FILAMENT MATERIAL EVALUATION FOR BREAST PHANTOM FABRICATION USING THREE-DIMENSIONAL PRINTING

by

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In this study, a method of directly evaluating the dose received by the highly radiation-sensitive mammary gland during mammography was investigated, and a corresponding breast phantom was produced that expresses a mammary gland, as an alternative to the existing mixed-form phantom. After designing this breast phantom by performing Monte Carlo simulations, the glandular dose was evaluated and compared with that of a mixed-form phantom. Then, dose evaluation was conducted for current commercial filament materials that could be used to fabricate the phantom by 3-D printing. The results showed that the dose received by the mammary gland was in the range of 1.089-1.237 mGy, and the average difference from that determined using the mixed-form phantom was approximately 1.2 %. Among the filament materials, polylactic acid showed the dose that was the most similar to that of the mammary gland tissue, differing by approximately 2.4 %. Overall, the research results suggest that it is meaningful to evaluate the glandular dose using the developed phantom instead of a mixed-form phantom. Besides, polylactic acid is the most appropriate material for fabricating the mammary gland tissue using a 3-D printer.

Key words: breast phantom, glandular dose, simulation, 3-D printer, filament material

INTRODUCTION

According to the Korea Central Cancer Registry, breast cancer is the second most common cancer in women after thyroid cancer [1]. Hence, the Korean Ministry of Health and Welfare provides breast cancer screening tests every two years for women over 40 years of age. The global incidence of breast cancer is also high, accounting for 25 % of all cancer diagnoses in women [2]. Therefore, breast cancer testing is essential for women. Breast cancer testing methods include computed tomography, magnetic resonance imaging, and ultrasonography, but the most basic method is mammography. Mammography is known to be the most effective and general method of early breast cancer diagnosis and screening [3]. Compared with other breast cancer testing methods, mammography has advantages in terms of time and cost, and above all, it is highly advantageous for detecting microcalcification. Furthermore, the introduction of digital mammography equipment has enhanced the diagnostic ability and maximized the convenience of this method [4]

However, some reports have claimed that mammography can increase radiation exposure because it uses a low tube voltage and high tube current, thereby increasing the incidence of cancer [5-10]. Therefore, accurate evaluation of the amount of radiation entering the breast when conducting mammography is important. In particular, the breast consists of adipose and mammary gland tissues, and the mammary gland tissue is sensitive to radiation. In other words, a quantitative evaluation of the dose received by the mammary gland is required.

Current methods of glandular dose evaluation involve measuring the air kerma rate, incident dose, and emitted dose using an American College of Radiology (ACR) or polymethylmethacrylate (PMMA) phantom for image evaluation and then converting the measurements using factors according to the ratio between the mammary gland and adipose tissues [11-13]. Furthermore, in most studies using Monte Carlo simulations, the breast has been expressed as a mixed form instead of evaluating the mammary gland and adipose tissues separately [14-16]. In other words, the previous studies involving an evaluation of the dose received by the mammary gland have been limited in that the evaluation has been performed indirectly rather than directly.

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Therefore, a method of directly evaluating the glandular dose needs to be developed. One means of achieving this objective is to produce a phantom that expresses the mammary gland in the breast using a 3-D printer and to evaluate the glandular dose using this phantom. To fabricate a phantom using a 3-D printer, a phantom that expresses the mammary gland was designed in this study by performing Monte Carlo simulations, and a filament material similar to an actual mammary gland tissue was searched through dose evaluation.

MATERIALS AND METHODS

Before fabricating the breast phantom that expresses the mammary gland using a 3-D printer, experiments were performed to evaluate the dose received by the mammary gland directly and to find a filament material resembling the mammary gland tissue for use in the phantom. For this simulation, we used MCNP 6.1 [17], which is based on the Monte Carlo method, and the relative error was kept within 3 % to ensure the reliability of the experimental results.

