Dual-Energy Low-Scattering X-Ray Computed Tomography Using a Lutetium-Oxyorthosilicate Crystal and a Small Photomultiplier Tube

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Abstract: ***To perform low-dose low-scattering X-ray computed tomography (CT), we have constructed a dual-energy (DE) X-ray photon counter with a high-count-rate detector system and energy-range and -region selectors. The detector system consists of a lutetium-oxyorthosilicate (LSO) crystal, a small photomultiplier tube (sPMT), and a simple inverse amplifier for LSO-sPMT with a pulse-width extender. In DE-CT, both the X-ray source and the detector module are fixed, and the object on the turntable oscillates on the translation stage. Line beams for DE-CT are formed using a lead pinhole and a front tantalum (Ta) x-y slit placed just in front of the object. The scattering-photon count from the object is reduced using a back Ta slit. X-ray photons are detected using the detector system, and the event pulses are input to the two energy selectors. In DE-CT, the tube voltage and current were 60 kV and 1.0 mA, respectively. The energy range and region for soft and iodine-K-edge CT are 12-31 and beyond 35 (35-60) keV, respectively. The maximum count rate of DE-CT was 75 kilocounts per second, and the exposure time for tomography was 19.6 min at a total rotation angle of 360°. Outlines of the objects were clearly visible by reducing scattering-photon counts.***

Keywords: LSO-sPMT Detector, X-Ray CT, Dual-Energy Dispersion, Low-Dose CT, Low-Scattering Count, I-K-Edge CT

1. Introduction

Quasi-monochromatic radiography is useful for performing K-edge imaging using iodine (I) contrast media, and a cerium (Ce) X-ray generator [1] has been developed to carry out I-K-edge computed tomography (CT). The Ce-K photons with photon energies beyond I-K-edge energy are absorbed effectively by I atoms, and fine blood vessels can be observed at high contrasts.

Photon-counting energy-dispersive (ED) radiography can be applied to enhanced I-K-edge radiography, and several ED cameras [2, 3] have been developed and applied to perform K-edge angiography and K-fluorescence analysis for mapping I and gadolinium (Gd) atoms in living bodies.

We have developed several first-generation ED-CT scanners [4, 5] to perform K-edge CT using I and Gd media. In particular, a triple-energy CT [6] using a high-energy-resolution cadmium telluride (CdTe) detector is useful for obtaining I- and Gd-K-edge tomograms simultaneously at high contrasts. In addition, it is not easy to increase the photon count rate per pixel using the CdTe, and several ED-CT scanners have been developed using CdTe arrays [7, 8].

The count rate can be increased beyond 1 mega-counts per second (Mcps) [9] using scintillation-type detectors with short-decay-time crystals, and a lutetium-oxyorthosilicate multipixel-photon (LSO-MPPC) detector [10] has been constructed to perform dual-energy CT (DE-CT). Subsequently, we are interested in the detector consisting of LSO crystal and a small photomultiplier tube (sPMT). Using first-generation DE-CT, the incident dose for an object decreases with reducing line-beam sizes using a tantalum (Ta) x-y slit [11] in front of the object, and the image quality improves with reducing scattering photon count from the object using a Ta slit behind the object.

In our research, major objectives are as follows: to form 0.5×0.5-mm^2-size line beams, to reduce incident doses for the object, to improve an inverse voltage-voltage amplifier for sPMT, to perform DE-CT for fundamental studies using a detector consisting of an LSO crystal and an sPMT, to improve tomogram quality by reducing the scattering photon count from the object, and to perform I-K-edge CT. Therefore, we constructed a low-dose low-scattering DE-CT scanner operated at a tube voltage of 60 kV to carry out K-edge CT using I media.

2. Methods

2.1 DE Photon Counter

Figure 1 shows a block diagram of DE X-ray photon counting. The DE counter consists of the LSO-sPMT detector, an inverse high-speed voltage-voltage (V-V) amplifier with a pulse-width extender, and energy-range and -region selectors. X-ray photons passing through a 0.5-mm-diam 3.0-mm-thick lead (Pb) pinhole are detected by the LSO single crystal with a decay time of 40 ns, and the scintillation photons are detected using an sPMT (Hamamatsu, H10721P-110). The negative output pulses produced in the sPMT are amplified using the inverse V-V amplifier, and the positive 200-ns-width pulses from the amplifier are input to the pulse extender with a 1-μs-time-constant integrator. The event pulses from the extender are sent to the two selectors simultaneously to determine the energy range and region. The range selector determines the energy range of 12-31 keV for soft CT, and the region selector decide the energy region beyond 35 keV

(35-60 keV). Subsequently, the two-selector outputs are sent to a personal computer (PC) through an analog to digital converter (ADC; Contec, AI-1608AY-USB) to reconstruct tomograms. The block diagram of the V-V amplifier is shown in Figure 2. The negative output pulses from the sPMT are input to a 20-gain inverse amplifier with an operational amplifier (Analog Devices, AD8032), and the positive outputs are sent to 1.0-μs time-constant integrating circuit to increase the pulse width. The outputs are then amplified again using a 3-gain amplifier. Approximately 10-ns-width dark counts form the sPMT are not detected at all and only photons can be detected. Although the 200-ns-event pulses can be counted using the DE counter, the pulse-width extender is useful for measuring the output pulse height correctly.

