Dual-energy X-ray computed tomography scanner using an energy-selecting device and a cadmium telluride detector

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Abstract
Dual-energy photon counting was performed using an energy-selecting device (ESD) and a cadmium telluride detector. The ESD is used to determine a low-energy range for computed tomography (CT) and consists of two comparators and a microcomputer (MC). The two threshold energies are determined using low and high-energy comparators, respectively. The MC in the ESD produces a single logical pulse when only a logical pulse from the low-energy comparator is input to the MC. To determine the high-energy range, logical pulses from the high-energy comparator are input to the MC outside the ESD. Logical pulses from the two MCs are input to frequency-voltage converters (FVCs) to convert count rates into voltages. The output voltages from the two FVCs are sent to a personal computer through an analog-digital converter to reconstruct tomograms. Dual-energy CT was accomplished at a tube voltage of 70 kV and a maximum count rate of 4.5 kilocounts per second, and two-different-energy tomograms were obtained simultaneously using iodine media.

Key words: Dual-energy photon counting, X-ray CT, Energy-selecting device, CdTe detector, Iodine imaging

1. Introduction

Currently, energy-selective X-ray imaging is performed using monochromatic photons, and enhanced iodine (I) K-edge imaging (Mori et al., 1996; Hyodo et al., 1998) has been performed using extremely clean monochromatic parallel beams formed by silicon (Si) single crystals. The energies of monochromatic photons are approximately 35 keV beyond I-K-edge energy of 33.2 keV; these photons are absorbed effectively by I atoms. On the contrary, monochromatic imaging can also be performed using photon-counting energy-dispersive imaging, and several cadmium-telluride (CdTe) detector arrays (Feuerlein et al., 2008; Wang et al., 2011; Ogawa et al., 2012) have been developed to perform energy-dispersive (ED) K-edge imaging including computed tomography (CT) using I and gadolinium (Gd) contrast media.

To perform fundamental studies on photon-counting X-ray imaging, we have developed several ED-CT scanners using CdTe and Si-PIN detectors. First, the photon energy range was determined using a multichannel analyzer (MCA) (Matsukiyo et al., 2011), and the photon count rate was measured using a counter. Second, the threshold energy was determined by a comparator, and the photon-count energy subtraction (Sato et al., 2012) was performed by a personal-computer (PC) program using two sets of projection data, which were not obtained simultaneously.

In the cases where a fairly available CdTe detector for measuring X-ray spectra is used, the energy resolution and the maximum count rate without pileups of event pulses were approximately 1% at 122 keV and 5 kilocounts per second (kcps), respectively. Therefore, we have developed a frequency-voltage converter (FVC) (Shimamura et al., 2014) to improve the image granulation of ED tomograms owing to low count rates of the CdTe detector. Subsequently, an energy-
selecting device (ESD) (Watanabe et al., 2015) has been developed to perform photon-count energy subtraction using a microcomputer without a PC.

In our research, major objectives are as follows: to develop a photon-counting dual-energy (DE) CT scanner using only an ESD, to perform photon-count subtraction using an MC program, to obtain two-different-energy tomograms simultaneously, to keep an energy resolution, and to confirm the image-contrast variations with changes in the selected energy range. Therefore, we developed a DE-CT scanner using an ESD and a CdTe detector and observed image contrast variations using 1 media at a tube voltage of 70 kV and a maximum photon count rate of 4.5 kcps.

2. Experimental procedure

2.1 DE photon counting

Fig. 1 shows the block diagram for performing DE X-ray photon counting using an ESD and a CdTe detector. The ESD is used to determine a low-energy range, and a high-energy range is selected by the HEC and the tube voltage. The output voltages from the two MCs are input to the two FVCs to convert the count rates into voltages.

Fig. 2 Circuit diagram of the FVC consisting of two integrators and a V-V amplifier.
logical pulse when only a logical pulse from the LEC is input to the low-energy input (LEI) in the first MC. Next, the MC never produces the pulse when two pulses from the two comparators are input to the MC, simultaneously. Subsequently, the logical pulse from the HEC is input to the LEI in the second MC outside the ESD. Thus, the ESD selects a low-energy range between the low and high threshold energies and performs photon-count energy subtraction, and the HEC determines the low-energy threshold of a high-energy range; the maximum energy is determined by the tube voltage. The logical pulses from the two MCs are input to two FVCs to convert count rates into voltages; the rate is proportional to the voltage. The output voltages from the FVCs are sent to a PC through an analog-digital converter (ADC) to reconstruct tomograms.

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 (Texas Instruments, LMC662). The electric noises are reduced using the second integrator. The maximum output voltages are regulated to approximately 5 V using 1.0 MΩ variable resistors.

2.2 CT scanner

Fig. 3 shows the experimental setup of the main components in the DE-CT scanner. The distance between the X-ray source and the detector set is 1.00 m [Fig. 3(a)], and the 100-mm-diam irradiation field is formed at 1.0 m from the source using a lead diaphragm. The distance from the center of turntable to the detector set is 40 mm to decrease magnification ratio of an object [Fig. 3(b)], 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, the scanning is conducted in both directions of its movement, and the tomograms are reconstructed using the simplest convolution back projection method. 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 9.8 min.

2.3 Measurements of X-ray dose rate and spectra

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 10 μA without filtration. The chamber was placed 1.0 m from the X-ray source.