Simulation of mammography equipment

Figure 1 shows the mammography equipment simulated using MCNP. General mammography equipment was simulated by referring to existing reports [13, 15, 16, 18] based on the Selenia model produced by HOLOGIC in the U.S. The overall structure of the simulated mammography equipment was divided into an X-ray tube, a target, a unique filter, an added filter, a compression paddle, and a support plate. To examine these components in more detail, the target material was set to molybdenum (atomic number 42, density 10.28 gcm^{-3}) or tungsten (atomic number 74, density 19.25 gcm^{-3}). The tilting angle of the target was set to 16°, and the size of the focus of thermion collision with the target was set to 0.3 mm. The unique filter was simulated using beryllium (atomic number 4, density 1.85 gcm^{-3}) with a thickness of 0.5 mm. The added filter was simulated using rhodium (atomic number 45, density 12.41 gcm^{-3}) and molybdenum with a thickness of 0.06 mm. Finally, the compression paddle and support plate were simulated using polycarbonate (density 1.2 gcm^{-3}), and the thicknesses of the compression paddle and support plate were set to 2 mm and 5 cm, respectively.

Breast phantom simulation

Figure 2 shows the compressed breast during mammography expressed with the breast phantom simulated in this study, which is divided into the skin, adipose tissue, and mammary gland tissue. Table 1 summarizes the compositions and densities of the tissues that make up the breast phantom. First, the overall geographic structure of the breast was simulated based on existing studies [11, 18]. Then, this structure was complemented by applying the characteristics of Korean women. The shape was set as a half-cylinder with a radius of 8 cm, and the compression thickness of the breast was simulated as 4.5 cm. The skin thickness was set to 1.5 mm as reported by Lee *et al*. [19], who investigated the skin thickness of each body part for Korean adults, and it was simulated as a shape surrounding the breast parenchyma. The breast parenchyma was expressed as an elliptical shape because it is composed of the mammary gland and adipose tissues, and the mammary gland tissue usually extends from the nipples toward the chest wall. Other parts of the breast parenchyma excluding the mammary gland tissue were set as adipose tissue. Since the proportion of the mammary gland tissue varies by individual, phantoms were simulated with three proportions of the mammary gland tissue (25 %, 50 %, and 75 %) to evaluate the dose according to the proportion of the mammary gland tissue.

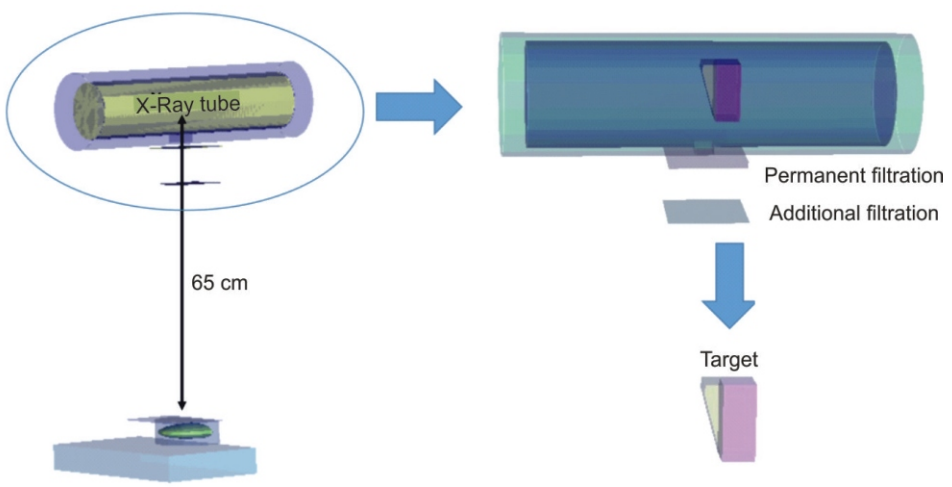

Figure 1. Mammography equipment simulated in a virtual 3-D space using MCNP

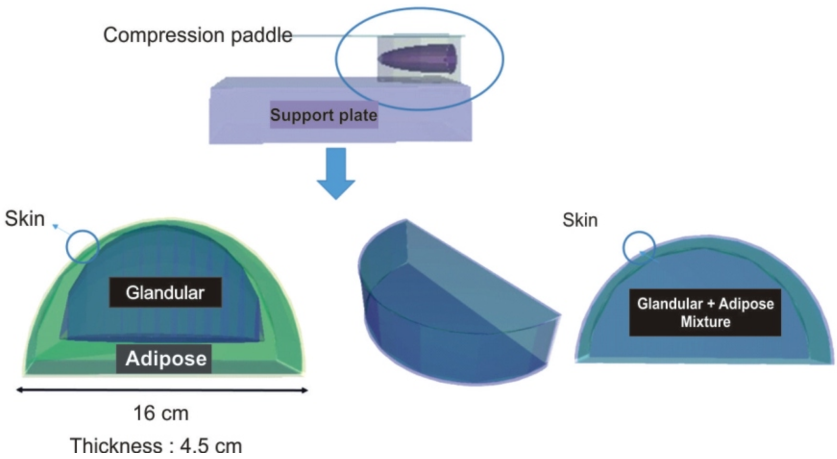

Figure 2. Models of mixed and non-mixed breast phantoms simulated using MCNP code

