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Evaluation of the Effectiveness of Silicon for Radiation Shielding in Mammography

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Mammography is one of the most important test techniques for screening and diagnostic examinations of breast diseases. Recently, the incidence of breast cancer has increased and the demand for mammography is increasing through the cancer screening programs in each country. Therefore, research on shielding materials is actively being pursued to reduce radiation exposure during mammography. The purpose of this study is to verify and compare the GATE simulation and experiment in terms of the shielding performance under the experimental conditions of tube voltage (25, 30, 35 kVp) and silicon thickness (1, 2, 3, 4, 5, 6 mm). Through MCNP simulation, the absorbed dose reduction rate of breast tissue according to tube voltage/silicon shielding thickness is presented. The GATE simulation and experimental results were within the error range of 0.07 to 1.42 % under all conditions. In addition, through simulations and experiments, it was confirmed that silicon can offer more than 80 % shield regardless of automatic exposure control (AEC) of mammography equipment when 5 mm of silicon is used. Therefore, the results of the study can serve as useful basic data for the development of a shielding suit or shield that can reduce the exposure of other surrounding tissues due to scattered rays during mammography.

Keywords : mammography, electromagnetic waves, monte carlo simulation, silicon, shielding material, radioprotection

1. Introduction

Breast cancer is the most common non-cutaneous form of cancer in women worldwide. It is estimated that more than 2 million people are diagnosed with breast cancer annually [1, 2]. It also accounted for 24 % of newly diagnosed cancer types in 2018, and this figure is expected to increase by more than 46 % by 2040 [3]. Therefore, in order to reduce the incidence of breast cancer in many countries, each country operates cancer screening programs, with mammography recommended for women over 40 years old [4]. However, the American Cancer Society recently recommended that those aged 45 to 54 undergo mammography every year, and those aged 55 and older receive a mammography once every two years [5]. In addition, those who underwent two or more breast cancer screening examinations before being diagnosed with breast cancer have a 49 % lower breast cancer mortality rate than those who do not undergo an examination. Thus, the importance of continuous mammography is further emphasized. [6].

According to the radiographic tissue weights presented by the International Commission on Radiological Protection (ICRP), the breast is one of the tissues with the largest tissue weighting factor (0.12). Even if exposed to the same amount of radiation, exposure management is necessary to avoid more damage. In particular, compared to general diagnostic X-ray examination, mammography uses a low energy of 25-35 kVp, but uses a high tube current (mAs) to increase the contrast, resulting in an increase in the absorbed dose to the breast tissue [7]. In addition, in recent mammography equipment, the tube voltage and tube current lead to automatic exposure according to the density of the breast. Therefore, patients

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with high density breast tissue have a higher radiation risk as they are exposed to X-rays formed by high tube voltage and tube current in order to obtain an optimal image compared to patients with low density breast tissue [8].

Radiation used for diagnosis and treatment in the medical field does not apply a dose limit in accordance with the ICRP's recommendation. As the use increases, cases of radiation damage also increase. Therefore, efforts should be made to minimize the occurrence of damage in the human body attributed to the use of radioisotopes and radiation generators [9]. In addition to stable devices, the development and utilization of materials capable of shielding radiation are needed. In mammography, clinical hospitals use lead or bismuth shielding materials equivalent to 0.06 mmPb. Lead is publicly known to be harmful to humans, so its use should be avoided. Bismuth cannot be manufactured as a single element, and its high price can cause a burden on its application.

Silicon is being actively treated as a material for shielding evaluation studies for X-rays and gamma rays. In particular, research on polymer materials comprising silicone mixed with various materials is in progress, and its shielding ability has been proven in various studies [10-12]. Therefore, in this study, silicon was adopted as an eco-friendly shielding material that can replace lead and bismuth. The purpose of this study is to evaluate the shielding ability of silicon as a shielding material in mammography through Monte Carlo simulation and experiment. Through this, we intend to provide useful basic data for the development of a shielding suit or shielding film that can reduce the exposure of the contralateral breast, thyroid gland, lens, and other surrounding tissues due to scattered rays during mammography.

2. Materials and Methods

2.1. GATE simulation setup

The simulation study used the GATE 8.0 code based on the Geant4 toolkit to evaluate the effectiveness of the shield. GATE code is an open-source software that is applied to Positron Emission Tomography (PET), Single Photon Emission Computed Tomography (SPECT), Computed Tomography (CT), Radiation Therapy, and Dose Measurement [13].

