Investigation of dual-energy X-ray photon counting using a cadmium telluride detector with dual-energy selection electronics

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ABSTRACT

To obtain two kinds of tomograms at two different X-ray energy ranges simultaneously,

we have developed a dual-energy X-ray photon counter with a cadmium telluride (CdTe) detector and two energy-selecting devices (ESDs). The ESD consists of two comparators and a microcomputer (MC). X-ray photons are detected using the CdTe detector, and the event pulses from a shaping amplifier are sent to two ESDs simultaneously to determine two energy ranges. X-ray photons in the two ranges are counted using the MCs, and the logical pulses from the MCs are input to frequency-to-voltage converters (FVCs). The outputs from the two FVCs are input to a personal computer through an analog-to-digital converter to carry out dual-energy computed tomography. The tube voltage and current were 80 kV and 8.5 μ A, respectively. Two tomograms were obtained simultaneously with two energy ranges. K-edge CT using iodine and gadolinium media was carried out utilizing two energy ranges of 33-45 and 50-65 keV, respectively. The maximum count rate was 6.8 kilo-counts per second with energies ranging from 10 to 80 keV, and the exposure time for tomography was 9.8 min.

1. Introduction

Energy-dispersive photon counting can be used to perform quasi-monochromatic X-ray imaging, and a cadmium telluride (CdTe) detector is quite useful for dispersing photons with a high-energy resolution. Therefore, several preclinical energy-dispersive computed tomography (ED-CT) scanners (Feuerlein et al., 2008; Schlomka et al., 2008; Ogawa et al., 2012) with CdTe array detectors were developed to perform K-edge CT.

We have carried out investigations of ED-CT scanners (Matsukiyo et al., 2011; Sato et al., 2012) using a fairly available CdTe detector with an energy resolution of approximately 1% at 122 keV, and K-edge CT has been carried out using iodine (I) and gadolinium (Gd) media. The K-edge energies of the I and Gd atoms are 33.2 and 50.2 keV, respectively, and X-ray photons in the two energy ranges of approximately 33-43 and 50-60 keV are useful for carrying out I- and Gd-K-edge CT.

Recently, a dual-energy (DE) CT scanner (Hagiwara et al., 2014) has been developed by determining two threshold energies using two comparators. Using this DE-CT, the maximum photon energies are the same, and the photon-energy range is selected by a program for carrying out photon-count energy subtraction using a personal computer

(PC). Therefore, we have developed an energy-selecting device (ESD) (Watanabe et al., 2015) to perform quasi-monochromatic CT by determining an energy range. In addition, the image granulation caused by the low count rates has been improved.

To perform energy subtraction, two different energy tomograms are desired and should be obtained simultaneously to decrease statistic errors. Although an ESD can be used to perform ED-CT, the optimal energy range should be selected and reduced to carry out quasi-monochromatic CT. Furthermore, photon-count energy subtraction should be performed in the counting system to reduce data amount for ED-CT without computer calculation.

In our research, our major objectives are as follows: to develop a DE counter using four comparators, to perform photon-count energy subtraction using a microcomputer (MC), and to obtain two kinds of tomograms at two different X-ray energy ranges simultaneously. Therefore, we constructed a DE-CT scanner with a CdTe detector and two ESDs operated at a tube voltage of 80 kV and a current of 8.5 μ A. We also performed I- and Gd-K-edge CT simultaneously with count rates of 1.8 and 1.5 kilocounts per second (kcps), respectively.

2. Experimental methods

2.1. DE photon counting

In the present research, although we developed a DE-photon-counting system for various detectors, we used a fairly available CdTe detector with an energy resolution of approximately 1% at 122 keV.

Figure 1 shows a block diagram of DE X-ray photon counting using a CdTe detector (Amptek XR-100T) and two ESDs. An ESD consists of two comparators (STMicroelectronics TS3022) and an MC (Atmel ATMEGA168P-20PU). X-ray photons are detected using a CdTe detector, and the electric charges produced in the CdTe are converted into voltages using a charge-sensitive amplifier. Subsequently, the output voltages from the charge amplifier are amplified using a shaping amplifier. The event pulses from the shaping amplifier are sent to two ESDs simultaneously. In the ESD, the energy range is determined by the two comparators, and the MC produces a logical pulse when only a logical pulse from the low-energy comparator (LEC) is input to the MC. Thus, the MC never produces the pulse when two logical pulses from the LEC and

high-energy comparator (HEC) are input to the MC simultaneously. Thus, ESD1 selects photons with an energy range between 33 and 45 keV because X-ray photons with energies just beyond the I-K-edge energy are absorbed effectively by I atoms. Next, the Gd atoms easily absorb the photons with energies beyond Gd-K-edge energy, and ESD2 counts photons between 50 and 65 keV. The two energy ranges are extended slightly to increase the count number per measuring point.

