (g/cm^3)	2.23	11.34	9.75	19.25

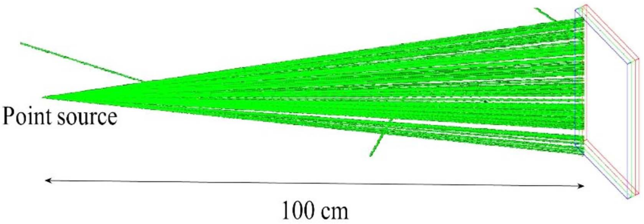

Fig. 1. (Color online) Geant4 Application for Tomographic Emission simulation modeling for penetration evaluation.

2.2. MCNP code modeling

Monte Carlo N-Particle (MCNP) is a general-purpose code that simulates the process in which radiation, such as X-rays and γ-rays, interacts with materials and transfers energy. It is applied to simulate the interaction process between radiation and materials and to statistically simulate the radiation transmission area [11]. In this study, the decrease ratio of absorbed dose by tissue organ was measured using the Korean adult female voxel phantom (HDRK-Woman, High-Definition Reference Korean-Woman) based on the material composition and thickness values derived from the GATE simulation code [12]. The tube voltage was set to 30 kV, and the composition of the breast in the HDRK-Woman phantom was 10.6 % hydrogen, 33.2 % carbon, 3 % nitrogen, 52.7 % oxygen, 0.1 % sodium, 0.1 % phosphorus, 0.2 % sulfur, and 0.1 % chlorine.

To calculate the absorbed dose to the breast using HDRK-Woman in the MCNPX condition, the following equation for entrance air kerma (EAK) was used:

$$EAK\ (\text{mGy}) = NDD\ (\text{k}) \times mAs \times \left(\frac{1}{FSD}\right)^2 \tag{1}$$

where NDD is the radiation dose calculation factor considering tube voltage (kVp) and filter thickness (mmAl), mAs is the product of the tube current (mA) and the irradiation time (s), and FSD is the distance (m) between the focal point and the surface.

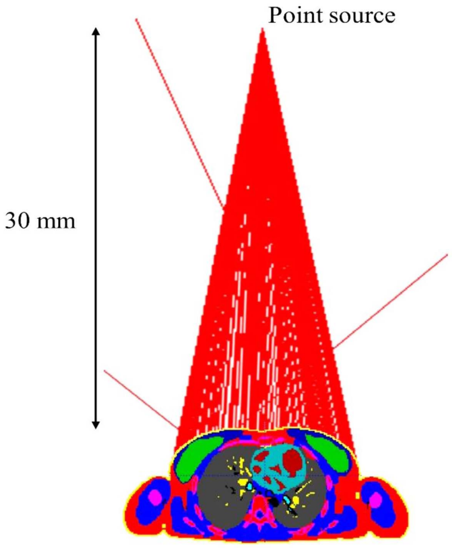

Fig. 2. (Color online) Monte Carlo N-particle simulation modeling for breast absorbed dose evaluation.