Fig. 1 shows the schematic diagram of the mammography system as simulated. In order to perform under the same conditions as the experiment, the target and filter were composed of a W/Rh combination, and the source to surface distance (SSD) between the X-ray tube and the

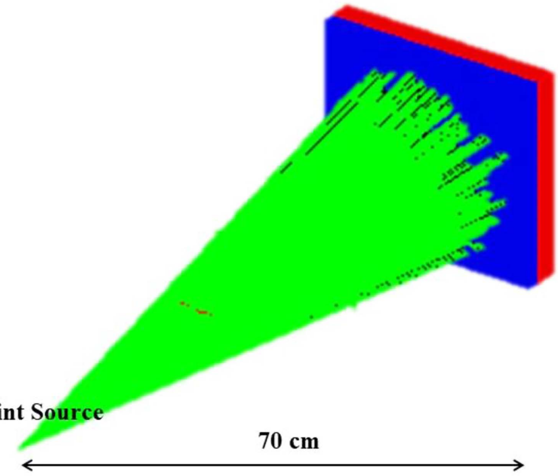

Fig. 1. (Color online) Schematic diagram of the mammography system and GATE simulation modeling. The SSD was composed of 70 cm, and the shielding materials were used in the order of silicon and perfect absorber.

Fig. 2. (Color online) Equipment used for the experiment. Shows the mammography X-ray generator and dosimetry setting. (a) X-ray generator, (b) Solid state detector (Multimeter magicmax RQM).

detector was set to 70 cm. As a variable, tube voltage was set to 25, 30, and 35 kVp.

2.2. MCNP simulation setup

MCNPX is a code designed for use in Monte Carlo-based radiation transmission codes because it is difficult to directly measure human exposure to radiation [14]. In this study, the reduction rate in breast tissue absorption dose in the MCNPX environment was evaluated by simulating under the same conditions as the GATE simulation.

To simulate the absorption dose of breast tissue, Korean adult female voxel phantoms (HDRK-Woman, High-Definition Reference Korean-Woman) were used, and the X-ray spectra used in the simulation are shown in Fig. 3. Tally 6 was used to calculate the absorbed dose, and it is evaluated in units of MeV/g per photon. This value was then converted into Gy units using a conversion factor [15]. The calculated dose was normalized to absolute dose to evaluate the rate of reduction of absorbed dose by shielding thickness [16].

2.3. Mammography equipment

The mammography x-ray generator used Selenia Dimensions (Hologic Inc., USA), the X-ray gantry of the device is equipped with a tungsten (W) target, and the filter is composed of rhodium (Rh). The imaging conditions were irradiated with 25, 30, 35 kVp, and 120 mAs at 70 cm SSD. For dose evaluation, a Solid State Detector (RQM) from Multimeter magicmax (IBA, Germany) was used. RQM has a range of 25-35 kV and is a mammography specific detector that can measure from 500 nGy to 9.99 Gy. Silicon (Si) was used for the shield material, and the manufactured silicon had a density of 1.25 g/cm^3, 10 × 10 cm^2 in size, and a thickness of 1, 2, 3, 4, 5, and 6 mm. Each tube voltage and thickness were divided and measured three times.

2.4. Reference energy spectra

The energy spectrum was calculated using the Tungsten Anode Spectral Model with Interpolating Polynomials (TASMIP) X-ray spectra [19]. The TASMIP spectra calculator algorithm uses a tungsten target and provides a reference energy spectrum according to the tube voltage up to 140 kVp and the change in intrinsic filter material and thickness [20]. In this study, a simulation was conducted by setting the intrinsic filtration to 0.05 mmRh.