The circuit diagram of a frequency-to-voltage converter (FVC) is shown in Fig. 2. The logical pulses from the MC are input to the FVC to convert count rates into voltages and to improve the image granulation owing to low count rates. In an FVC, the logical pulses from the comparator are shaped into long pulses and piled up using a 51-ms time-constant integrator, and the voltage is amplified using a voltage-voltage amplifier. The second 51-ms integrator is used to reduce the electric noises. The output voltages from the two FVCs are sent to a PC through an analog-to-digital converter (ADC; Contec AI-1608AY-USB).

2.2. DE-CT scanner

Figure 3 shows an experimental setup of the main components in the DE-CT scanner. The CT scanner consists of an X-ray generator (R-tec RXG-0152) with a tungsten-target tube, a turntable (Siguma Koki SGSP-60YAW-OB), a scan stage (Siguma Koki SGSP-26-100), a two-stage controller (Siguma Koki SHOT-602), and a DE X-ray photon counter. The distance between the X-ray source and the detector set is 1.00 m. The distance from the center of turntable to the detector set is 40 mm to decrease magnification ratio of an object, and 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 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. Both the 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. Using this CT system, the exposure time is 9.8 min.

2.3. Measurements of X-ray dose rate and spectra

The measurement of X-ray dose rate is important to infer skin dose for patients. 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 8.5 μ A without filtration. The chamber was placed 1.0 m from the X-ray source, and we measured the dose rate with changes in the tube voltage from 60 to 100 kV.

To measure X-ray spectra, we used the CdTe detector in the DE-CT scanner, and the detector with a lead pinhole was also set 1.0 m from the X-ray source. The photon energy was calibrated by a tungsten (W) $K\alpha$ energy of 59.3 keV.

2.4. Real animal phantoms

In the DE-CT, we used two real dog-heart and rabbit-head phantoms. These phantoms were made approximately twenty years ago, and the operations on animals were carried out in accordance with the animal experiment guidelines of our university.

3. Results

3.1. X-ray dose rate and spectra

Figure 4 shows the X-ray dose rate at a constant tube current of 8.5 μ A. X-ray dose rate increased with increasing tube voltage. At a tube voltage of 80 kV, the X-ray dose rate was 0.58 μ Gy/s.

The X-ray spectra used for CT are shown in Fig. 5. During the spectrum acquisition, the count rate was 6.8 kcps. The I- and Gd-K-edge energies are 33.2 and 50.2 keV, respectively, and shown in the same figure for reference. W $K\alpha$ and $K\beta$ photons from the X-ray-tube target and the maximum energy, corresponding to the tube voltage of 80 kV, are seen in the spectrum.

Figure 6 and Table 1 show selected X-ray spectra and their characteristics, respectively, and the photons with a range of 33-45 keV are useful for carrying out I-K-edge CT. Next, the photons with a range of 50-65 keV beyond Gd-K-edge energy are also useful for imaging Gd atom. The photon count rates of 33-45 and 50-65 keV were 1.8 and 1.5 kcps, respectively.

3.2. Tomography

Tomography was performed at a constant tube voltage of 80 kV and a tube current of 8.5 μ A, 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 I (iopamidol) and Gd (meglumine gadopentetate) media with densities of both 30 mg/ml are shown in Fig. 7. Using I-K-edge CT with a range of 33-45 keV, the density of I medium was higher than that of Gd. When using Gd-K-edge CT, the density of I medium was lower than that of Gd. The gray-value density analysis of the two glass vials was performed using a free program (ImageJ) [National Institute of Health]. Compared with Gd medium, the I-medium density was high, and glass walls could be seen using I-K-edge CT. Utilizing Gd-K-edge CT, the Gd-medium density was high, and it was difficult to image glass walls clearly.

Tomography images of a dog-heart phantom are shown in Figs. 8(a) and 8(b). Coronary arteries are filled with I-based microspheres 15 μ m in diameter. When I-K-edge CT with a range of 33-45 keV was used, the muscle density decreased, and the arteries were visible [Fig. 8 (a)]. Using a range of 50-65 keV, the muscle density increased, and the image contrast of arteries slightly fell [Fig. 8(b)].

Tomography images of a rabbit-head phantom are shown in Figs. 9(a) and 9(b). The blood vessels were filled with gadolinium oxide (Gd_2O_3) microparticles. Radiography (angiography) was performed with a flat-panel detector (FPD; Rad-icon Imaging 1024EV) to observe blood vessels. In radiography, fine blood vessels were observed because the pixel sizes were $48 \times 48 \mu m^2$. When the energy range of 33-45 keV was used, the densities of bones and vessels were high, and it was difficult to image blood vessels [Fig. 9(a)]. Using Gd-K-edge CT with a range of 50-65 keV, the muscle density substantially decreased, and thick vessels were visible [Fig. 9(b)].

