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Dual-energy-dispersive X-ray computed tomography using a ceramic-substrate silicon diode

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Abstract

X-ray photon counting was performed using a silicon X-ray diode (Si-XD) at tube voltages ranging from 35 to 60 kV. The Si-XD is a high-sensitivity Si photodiode selected for detecting X-ray photons, and the photons are directly counted using the Si-XD. Electric charges produced in the diode are converted into voltages and amplified using charge-sensitive and shaping amplifiers. To investigate the X-ray-electric conversion, we measured event-pulse-height (EPH) spectra using a multichannel analyzer (MCA). In the EPH spectra, the maximum photon energy corresponded to the tube voltage, and the photon count substantially increased with decreasing photon energy. Dual-energy computed tomography is accomplished by repeated linear scans and rotations of an object, and two different energy tomograms were obtained simultaneously using two comparators at a tube current of 1.5 mA and a tube voltage of 60 kV. Iodine K-edge imaging was accomplished with an energy range of 35-60 keV.

Keywords : X-ray CT, energy-dispersive CT, dual-energy CT, Si X-ray diode, two comparators

1. Introduction

Recently, we found a high-sensitivity ceramic-substrate silicon photo diode for detecting X-rays and performed computed tomography (CT) without scintillators [1, 2]. In this silicon X-ray diode (Si-XD), X-ray photons are directly detected from the front Si side, and penetrating photons are also detected from the back side by Compton scattering.

We usually perform photon-counting energy-dispersive CT (ED-CT) [3−7] using a cadmium

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telluride (CdTe) detector with an energy resolution of 1 % at 122 keV to carry out enhanced K-edge imaging using iodine (I) and gadolinium (Gd) contrast media. In addition, K-edge imaging can also be carried out using the Si-XD and a single comparator for determining a threshold energy. Therefore, dual-energy CT (DE-CT) can be performed using two comparators to determine the two threshold energies.

In this research, our major objectives are as follows: to load two high-speed comparators, to reduce electric noises using frequency-voltage converters (FVCs) [5 − 7], and to carry out DE-CT. Therefore, we measured event-pulse-height (EPH) spectra using a Si-XD. We also developed a DE-CT system using a Si-XD detector and obtained two different energy tomograms simultaneously.

2. Experimental setups

2.1. EPH spectra measurement

Figure 1 shows a block diagram for measuring EPH spectra using a Si-XD. The X-ray photons from an X-ray tube are detected by the Si-XD, and electric charges produced in the Si-XD are converted into voltage and amplified by the charge-sensitive and shaping amplifiers. The event pulses from the shaping amplifier are sent to an MCA (γPGT, MCA 4000) to measure EPH spectra with changes in the tube voltage. In the Si-XD, a ceramic-type Si photodiode (Hamamatsu, S1087-01) is covered with an Al cap with a 0.2-mm-thick Al window, and the dimensions of the light-receiving surface are $1.3 \times 1.3\,mm^2$. Successively, the Si-XD is shielded using both an Al case with a 25-μm-thick Al window and a BNC connector, and the bias voltage of the Si-XD is 10 V. The distance between the target in the X-ray tube and the shielded Si-XD was 1.00 m.

In the photon-energy calibration, we utilized logarithmic spectra with a minimum photon count of 10 to determine the maximum energy. Because it is unable to regulate the tube voltage to 35 kV using the X-ray generator in the CT system, we used a soft X-ray generator (R-tec, RIX-20) with a 0.5-mm-thick beryllium window with tube voltages ranging from 15 to 100 kV.

2.2. DE photon counting

Figure 2 shows a block diagram of DE X-ray photon counting using two sets of comparators and FVCs. The event pulses from the shaping amplifier are sent to the two comparators simultaneously, and logical pulses from the two comparators are input to the FVCs. In an FVC, the count rates are converted

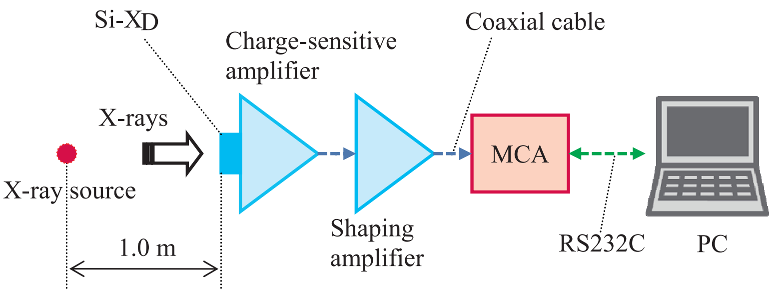

Fig. 1. Block diagram for measuring EPH spectra using a Si-XD.