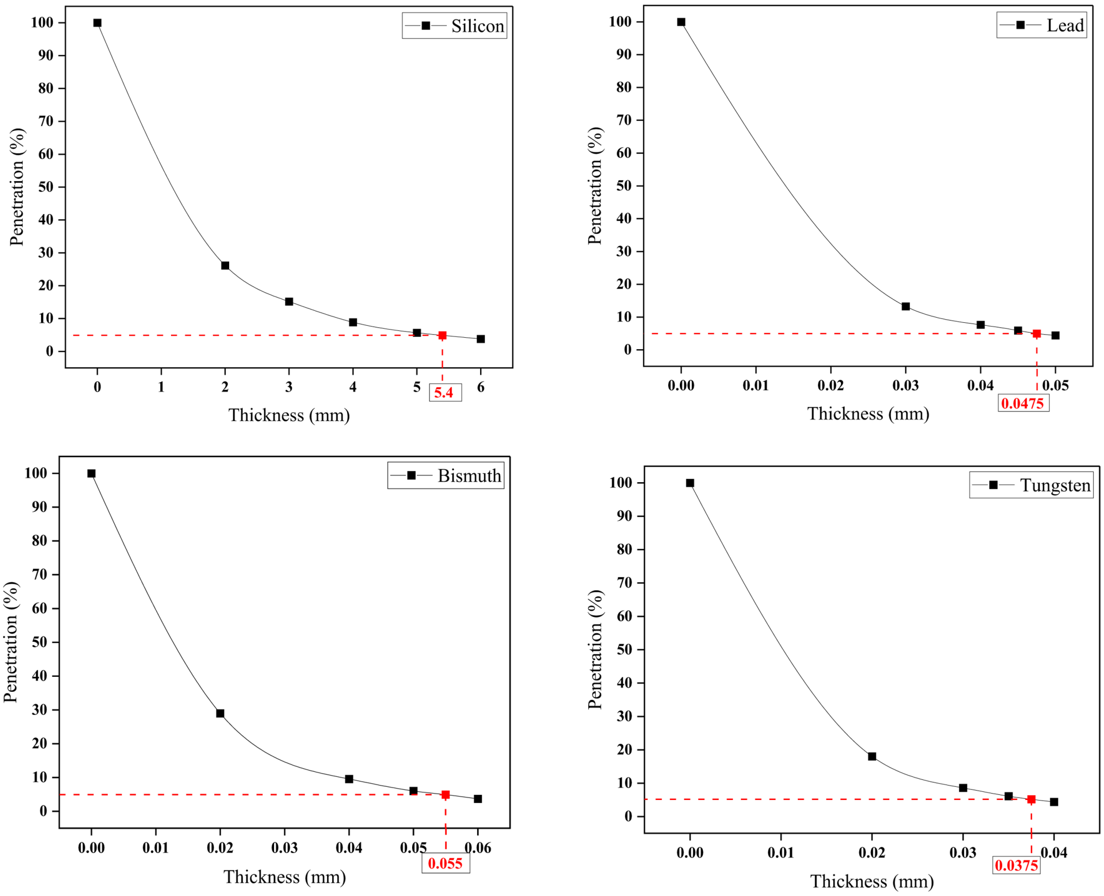

Fig. 3. (Color online) Optimization of thickness for each material showing 95 % shielding effectiveness in the 30-kVp energy region.

The following equation was used to convert Jerks/g, the unit of the result value of Tally *6, into mGy. In equations (2) and (3), the normalized factor (NF) is defined as a factor that allows the value derived from the MCNP to be applied in the actual experimental condition. The measured dose under specific conditions was calculated by dividing the measured dose in the simulation under the same conditions [13].

$$D_{absorbed} = NF \times D_{simulated} \tag{2}$$

$$NF = \frac{\text{Measured dose under specific conditions (mGy)}}{\text{Measured dose in simulation under the same conditions (jerks/g)}} \tag{3}$$

3. Results and Discussion

Using GATE, the thickness of material X used in the Si-X-Si system was optimized to a 95 % shielding rate. Silicon was used to prevent leakage due to cracks while wrapping material X.

In the case of 30 kVp, the thicknesses of lead, bismuth, and tungsten were optimized so that the shielding rate was approximately 95 % (Table 2). In the case of silicon shielding currently used in medical institutions, a thickness of 5.4 mm is required to represent a 95 % shielding rate, and so the weight is 120.42 g when considering the density. Therefore, it was found that the

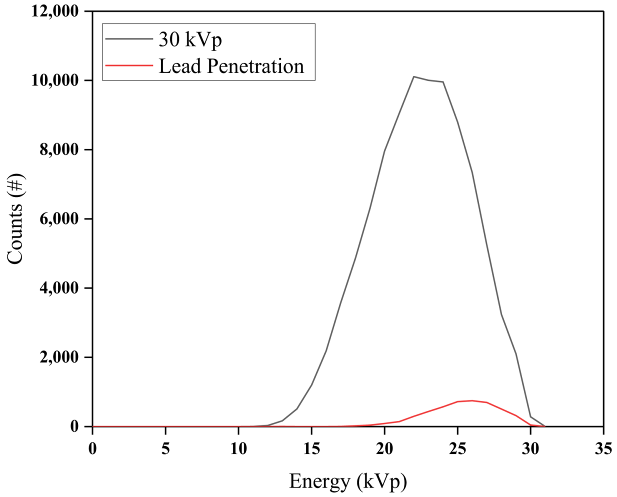

Fig. 4. (Color online) Shielding effectiveness at 30 kVp.

Table 2. The 95 % shielding thickness optimization of material X.

Materials	Silicon	Material X		
		Lead	Bismuth	Tungsten
Energy (kVp)	30			
Shielding rate (%)	95.11	95.02	95.08	94.83
Total thickness (mm)	5.4	0.0475	0.055	0.0375
Total weight (g)	120.42	5.42	5.36	7.24

Table 3. Absorbed dose to the breast according to the use of shielding material.