4. Discussion

Table 2 shows specifications and characteristics of the DE-CT scanner. We performed

DE X-ray photon counting using a CdTe detector with a maximum count rate of 6.8 keps and an energy range of 10-80 keV. Therefore, the maximum count per measuring point was 0.18 kilocounts with a scan step of 0.5 mm and a CdTe-scan velocity of 25 mm/s.

The photon-count numbers for I- and Gd-K-edge CT per measuring point were approximately 40 and 30 counts, respectively, and the count number should be increased by decreasing event-pulse width of the CdTe detector system at a constant scan velocity of 25 mm/s. The image quality improves with increasing count number per measuring point, and the scan velocity should be reduced to increase the count number using a first-generation DE-CT scanner. Furthermore, a CdTe array detector is quite useful for reducing exposure time in the case where the energy resolution is kept to an optimal value for DE-CT.

The pixel dimensions of the reconstructed CT image were $0.5 \times 0.5 \text{ mm}^2$ 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 $1.0 \times 1.0 \text{ mm}^2$. In addition, the image quality improves with decreasing scan and rotation steps.

5. Conclusions

We developed a DE photon counter using two ESDs and a CdTe detector and performed quasi-monochromatic DE-CT without a PC-subtraction program. At a tube voltage of 80 kV, the two energy ranges were 33-45 and 50-65 keV, and K-edge CT using I and Gd media was performed simultaneously. The photon-count energy subtractions at two energy ranges were carried out simultaneously by two MCs.

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Figure captions

Fig. 1. Block diagram of dual-energy photon counting electronics using a CdTe detector and two ESD blocks. The MC registers photon-counts if the energy is between the corresponding LEC and HEC values.

Fig. 2. Circuit diagram of the FVC consisting of two integrators and a V-V amplifier.

Fig. 3. Experimental setup of the main components in the DE-CT scanner. The DE-CT is performed by repeated linear scans using a CdTe linear scanner and rotations of the object.

Fig. 4. X-ray dose rate measured at 1.0 m from the X-ray source and a tube current of 8.5 μ A.

Fig. 5. Entire X-ray spectra measured using a CdTe detector in the DE-CT scanner at a tube voltage of 80 kV. I- and Gd-K-edge energies are shown in the same figure for reference.

Fig. 6. Selected X-ray spectrum regions for DE-CT at a tube voltage of 80 kV. (a) X-ray photons ranging from 33 to 45 keV for I-K-edge CT and (b) photons ranging from 50 to 65 keV for Gd-K-edge CT.

Fig. 7. Tomograms of two glass vials filled with I and Gd media with the same densities of 30 mg/ml. Using I-K-edge CT with an energy range of 33-45 keV, the image density of I medium was higher than that of the Gd. On the contrary, the density of Gd medium was higher compared with the one of I medium when Gd-K-edge CT was utilized. Image density analysis using ImageJ is shown in the same figure.

Fig. 8. Tomograms of a dog-heart phantom. Coronary arteries were filled with I-based microspheres. (a) Thick arteries were observed at a high contrast using the I-K-edge CT with a range of 33-45 keV, and (b) the image contrast of arteries fell with increasing energy-range level.

Fig. 9. Tomography of a rabbit-head phantom. The blood vessels were filled with gadolinium oxide (Gd_2O_3) microparticles. (a) In the energy range of 33-45 keV, blood vessels were not seen. (b) Using Gd-K-edge CT with a range of 50-65 keV, the muscle density decreased, and thick vessels were visible.

Table 1. Photon energy ranges and characteristics of DE-CT at a tube voltage of 80 kV and a current of 8.5 μ A.

Table 2. Various specifications of the DE-CT scanner.

Figure

Fig. 1

Fig. 2

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Fig. 7

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Fig. 9

Table 1

Tube voltage=80 kV, tube current=8.5 μA		
Energy range (keV)	33-45	50-65
Use	I-K-edge CT	Gd-K-edge CT
Count rate [kcps]	1.8	1.5

Table 2

Specifications of DE-CT scanner	
Generation type	1st
Beam type	Cone
Detector	CdTe linear scanner
Detector number	1
Stroke [mm]	60
Turntable diameter [mm]	60
Pinhole diameter of detector [mm]	1.0
Scan velocity [mm/s]	25
Scan step [mm]	0.5
Rotation step [°]	1.0
Exposure time [min]	9.8
Reconstructed pixel dimensions [mm ²]	0.5×0.5
Spatial resolution [mm ²]	1.0×1.0