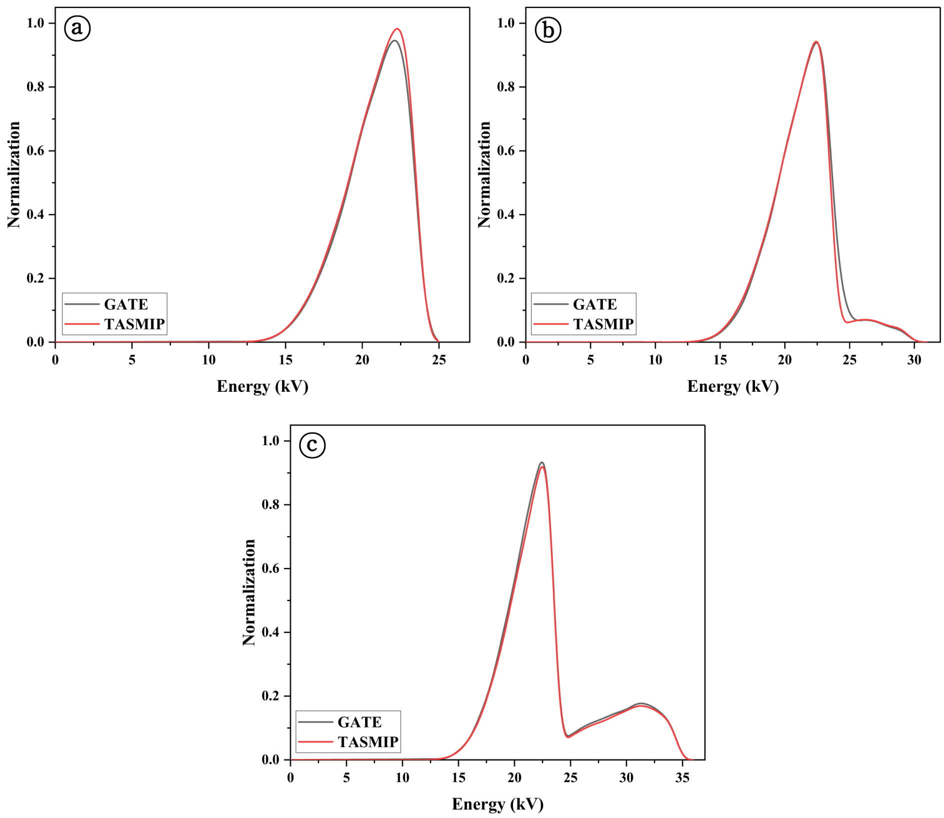

Fig. 3. (Color online) Comparison of X-ray spectra produced by GATE and TASMIP for a W anode with 0.05 mmRh filter. The normalized results show similar in all energy ranges. (a) 25 kVp, (b) 30 kVp, (c) 35 kVp.

Table 1. Composition of the breast in HDRK-Woman phantom.

Element	H	C	N	O	Na	S	Cl	Total
Percent (%)	11.4	59.8	0.7	27.8	0.1	0.1	0.1	100

Table 2. Measurement parameters with solid state detector RQM.

Dose	500 nGy~9999 mGy
Dose rate	1.5 μGy/s~300 mGy/s
Time	1 ms~19999 s
Possible Energy range	25~5 kV
Possible Target-Filter combinations	Mo/Mo, Mo/Rh, Rh/Rh, W/Rh, W/Ag

Table 3. Absorbed dose results of experiment for each tube voltage.

Silicon Thickness \ kVp	25 kVp	30 kVp	35 kVp
0 mm	3.795 ± 0	5.928 ± 0.0009	8.062 ± 0.0053
1 mm	2.408 ± 0.0017	3.904 ± 0.0031	5.424 ± 0.0042
2 mm	1.623 ± 0.0005	2.695 ± 0.0012	3.861 ± 0.0017
3 mm	1.124 ± 0	1.902 ± 0.0017	2.811 ± 0.0036
4 mm	0.782 ± 0.0003	1.36 ± 0.0005	2.062 ± 0.0009
5 mm	0.562 ± 0.0002	0.994 ± 0.0011	1.551 ± 0.0005
6 mm	0.415 ± 0.0003	0.761 ± 0.0008	1.217 ± 0.0008

3. Results and Discussion

Depending on the patient during general mammography, i an automated equipment takes the images under the following conditions: 120 mAs, 25-35 kVp. In this study, usefulness was evaluated using GATE, a Monte Carlo simulation tool, for each silicon thickness at 25, 30, and 35 kVp, and a shielding material was manufactured to investigate the radiation shielding characteristics of silicon during mammography. Table 3 shows the experimental results by energy and shielding material. The statistical deviation of the experimental results is very small,

