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Quasi-monochromatic X-ray computed tomography system using a cadmium telluride detector and its application to gadolinium imaging

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Abstract

Quasi-monochromatic photon counting was performed using a cadmium telluride detector and an energy-selecting device, consisting of two comparators and a microcomputer (MC). The two threshold energies are determined using low and high-energy comparators, respectively. The MC produces a single logical pulse when only a logical pulse from a low-energy comparator is input to the MC. Next, the MC never produces the pulse when two pulses from low and high-energy comparators are input to the MC, simultaneously. The logical pulses from the MC are input to a frequency-voltage converter (FVC) to convert count rates into voltages; the rate is proportional to the voltage. The output voltage from the FVC is sent to a personal computer through an analog-digital converter to reconstruct tomograms. The X-ray projection curves for tomography are obtained by repeated linear scans and rotations of the object at a tube voltage of 90 kV and a current of 11 μA. Gadolinium (Gd) K-edge CT was performed using contrast media and X-ray photons with a count rate of 1.8 kilocounts per second and energies ranging from 51 to 72 keV, since these photons with energies beyond I-K-edge energy 50.2 keV are absorbed effectively by Gd atoms.

Keywords: quasi-monochromatic photon counting, CdTe detector, energy-selecting device, monochromatic X-ray CT, Gd imaging

1. Introduction

Recently, we have developed several photon-counting energy-dispersive X-ray computed tomography (ED-CT) systems [1−6] to perform enhanced K-edge imaging using iodine (I) and gadolinium (Gd) contrast media. In particular, X-ray photons with energies just beyond Gd-K-edge

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energy of 50.2 keV are useful for performing the K-edge imaging because these photons are absorbed effectively by Gd atoms.

In the former experiment, although we used a multichannel analyzer (MCA) to select a photon-energy range for K-edge imaging, the range can be selected using two comparators. In this case, quasi-monochromatic ED-CT is performed by photon-count subtraction using a computer (PC) program. Therefore, we have developed an energy-selecting device (ESD) [7] consisting of two high-speed comparators and a microcomputer (MC) and performed the subtraction using the MC program.

In this research, our major objectives are as follows: to load the ESD into an ED-CT system, to perform photon-count subtraction using an MC, and to carry out quasi-monochromatic CT. Therefore, we used an ESD and loaded it in the ED-CT system with a cadmium telluride (CdTe) detector. We also performed Gd-K-edge CT for imaging two vials and a rabbit-head phantom filled with Gd media at a tube voltage of 90 kV and a photon count rate of 1.8 kilocounts per second (kcps).

2. Experimental setup

2.1. Quasi-monochromatic photon counting

Figure 1 shows the block diagram for performing quasi-monochromatic X-ray photon counting using a CdTe detector (Amptek, XR-100T). The X-ray photons are absorbed by the CdTe detector, and the electric charges produced in the detector are converted into voltages and amplified using charge-sensitive and shaping amplifiers. The event pulses from the shaping amplifier are sent to an ESD. The ESD consists of two comparators and an MC (Atmel, ATMEGA168P-20PU). The low and high-threshold energies are determined using low-energy (LEC) and high-energy comparators (HEC), respectively. The MC produces a 10-μs-width positive single logical pulse when only a logical pulse from the LEC is input to the MC. Next, the MC never produces the pulse when two pulses from the two comparators are input to the MC, simultaneously.

The logical pulses from the MC are input to a frequency-voltage converter (FVC) [6] to convert

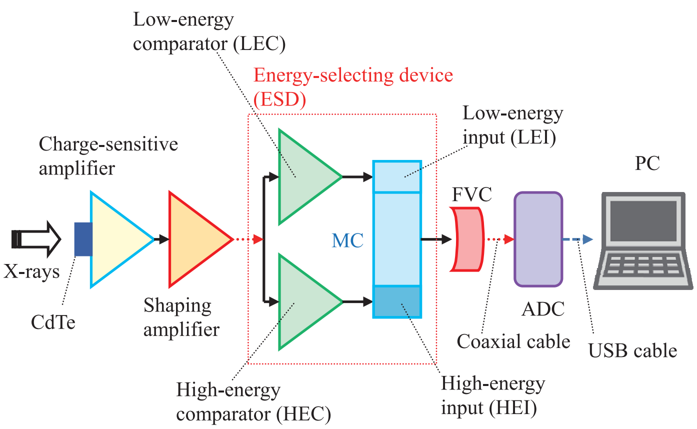

Fig. 1. Block diagram for counting quasi-monochromatic X-ray photons using a CdTe detector and an ESD. The ESD consists of a LEC, a HEC, and an MC.

