International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2016): 79.57 | Impact Factor (2017): 7.296

Dual-Energy Low-Dose X-Ray Computed Tomography Scanner Using a Room-Temperature Cadmium Telluride Detector

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Abstract: ***To obtain two kinds of tomograms at two different X-ray energy ranges simultaneously, we have constructed a dual-energy (DE) X-ray photon counter with a room-temperature cadmium telluride (CdTe) detector. X-ray photons are detected using the CdTe detector system, and the event pulses from amplifiers are sent to three comparators simultaneously to regulate three threshold energies of 33, 50 and 54 keV. The DE counter consists of energy-range and -region selectors, and the energy ranges are 33-54 and 50-100 keV; the maximum energy corresponds to the tube voltage. We performed DE computed tomography (DE-CT) at a tube voltage of 100 kV. Using a 0.6-mm-diam lead pinhole, K-edge tomograms using iodine and gadolinium media were obtained simultaneously at two energy ranges of 33-54 and 50-100 keV, respectively. At a tube voltage of 100 kV and a current of 100 μA, the count rate was 25 kilocounts per second (kcps), and the minimum count rates after penetrating objects in DE-CT were regulated to approximately 2 kcps by the tube current.***

Keywords: CdTe, Room-Temperature Detector, Dual-Energy X-ray CT, Penetrating-Count Regulation, K-Edge CT, Low-Dose CT

1. Introduction

To measure X-ray spectra in medical radiography, we usually use cadmium telluride (CdTe) detectors, and the energy resolution has been improved to approximately 1% at 122 keV [1]. Therefore, fundamental studies on photon counting energy-dispersive (ED) X-ray imaging have been carried out. First, several ED X-ray cameras have been developed to perform K-edge angiography [2, 3] using iodine (I) and gadolinium (Gd) contrast media and to carry out X-ray fluorescence analysis for mapping I and Gd atoms in the living body [4].

We have also developed several first-generation ED computed tomography (CT) scanners using cooled CdTe detectors to perform K-edge CT using the I and Gd media. Using these dual- and quad-energy CT scanners [5, 6], I- and Gd-K-edge tomograms can be obtained simultaneously.

Recently, CdTe-array detectors [7, 8] operated at room temperature have been developed to perform pre-clinical ED-CT, and we have also constructed an ED-CT scanner using a high-spatial-resolution dual-energy (DE) array detector [9]. In addition, we are interested in the application of a room-temperature single CdTe detector to DE-CT, since the detector price in the DE-CT can be reduced. Using the first-generation DE-CT scanner, the count rate can be increased easily by increasing the energy-range width using DE counter consisting of energy-range and -region selectors.

To reduce the incident dose for objects, linear X-ray beams are useful. In addition, scattering photon counts from the objects should be reduced to improve the image quality. In these regards, a small-diam lead (Pb) diaphragm might be useful for forming line beams and for reducing scattering photons.

In our research, major objectives are as follows: to form line beams using a Pb diaphragm and a tantalum (Ta) slit, to keep the minimum count rate after penetrating the objects, to reduce the incident dose for objects, to reduce the scattering photon counts using a small-diam long Pb collimator, to perform DE-CT for fundamental studies using a room-temperature CdTe detector, and to perform K-edge CT. Therefore, we constructed a low-incident-dose DE-CT scanner using line beams operated at a tube voltage of 100 kV to carry out both the I- and Gd-K-edge CT simultaneously at the two energy ranges.

2. Methods

2.1 DE Photon Counting

Figure 1 shows a block diagram of a DE X-ray photon counter using three comparators (STMicroelectronics, TS3022) and two microcomputers (MCs; Atmel, ATMEGA168P-20PU). X-ray photons are detected using a room-temperature CdTe detector system (Raytech, SPES-02S), and the electric charges produced in the CdTe are converted into voltages and amplified using charge-sensitive and shaping amplifiers in an amplifier module. The event pulses from the amplifier module are sent to three comparators simultaneously to determine three threshold energies of 33, 50 and 54 keV. The photon energy is determined by two-point calibration using Kα photons of tungsten (W; 58.9 keV) and I fluorescence (28.5 keV).

