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Simulation Study of a Monochromatic X-ray Beam with K-edge Filter for Low Dose Mammography

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X-ray mammography can be used to acquire images useful for early breast cancer detection in medical applications. There have been a number of approaches to diagnostic low-dose mammography. The purpose of this study was to design a concept for use of monochromatic X-ray beams by using K-edge filters for low dose mammography. The SRS-78 X-ray simulation code and Monte Carlo simulation GATE code were used to model the X-ray tube, target material, filter material, breast phantom, and detector. To achieve a monochromatic X-ray beam, molybdenum (Mo) and rhodium (Rh) were used as filter materials in various thicknesses. The direct conversion detector (FDXD 1417, Drtech, Seongnam, Korea) composed of thin-film transistor (TFT)-amorphous selenium (*a*-Se) was modelled through Monte Carlo simulation. According to the CVR and EER results, the filter thickness for optimal mammographic imaging is set to 6 and 3 HVL for Mo and Rh, respectively. SNR values with the Rh filter improved by 1.01, 6.28, 5.60, 5.60, 5.60, 5.60 % over the range from 0.1 to 0.6 μGy compared to analogous SNR values without filter. The present work demonstrates that monochromatic X-ray beams can be generated for low dose mammography. According to the results, Rh filter could be useful for enhancing calcification while absorbed dose is reduced.

Keywords : monochromatic X-ray, K-edge filter, Monte Carlo simulation, mammography

1. Introduction

X-ray mammography can acquire images with greater information density for early breast cancer detection in medical applications than other extant imaging techniques. Better screening for cancer using mammography could therefore reduce mortality rates significantly. In mammography, the small difference between the absorption coefficients of normal breast tissue and cancerous tissue results in their poor differentiability in diagnostic information. Further, mammography requires using the relatively low energy end of the X-ray spectrum for maximum contrast between normal tissue and cancer. The possibility of tuning the X-ray energy spectrum as a function of the breast composition would reduce the radiation dose to the patient and optimize the image quality.

There have been a number of approaches for low-dose mammography. In previous studies, quasi-monochromatic X-ray beams from Compton scattering and monochromatic X-ray beams from a synchrotron were used to reduce the dose in mammography imaging [1, 2]. However, both Compton scattering and synchrotron-based X-ray beams require such specialized facilities for their generation, including accelerators, that they are rendered impractical for the clinical setting.

A monochromatic imaging system using Bragg diffraction was developed in a previous work [3]. They dealt with a tunable energy range produced by Bragg diffraction on a highly oriented pyrolytic graphite crystal. Filter design technology was also introduced for a monochromatic X-ray beam [4]. These studies focused on how the monochromatic X-ray beam is expected to yield enhanced image quality.

It is challenging to enhance signal and reduce radiation dose in mammography. Therefore, the purpose of this study was to design a low dose mammography system using monochromatic X-ray beam. We have proposed a method for generating monochromatic X-ray based on K-edge filters in front of a conventional X-ray tube by using a Monte Carlo simulation toolkit. In this low dose mammography simulation study, we have also investigated appro-

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priate filter materials for maintaining image quality at low absorbed dose.

2. Materials and Methods

2.1. X-ray source and filter materials

The SRS-78 (Institute of Physics and Engineering in Medicine, York, UK) X-ray simulation code and GATE [5] Monte Carlo simulation code were used to model the X-ray tube, target material, filter material, breast phantom, and detector. The polychromatic X-ray spectrum was generated by the SRS-78 code for the specifications of a rhodium target, 30 kV tube voltage, intrinsic filter of 0.025 mm-thick rhodium, and 1.5 mm-thick glass. To achieve monochromatic X-ray beam, molybdenum (Mo) and rhodium (Rh) are used as additional filter materials in various thicknesses. The K-edge energies of Mo and Rh are 20.00 and 23.22 keV, respectively. The thickness of Mo and Rh is varied from 1 to 7 half-value layers (HVL).