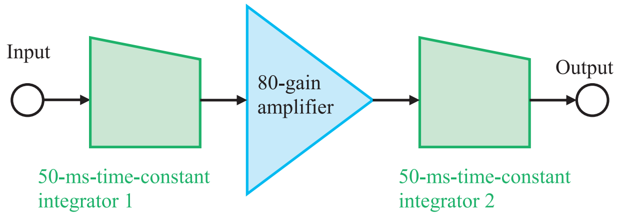

Fig. 2. Block diagram of the FVC. The logical pulses from the MC are converted into long-pulse voltages and piled up in the first integrator, and the integrator output is amplified by a V-V amplifier. The second integrator is used to reduce the electric noises.

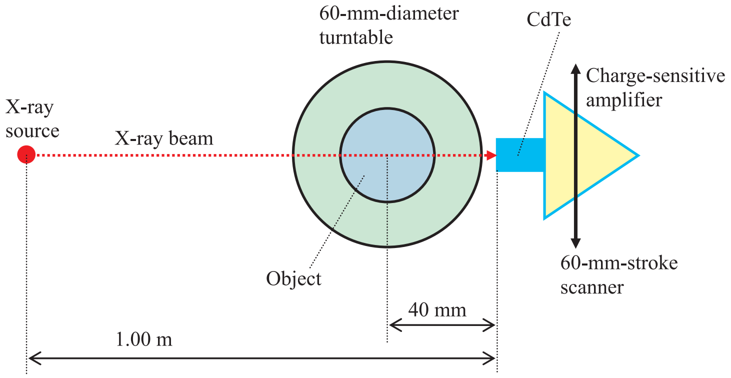

Fig. 3. Experimental setup of the main components in the quasi-monochromatic ED-CT system. The ED-CT is performed by repeated linear scans and rotations of the object.

count rates into voltages; the rate is proportional to the voltage. The FVC consists of two integrators and a voltage-voltage (V-V) amplifier (Fig. 2). The logical pulses from the MC are shaped into long pulses and piled up in the first integrator, and the output voltage is amplified using the V-V amplifier with an operational amplifier. The electric noises are reduced using the second integrator. The output voltage from the FVC is sent to a PC through an analog-digital converter (ADC) to reconstruct tomograms.

2.2. CT system

Figure 3 shows the experimental setup of the main components in the quasi-monochromatic ED-CT system. The distance between the X-ray source and the detector set is 1.00 m, and the distance from the center of turntable to the detector set is 40 mm to decrease magnification ratio of an object. A 1.0-mm-diam 2.0-mm-thick lead pinhole is set in front of the CdTe detector to improve the spatial resolution. The CdTe 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, the scanning is conducted in both

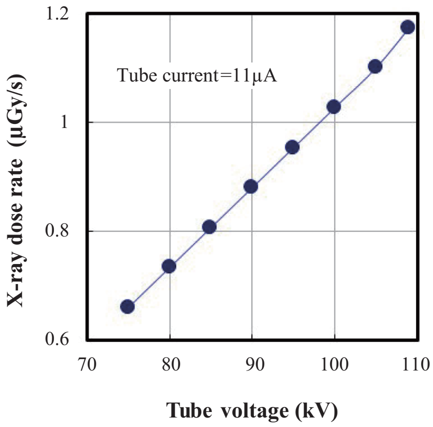

Fig. 4. X-ray dose rate measured at 1.0 m from the X-ray source and a tube current of 11 μA.

directions of its movement, and the tomograms are reconstructed using the simplest convolution back projection method. Both scan stage and turntable are driven by the two-stage controller. Two step values of the linear scan and rotation are selected to be 0.5 mm and 1.0°, respectively, and the exposure time for CT is 10 min.

3. Results

3.1. X-ray dose rate

The measurement of X-ray dose rate is quite important for inferring the skin dose for objects. The X-ray dose rate from an X-ray generator was measured using an ionization chamber (Toyo Medic, RAMTEC 1000 plus) at a tube current of 11 μA without filtration. The chamber was placed 1.0 m from the X-ray source. At a constant tube current, the X-ray dose rate increased with increasing tube voltage (Fig. 4). At a tube voltage of 90 kV, the X-ray dose rate was 0.88 μGy/s.