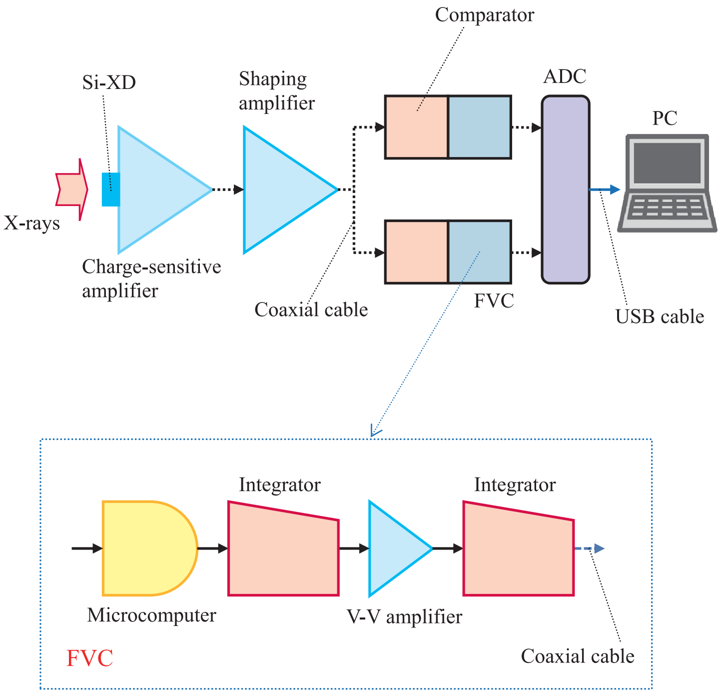

Fig. 2. Block diagram for performing dual-energy X-ray photon counting using a Si-XD. Photons are counted directly using the Si-XD without a scintillator.

into voltages using an integrator to compensate for the voltage fluctuation caused by the statistical error. The output voltages from the two FVCs are sent to a personal computer (PC) through an analog-digital converter (ADC; Contec, AI-1608 AY-USB). The comparators are used to determine the two threshold energies, and the maximum energy of 60 keV corresponds to a tube voltage of 60 kV.

The block diagram of the FVC is shown in the same figure. When a logical pulse from the comparator is sent to a microcomputer, the microcomputer produces a 5-μs-width 5-V-height logical pulse. The MC output is then input to the first integrator with a time constant of 50 ms to produce a long pulse for piling up. The integrator output is amplified using a voltage-voltage (V-V) amplifier, and electric noises are reduced using the second integrator.

2.3. DE-CT system

The experimental setup of the main components in the ED-CT system is shown in Fig. 3. The distance between the X-ray source and the Si-XD detector is 1.00 m, and the distance from the center of the turntable to the detector is 40 mm to decrease the magnification ratio of an object. The Si-XD detector with the charge-sensitive amplifier oscillates on the scan stage with a maximum velocity of 25 mm/s and a stroke of 60 mm. The X-ray projection curves for tomography are obtained by repeated linear scans and rotations of the object, and the scanning is conducted in both directions of its movement. Two step values of the linear scan and rotation are selected to be 0.5 mm and 1.0°, respectively. Using this CT system, the exposure time is 10 min.

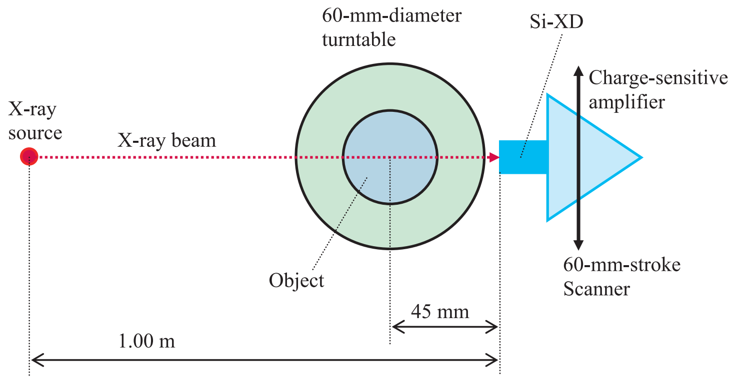

Fig. 3. Experimental setup of the main components in a DE-CT system using a 25-mm/s Si-XD scanner. CT is carried out by repeated linear scanning and rotation of the object.