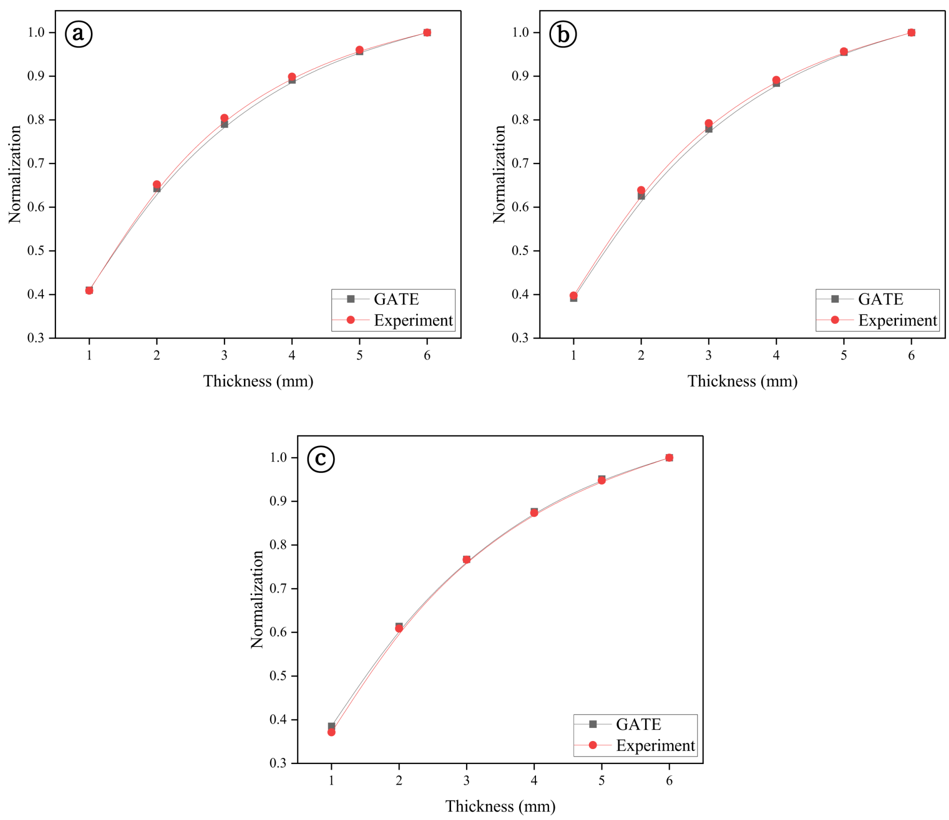

Fig. 4. (Color online) Comparison of shielding rates between GATE simulation and experiment for each tube voltage. The GATE simulation and experimental results are consistent in all energy ranges. (a) 25 kVp, (b) 30 kVp, (c) 35 kVp

indicating correct calibration, excellence, and high accuracy of the dosimetry used in the experiment [21]. In general, in diagnostic radiation, a shielding with a lead equivalent of 0.25 mmPb is used, and this shows a shielding rate of 80 % or more. Therefore, in order to exceed 80 % of the shielding rate, a silicon shield of 5 mm must be used under all tube voltage conditions. The following were obtained; 85.2 % shielding rate (0.0227 mmPb equivalent) at 25 kVp, 83.24 % (0.0226 mmPb equivalent) at 30 kVp, and 80.76 % (0.026 mmPb equivalent) at 35 kVp.

As can be seen in Fig. 4, the normalized experimental results are very consistent with the GATE simulation results. At 25 kVp, the minimum error of the experiment and the GATE simulation was 0.13 % at 1 mm thickness, while the maximum error was 1.42 % at 3 mm thickness. Under the 30 kVp condition, the minimum error was 0.19 % at 5 mm, while the maximum error was 1.32 % at 2 mm and 3 mm. At 35 kVp, the minimum error was 0.07 % at 3 mm and the maximum error was 1.4 % at 1 mm.

Results were obtained using the HDRK-Woman Phantom in the MCNPX environment of the absorbed dose of the breast when a silicone shield was used. Fig. 5 shows the absorbed dose reduction rate for the primary beam incident on the breast during mammography. When 1 mm of 25 kVp silicon was used, the absorbed dose decreased by 52.44 %, and for each 1 mm increase in thickness, the dose reduction rates were 76.91 %, 88.31 %, 93.81 %, 96.69 %, and 98.16 %. Under the 30 kVp condition, absorbed dose reduction rates were shown in the order of 74.49 %, 86.53 %, 92.41 %, 95.42 %, and 97.25 % starting from 50.22 %. Finally, under the 35 kVp condition, rates were 43.66 %, 66.57 %, 78.61 %, 85.81 %, 89.87 %, and 92.70 %. In order to exceed 80 % of the dose reduction rate, silicon with a thickness of 2.16 mm at 25 kVp and 2.34 mm at 30 kVp was required, while 3.15 mm thickness was required at 35 kVp. Although the detector was used in the GATE simulation and experimental results, the absorbed dose of breast tissue using MCNP also considers the human shielding according to the tissue, so it is confirmed that thinner silicon can be used for practical tissue protection.

