The potential of spectral-CT for material decomposition with gold-nanoparticle and iodine contrast

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Abstract— **The objective of the this study was to demonstrate feasibility of using gold contrast-agent as a new contrast agent for spectral-computed tomography (CT) system and decompose the iodine and gold materials in the spectral-CT system using K-edge imaging technique. Recently, gold based nanoparticles contrast-agent has been introduced for vulnerable plaque imaging in CT system. The spectral-CT system equipped with Cadmium Zinc Telluride (CZT)-based photon-counting detector has energy-discrimination capabilities and high resolution image acquisition capabilities. We performed a simulation study using the Geant4 Application for Tomographic Emission (GATE) simulation. The CZT detector contained four CZT crystals and total detector length is 51.2 mm with 64 channel array. The results showed that the contrast-to-noise ratios of iodine and gold contrast-agent materials in energy window included K-edge energy of materials (33-49 keV for iodine, 66-81 keV for gold) were increased approximately 1.9 and 1.7 times higher than others. These results also show the possibility of potential of using two contrast-agents at a time to provide the various information of image such as plaque vulnerability assessment.**

Keywords— **Gold-nanoparticle, K-edge imaging, Photon counting detector, Spectral-CT**

I. INTRODUCTION

Contrast agents in X-ray radiographic imaging provide morphologic data. Iodinated agents are the most commonly used contrast materials to find out coronary artery shape. Recently, gold based nanoparticles contrast-agent has been introduced for vulnerable plaque imaging in computed tomography (CT). The gold-nanoparticle can be used to identify the degree of inflammation in the plaque at coronary artery. However, mean size of coronary artery is about 0.3 mm. Therefore, high resolution detection system needs to assess the vulnerable plaques which are smaller than coronary artery [1].

Recently, the spectral-CT system equipped with Cadmium Zinc Telluride (CZT)-based photon-counting detector has also been developed. This system has energy-discrimination capabilities and high resolution image acquisition capabilities. In addition, the material decomposition technique can be applied with energy-dependent spectral information [2-4].

In this study, we focused on the feasiblility to accurately measure iodine, gold contrast-agent concentrations in the high resolution spectral-CT system. The accuracy of decomposition images was evaluated with K-edge imaging technique using five energy windows.

II. METHODS AND MATERIALS

To validate the potential of development new contrast agent for spectral-CT system with material decomposition. We evaluated the performance of contrast agents in spectral-CT system with CZT-based photon counting detector using Monte Carlo simulations.

A. CZT-based photon counting detector and Spectral-CT system

The spectral-CT system is made up of a micro-focus X-ray tube (L8601-01, Hamamatsu, Japan), a high precision motor-controlled rotary stage and a CZT based- photon counting detector (eValuator-2500, eV Products, Saxonbrug, PA) and installed on the optical table as shown in figure 1.

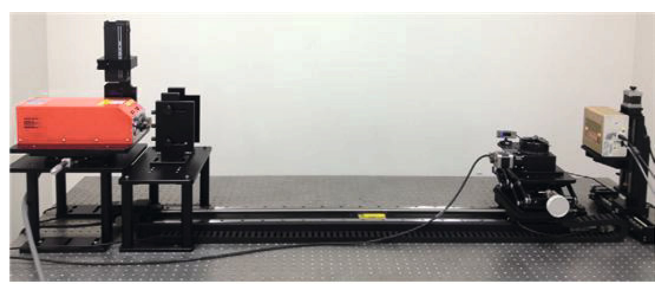

Fig. 1 From left to right side, spectral CT system with the micro-focus X-ray tube, additional 2 mm aluminum X-ray filter, high precision motor and CZT-based photon-counting detector.

The CZT detector contained four CZT crystals. Each crystal contained 0.8 x 0.8 mm^2 pixels and has a length of 12.8 mm, a thickness of 3 mm. Total detector length is 51.2 mm with 64 channel array.

The X-ray tube focal spot is 5μm and beryllium exit window has a thickness of 0.15 mm with a 39° tungsten target

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angle. The X-ray beam was filtered using 2mm aluminum and collimated to provide a fan beam of X-ray irradiation in front of the detector by a 0.7 mm brass collimator.

B. Energy-dependent X-ray attenuation

In X-ray spectral-CT, the linear attenuation μ(E) is determined by the energy-dependent probability of Compton scattering and photoelectric absorption cross sections. μ(E) can be described by weighted combination of two basis functions

$$\mu(E) = \rho(a_1 f_{Compton}(E) + a_2 g_{PE}(E)) \quad (1)$$

where ρ is the material's mass density, $f_{Compoton}(E)$ approximates the energy dependence of Compton scattering and photoelectric absorption [5].