Table 1. Compositions and densities of breast tissues [15, 18]

Element	Composition [%]		
	Skin	Glandular	Adipose
H	10	10.6	11.4
C	20.4	33.2	59.8
N	4.2	3	0.7
O	64.5	52.7	27.8
Na	0.2	0.1	0.1
P	0.1	0.1	–
S	0.2	0.2	0.1
Cl	0.3	0.1	0.1
Density [gcm^{-3}]	1.09	1.02	0.95

Photon spectrum analysis

Since the dose received by the mammary gland during mammography was evaluated quantitatively in this study, it was critical to ensure that the simulated mammography equipment was sufficiently resemblant to the actual equipment. Thus, the spectrum of the X-rays that occurred in the simulated mammography equipment was evaluated and compared with that obtained using the SRS-78 program [20] and the results of existing studies to ensure reliability.

To obtain the simulated spectrum, as shown in fig. 3, a virtual sphere with a radius of 5 cm was set as a detector 20 cm from the focus, and the spectrum was analysed in 0.5 keV intervals with a tube voltage of 28 kVp and a tube current of 1 mAs. The X-rays acquired through the detector were analysed and represented in terms of the number of particles per unit volume (particles per cm^3).

Evaluation of glandular dose

The most notable difference between this study and the existing studies is the expression of the mammary gland. As shown in fig. 2, the mammary gland and adipose tissues have been expressed in a mixed form previously, whereas, in this study, the mammary gland and adipose tissues were expressed separately. Therefore, the doses received by the mammary gland were compared between the mixed and non-mixed forms, and their trend was examined. The dose received by the mammary gland was calculated first by setting the tube voltage to a 28 kVp according to the combination of the target and added filter. Then, this dose was converted into the dose absorbed by the mammary gland by setting the tube current to 55 mAs [14]. After acquiring data using the energy per unit mass (MeVg^{-1}) by setting the tally to 6, the absorbed dose (mGy) was obtained.

Evaluation of filament material

In general, the breast phantom used to evaluate glandular dose is an ACR phantom made of PMMA material. The ACR phantom is used in a uniform ex-

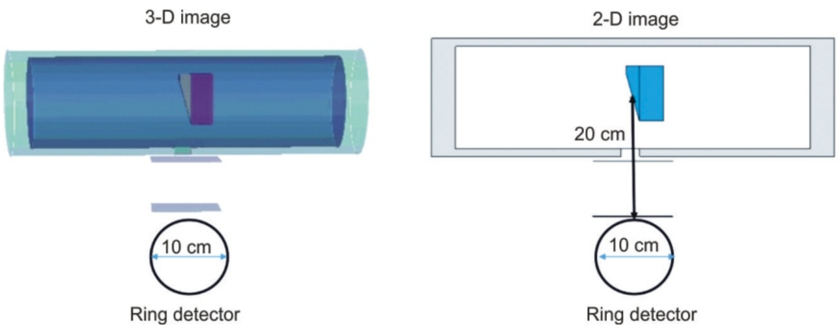

Figure 3. Ring detector used to analyse the photon spectrum in MCNP code

Table 2. The elemental compositions of the substitute materials [21]