2.2. Detector and phantom

The direct conversion detector (FDXD 1417, Drtech, Seongnam, Korea) composed of thin-film transistor (TFT)-amorphous selenium (*a*-Se) was modelled through Monte Carlo simulation. The GATE simulation used in this study toolkit models the detector signal as the absorbed energy of all primary and secondary absorption events. It has dimensions of 50×50 mm^2, a 100×100 array of pixels, a pixel pitch of 139×139 μm^2, and a thickness of 500 μm. The cubic phantom consisted of breast tissue (density = 1.02 g/cm^3) used as breast model. It has dimensions of $40 \times 40 \times 63$ mm^3 including $CaCO_3$ disk (density = 2.71 g/cm^3) phantom. The diameter and thickness of $CaCO_3$ disk are 5 mm and 2 mm, respectively.

2.3. Monochromatic X-ray beam evaluation

Contrast variation ratio (CVR) and exposure efficiency ratio (EER) were estimated to determine the most appropriate filter thickness for mammography imaging in this study. CVR can be defined as the ratio of contrast obtained in the filtered beam case to contrast in the unfiltered beam case at the same tube operating potential, and is given by the following equation [6]:

$$CVR = \left(\frac{C_{filt}}{C_{unfilt}}\right) \tag{1}$$

where C_{filt} is the contrast when the X-ray beam is filtered, and C_{unfilt} is the contrast when the X-ray beam is unfiltered at same tube voltage.

To evaluate exposure efficiency ratio of the monochromatic X-ray beam, the following equation [6] was used:

$$EER = \left(\frac{S_b - S_s}{N_b}\right)^2 / ESE \tag{2}$$

where S_b and S_s are the mean values of the signal and background in an image, respectively, N_b is the standard deviation of the background region in the image, and ESE is the yielded entrance skin dose.

2.4. Absorbed Dose

The absorbed dose (D) in the breast tissue was calculated from the photon flux, photon energy, and the mass energy-absorption coefficient according to following equation [7]:

$$D = \Phi \times E \times \left(\frac{\mu_{en}}{\rho}\right) \tag{3}$$

where Φ is the photon flux at the photon energy E and $\frac{\mu_{en}}{\rho}$ is the mass energy-absorption coefficient. The mass energy-absorption coefficient of breast tissue is derived from National Institute of Standards and Technology (NIST) data [8]. The photon flux at the photon energy is calculated from SRS-78 code. The absorbed dose in the breast tissue is calculated by multiplying the photon flux,

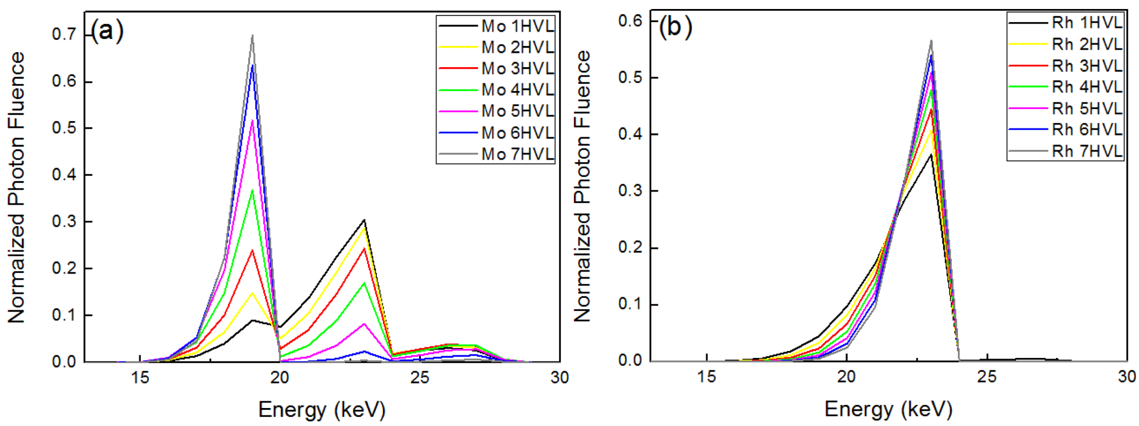

Fig. 1. (Color online) (a) Mo-filtered and (b) Rh-filtered normalized X-ray spectra according to filter thickness from 1 to 7 HVLs.

the photon energy, and the mass-absorption coefficient.

