Optimization of energy-separation filter in multilayer detectors for single-shot dual-energy x-ray imaging

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1. Introduction

A conventional dual-energy (DE) x-ray imaging technique as a combination of two distinct energies (low and high) has been introduced [1,2]. Motion artifacts occur because DE images are acquired through two exposures. To minimize these motion artifact problems due to patient motion, respiration and heart rate, a single shot DE technique using a sandwich-like multilayer detector was proposed [3]. By inserting intermediate filter between the two detector layers, the sandwich detector can produce low- and high-energy separated images, thereby resulting in higher contrast in the single-shot DE images [4,5,6].

However, the single-shot DE technique is less effective in the separation of two energies than the conventional DE technique and can further increase image noise. Because the single-shot DE technique is made with the two images separated by the intermediate filter that absorbs the low energy photons while transmitting the higher energy photons. Therefore, the design of the energy separation filter should be performed first for the successful single-shot DE x-ray imaging technique (i.e., optimal material and thickness) [7].

In this study, we investigate an optimal filter material and thickness that can give rise to the best signal-to-noise performance.

2. Theoretical background

2.1 Sandwich detector

In previous study, the sandwich detector was theoretically modeled using cascaded-systems model (CSA) [8,9], and the performance of the sandwich detector for various kVp and intermediate filter thickness was analyzed [5,6]. The sandwich detector consisted of phosphor screens with different thickness: thinner for the front and thicker for the rear detector layers, respectively and intermediate filter for various materials and thickness. Therefore, the x-ray transmitted through the front detector and the intermediate filter reaches the rear detector, and the image corresponding to the relatively higher energy can be obtained the rear detector.

2.2 Numerical phantom

A numerical phantom was used to mimic a mouse for the optimization calculations as illustrated in Fig. 1, consisting of four polyurethane (PU, 0.59 g cm^{-3}) disks with a thickness of 3 mm and an Al (2.7 g cm^{-3}) bar with a thickness of 1 mm embedded in 30 mm of polymethyl methacrylate (PMMA, 1.18 g cm^{-3}). The disks and bar mimicked soft tissue and bone, respectively. This phantom was calculated from the attenuation coefficient for the 3% contrast of PU.

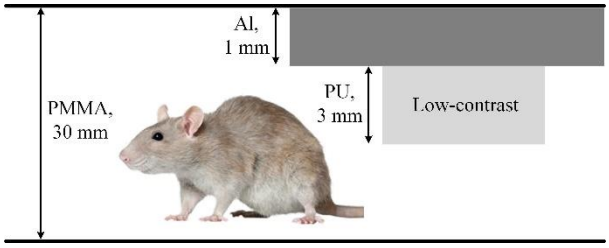

Figure 1. Numerical low-contrast phantom used to mimic a mouse.

2.3 Dual-energy image signal, noise

A CSA model was previously introduced to address the signal and noise propagation in a sandwich detector and it is expanded in this study to include an expanded investigation of performance of each detector layer with respect to the applied kVp, the material and thickness of energy separation filter. For the average number of incident x-ray photon $\bar{q}$ (quanta mm^{-2}) at the entrance surface of the sandwich detector, the CSA model gives the average signal at the output of the j-th detector layer (F and R denotes the front and rear detector, respectively):

$$\bar{d}_j = ka^2\bar{q}\bar{\tau}_j\bar{g}_j \quad (1)$$

The variance of signal measured from each detector layer can be calculated by the quadrature sum of each noise component:

$$\sigma^2_{j,total} = \sigma^2_{j,indirect} + \sigma^2_{j,direct} + \sigma^2_{j,add} \quad (2)$$

The relative variance due to indirect interaction can be estimated from the presampling NPS.

For the reconstruction of single-shot DE images, we apply the weighted log-subtraction method to the low- and high-energy images [11]:

$$I_{DE}(x,y) = I_R(x,y) - wI_F(x,y) \quad (3)$$

where, w is the weight for cancellation of uninterested objects.