Material	Densit [gcm^{-3}]	Composition [%]										
		C	N	O	Na	Mg	Al	Si	S	Cl	K	Ca
Polylactic acid (PLA)	1.25	54.76	–	44.99	–	–	–	–	0.13	–	0.12	–
Acrylonitrile butadiene styrene (ABS)	1.05	92.44	–	5.68	1.79	–	–	–	0.09	–	–	–
Polyethylene terephthalate (PETG)	1.27	70.45	–	29.33	0.07	–	0.11	–	0.15	–	–	–
Thermoplastic elastomers (TPE)	0.935	96.71	–	2.69	0.13	–	0.06	0.10	0.13	0.09	–	0.13
Thermoplastic polyurethane (TPU)	1.1	66.63	8.98	24.13	–	–	–	–	–	–	–	0.09
High-impact polystyrene (HIPS)	1.045	97.88		1.88	0.11	–	–	–	–	0.13	–	–
Polyamide-nylon (PA-nylon)	1.16	69.53	13.16	17.31	–	–	–	–	–	–	–	–
WOOD	1	61.48	–	37.65	–	0.26	–	0.47	–	0.15	–	–

pression without separating the mammary gland and fat. [13] That is, the PMMA material is representatively used when manufacturing a phantom with a human equivalent material. However, because the density and composition of human organs differ depending on the organ, a simple expression can be used for an organ with one PMMA material. Therefore, in this study, we attempted to fabricate a breast phantom using a material most similar to the fat, mammary gland, and skin tissues that make up each breast. To fabricate a phantom expressing the mammary gland using a 3-D printer, it was necessary to perform dose evaluation for the filament material. In other words, as the goal was to fabricate a phantom similar to the human body, it was critical to select a filament material that resembled the mammary gland, which was the focus of this study. Thus, we searched for a commercial filament material sold in the market that could replace the mammary gland tissue. Table 2 summarizes the details of the selected commercial filament materials that have compositions and densities similar to the human body [21]. After evaluating the dose of each material, we searched for the filament material that showed a dose that was the most similar to that of an actual mammary gland tissue. The phantom with a 50 % mammary gland ratio was selected as a representative one, and the dose was evaluated and compared among four different target and filter combinations.

RESULTS

X-ray spectrum analysis

To ensure the reliability of the X-rays in this study, the spectrum and average energy of the X-rays from the mammography equipment were analysed as shown in fig. 4.

The average energy is higher in the MCNP, but the difference is not significant, being in the range of only 0.5-2.8 %. Regarding the X-ray spectrum, the graphs are generally similar in terms of the peak energy area, but there are slight differences. The peak height is higher by approximately 25-30 %, and the peak energy area is higher by 0.5 keV.

Evaluation of glandular dose

Figure 5 compares the radiation doses received by the mammary gland determined using a mixed form with no distinction between the mammary gland and adipose tissues and a non-mixed form in which the mammary gland and adipose tissues were separately expressed.

The absorbed doses are generally in the range of 1.089-1.237 mGy. There is almost no difference in dose by target type, but the dose is quite high with the Rh added filter. Specifically, when the Rh filter is used, the dose is higher by approximately 0.099 mGy than when the Mo filter is used. Also, the higher the mammary gland ratio, the lower the calculated dose when the mammary gland and adipose tissues are expressed separately. Furthermore, the higher the mammary gland ratio, the higher the evaluated dose when the mixed form is used.

Evaluation of filament material

The dose was evaluated to find a filament material similar to the mammary gland tissue for breast phantom fabrication using a 3-D printer. Seven commercial filament materials that were similar to human tissues were selected and evaluated. Figure 6 presents the evaluation results.

Among the filament materials, the material that shows the values that are the most similar to those of the actual mammary gland tissue is PLA, which exhibits a difference of approximately 2.4 %.

DISCUSSION

In this study, the radiation dose received by the mammary gland tissue was evaluated by performing Monte Carlo simulations. This was a preliminary study focused on quantifying the doses separately for mammary gland and adipose tissues, rather than in a mixed form, and evaluating the appropriate filament material before fabricating a human-like breast phantom using a 3-D printer.

