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Comparison of spectral CT imaging methods based a photon-counting detector: Experimental study

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ABSTRACT

Photon-counting detectors allow spectral computed tomography (CT) imaging using energy-resolved information from a polychromatic X-ray spectrum. The spectral CT images based on the photon-counting detectors are dependent on the energy ranges defined by energy bins for image acquisition. In this study, K-edge and energy weighting imaging methods were experimentally implemented by using a spectral CT system with a cadmium zinc telluride (CZT)-based photon-counting detector. The spectral CT images were obtained by various energy bins and compared in terms of CNR improvement for investigating the effect of energy bins and the efficiency of the spectral CT imaging methods. The results showed that the spectral CT image quality was improved by using the particular energy bins, which were optimized for each spectral CT imaging method and target material. The CNR improvement was different for the spectral CT imaging methods and target materials. It can be concluded that an appropriate selection of imaging method for each target material and the optimization of energy bin can maximize the quality of spectral CT images.

1. Introduction

Energy-integrating detectors currently used in X-ray imaging systems provide information of the attenuation properties of target objects determined by those chemical compositions and mass densities. However, the energy-integrating detectors are insensitive to spectral information because the detectors accumulate the charges generated by photon interactions in each detector pixel over acquisition time, regardless of photon energies. This detection mechanism is limited to provide the sufficient contrast between different materials, reflect tissue-type specific information, and reduce radiation dose for multi-energy imaging [1–3]. Recently, photon-counting detectors based on semiconductor materials have been developed for medical X-ray imaging [4–6]. Different from the energy-integrating detectors, the photon-counting detectors with energy-discrimination capabilities are able to count the number of photons passed through an object. The detectors also allow the multi-energy and novel X-ray imaging because these detectors can measure the photon energy deposited by each event and provide energy-resolved information from a polychromatic X-ray spectrum by using multiple energy thresholds [7,8].

One of the novel X-ray imaging methods is able to dramatically improve the contrast of the high atomic number materials, which have K-edge discontinuities at specific energy levels in attenuation coefficient curves. Several methods have been proposed to improve the contrast of the high atomic number materials, including material decomposition and subtraction techniques [9–11]. We investigated the reconstruction of a single energy bin above the K-edge absorption energy of a material in order to improve contrast. This imaging method is called K-edge imaging and can be implemented by using the energy thresholds of photon-counting detectors [12,13]. Energy weighting imaging can also be realized by using energy-resolved information obtained from the photon-counting detectors. The energy weighting imaging is able to improve the contrast between materials using the weighting schemes, which are different from the energy-integrating detectors [7,14]. The energy weighting imaging can be categorized into two techniques: projection-based energy weighting and image-based energy weighting. In the projection-based energy weighting technique, projections are weighted by the weighting factors calculated from the difference between the number of photons passed through a background and those traveling through a target material [7]. The image-based energy weighting technique assigns the weighting factors, which are

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calculated to be proportional to the contrast and inversely proportional to the noise variance for each energy bin image, to reconstructed images [14].

Although the K-edge and energy weighting imaging methods based on the photon-counting detectors can improve image quality, these imaging methods are affected by the energy bins, which are defined to obtain energy-resolved information. Also, the characteristics of images are various for each imaging method due to different imaging schemes. Several groups implemented the K-edge and energy weighting imaging using the photon-counting detectors [7,13–15]. However, the energy bins for these imaging methods were empirically determined, and the effect of energy bins in computed tomography (CT) images was not discussed. Also, the K-edge and energy weighting imaging methods should be experimentally validated and compared in order to optimize the image quality for target materials.

In this study, the K-edge, projection-based energy weighting, and image-based energy weighting imaging methods were implemented by using a spectral CT system equipped with the photon-counting detector. The spectral CT images were obtained with various energy bins, and the image quality was evaluated in terms of contrast-to-noise ratio (CNR).

2. Materials and methods

2.1. Spectral CT Imaging Methods

2.1.1. K-edge Imaging

The linear attenuation coefficient (LAC), $\mu(E)$, of a material can be generally described by a linear combination of the photoelectric and Compton cross-sections in the diagnostic energy range [16]. The photoelectric cross-section can be approximated by its E^{-3} energy dependence. The Compton cross-section, $f_{KN}(E)$, was derived by Klein and Nishina and is a function of photon energies [17]. However, the general relationship between LACs and photon energies should be modified to consider the K-edge discontinuity, which results in a sudden increase in a LAC curve, as shown below [18]:

$$\mu(E) = a_{ph}\frac{1}{E^3} + a_{Co}f_{KN} + a_{K-edge}f_{K-edge}(E), \tag{1}$$

where a_{ph} and a_{Co} are the constants corresponding to the photoelectric effect and Compton scattering, respectively, and a_{K-edge} and $f_{K-edge}(E)$ are the local density and mass attenuation coefficient of the material with the K-edge discontinuity, respectively.