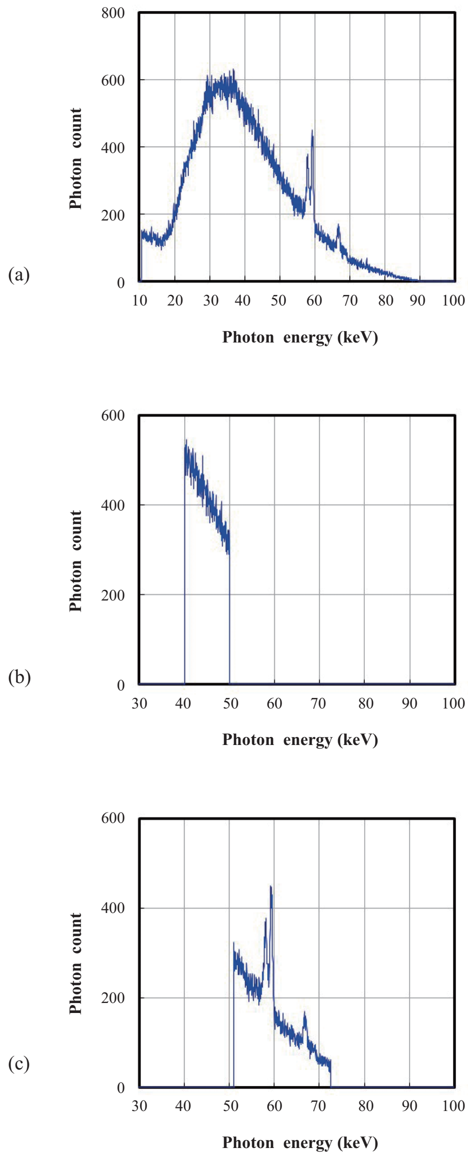

Fig. 5. The X-ray spectra measured using the CdTe detector in the quasi-monochromatic ED-CT system. (a) Entire spectra with energies ranging from 10 to 90 keV, (b) discriminated photons with energies ranging from 40 to 50 keV, and (c) discriminated photons with energies ranging from 50 to 72 keV for Gd-K-edge CT.

3.2. X-ray spectra

To measure X-ray spectra, we used the CdTe detector in the quasi-monochromatic ED-CT system (Fig. 5). In the entire spectra with energies ranging from 10 to 90 keV, the bremsstrahlung peak energy was 33 keV [Fig. 5(a)]. The X-ray photons with

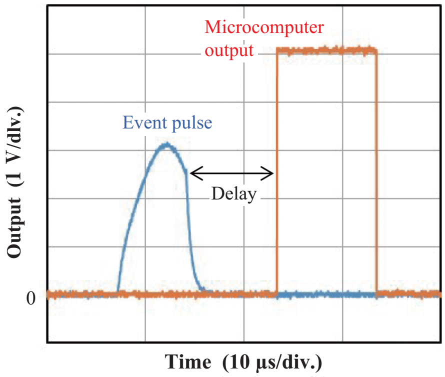

Fig. 6. Time relationship between the event-pulse and the MC outputs.

energies ranging from 40 to 50 keV are useless for obtaining high-contrast Gd images, since these photons easily penetrate Gd atoms [Fig. 5(b)]. In contrast, the enhanced Gd-K-edge imaging can be performed using photons with energies ranging from 51 to 72 keV [Fig. 5(c)].

3.3. Electric characteristics

To measure the output voltages, we used a digital oscilloscope (Tektronix, TDS 2012C). Figure 6 shows the time relationship between the event pulse from the shaping amplifier and the MC output; these outputs were measured simultaneously. The pulse width of the MC output was regulated to 10 μs by the MC program. Although the delay time was not set at a threshold energy of 51 keV, the delay time between the event-pulse fall and the MC-voltage rise was 9 μs.

3.4. Tomography

Tomography was performed at a tube voltage of 90 kV and a tube current of 11 μA, and the reconstructed maximum and minimum relative photon counts are denoted in 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.

Tomograms of two glass vials filled with Gd media (meglumine gadopentetate) of two different densities 15 and 30 mg/ml are shown in Fig. 7. Compared with a tomogram using photons below 50 keV, the image density difference between the two media was large utilizing Gd-K-edge CT.

The result of the tomography of a rabbit-head phantom is shown in Fig. 8. Blood vessels are filled with gadolinium oxide (Gd_2O_3) microspheres. The animal operation was carried out in accordance with the animal experiment guidelines of our university. Using Gd-K-edge CT, the image density of muscle decreased, and the image contrast of blood vessels was high.