The comparators are used to determine the threshold voltages V_t (V) in proportion to the threshold energies E_t (keV) of the spectra. In this experiment, the CdTe detector is driven without pileups, and E_t is given by

$$E_t = 21.3\ V_t. \quad (1)$$

The energy range is primarily determined by the two comparators, and the range selector counts photons at an energy range between two thresholds and produces logical pulses corresponding to the selected photons. In this experiment, the range selector counts photons at an energy range between 33 and 54 keV, and the region selector counts photons beyond 50 keV (50-100 keV); the maximum energy corresponds to the tube voltage. The logical pulses from the two selectors are input to two frequency-voltage converters (FVCs) to convert count rates into voltages, and the output voltages from the FVCs are sent to a personal computer (PC) through an analog-digital converter (ADC; Contec, AI-1608AY-USB).

In the DE-CT at a tube voltage of 100 kV and a current of 50 μA, the two FVC output voltages are regulated to the same maximum output voltages of 5.0 V utilizing the amplifier-gain controls. For imaging thick objects, the tube current is increased to 100 μA to regulate the penetrating minimum count rate.

2.2 DE-CT Scanner

The experimental setup of the DE-CT scanner is shown in Fig. 2. The distance between the X-ray source (R-tec, RXG-0152) and the detector set is 1.00 m, and the distance from the center of turntable (Siguma Koki, SGSP-60YAW-OB) to the detector set is 0.20 m to decrease scattering photon counts from the object. In the DE-CT, the X-ray beam sizes are stopped down to 1×1 mm^2 by a Ta x-y slit (Siguma Koki, SLX-1) to decrease the incident dose for the object. To improve the spatial resolution and to reduce counts by the scattering photons, a 0.6-mm-diam 6.0-mm-thick lead collimator is set in front of the CdTe detector.

In the scanner, both the X-ray source and the CdTe detector are fixed, and the object on the turntable oscillates on the translation stage (Siguma Koki, SGSP-26-100) 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 translation stage and the turntable are driven by the two-stage controller (Siguma Koki, SHOT-602). Two step values of the linear translations and rotations are selected to be 0.5 mm and 1.0°, respectively. Using this CT scanner, the exposure time is 9.8 min at a total rotation angle of 180°.

2.3 Measurements of X-Ray Dose Rate and Spectra

The measurement of X-ray dose rate is important to calculate the incident dose for objects. To measure the dose rate from an X-ray generator, we used an ionization chamber (Toyo Medic, RAMTEC 1000 plus) placed 1.0 m from the X-ray source at a constant tube current of 100 μA without filtration.

To measure X-ray spectra, we used the CdTe detector in the DE-CT scanner and a multichannel analyzer (MCA; γPGT, MCA4000), and the detector with a Pb collimator was also set 1.0 m from the X-ray source. The photon energy was also determined by the two-point calibration. In addition, the photon-energy resolution of the CdTe detector was measured without the collimator using an americium-241 standard radioisotope with a typical maximum-count energy of 59.5 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 20 years ago, and the operations on animals were carried out in accordance with the animal experiment guidelines of our university.

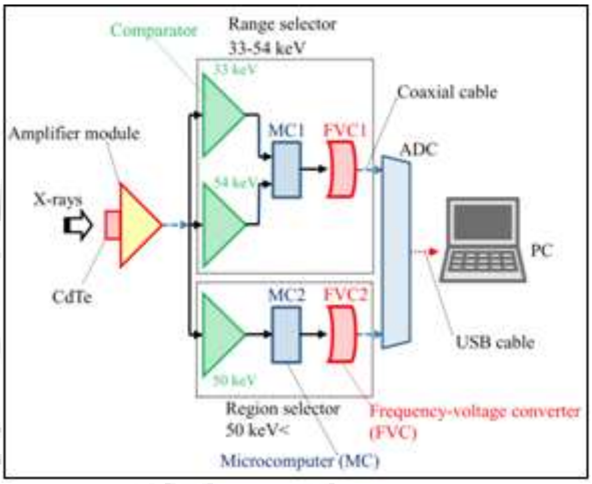


Figure 1: Block diagram of DE photon counting using a room-temperature CdTe detector, three comparators and two MCs. The MC in the range selector performs photon-count energy subtraction between two threshold energies.

