

Optimum filter selection for Dual Energy X-ray Applications through Analytical Modeling

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Abstract. In this simulation study, an analytical model was used in order to determine the optimal acquisition parameters for a dual energy breast imaging system. The modeled detector system, consisted of a 33.91mg/cm^2 $\text{Gd}_2\text{O}_2\text{S:Tb}$ scintillator screen, placed in direct contact with a high resolution CMOS sensor. Tungsten anode X-ray spectra, filtered with various filter materials and filter thicknesses were examined for both the low- and high-energy beams, resulting in 3375 combinations. The selection of these filters was based on their K absorption edge (K-edge filtering). The calcification signal-to-noise ratio (SNR_{tc}) and the mean glandular dose (MGD) were calculated. The total mean glandular dose was constrained to be within acceptable levels. Optimization was based on the maximization of the $\text{SNR}_{\text{tc}}/\text{MGD}$ ratio. The results showed that the optimum spectral combination was 40kVp with added beam filtration of $100\ \mu\text{m}$ Ag and 70kVp Cu filtered spectrum of $1000\ \mu\text{m}$ for the low- and high-energy, respectively. The minimum detectable calcification size was $150\ \mu\text{m}$. Simulations demonstrate that this dual energy X-ray technique could enhance breast calcification detection.

1. Introduction

Breast cancer is the most common cancer in women both in the developed and the developing world. According to World Health Organization (WHO), early detection in order to improve breast cancer outcome and survival remains the key of breast cancer control [1]. Dual energy (DE) imaging technique can enhance the visualization of microcalcifications (μC), which are the principal indicator of breast cancer. Previous dual energy numerical calculations showed that the minimum detectable calcification size was $250\ \mu\text{m}$ to $300\ \mu\text{m}$ using polyenergetic X-rays and flat panel detectors [2,3]. The signal to noise ratio (SNR) in the subtracted (dual energy) image depends on various parameters such



as: (i) the low- and high-energy X-ray spectra, (ii) the elemental composition of the breast, the microcalcifications, and (iii) the efficiency of the image receptor [2].

A wide range of X-ray pairs can be used in dual energy breast applications, resulting in the same SNR for calcification detection. In general, optimization can be performed with respect to patient entrance dose, mean glandular dose, image acquisition time, or X-ray tube heat loading [4].

In this simulation study, an analytical model was developed in order to determine the optimal acquisition parameters for a dual energy breast imaging system. The system modeled, consisted of a tungsten anode and a high resolution CMOS sensor. The calcification signal-to-noise ratio (SNR_{tc}) and the mean glandular dose (MGD) were calculated. Optimization was based on the maximization of the SNR_{tc}/MGD ratio.

2. Materials and Methods

The calcification SNR was determined considering a three-component system: adipose tissue of thickness t_a , glandular tissue of thickness t_g , and cubic calcification of thickness t_c . Two images are used, obtained with exposures R_{low} , R_{high} and polyenergetic X-ray spectra at different kVp $\Phi_{low}(E_i)$, $\Phi_{high}(E_i)$ at the entrance of the breast. The digital detector system has a pixel size d , spectral matching factor A_s , and quantum detection efficiency per unit energy $Q(E_i)$. The mean signals in the low- and high-energy images, S_{low} and S_{high} , can be calculated by [3]:

$$S_j = \int_{E_{min}}^{E_{max}} dE \cdot R_j \cdot d^2 \cdot \Phi_j(E_i) \cdot e^{-\frac{\mu}{\rho} a(E_i) \rho_a t_a - g_r \left(\frac{\mu}{\rho} g(E_i) \rho_g - \frac{\mu}{\rho} a(E_i) \rho_a \right) t} \cdot e^{-\frac{\mu}{\rho} c(E_i) \rho_c t_c} \cdot A_s \cdot Q(E_i), \quad j = low, high \quad (1)$$

where μ/ρ_a , μ/ρ_g , μ/ρ_c are the mass attenuation coefficients and ρ_a , ρ_g , ρ_c are the densities of the glandular, adipose tissue and μC , respectively. The calcification SNR can be expressed as [3]:

$$SNR_{tc} = \frac{t_c}{\sqrt{\sigma_{tc}^2}} \quad (2)$$

where σ_{tc}^2 represents the noise level in the subtracted image.