Shielding material	Absorbed dose (μGy)	Dose decrease rate (%)
No shielding	5.15E+05	-
Lead	1.35E+03	99.74
Bismuth	1.09E+03	99.79
Tungsten	1.27E+03	99.75

use of either lead, bismuth, or tungsten reduced the weight of the shielding materials.

The thickness of each material showing a 95 % shielding rate was 0.0475 mm for lead, 0.055 mm for bismuth, and 0.0375 mm for tungsten. Tungsten exhibited the best thickness parameters. However, considering the density of each material, the total weights were 5.42 g for lead, 5.36 g for bismuth, and 7.24 g for tungsten. Bismuth exhibited the greatest weight reduction.

The measurement of the absorbed dose to the breast according to the presence or absence of a shield was derived from the MCNP simulation using the optimal thickness of the material derived through the GATE simulation. As shown in Table 3, at the optimal thickness designed with 95 % shielding, all materials exhibited a dose decrease rate of more than 99.7 %, leading to excellent shielding results.

Therefore, to reduce a patient's exposure during mammography in the 30-kVp energy range, a shielding ability of 95 % was confirmed using lead, bismuth, and tungsten. Although the number of examinations for mammography is increasing every year, patients complain due to the weight of the shield and the inconvenience of wearing it, and so the development of an appropriate shield is very important. Currently, the MammoPad (Hologic, Marlborough, MA) imported and used by medical institutions is made of silicon, which may not be the optimal shielding material.

Based on the results presented in this study, when considering the price of raw materials and the weight of the shield, lead is the best shielding material. Although lead is is harmful to humans, lead may be wrapped with silicon to prevent internal components from leaking to the outside.

4. Conclusions

The importance of radiation shielding during mammography has been continuously highlighted, and although many related studies have been conducted, the optimal shielding material has not identified until now. In this study, lead, bismuth, and tungsten were assessed to determine which was the optimal shielding material. Lead at a thickness of 0.0475 mm shows more than 95 % shielding ability. In addition, when compared to bismuth and tungsten, lead is the best material when evaluating the price of raw materials, thickness, and weight. Therefore, although lead can be harmful, it can be wrapped in silicon to block harmful components and reduce thickness and weight. These findings should be considered a reference point for application research on radiation shielding.

References

[1] Global Burden of Disease Cancer Collaboration, C. Fitzmaurice, D. Abate, N. Abbasi, H. Abbastabar, *et al.*, JAMA Oncol. **5**, 1749 (2019).

[2] C. E. DeSantis, J. Ma, M. M. Gaudet, L. A. Newman, K. D. Miller, *et al.*, CA Cancer J. Clin. **69**, 438 (2019).

[3] N. Tamam, H. Salah, M. Rabbaa, M. Abuljoud, A. Sulieman, *et al.*, Radiat. Phys. Chem. **188**, 109680 (2021).

[4] S. Mubarik, F. Wang, S. S. Malik, F. Shi, Y. Wang, *et al.*, Int. J. Environ. Res. Public Health. **17**, 1367 (2020).

[5] S. Iranmakani, T. Mortezazadeh, F. Sajadian, M. F. Ghaziani, A. Ghafari, *et al.*, Egypt. J. Radiol. Nucl. Med. **51**, 57 (2020).

[6] H. Chai, X. Tang, M. Ni, F. Chen, Y. Zhang, *et al.*, J. Appl. Polym. Sci. **43012** (2016).

[7] N. J. AbuAlRoosa, N. A. B. Amina, and R. Zainona, Radiat. Phys. Chem. **165**, 108439 (2019).

[8] C. H. Baek and D. H. Kim, J. Magnetics **24**, 729 (2019).

[9] A. M. Hernandez, J. A. Seibert, A. Nosratieh, and J. M. Boone, Med. Phys. **44**, 2148 (2017).

[10] S. W. Jeung and C. H. Lim, Proceedings of the Korea Contents Association Conference, 207 (2014).

[11] R. R. W. Affonso, C. M. Barbosa, R. S. F. Dam, W. L. Salgado, A. X. da Silva, *et al.*, Appl. Radiat. Isot. **164**, 109226 (2020).

[12] Y. S. Yeom, J. H. Jeong, C. H. Kim, M. C. Han, B. K. Ham, *et al.*, Phys. Med. Biol. **59**, 3969 (2014).

[13] D. W. Sung, Research Report, Korea Food & Drug Administration, Korea (2013).