4. Discussion

We carried out quasi-monochromatic X-ray photon counting using a CdTe detector to perform Gd-K-edge CT with a maximum count rate of 1.8 kcps. Therefore, the maximum count per measuring point

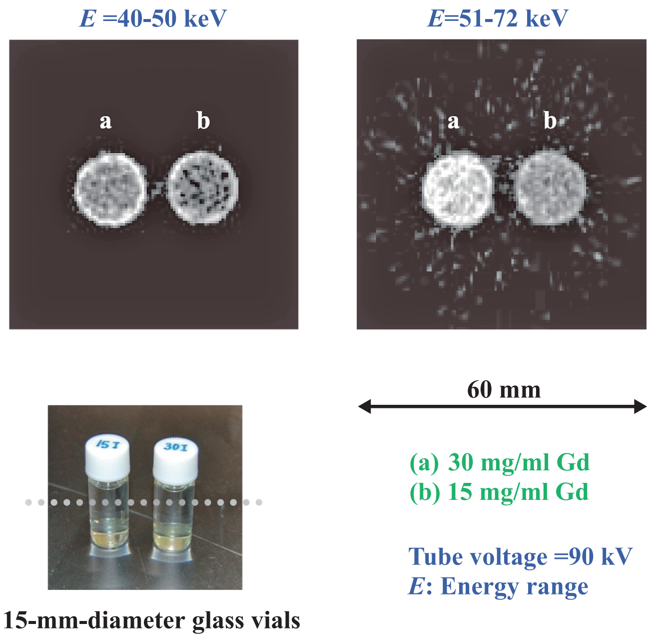

Fig. 7. Tomograms of two glass vials filled with Gd media of two different densities of 15 and 30 mg/ml.

was 36 counts with a scan step of 0.5 mm and a Si-PIN-scan velocity of 25 mm/s. To perform quasi-monochromatic ED-CT, an FVC was used to compensate for the image granulation owing to low count rates and to convert the count rates into voltages.

The image quality improves with increasing count rate, and the maximum rate described above was a lower-limit value for the Gd-K-edge CT. To solve this, it is necessary to develop a high-count-rate detector with a high energy resolution.

The pixel dimensions of the reconstructed CT image were $0.5 \times 0.5\ mm^2$ because the scan step was 0.5 mm. However, the original spatial resolution was primarily determined by the pinhole diameter of 1.0 mm, and the spatial resolutions were $1.0 \times 1.0\ mm^2$.

5. Conclusions

We used an ESD consisting of two comparators and an MC to count X-ray photons between the two threshold energies. The MC produced a single logical pulse when only a logical pulse from the LEC was detected. Thus, the MC performed the photon-count energy subtraction at a tube voltage of 90 kV and a current of 11 μA.

In the spectrum measurement with energies ranging from 10 to 70 keV, the total count rate was 9.0 kcps under the CT condition. To perform Gd-K-edge CT, we selected photons with energies ranging from 51 to 72 keV, and Gd contrast media were observed at high contrast with a count rate of 1.8 kcps. On the contrary, low-contrast tomograms of Gd media were obtained using photons with energies

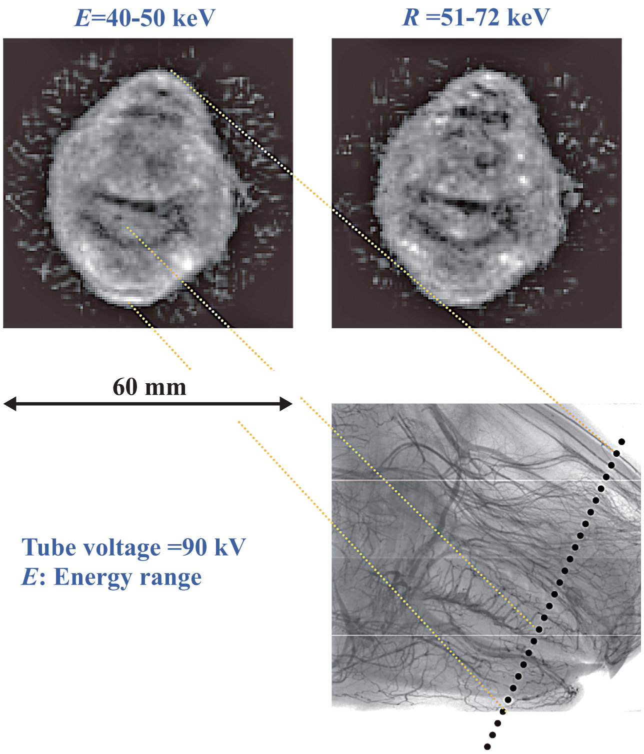

Fig. 8. Tomograms of a rabbit-head phantom. Blood vessels were filled with Gd-based microparticles.

ranging from 40 to 50 keV and a rate of 1.8 kcps.

Acknowledgments

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