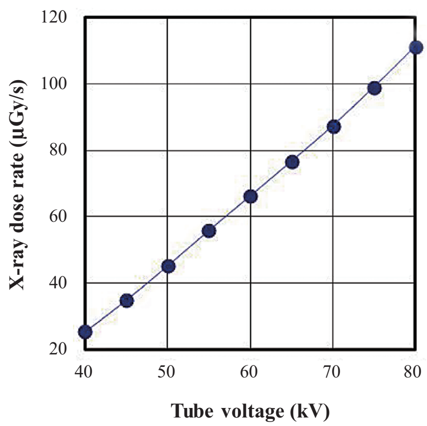

Fig. 4. X-ray dose rate measured using an ionization chamber placed 1.0 m from the X-ray source at a tube current of 1.5 mA.

3. Results

3.1. X-ray dose rate

The measurement of X-ray dose rate is very important for inferring the skin dose for objects. The X-ray dose rate from the X-ray generator was measured using an ionization chamber placed 1.0 m from the X-ray source (Fig. 4). At a constant tube current of 1.5 mA, the X-ray dose rate increased with increasing tube voltage. The X-ray dose rate at a tube voltages of 60 kV was 66.2 μGy/s, respectively.

3.2. X-ray spectra

Standard X-ray spectra used for CT are shown in Fig. 5. To measure spectra, we used a CdTe detector (Amptek, XR-100T). At a tube voltage of 60 kV without filtration, the maximum energy

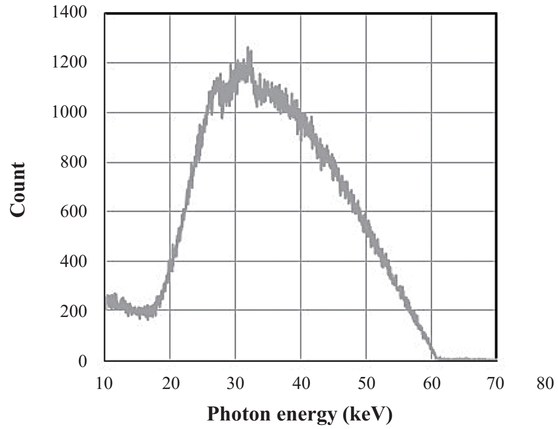

Fig. 5. Standard X-ray spectra measured using a CdTe detector at a tube voltage of 60 kV.

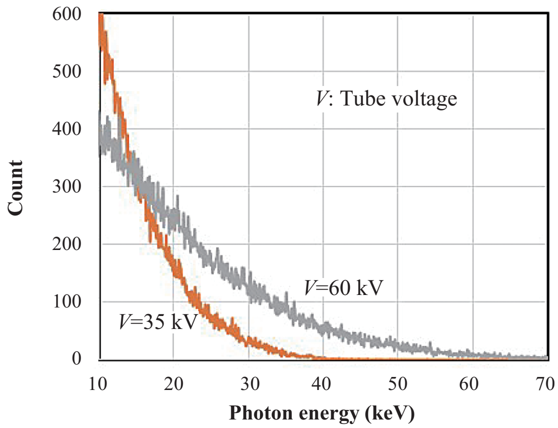

Fig. 6. EPH spectra at the indicated tube voltages. In all conditions, the photon count substantially increased with decreasing photon energy. The maximum photon energy corresponded to the tube voltage.

corresponded to tube voltage, and the peak energy was 31 keV.

3.3. EPH spectra

The EPH spectra obtained using the Si-XD is shown in Fig. 6. In the EPH spectra, the maximum photon energy corresponded to the tube voltage. In other results, the maximum photon energy seldom varied by the filtration at a constant tube voltage. In addition, the photon count substantially increased with decreasing photon energy. Therefore, X-ray photons were detected directly by the Si substrate, and the scattering photons from the ceramic were also detected as low-energy photons. Thus, the threshold energy could be regulated by the comparator.

