Material Discrimination with an Energy Binned X-ray CT

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Purpose

Modern x-ray CT systems measure data corresponding to the sum of the energy of x-ray photons incident to a detector. Thus reconstructed values are a kind of average of linear attenuation coefficients (LACs) over the whole energy range. So it is hard to measure the true LAC of a target medium, because an LAC of a medium is a function of x-ray energies [1]-[2]. To discriminate materials many methods have been proposed and most of the methods use dual energy x-rays [3]. However, even though with an x-ray tube, if we could measure an energy spectrum of detected photons with several energy windows with an x-ray CT system, we would be able to identify a medium with its LACs in a region of interest [4]-[7]. And, in addition, several researchers developed a new detector which is able to detect the photon energy of an x-ray [8]-[10]. The identification of a medium with the x-ray CT would enable us to evaluate the degree of calcification in a vein, and to improve the accuracy of treatment planning in a heavy ion therapy. The aim of this study is to accurately identify a medium with an x-ray CT system, in which data are measured with several energy windows.
Methods and Materials

Proposed method

The procedures to determine an unknown object are as follows:

1. Reconstruct four CT images by using the x-ray photons measured with energy windows \(W_1 \sim W_4\) as shown in Fig. 1 on page 5.

2. Set an ROI for each reconstructed image, and calculate mean values \(m_1 \sim m_4\) as shown in Fig. 1 on page 5. This mean value corresponds to an averaged LAC of a narrow and specified energy range.

3. Compare the mean values with a set of pre-calculated reference values \(#_i\) \((i=1 \sim 4)\) of listed given media with the equation shown in Fig. 2 on page 5, and determine a medium whose distance \(d\) is the smallest one. The list of sample materials being evaluated is shown in Fig. 3 on page 6. \(#_i\) is a set of ideal LACs of a known and candidate material.

Simulations

We conducted Monte Carlo simulations with four energy windows. In these simulations we defined a detector with 64 pixels, and the size of a pixel was \(1 \times 1\) \(\text{mm}^2\). The sensitivity and efficiency of the detector was assumed to be 100 % and the energy resolution was 1 keV. From an x-ray source we emitted 90 kV x-rays. The energy spectrum generated was calculated based on a previous report [11]. To reduce the low energy photons we assumed use of an aluminum filter with a thickness of 10 mm. The number of photons emitted was 1,000,000 per detector pixel in a view, and the number of views was 180 over 360 deg. We set five thresholds (40, 50, 60, 70 and 80 keV) for the energy of photons, and calculated the number of photons in the following windows: \(W_1\) (40 ~ 49 keV), \(W_2\) (50 ~ 59 keV), \(W_3\) (60 ~ 69 keV) and \(W_4\) (70 ~ 79 keV). The distance between the x-ray source and an object was 40 cm and the object to the detector was 10 cm. The phantom consisted of five materials (calcium, aluminum, magnesium, ethanol and water). Image reconstruction was performed with a filtered backprojection method with a matrix size of \(64 \times 64\).

Experiments
We conducted experiments with almost the same conditions as those in the simulation. In the experiments we used the CdTe detector 64CHPC-HS1 (Hamamatsu Photonics, Japan). The detector consisted of 64 elements (pixels), with the size of a pixel $1 \times 1 \text{mm}^2$ and its thickness 5 mm. The maximum count rate was $2 \times 10^6 /\text{s} \# \text{mm}^2$. We set five threshold energies in the measurement of x-rays, and measured the number of x-ray photons having energy within a range of the four energy windows. We used the micro-focus x-ray tube L9121 (Hamamatsu Photonics, Japan) in the experiment. The size of a focal spot was 7 µm. We used a tube voltage of 90 kV and a tube current of 10 µA. The geometry of our experimental system was the same as that of the simulation. We used a 10 mm-thick piece of aluminum as a filter to reduce the number of low energy photons, and the data acquisition time was 10 sec/view. The number of projections was 180 over 360 deg. To calculate the reference value we used a measured energy spectrum of the x-ray tube. The energy spectrum was measured with CdTe detector XR-100 (Amptek, USA). Image reconstruction was performed in the same manner as that in the simulation. We used two kinds of liquid medium in a cylinder made of polymethyl methacrylate. We filled the cylinder (diameter: 35 mm) with water or ethanol.

**Accuracy of determination**

The accuracy of determination was calculated with the averaged error ratio (%), that is, $1/4 \times |(m_i-#i)/#i| \times 100$. 


Images for this section:

**Fig. 0:** Energy window setting and reconstructed images.

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\[ d = \frac{1}{4} \sum_{i=1}^{4} \left| m_i - \eta_i \right| \]

where \( \eta_i = \frac{1}{l} \log_e \left( \frac{\sum_{E} w_i p(E) \exp\{-l\mu(E)\}}{\sum_{E} w_i p(E)} \right) \)

- \( l \) : distance passed through (cm)
- \( E \) : energy of photons (keV)
- \( \mu(E) \) : linear attenuation coefficient (1/cm)
- \( p(E) \) : energy spectrum

**Fig. 0:** Difference between the measured LACs and ideal LACs of a candidate medium.

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**Fig. 0**: LACs of several media as a function of the four energy bins.
Results

Simulations

Figure 1 on page 9 shows the results of simulations; (A) shows the reconstructed image for each energy window, and (B) shows the profiles along a line indicated by two arrows. In each image we set five ROIs and measured the average LACs.

Figure 2 on page 9 shows the distance d between the set of measured LACs and that of ideal LACs for candidate materials. We determined that the five unknown materials were calcium, aluminum, magnesium, ethanol and water, because these distances were the smallest ones.

Experiments

Figure 3 on page 10 shows the results of experiments; (A) shows the reconstructed image for each energy window and (B) shows the profiles along a line indicated by two arrows. In each image we set an ROI and measured the average LACs.

Figure 4 on page 11 shows the distance d between the set of measured LACs and that of ideal LACs for candidate materials. We determined that these unknown materials were ethanol and water, because these distances were the smallest ones.

The results of simulations and experiments showed that our proposed method could identify several media accurately. In the experiment the quality of reconstructed images was degraded due to the lack of photons, especially in the lower energy range. However, we used the mean value in the ROI, and thus the accuracy was not so affected by the distortion. The accuracy of identification was less than 0.1 % for simulated data and around 1% for experimental data.
Fig. 0: Simulation results. (A) Reconstructed images of a phantom consisted of five media for four energy bins, (B) Profiles of reconstructed images along a line indicated by two arrows.
Fig. 0: Material discrimination for the simulation data. From the distance $d$ between the measured LACs and LACs of candidate materials, each unknown medium was determined correctly.

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Fig. 0: Experimental results. (A) Reconstructed images of water and ethanol phantoms for four energy bins, (B) Profiles of reconstructed images along a line indicated by red arrows.

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Fig. 0: Material discrimination for the experimental data. From the distance $d$ between the measured LACs and LACs of candidate materials, the unknown media were determined correctly.

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Conclusion

We evaluated the validity of our proposed identification method of a medium with a photon counting x-ray CT. The results showed that the proposed method made it possible to identify the medium of a targeted object.
References


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