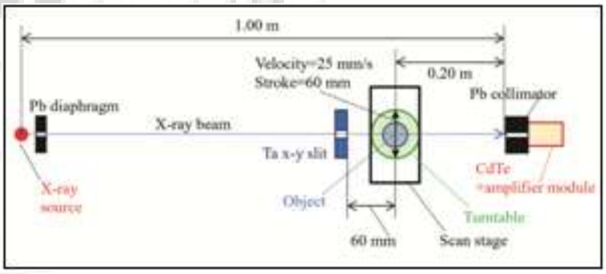


Figure 2: Experimental setup of the main components in the DE-CT scanner. In the DE-CT, both the X-ray source and the CdTe detector are fixed, and the object on the turntable is moved by the translation stage and turned using the turntable. Tomography is performed by repeated linear translations and rotations of the object. In particular, the Ta x-y slit is used to stop down the line-beam sizes.

3. Results

3.1 X-Ray Dose Rate and Spectra

Figure 3 shows X-ray dose rate at 1.0 m from the X-ray source. The X-ray dose rate increased with increasing tube voltage at a constant tube current of 100 μA. At a tube voltage of 100 kV, the X-ray dose rate was 7.29 μGy/s.

The X-ray spectra used for CT are shown in Fig. 4. The K-edge energies of I and Gd are 33.2 and 50.2 keV, respectively, and shown in the same figure for reference. The maximum photon energy almost corresponded to the tube voltage of 100 kV, and W-K lines were observed. The energy resolution of the CdTe detector was 3.5% at 59.5 keV.

Figure 5 shows selected X-ray spectra, and the photons at a range of 33-54 keV are useful for carrying out I-K-edge CT because the photons with energies just beyond I-K-edge energy are absorbed effectively by I atoms. The photons at a range of 50-100 keV beyond Gd-K-edge energy are also useful for imaging Gd atoms.

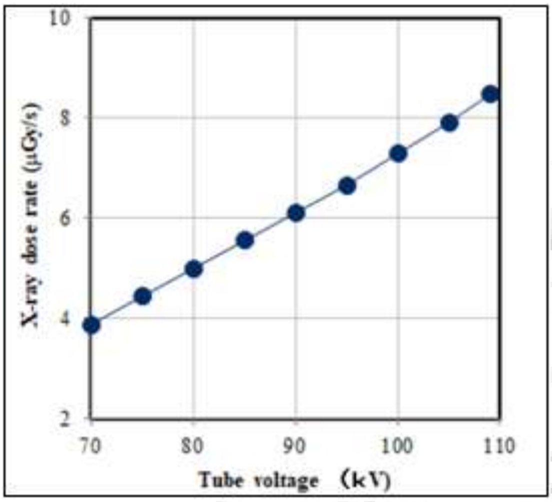


Figure 3: X-ray dose rate at 1.0 m from the X-ray source and a tube current of 100 μA.

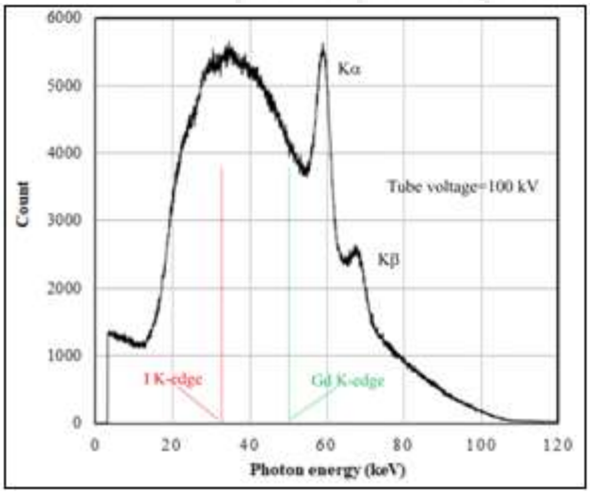


Figure 4: Entire X-ray spectra measured using the CdTe detector in DE-CT scanner at a tube voltage of 100 kV. K-edge energies of I and Gd are shown in the same figure for reference