3. Results

The polychromatic X-ray spectrum was generated according to the SRS-78 code. Then, the polychromatic X-ray beam was altered with additional filters of a range of thicknesses. As shown in Fig. 1, to achieve a monochromatic X-ray beam, Mo and Rh were used as additional filter materials in thicknesses ranging from 1 to 7 HVL. The shapes of the X-ray energy spectra were highly dependent on the K-edge energy values of the Mo and Rh filters. In Fig. 1(a), the peak energy of the X-ray spectrum is close to 20.00 keV while the photon fluence of the K-edge energy at the Rh target is reduced to zero when the Mo thickness is increased from 1 to 7 HVL. Fig. 1(b) shows the altered X-ray beam shape with the Rh filter thickness increasing from 1 to 7 HVL. The X-ray beam filtered with thicker HVL is more narrow than the beam filtered with thinner HVL. The mean energy of the narrow beam is expected to be close to the 23.22 keV value of Rh K-edge energy filter.

From the photon fluence energy spectra, CVR and EER were estimated to determine the filter thickness for mammography imaging in this study. The equations for CVR and EER [6] have already been given as equations (1) and (2), respectively. Fig. 2 shows the CVR and EER values by filter thickness. Fig. 2(a) shows the CVR and EER for the Mo filter. The Mo CVR values range from a minimum of 0.98 to a maximum of 1.00. The Mo EER values range from a minimum of 0.93 to a maximum of 1.17. As illustrated in Fig. 2(b), the Rh filter CVR ranges from a filter thickness minimum of 0.97 to a maximum of 1.00. The Rh filter EER thickness ranges from a minimum of 0.51 to a maximum of 1.01. According to CVR and EER results, optimal mammographic imaging filter thickness is 6 HVL for Mo and 3 HVL for Rh.

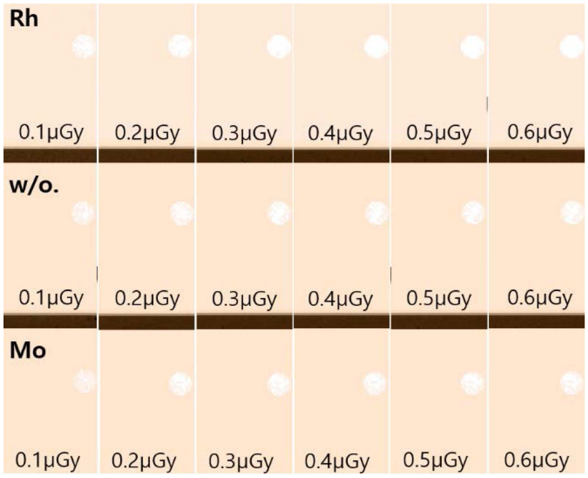

Fig. 3. (Color online) Phantom images (upper row: Rh-filter, middle row: without filter, lower row: Mo-filter) for measuring SNR values with respect to absorbed dose.

Fig. 3 shows the phantom images, and signal-to-noise ratio (SNR) is measured in the images obtained with three types of X-ray beams: beam without any filter, beam with

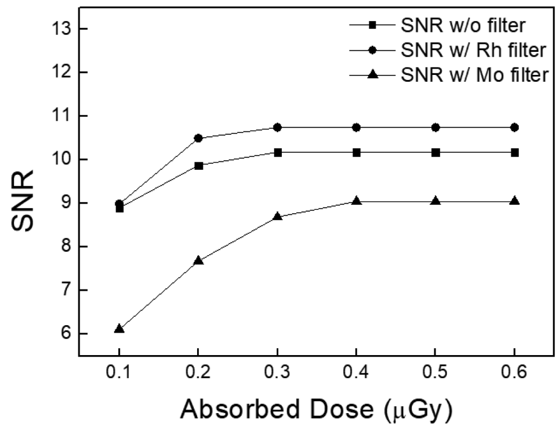

Fig. 4. SNR values with Rh and Mo filters and without any filter measured at given absorbed doses (μGy).