The elemental compositions of adipose and glandular breast tissue were obtained from a previous study [5]. Hydroxyapatite, which is a calcium-phosphate mineral form, was used to simulate microcalcifications. The mass attenuation coefficients were calculated by NISTIR published data using the computer program XMuDat [6]. The SNR_{tc} has been evaluated for the subtracted digital images of 4cm thick compressed breast, with composition of 50% glandular and 50% adipose tissue. The microcalcification sizes tested were 100 μm to 500 μm , in 50 μm increments.

The low- and high-energy unfiltered spectra were obtained from Boone *et al* for a tungsten anode [7]. The kVp examined were 40kVp for the low-energy (LE) and 70kVp for the high-energy (HE). The filter materials tested were silver (Ag), cadmium (Cd), palladium (Pd) and copper (Cu), europium (Eu), neodymium (Nd), samarium (Sm), holmium (Ho) for the low- and high-energy respectively [8]. The filter thicknesses varied from 10-150 μm and 100-1500 μm for the low- and high-energy respectively.

The assumed digital detector consisted of a 33.91mg/cm² terbium-doped gadolinium oxysulfide (Gd₂O₂S:Tb) placed in direct contact with the RadEye HR CMOS sensor. This scintillator was selected due to its efficiency and imaging properties, which are superior in comparison to other detectors [9]. The sensor pitch is 22.5 μm . The matching factor A_s and the quantum detection efficiency per unit energy $Q(E_i)$ were calculated according to Michail *et al* [10,11].

The mean glandular dose (MGD) was calculated for all the filtered X-ray spectra according to the following equation [12]:

$$MGD = DgN \cdot K_a \quad (3)$$

where DgN is a numerical factor [13], and K_a is the entrance dose. MGD was calculated for the low- and the high-energy exposures and then summed to obtain the total glandular dose. DgN data for a breast thickness of 4cm, with 0% and 100% glandularity, were obtained from published data [13]. For 50% glandular tissue the mean MGD value was used.

Optimization was based on the maximization of the SNR_{tc}/MGD ratio. SNR_{tc}/MGD was calculated for every possible filtered spectrum resulting in 3375 combinations. The SNR_{tc} threshold was set to be 3 ($SNR_{tc} \geq 3$) [3]. The MGD was limited to be below 2mGy, which lies within the EUREF acceptable limit [14].

3. Results and Discussion

In the following figures, the numbers of y-axis correspond to the examined thicknesses of the low energy (Ag:1-15, Cd:16-30, Pd:31-45). Respectively, the numbers of x-axis correspond to the examined thicknesses of the high energy (Cu:1-15, Eu:16-30, Nd:31-45, Sm:46-60, Ho:61-75).

Figure 1 shows SNR_{tc}/MGD values as a function of all low- and high-energy filter materials and thicknesses for 150 μm calcification size. Holmium with thicknesses in the range of 500-1000 μm gave values between 1.75 and 2.23. Copper combined with all low-energy filters resulted in the highest values ($SNR_{tc}/MGD \geq 2.5$).

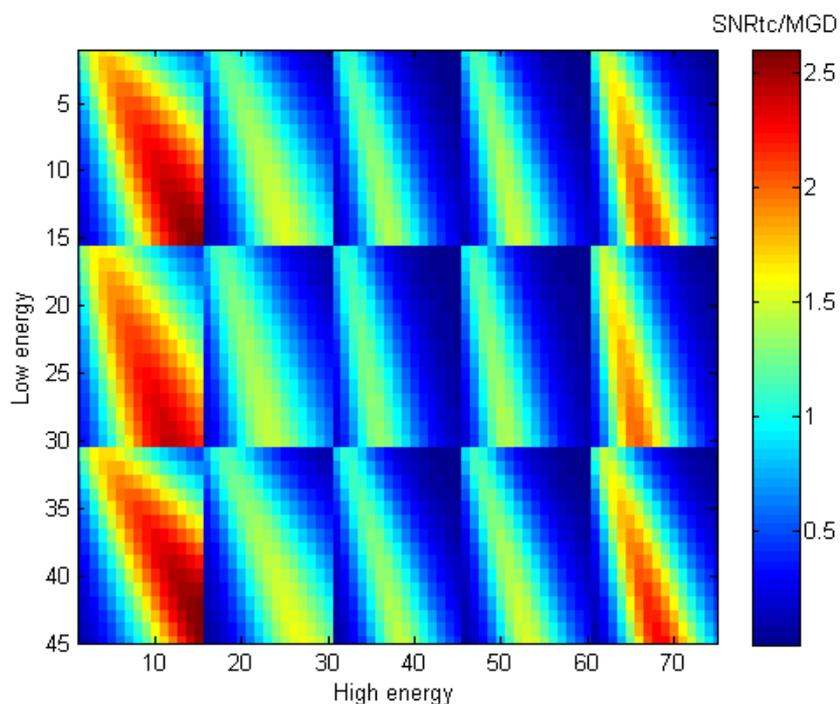


Figure 1. SNR_{tc}/MGD values as a function of low- and high-energy filter materials and thicknesses.