In the presence of elements with a high atomic number Z, the equation 1 has to be modified to

$$\mu(E) = \rho(a_1 f_{Compton}(E) + a_2 g_{PE}(E) + a_3 g_{PE-Kshell}(E) \quad (2)$$

The K-edge discontinuities are characteristics of the elements in a material and produce a sudden increased in the attenuation coefficient of a material as shown in figure 2.

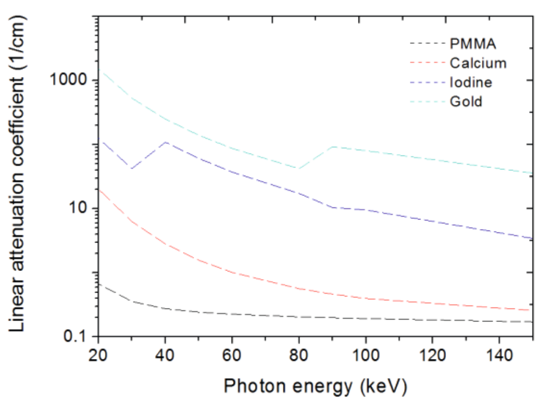

Fig. 2 Linear attenuation coefficient as a function of photon energy for PMMA, calcium, iodine and gold.

C. Monte Carlo simulation

Geant4 Application for Tomographic Emission (GATE) simulation

Monte Carlo simulations were performed to simulate the spectral-CT system based on CZT photon counting detector and evaluate image quality of two contrast agents using GATE version 6.1. GATE is dedicated to numerical simulations in medical imaging and developed by the international OpenGATE collaboration [6]. In addition, the X-ray spectrum was simulated using SRS-78 program, a diagnostic X-ray spectra generator, for the X-ray transport simulation.

Phantom description

Polymethyl methacrylate (PMMA) phantom was 3 cm in both height and diameter. The phantom contained several materials, which were cylindrical in shape and 0.6 cm in diameter to determine the size of artery with vulnerable plaque. Each hole contained a gold, iodine, calcification and air, respectively. The schematic of the phantom is shown in figure 3.

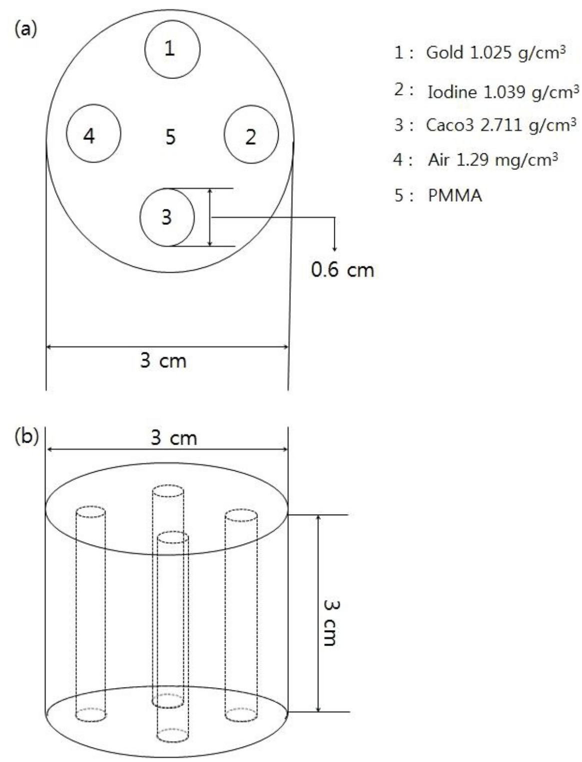

Fig. 3 Phantom used in simulations : Each hole filled with gold, iodine, calcification and air. (a) top view and (b) side view.

D. Data analysis

Dual-energy index (DEI)

The degree of spectral differentiation of different materials can be determined by using spectral dependence of the X-ray absorption in the object as [7]

$$DEI = \frac{x_{low} - x_{high}}{x_{low} + x_{high} + 200} \quad (3)$$

Contrast-to-noise ratio (CNR)

The contrast-to-noise ratio (CNR) is an object size-independent measure of the signal level in the presence of noise and is the image quality determination. The contrast is the relative difference of signal intensities in two adjacent regions of an image and noise is the standard deviation in the number of quanta in an equal area of uniform background. Then, the CNR is given by

$$CNR = \frac{|A-B|}{\sqrt{A_{SD}^2+B_{SD}^2}} \tag{4}$$

III. Results

Figure 4 shows the calculated separation angles for all contrast-agent materials. The separation angle Θ is defined as the angle between vector of linear attenuations coefficients for two materials and we calculated mean separation angle Θ by using adjacent energy window at K-edge range [7]. The energy resolved photon counting detector used 5 energy thresholds (23-32 keV, 33-49 keV, 50-65 keV, 66-81 keV, 82-120 keV). Comparing attenuation coefficients below and above a K-edge for three materials provided high separation constant with respect to the background.