In the CT image obtained from the energy-integrating detector, the CNR can be measured as below:

$$\mathrm{CNR} = \frac{\mu_t - \mu_{bg}}{\mu_{bg}} / \sigma_{bg}, \tag{2}$$

where μ_t and μ_{bg} are the LACs of target material and background, respectively, and σ_{bg} is the standard deviation of background. The CNR of the CT image obtained from the photon-counting detector can be defined for a particular energy bin because the photon-counting detector has the energy-resolved capability with multiple energy thresholds, and Eq. (2) becomes

$$\mathrm{CNR}_i = \frac{a^t_{K-edge}\int_{E=L_i}^{U_i} f^t_{K-edge}(E)dE + F(E)}{a^{bg}_{ph}\int_{E=L_i}^{U_i} 1/E^3 dE + a^{bg}_{Co}\int_{E=L_i}^{U_i} f_{KN}(E)dE} / \sigma_{bg} \quad \text{and}$$

$$F(E) = (a^t_{ph} - a^{bg}_{ph})\int_{E=L_i}^{U_i} 1/E^3 dE + (a^t_{Co} - a^{bg}_{Co})\int_{E=L_i}^{U_i} f_{KN}(E)dE, \tag{3}$$

where U_i and L_i are the upper and lower energy thresholds, respectively, for determining an energy bin i. Eq. (3) represents that the contrast of a material with the K-edge discontinuity can be improved by the energy bin, which is defined at the K-edge discontinuity of the material in the attenuation curve for image acquisition. Also, the K-edge imaging technique proposed in this study can be simply implemented by using a single energy bin, and the proposed technique improves contrast without the statistical and mathematical errors, which are caused by subtraction and material decomposition processes and distort the quality of subtracted and decomposed images. On the other hands, the image noise is increased by the defined energy bin, which contains the small number of photons, because the statistical noise is inversely related to the square root of the number of photons, which contributes to the image formation [19]. Thus, the energy bin should be optimized for maximizing the CNR of the CT image obtained from the photon-counting detector.

2.1.2. Projection-based energy weighting imaging

The improvement of contrast in projections results in the contrast improvement in reconstructed images because the image quality properties of reconstructed images are dependent on the image quality properties of projections. The contrast in projections can be improved by the energy-dependent weighting factors, which are obtained from energy-resolved information. Considering a background material with a LAC, $\mu_b(E)$, and a thickness of D, which includes a target material with a LAC, $\mu_t(E)$, and a thickness of d for the photon energy, E, the transmissions of the photons passed through the background material, T_b, and target material, T_t, can be calculated as shown below [20]:

$$T_b(E) = N_b(E)/N_0(E) = \exp(-\mu_b(E)\cdot D) \quad \text{and}$$

$$T_t(E) = N_t(E)/N_0(E) = \exp(-\mu_b(E)\cdot D - (\mu_t(E) - \mu_b(E))\cdot d), \tag{4}$$

where $N_0(E)$, $N_b(E)$, and $N_t(E)$ are the numbers of photons in the incident beam, the beam attenuated by the background material, and the beam attenuated by the background and target materials, respectively. The projection-based energy weighting factor, $\omega^p(E)$, is defined as the difference in the transmissions divided by the sum of the transmissions for maximizing the signal as follows [1,7]:

$$\omega^p(E) = \frac{T_b(E) - T_t(E)}{T_b(E) + T_t(E)}. \tag{5}$$

The projection-based energy weighting factor depends on the energy range defined by the energy bin of the photon-counting detector. Eq. (5) can be rewritten by substituting Eq. (4) as shown below:

$$\omega^p_i(L_i, U_i) = \frac{1 - \exp\left(-d\int_{E=L_i}^{U_i}(\mu_t(E) - \mu_b(E)dE)\right)}{1 + \exp\left(-d\int_{E=L_i}^{U_i}(\mu_t(E) - \mu_b(E)dE)\right)}, \tag{6}$$

where $\omega^p_i(L_i, U_i)$ is the energy weighting factor for an energy bin i defined by the lower energy threshold of L and the upper energy threshold of U. As can be seen from Eqs. (5) and (6), the energy weighting factor increases for the energy ranges, which have the large difference in photon transmissions. It represents that the signal from a low-energy photon is more heavily weighted than that from a high-energy photon. Therefore, the contrast can be improved by using the projection-based energy weighting scheme because the contrast in X-ray images is dominantly determined by low-energy photons. The projections obtained from each energy bin are weighted by the weighting factors calculated from the corresponding energy bins, and then the weighted projections are linearly combined prior to log normalization and reconstruction. The projection-based energy weighting scheme should be also optimized in terms of the number of energy bins and the energy range for each energy bin in order to maximize the image quality.