Fig. 4 shows the block diagram for measuring X-ray spectra using the CdTe detector in the DE-CT system and a multichannel analyzer (MCA; γPGT, MCA4000). The event pulses from the shaping amplifier are sent to the MCA to perform pulse-height analysis in conjunction with a PC. The photon energy was determined by the one point calibration using tungsten-Kα1 photons with an energy of 59.3 keV.
3. Results

3.1 X-ray dose rate and spectra

The measurement of X-ray dose rate is quite important for inferring the skin dose for objects. At a constant tube current of 10 μA, the X-ray dose rate increased with increasing tube voltage (Fig. 5). At a tube voltage of 70 kV, the X-ray dose rate was 0.52 μGy/s.

Fig. 6 shows the measured and selected X-ray spectra for the DE-CT. At a tube voltage of 70 kV and an energy range $E$ of 10-70 keV, the bremsstrahlung peak energy was approximately 30 keV, and the maximum energy corresponded to the tube voltage [Fig. 6(a)]. To perform low-energy CT, we selected photons in an $E$ of 19.0-33.2 keV [Fig. 6(b)]. Next, an $E$ of 33.2-70.0 keV was selected to carry out high-energy CT [Fig. 6(c)]. At a tube current of 10 μA, the count rates of the spectra in Fig. 6(a), (b) and (c) were 4.5, 1.9 and 2.2 kcps, respectively.

![Block diagram for measuring X-ray spectra using an MCA and a CdTe detector in the DE-CT system.](image)

![X-ray spectra measured using the CdTe detector in the DE-CT system. (a) Entire spectra with an $E$ of 10.0-70.0 keV, (b) selected low-energy spectra with an $E$ of 19.0-33.2 keV, and (c) selected high-energy spectra with an $E$ of 33.2-70.0 keV.](image)
3.2 Electric characteristics

Fig. 7 shows the time relationship between the event pulse and the output from the second MC measured using a digital oscilloscope (Tektronix, TDS2012C). The photon energy $E_p$ (keV) is determined by the pulse height $h$ (V), and $E_p$ is given by:

$$E_p = 20h$$  \hspace{1cm} (1)

In this experiment, the $h$ was 2.6 V, and the $E_p$ is calculated as 52 keV. The pulse width of the MC output was regulated to 10 $\mu$s by the MC program. Although the delay time was not set, the delay time between the event-pulse fall and the MC-voltage rise was 9 $\mu$s with a threshold energy of 33.2 keV.

3.3 Tomography

Tomography was performed at a tube voltage of 70 kV and a tube current of 10 $\mu$A. Tomograms are obtained as JPEG files, and the maximum and minimum densities are defined as white and black, respectively.

Tomograms of two glass vials filled with I media (ipamidol) of two different densities 15 and 30 mg/ml are shown in Fig. 8. Compared with glass-vial density, two densities of I media were quite low using low-energy CT with an $E$ of 19.0-33.2 keV. Utilizing high-energy CT with an $E$ of 33.2-70.0 keV, although the image-density difference between the two media was large, it was difficult to image glass vials at high contrast.

The result of the tomography of a dog-heart phantom is shown in Fig. 9. Coronary arteries are filled with I-based microspheres of 15 $\mu$m in diameter. The animal operation was carried out in accordance with the animal experiment guidelines of our university. Using low-energy CT, the image density of muscle was high, and the image contrast of coronary arteries was low. In contrast, because the heart-muscle density decreased utilizing high-energy CT, the image contrast of arteries was high.

4. Discussion

We performed DE X-ray photon counting using a CdTe detector with a maximum count rate of approximately 4.5 kcps/pixel. Therefore, the maximum count per measuring point was 90 counts with a scan step of 0.5 mm and a scan velocity of 25 mm/s.

The pixel dimensions of the reconstructed CT image were 0.5×0.5 mm² because the scan step was 0.5 mm. However, the original spatial resolution was primarily determined by the lead pinhole diameter of 1.0 mm, and the spatial resolutions were 1.0×1.0 mm².

The FVC is used to compensate for the image granularity in a low-count-rate condition below 10 kcps. The maximum count rates of the low and high-energy ranges were 1.9 and 2.2 kcps, respectively, and these rates were low limitations.
for performing DE-CT. Using this CdTe detector, the maximum-total count rate without pileups is approximately 5 kcps, and a short event-pulse-width CdTe detector should be used to increase the rate. To obtain sufficient counts for DE-CT using this detector, the scan velocity of the detector should be reduced.

In the high-energy CT with an $E$ of 33.2-70.0 keV, although we observed I media at high contrast, the maximum energy should be minimized to improve image contrast. In this regard, we are constructing a DE-CT system with two ESDs, and I-K-edge imaging with an $E$ of 33.2-45.0 keV will be carried out.

At a constant amplifier gain, the FVC output is proportional to the count rate and also increases with increasing output-pulse width from the MC. Using this MC, we controlled the output pulse width to 10 $\mu$s, and the minimum width without controlling was 5 $\mu$s. Therefore, the maximum count rate using the FVC is below 100 kcps, and high-speed MC should be used to increase the rate.

5. Conclusions

We developed a DE-CT scanner using an ESD and a CdTe detector and performed low and high-energy CT simultaneously by selecting two photon-energy ranges. The low-energy range was determined using the LEC and HEC in the ESD, and the threshold energy of the high-energy range was also determined by the HEC. Thus, the low and high-
energy ranges were 19.0-33.2 and 33.2-70.0 keV, respectively.

At a tube voltage of 70 kV and a current of 10 μA, the maximum count rates of the low and high-energy ranges were 1.9 and 2.2 kcps, respectively. Using the high-energy CT, the image contrasts of I media were high, and we observed the image-contrast variations with changes in the energy range.

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