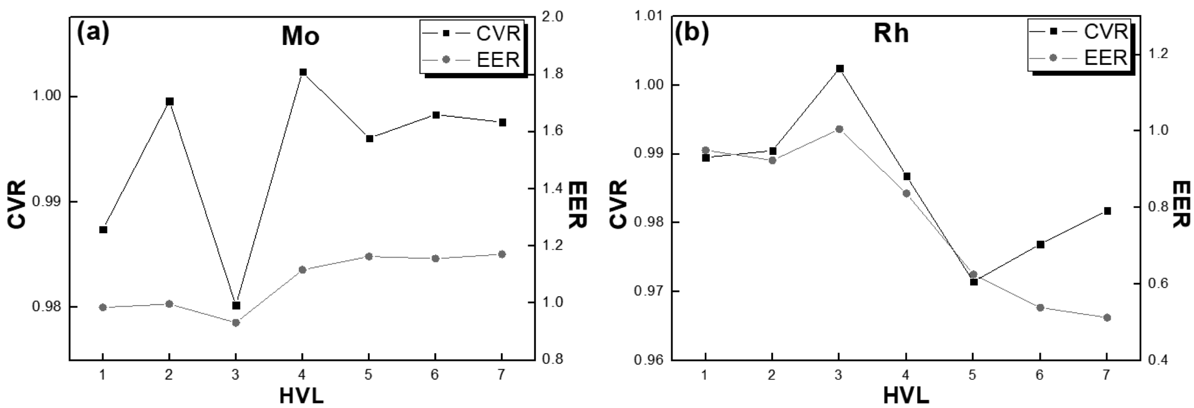

Fig. 2. (a) Mo-filter and (b) Rh-filter CVR and EER values for various HVL thicknesses.

a 6 HVL Mo filter, and beam with a 3 HVL Rh filter.

Fig. 4 shows the SNR with respect to absorbed dose measured from Fig. 3. The absorbed dose was calculated by equation (3). The SNR increased from 0.1 to 0.3 μGy for the X-ray beam without a filter and the X-ray beam with the Rh filter. However, the SNR increased from 0.1 to 0.4 μGy for the X-ray beam with a Mo filter. Saturated SNR is 10.18, 10.75, and 9.05 for X-ray beam without a filter, with an Rh filter, and with a Mo filter, respectively. The percentage improvement in SNR values with the Rh filter compared to without is 1.01, 6.28, 5.60, 5.60, 5.60, 5.60 % from 0.1 to 0.6 μGy in 0.1 increments, respectively.

4. Discussion

X-ray mammography could reduce mortality rates by detecting early breast cancer in medical applications. Further, reducing patient exposure to radiation and maintaining image quality are important factors to consider. Therefore, we have proposed the monochromatic X-ray beam with K-edge filter and evaluated its effect by image quality and absorbed radiation dose. We used CVR and EER to determine monochromatic X-ray beam exposure.

In this study, the CVR on both the Mo and Rh filters is appropriate for obtaining images because they range from 0.97 to 1.00, as shown in Fig. 2. In Figs. 2(a) and (b), the EER is also measured for Mo and Rh. According to the EER results, the Mo EER trend increased from 3 to 7 HVL, while the Rh EER decreased from 3 to 7 HVL. For the Mo filter, the mean energy of the X-ray beam is lower when the Mo filter thickness is increased. For the Rh filter, the mean energy of the X-ray beam is higher when the Rh filter thickness is increased. According to these results, monochromatic X-ray beams acquired with low energy K-edge filters improve the contrast and reduce the exposure dose while maintaining exposure efficiency.

Fig. 4 shows the correlation between the absorbed dose and SNR for three types of X-ray beams. Saturation of the SNR is observed, and the SNR of the Rh filter is higher than that of Mo and with no filter. We used an X-ray tube model as the Rh target so that the K-edge energy of the Rh filter is matched to that of the Rh target. Monochromatic X-ray through the Rh filter has a higher energy. The image noise was reduced when the X-ray energy increased. Therefore, the SNR of the Rh filter is higher than that of the other X-ray beams, and the effects of reduced radiation dose are expected.

The optimal filter thickness for mammographic imaging was determined at 3 HVL for Rh. However, if we perform experimental approach, filter thickness including HVL is considered due to starvation of photon number by using thicker filter.

5. Conclusions

The present work demonstrates monochromatic X-ray beams for low dose mammography. According to the results, an Rh filter could be useful for enhancing calcification while the absorbed dose is reduced. Further studies, including experimental validation, will be performed.

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