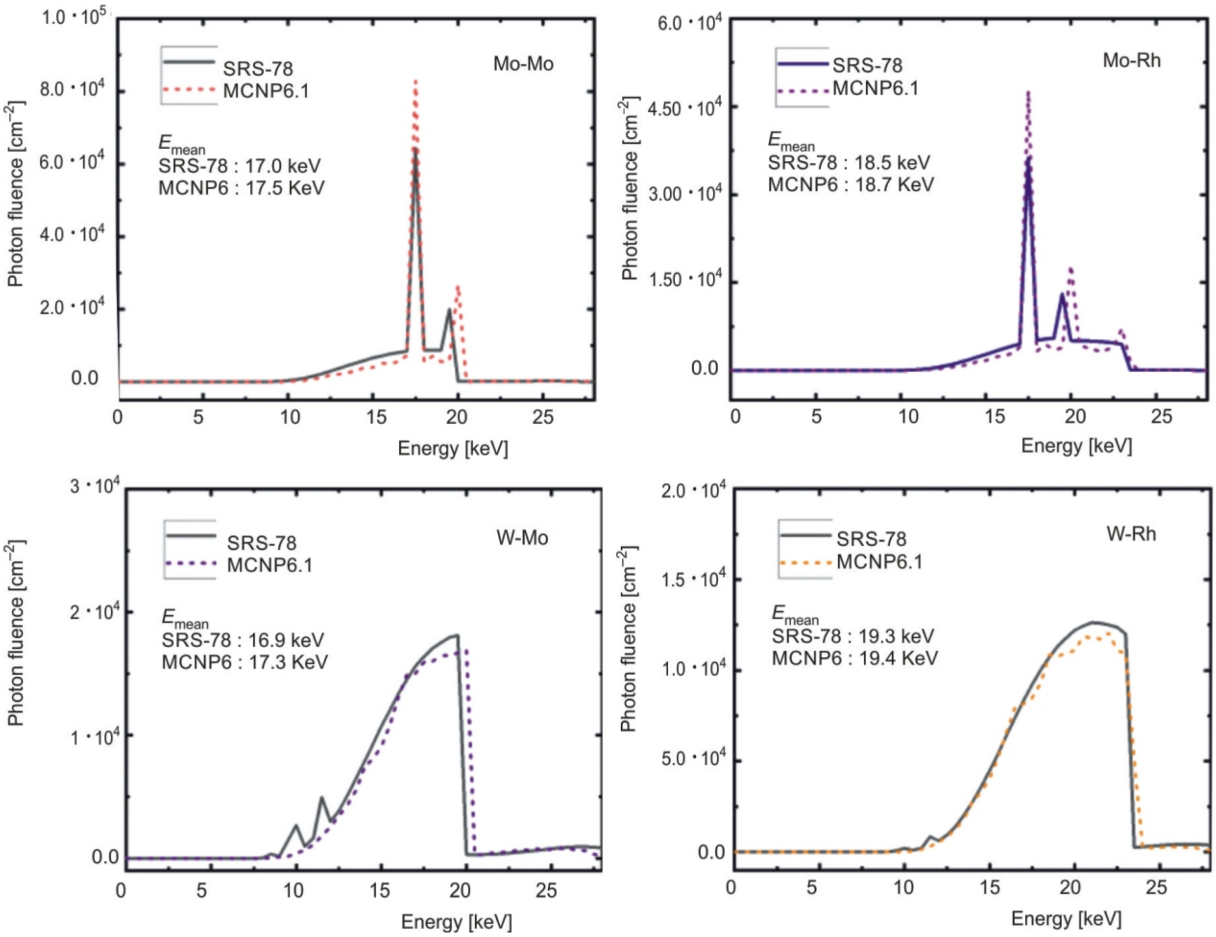

Figure 4. Comparison of X-ray spectra obtained through the SRS-78 program and MCNP6

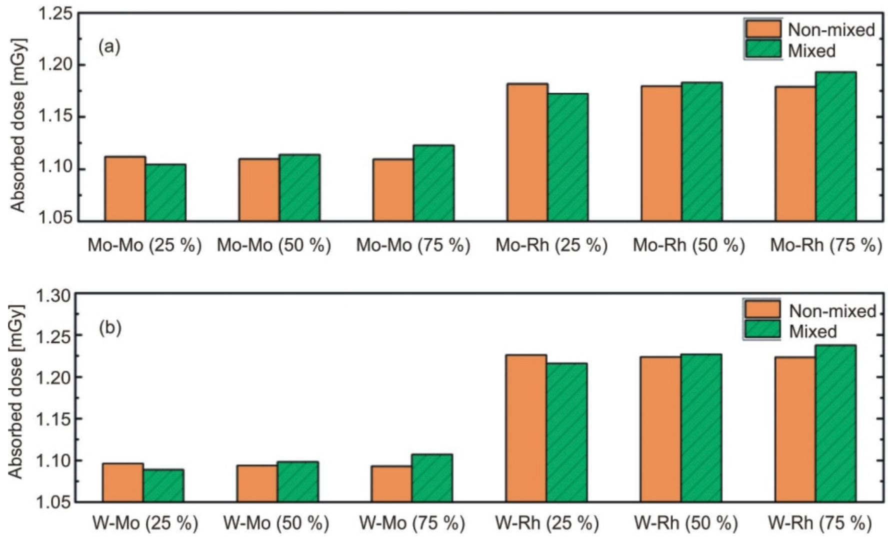

Figure 5. Comparison of glandular dose according to target filter combination and glandular ratio: (a) Mo target and (b) W target