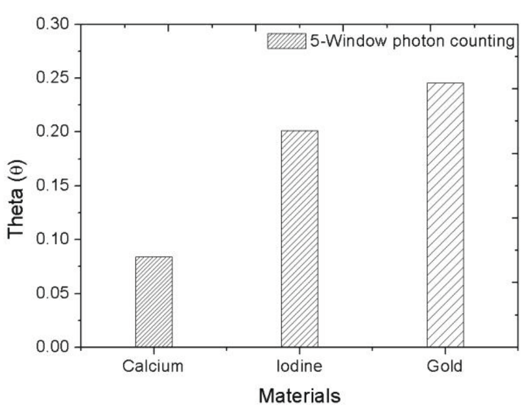

Fig. 4 The separation angles (mean cosΘ) were computed for all contrast-agent materials in spectral-CT system with CZT-based photon-counting detector.

We set five energy windows below and above the K-edge absorption energies of gold and iodine, respectively. Figure 5 shows the reconstructed image of the phantom in five energy windows.

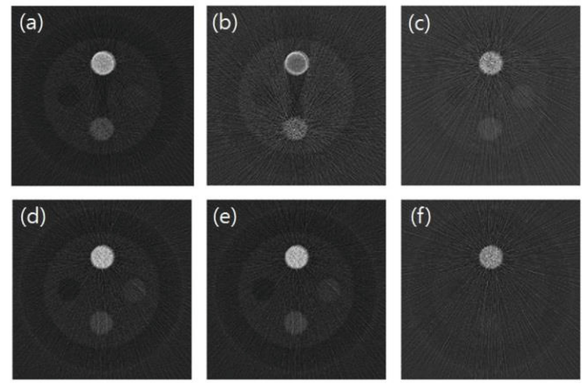

Fig. 5 Reconstructed image of the integrated (a), 23-32 keV (b), 33-49 keV (c), 50-65 keV (d), 66-81 keV (e), 82-120 keV (f) energy window.

For quantitative phantom study, the CNR between the contrast-agent materials and PMMA for each energy thresholds are calculated and plotted in figure 6 [8].

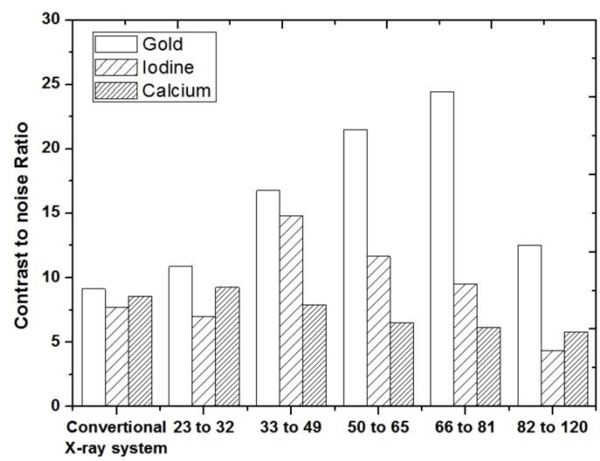

Fig. 6 CNR of gold, iodine and calcium in conventional X-ray system and spectral-CT system with CZT-based photon-counting detector.

The CNRs of iodine and gold contrast-agent materials in some energy threshold included K-edge energy of materials (33-49 keV for iodine, 66-81 keV for gold) were increased approximately 1.9 and 1.7 times higher than the other energy windows.

Figure 7 shows the K-edge decomposition images on the phantom. The bright spot on both images, however, both K-edge decomposed images properly identified iodine and gold materials in the phantom [9, 10].

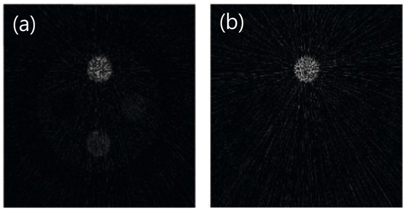

Fig. 7 Results of K-edge decomposition performed on phantom in spectral-CT system with CZT-based photon-counting detector. (a) iodine, (b) gold materials.

IV. CONCLUSIONS

The goal of the paper was to show that it is feasible to accurately measure iodine, gold contrast-agent concentrations in the spectral-CT system. While gold contrast-agent material would be identified in 66-81 keV energy window, iodine contrast-agent material would be identified in 33-49 keV energy window. Specially, we could use a gold contrast-agent material as a new biomarker in the spectral-CT system [5]. These results also show the possibility of potential of using two contrast-agents at a time to provide the various information of image such as plaque vulnerability assessment [8-10].

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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