Figure 2 shows SNR_{tc}/MGD values as a function of all low- and high-energy filter materials and thicknesses for a μC size of $150 \mu m$, after applying the limitations ($SNR_{tc} \geq 3$ and $MGD < 2mGy$). It is obvious that maximum values were obtained from Cu filter (1000-1200 μm thick) combined with Ag filter (90-110 μm thick) or Cd filter (100-130 μm thick). These differences in the thicknesses of LE filters can be explained by considering the density of the materials. However, the combination of Cd-100 μm filtered spectrum (LE) and Cu-1000 μm filtered spectrum (HE) led to maximization of the optimization parameter ($SNR_{tc}/MGD=2.34$). Particularly, for 150 μC size, the SNR_{tc} was 3.61 while the corresponding MGD was 1.54mGy.

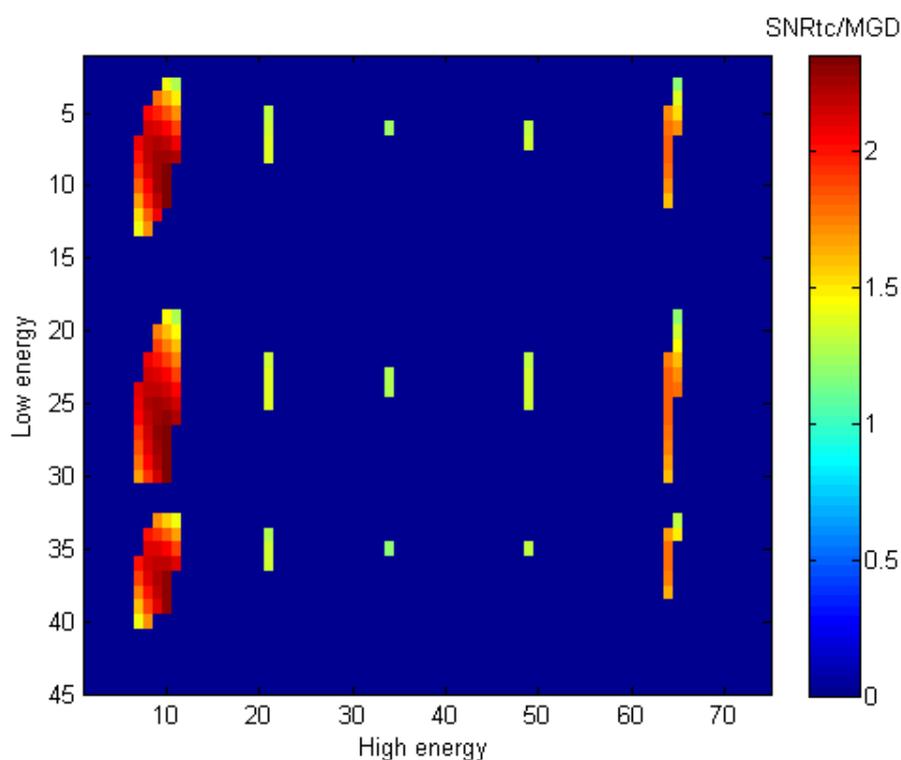


Figure 2. SNR_{tc}/MGD values as a function of low- and high-energy filter materials and thicknesses after applying the limitations.

4. Conclusion

In this simulation study, an analytical model was developed for optimal X-ray spectra determination using a dual energy breast imaging system. The modelled system consisted of a CMOS based imaging detector combined with different X-ray tungsten spectra. Optimization was based on the maximization of SNR_{tc}/MGD . Simulation results show that a SNR_{tc} value of 3.61 can be achieved for a calcification size of $150 \mu m$ using 40kVp with added beam filtration of $100 \mu m$ Cd and 70kVp Cu filtered spectrum of $1000 \mu m$ for the low- and high-energy, respectively. Compared with previous studies, this method can improve detectability of microcalcifications, while keeping mean glandular dose within acceptable levels.

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