First, to quantify the glandular dose and ensure the reliability of the results, it was necessary to verify that the generated X-rays were similar to the actual radiation. Therefore, the X-ray spectrum generated in the simulated X-ray tube was calculated and compared with the spectrum acquired from the SRS-78 program [20] in terms of average energy, peak energy, and spectrum shape. The resulting spectra showed numerically small differences of 2.8 % at most and exhibited similar shapes in general. Although there were small numerical and morphological differences, these appeared to be due to differences in the program

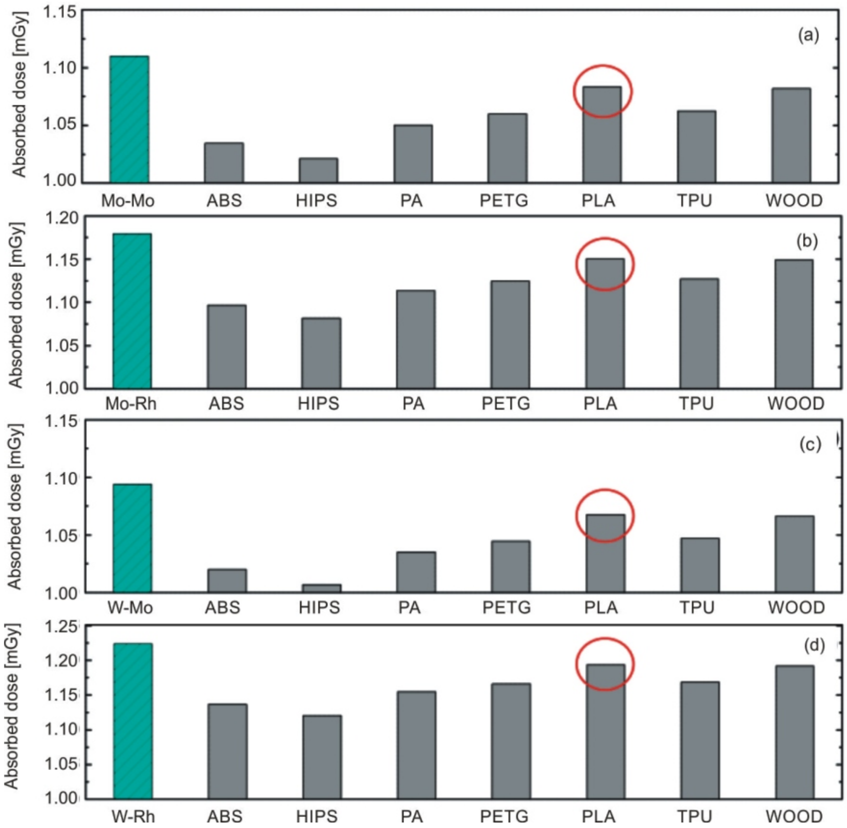

Figure 6. Comparison of estimated doses according to glandular and filament materials: *(a) Mo-Mo combination, (b) Mo-Rh combination, (c) W-Mo combination, and (d) W-Rh combination*

calculation methods, detailed geometric structures, and spectrum measurement positions. Furthermore, when the results of this study were compared with those of previous studies [22-24], they showed the same trends in terms of the spectrum shape and peak energy. Therefore, it is believed that the X-rays generated in this study were reliable.