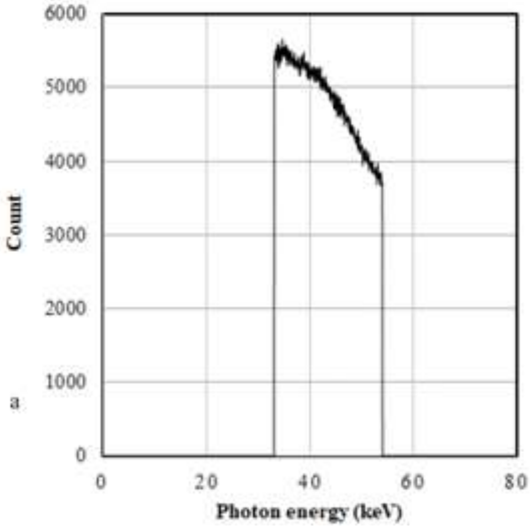
3.2 Tomography

Tomography was performed at a constant tube voltage of 100 kV, and the tube current was regulated to maintain the minimum count rate after penetrating the object. Tomograms are obtained as JPEG files, and the maximum and minimum gray-value densities are defined as white (255) and black (0), respectively. In the image reconstruction, the air and a minimum-count region are determined as the minimum and maximum values, respectively.

Tomograms of two glass vials filled with I (iopamidol) and Gd (meglumine gadopentetate) media at the same densities 30 mg/ml are shown in Fig. 6, and the gray-value density analysis of the two glass vials utilizing Image J is also shown in the same figure. The tube current was 50 μA, and the minimum count rate after penetrating the object was 2 kcps. By I-K-edge CT at a range of 33-54 keV, the density of I medium was higher than that of Gd, and it was easy to observe glass walls. When using Gd-K-edge CT at a range of 50-100 keV, the density of I medium was lower than that of Gd, and it was not easy to observe the glass walls.

Tomography of a dog-heart phantom was performed at a tube current of 50 μA (Fig. 7). Coronary arteries are filled with I-based microspheres 15 μm in diameter. When I-K-edge CT was used at a range of 33-54 keV, the muscle densities were low, and the arteries were visible. Using a range of 50-100 keV, the muscle densities slightly increased, and the image contrast of the arteries slightly fell.

Figure 8 shows the result of the tomography of a rabbit-head phantom. The tube current was increased to 100 μA to maintain the minimum count rate of 2 kcps. The blood vessels were filled with gadolinium oxide (Gd_2O_3) microparticles. Radiography (angiography) was performed for reference using a flat-panel detector (FPD; Rad-icon Imaging 1024EV) to observe blood vessels. In radiography, fine blood vessels were observed with pixel dimensions of 48×48 μm^2. At a range of 33-54 keV, the image densities of bones and muscles were high, and blood vessels were not so visible. Using Gd-K-edge CT at a range of 50-100 keV, the muscle density decreased, and thick vessels were observed at high contrasts.



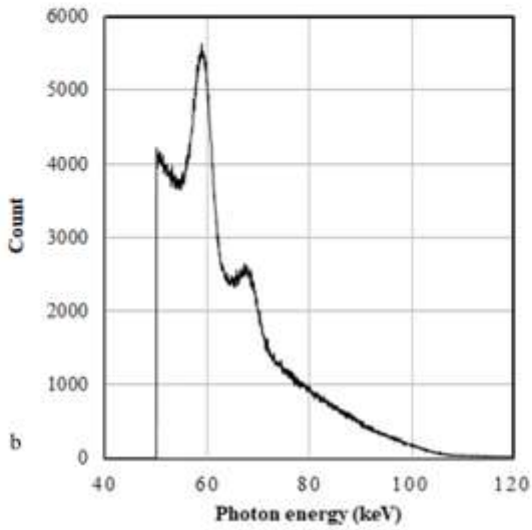


Figure 5: Selected X-ray photons for DE-CT at a tube voltage of 100 kV. (a) X-ray photons with energies ranging from 33 to 54 keV for I-K-edge CT, and (b) photons ranging from 50 to 100 keV for Gd-K-edge CT.