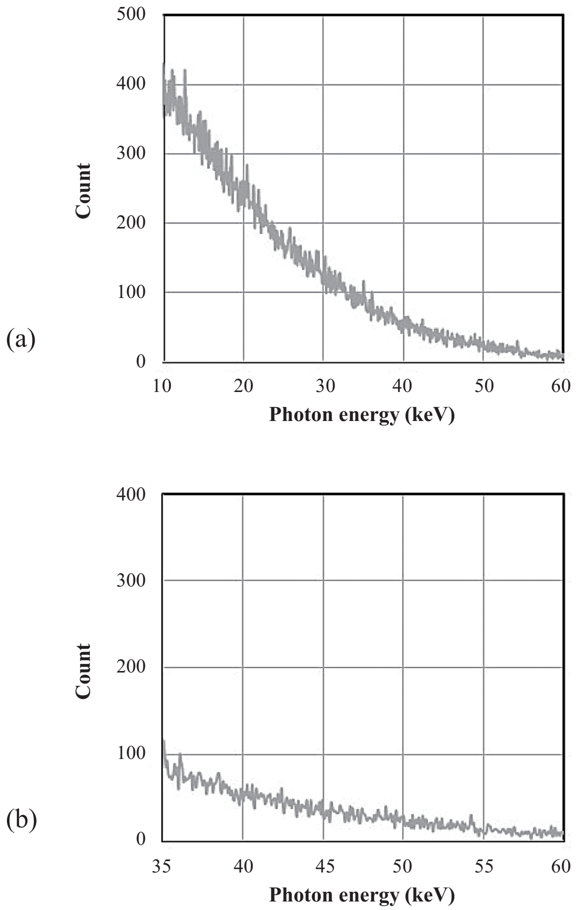

Fig. 7. Selected EPH spectra for DE-CT at a tube voltage of 60 kV. (a) Selected photons with energies ranging from 15 to 60 keV and (b) with energies ranging from 35 to 60 keV.

Figure 7 shows the selected spectra for the DE-CT at a tube voltage of 60 kV. Entire photons with an energy range of 15-60 keV are useless for imaging I atoms [Fig. 7(a)]. On the contrary, photons with an energy range of 35-60 keV are useful for performing I-K-edge CT [Fig. 7(b)].

3.4. Tomography

Tomography was performed at a scan step of 0.5 mm and a rotation step of 1.0°, and the maximum and minimum densities are denoted as black and white, respectively. On the other hand, tomograms are obtained as JPEG files, and the maximum and minimum gray-value densities are defined as white and black, respectively.

Figure 8 shows tomograms of two 15-mm-diam glass vials filled with I media of two different densities (iopamidol), 15 and 30 mg/ml, respectively. At a tube voltage of 60 kV, the image density

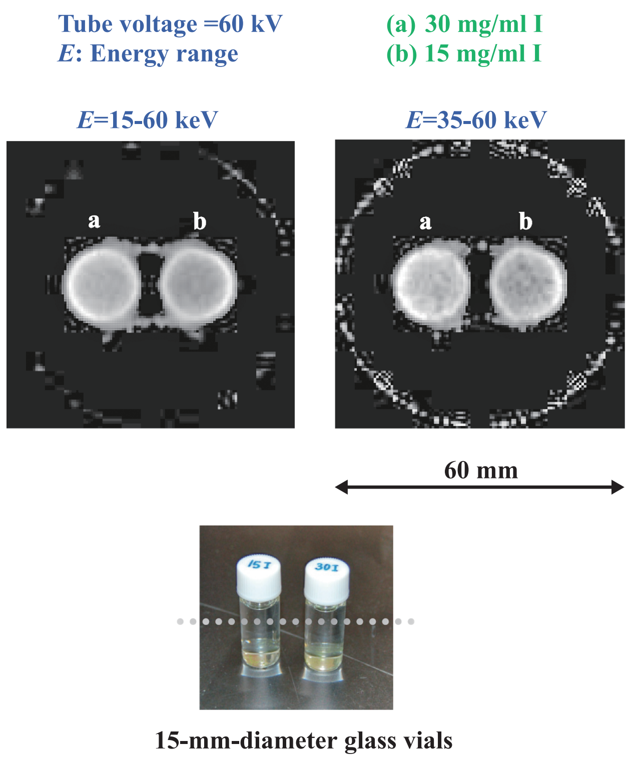

Fig. 8. Tomograms of two 15-mm-diameter glass vials filled with two I media of different densities. At a tube voltage of 60 kV, the image density difference between the two media increased with increasing threshold energy from 15 to 35 keV.

difference between the two media increased with increasing threshold from 15 to 35 keV.