Second, the doses received by the mammary gland were compared between a mixed form of the mammary gland and adipose tissues and a non-mixed form, and the results were compared with those of previous studies to ensure reliability. The mixed form produced a trend of increasing doses as the mammary gland proportion increased, and the same trend was found in the results of Park *et al*. [14] and Dance [18]. Meanwhile, in the non-mixed case, the doses tended to decrease as the mammary gland proportion increased. These values were similar to the results of Tzamicha *et al.* [25], who evaluated the mammary gland using a voxel phantom through simulations. The reason that the results corresponding to the mixed and non-mixed forms showed different trends is that the absorbed dose was calculated as the energy absorbed per unit mass. In the mixed case, the energy of the incident radiation was considered while the unit mass was fixed, whereas, in the non-mixed case, the unit mass changed depending on the proportion of the mammary gland tissue, leading to different results.

Finally, the doses were evaluated to select an appropriate filament material to replace the mammary gland in the fabrication of a breast phantom with a non-mixed form using a 3-D printer. The PLA, which has a density of 1.25 gcm^{-3}, yielded the most similar calculated doses, which differed by only about 2.4 %. The density of PLA is slightly higher than those of the other materials considering that the density of the mammary gland tissue is 1.02 gcm^{-3}. Nevertheless, it produced the doses that were the most similar to those of the mammary gland, and the component materials and proportions appear to have played a major role. Specifically, C and O account for about 75 % of the mammary gland tissue, and the ratio of C to O is 3:7. Meanwhile, C and O account for about 85 % of PLA, and the ratio of C to O is 3:5. Therefore, among the existing filament materials, the composition of PLA is the most similar to that of the mammary gland tissue. These values are the same as those reported by Alssabbagh *et al.* [21], who attempted to find filament materials with similar dose distributions according to the anatomical position.

CONCLUSION

The objective of this study was to evaluate the glandular dose quantitatively and directly by expressing the breast and mammary gland tissues in a non-mixed form instead of a mixed form. As a preliminary study for producing a breast phantom using a 3-D printer, the radiation dose received by the independently expressed mammary gland was determined by performing Monte Carlo simulations, and various filament materials were analysed to find appropriate material for the phantom. The glandular dose was found to differ between the mixed and non-mixed forms. It is considered reasonable to perform absorbed dose evaluations using the non-mixed form. Every individual has uniquely shaped mammary glands, and their precise simulation is limited. However, meaningful results can be obtained by taking a conservative approach in glandular dose evaluation. Next, PLA was found to be the most appropriate filament material to replace the mammary gland. The PLA was considered to be suitable as a breast phantom material in this study due to its high utility in that it is low-cost and commercialized. Finally, the dose evaluation data obtained for the filament materials investigated in this study will be useful as basic data for the current active research on the 3-D printing of human phantoms.

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AUTHORS' CONTRIBUTIONS

The idea for this study was initiated by D-Y. Lee and J-S. Lee. Data collection and statistical analysis were carried out by Y-I. Jo, Y-U. Kye, Y-R. Kang and I Park. D-Y. Lee supervised presented research and helped with its development that resulted in this paper. All the authors participated in the discussion of the presented results.

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ПРОЦЕНА ВЛАКНАСТОГ МАТЕРИЈАЛА ЗА ПРОИЗВОДЊУ ФАНТОМА ДОЈКЕ КОРИШЋЕЊЕМ 3-D ШТАМПЕ

У овом раду истражена је метода директне процене дозе коју је током мамографије примила високо осетљива млечна жлезда и произведен је одговарајући фантом дојке који одговара млечној жлезди, као алтернатива постојећем фантому мешовитог облика. Након дизајнирања овог фантома дојке извођењем Монте Карло симулација, доза жлезде је процењена и упоређена са дозом фантома мешовитог облика. Затим је извршена процена дозе за сада комерцијалне влакнасте материјале који би се могли користити за производњу фантома 3-D штампањем. Резултати су показали да је доза млечне жлезде била у опсегу од 1.089-1.237 mGy, а просечна разлика од оне утврђене коришћењем фантома мешовитог облика била је приближно 1.2 %. Међу материјалима са нитима, полимлечна киселина је показала дозу која је била најсличнија оној у ткиву млечне жлезде, која се разликовала за приближно 2.4 %. Укупни резултати истраживања упућују да је смислено проценити дозу жлезда помоћу развијеног фантома уместо фантома мешовите форме. Поред тога, полилактична киселина је најприкладнији материјал за израду ткива млечних жлезди помоћу 3-D штампача.

Кључне речи: фантом дојке, доза жлезде, симулација, 3-D штампач, влакнасти материјал