The shielding performance of silicon was investigated to reduce the patient's exposure during mammography, a

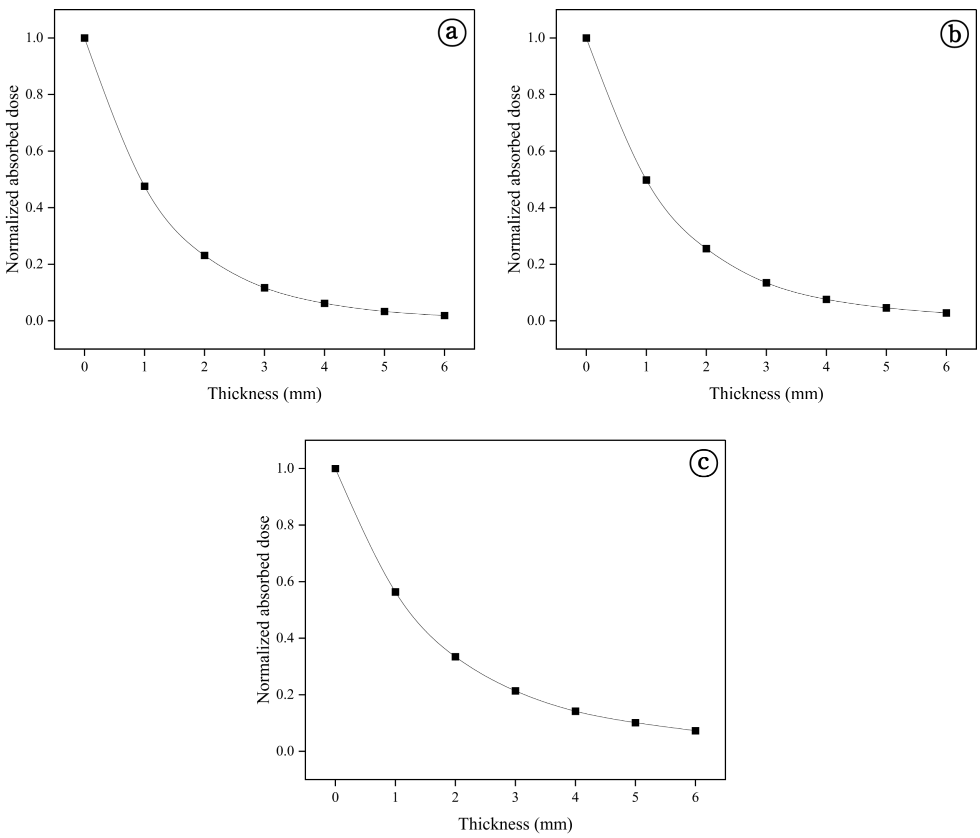

Fig. 5. Absorbed dose decrease ratio to the breast tissue according to the use of silicon shielding in MCNPX. To exceed 80 % of the dose reduction rate, 2.16 mm (25 kVp), 2.34 mm (30 kVp), and 3.15 mm (35 kVp) of silicon are required for each energy. (a) 25 kVp, (b) 30 kVp, (c) 35 kVp

diagnostic radiation that utilizes a tube voltage of 25-35 kVp energy range. In mammography, the shielding body is used in direct contact with the breast, so it has significant heterogeneity with respect to the material. This means silicon can be a great substitute material that can reduce heterogeneity. In addition, although active research is being conducted using eco-friendly materials such as bismuth, tungsten, and tin, silicon can be replaced with an optimal material considering the price of raw materials. The shielding ability of silicon was investigated only against primary radiation and a plurality of mammography devices cannot be used, reflecting a limitation of this study. During mammography, the importance of shielding the contralateral breast and surrounding tissues more than the photographed breast is emerging [22]. Therefore, based on the silicon shielding performance results of this study, it is necessary to additionally evaluate the effectiveness of the silicon shielding material against scattered rays.

4. Conclusions

As the incidence of breast cancer increases and regular mammography is performed, dosimetry and shield use are important even if the absorbed dose by the human is low due to low energy. In this study, it was possible to reduce the heterogeneity of the shielding to the patient and analyzed the effectiveness of inexpensive silicon as a shielding material for mammography. In mammography currently done in clinical hospitals, various tube voltages are automatically set due to automatic exposure control (AEC). Through this study, it was confirmed that when 5 mm thick silicon was conservatively used as a shielding material to reduce patient exposure, effective shielding effect could be exhibited in all energy domains regardless of AEC. Therefore, the results of the study can serve as useful basic data for the development of a shielding suit or shield that can reduce the exposure of the contralateral breast, thyroid gland, lens, and other surrounding tissues due to scattered rays during mammography.

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