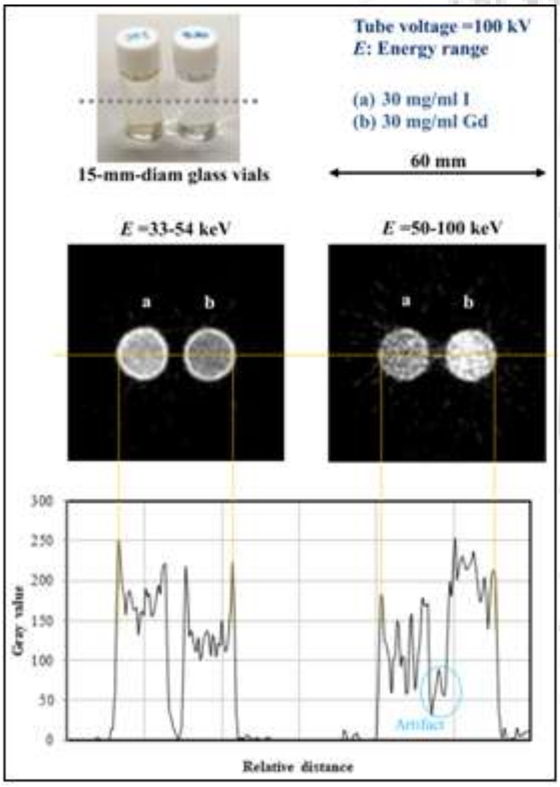


Figure 6: Tomograms of two glass vials filled with I and Gd media with the same densities of 30 mg/ml. The gray-value density analysis is shown in the same figure. Using I-K-edge CT at an energy range of 33-54 keV, the density of I medium was higher than that of the Gd, and the glass walls could be seen. On the contrary, the density of Gd medium was high compared with I medium utilizing Gd-K-edge CT, and it was not easy to image glass walls.

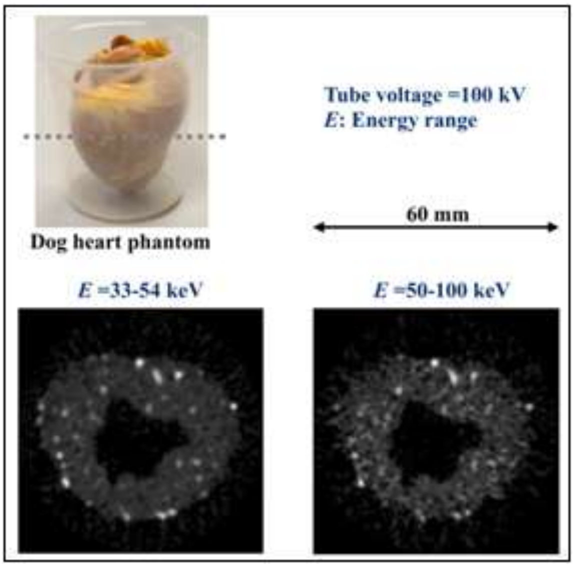


Figure 7: Tomograms of a dog-heart phantom. Coronary arteries were filled with I-based microspheres. Thick arteries were observed at high contrasts using the I-K-edge CT at a range of 33-54 keV. The image contrast of arteries fell with increasing energy-range level to 50-100 keV.

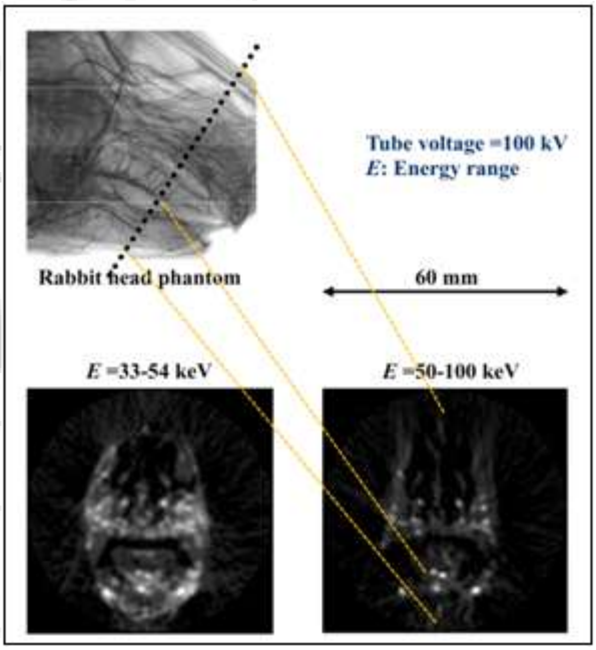


Figure 8: Tomography of a rabbit-head phantom. The blood vessels were filled with gadolinium oxide (Gd_2O_3) microparticles. At an energy range of 33-54 keV, the muscle and bone densities were high, and blood vessels were not so visible. Using Gd-K-edge CT at a range of 50-100 keV, the muscle and bone densities decreased, and thick vessels were observed at high contrasts.