The result of the tomography of a dog-heart phantom is shown in Fig. 9. The phantom was made from a real rabbit head, and the blood vessels were filled with gadolinium oxide (Gd_2O_3) microparticles. The animal operation was carried out in accordance with the animal experiment guidelines of our university. Radiography (angiography) was performed for reference with a flat-panel detector (FPD; Rad-icon Imaging, 1024 EV) to observe blood vessels. In radiography, fine blood vessels were observed because the pixel sizes are $48 \times 48\ \mu m^2$. In tomography, when the threshold was increased from 15 to 35 keV, the muscle density decreased, and the image contrast of the arteries improved.

4. Discussion

In this PC-CT with a tube voltage of 60 kV, a current of 1.5 mA, and a threshold of 15 keV, the maximum count rate was 9.5 kcps/pixel, and the photon count per measuring point was calculated as 0.19 kc/pixel.

The pixel sizes for reconstructing CT image were equal to the scan steps and had values of 0.5×0.5

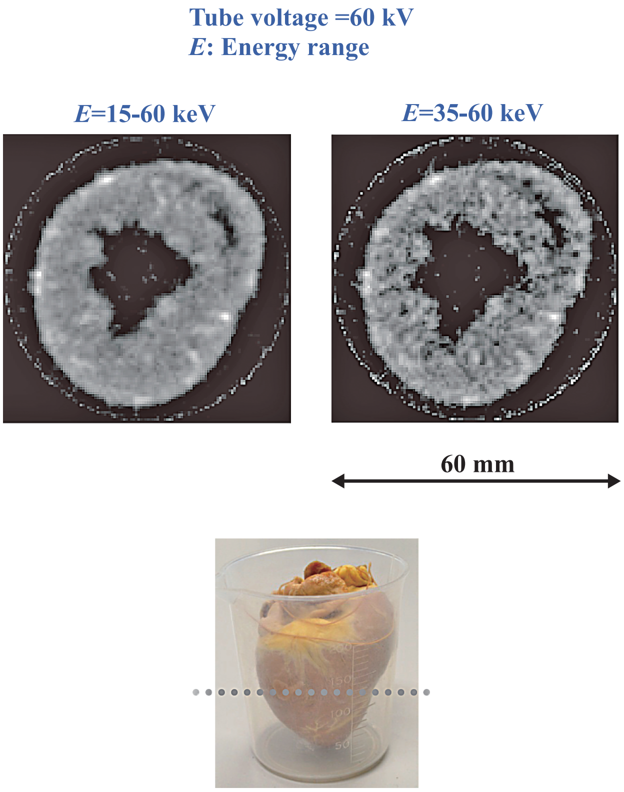

Fig. 9. Tomography of a dog-heart phantom. When the threshold energy was increased, the muscle density decreased, and arteries were visible.

mm^2. However, the spatial resolution is primarily determined by the dimensions of the X-ray-receiving area which are equal to the Si-XD pixel sizes of $1.3 \times 1.3\,mm^2$.

In the DE-CT, the image contrast of I media improved with increasing threshold from 15 to 35 keV, because the X-ray photons with energies beyond 33.2 keV are absorbed effectively by the I atoms. Using this Si-XD, although the threshold could be determined, the maximum energy for the CT was determined by only the tube voltage; most X-rays were detected as low energy photons. Therefore, the average photon energy increases with increasing threshold at a constant tube voltage.

5. Conclusions

We performed DE X-ray photon counting and measured the EPH spectra using a ceramic-substrate Si-XD and an MCA. In the EPH spectra, the photon count substantially increased with decreasing photon energy.

In the DE-CT, the threshold energy could be determined by the comparator, and the image contrast of I media improved with a threshold energy of 35 keV and a count rate of 2.5 kcps.

Acknowledgments

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