As a figure of merit (FOM) for filter optimization, we combine the measured signal difference (SD) and noise (σ) that is calculated from the CSA simulations:

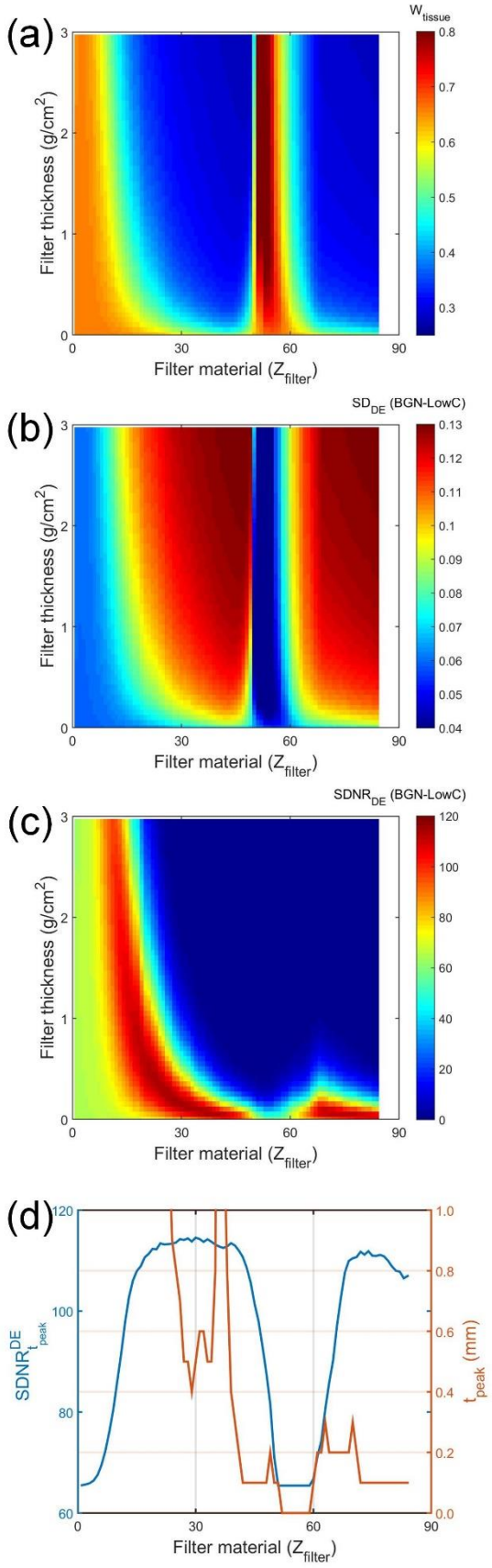

Figure 2 Effect of energy separation filter in dual-energy image performance. (a) tissue weighting parameter, w_s, (b) dual-energy signal difference, (c) dual-energy image signal-difference to noise ratio, $SDNR^{DE}$, (d) Peak $SDNR^{DE}$ and required filter thickness as a function of filter materials

$$\mathrm{FOM} = \frac{SD_{DE}}{\sigma_{DE}} \tag{4}$$

3. Preliminary results

The DE imaging performance metrics on energy separation filter is shown in Fig. 2. Calculations are shown as a function of filter material type (Z_{filter}) and thickness (s_{filter}), with the single-exposure at 60 kVp. Figure 2(a) shows the reduction in tissue weighting parameter, w_s. The effect of energy separation on SD^{DE} is similar, as shown in Fig. 2(b). The higher atomic number increases the spectral separation and increase the DE signal difference at Z_{filter}. While a higher atomic number increase PU contrast, the trade-off in image noise and $SDNR^{DE}$ is showed in Fig. 2(c). The peak $SDNR^{DE}$ from Fig. 2(c) and the associated filter thickness are shown in Fig. 3(d).

4. Further study

The remained further study before the meeting includes the followings:

- DE SDNR calculation based on low contrast percentage (i.e., 1 ~ 5 % contrast) using the CSA model;
- Calculation of x-ray Swank factor by filter materials, thickness and x-ray energy;
- Optimum energy separation filter material and thickness extraction form the highest DE SDNR;

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