Table 1: Various specifications of the DE-CT scanner using the room-temperature CdTe detector. The spatial resolutions were 0.6×0.6 mm^2, and the energy resolution was approximately 3.5% at 59.5 keV.

Specifications	
Generation type	1st
Beam type	Line
Beam sizes (mm^2)	Approx. 1×1
Detector	CdTe
Energy resolution of detector (% at 59.5 keV)	3.5
Energy range for I-K-edge CT (keV)	33-54
Energy range for Gd-K-edge CT (keV)	50-100
Detector number	1
Maximum count rate (kcps)	15
Stroke (mm)	60
Turntable diameter (mm)	60
Collimator diameter of detector (mm)	0.6
Sizes of xy-slit (mm^2)	Approx. 1×1
Scan velocity (mm/s)	25
Scan step (mm)	0.5
Rotation step (°)	1.0
Total rotation angle (°)	180
Exposure time (min)	9.8
Reconstructed pixel dimensions (mm^2)	0.5×0.5
Spatial resolution (mm^2)	0.6×0.6

4. Discussion

Various specifications of the DE-CT scanner are shown in Table 1. We performed DE X-ray photon counting using a room-temperature CdTe detector at a tube voltage of 100 kV, a maximum tube current of 100 μA, and a maximum count rate of 25 kcps. Therefore, the maximum count per measuring point was approximately 0.50 kilocounts with a scan step of 0.5 mm and a CdTe-translation velocity of 25 mm/s. Subsequently, the minimum penetrating rates were regulated to approximately 2 kcps corresponding to the object thickness by controlling the tube current, and the image quality of the thick object substantially improved.

The pixel dimensions of the reconstructed CT image were 0.5×0.5 mm^2 because the scan step was 0.5 mm. The original spatial resolution was primarily determined by the pinhole diameter of 0.6 mm, and the spatial resolutions were approximately 0.6×0.6 mm^2. In addition, the image quality improves with decreasing scan and rotation steps.

A Ta x-y slit is useful for reducing both the incident dose and the scattering photons of the object, and the incident beam sizes were reduced to 1×1 mm^2. In addition, an x-y slit just behind the object should be used to reduce scattering-photon counts from the object. In the DE-CT, although we used a 0.6-mm-diam 6.0-mm-length lead collimator, it was not easy to make the collimator hole. In this regard, a lead pinhole just behind the object is effective to decrease the scattering photon counts, and we are improving the DE-CT scanner.

At 1.0 m from the X-ray source, the dose rate measured was 7.29 μGy/s at a tube voltage of 100 kV and a current of 100 μA. In ideal, if we assume that the object is placed 1.0 m from the X-ray source, the incident dose using a 0.5-mm-diam line beam is 0.15 μGy at a measuring point and a rotation step of 1.0°, since the measuring time per point is 20 ms. Thus, the minimum incident dose at a total angle of 180° is calculated as 26.3 μGy. In the DE-CT, the beam width was 1.0 mm, and the incident dose of the object is roughly calculated as 52 μGy.

Now, we are constructing a DE-CT scanner with a CdTe detector, a 0.3-mm-diam lead collimator, and a high-speed counter. Using the DE-CT, the spatial resolution improves without any scan shakes. Therefore, 0.5-mm-diam vessels would be observed at high contrasts by K-edge CT using I and Gd media.

5. Conclusions

We developed a first-generation CT scanner using a DE photon counter with a room-temperature CdTe detector. At a tube voltage of 100 kV, the two energy ranges were 33-54 and 50-100 keV, and K-edge tomograms using I and Gd media were obtained simultaneously. The photon-count energy subtraction was carried out in the energy-range selector, and the energy-region selector counts photons beyond the threshold energy. The image quality substantially improved by maintaining the minimum count rate of 2 kcps after penetrating objects, and low-incident-dose DE-CT was performed.

Acknowledgments

This work was supported by Grants from Promotion and Mutual Aid Corporation for Private Schools of Japan, Japan Science and Technology Agency (JST), and JSPS KAKENHI (17K10371, 2017-2020). This was also supported by a Grant-in-Aid for Strategic Medical Science Research (S1491001, 2014–2018) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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