2.2 DE-CT Scanner

The experimental setup of the DE-CT scanner is shown in Figure 3. The distance between the X-ray source (R-tec, RXG-0152) and the detector set is 1.00 m, and the 20-mm-diam irradiation field is formed at 0.80 m from the source using a 2.0-mm-diam 3.0-mm-thick Pb pinhole behind the X-ray source. The distance from the center of turntable (Siguma Koki, SGSP-60YAW-OB) to the detector module is 0.20 m to decrease the scattering photon count from the object. The beams are formed into sizes of approximately 0.5×0.5 mm^2 using a Ta x-y slit (Siguma Koki, SLX-1) and are exposed to the object. The penetrating beams from the object are lead to the same-size Ta x-y slit to reduce the scattering photon count. To improve the spatial resolution, the 0.5-mm-diam 3.0-mm-thick Pb pinhole is set in front of the LSO-sPMT detector.

In the scanner, both the X-ray source and the detector are fixed, and the object on the turntable oscillates on the scan stage (Siguma Koki, SGSP-26-100) with a velocity of 25 mm/s and a stroke of 60 mm. The maximum scan velocity is selected to reduce the exposure time, and the stroke is equal to the turntable diameter. The X-ray projection curves for tomography are obtained by repeated translations and rotations of the object, and the scanning is conducted in both directions of its movement. Tomograms are reconstructed by the simplest convolution back projection method. Both the scan stage and turntable are driven by the two-stage controller (Siguma Koki, SHOT-602). Two step values of the linear scan and rotation are selected to be 0.5 mm and 1.0°, respectively. Using this CT scanner, the exposure time is 19.6 min at a total rotation angle of 360°.

2.3 Measurement of X-Ray Dose Rate

The measurement of X-ray dose rate is important to calculate incident dose for objects. To measure the dose rate from an X-ray generator (R-tec, RXG-0152), we used a dosimeter (Toyo Medic, RAMTEC 1000 plus) with an ionization chamber (Scanditronix, DC300). The chamber was placed 1.0 m from the X-ray source at a constant tube current of 1.0 mA.

2.4 Measurement of X-Ray Spectra Using CdTe

X-ray spectra for reference were measured using a readily available CdTe detector system (Amptek, XR-100T). In this system, a CdTe is fixed directly to the charge-sensitive amplifier, and the outputs are input to a shaping amplifier. The event pulses from the shaping amplifier are sent to a multichannel analyzer (MCA; γPGT, MCA 4000) to perform pulse-height analysis. The X-ray spectra are observed on the PC monitor. The photon energy was determined by two-point calibration using $K\alpha_1$ photons of I (28.6 keV) and tungsten (W; 59.3 keV).

2.5 Measurement of X-Ray Spectra Using LSO-sPMT

Using the LSO-sPMT detector, the event pulses from the pulse-width extender were also input to the MCA to measure X-ray spectra. A 0.5-mm-diam 3.0-mm-thick Pb pinhole was used, since DE-CT was performed using the pinhole to improve spatial resolutions. The photon energy was determined by two-point calibration using Kα photons of I (28.5 keV) and W (58.9 keV). Subsequently, the energy resolution of the LSO-sPMT detector was measured using an americium-241standard γ-ray source at typical peak energy of 59.5 keV without the Pb pinhole.

2.6 Real Animal Phantom

In the DE-CT, we used a real dog-heart phantom. This phantom was made approximately 20 years ago, and the operations on animals were carried out in accordance with the animal experiment guidelines of our university.

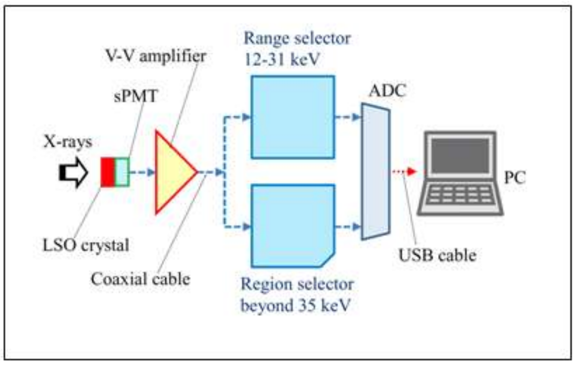

Figure 1: Block diagram of the DE photon counter using an LSO-sPMT detector. The DE counter has the energy-range and -region selectors, and the energy range and region are 12-31 keV and beyond 35 keV (35-60 keV), respectively.

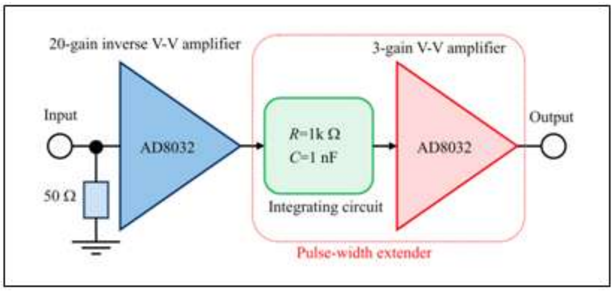

Figure 2: Block diagram of the high-speed inverse V-V amplifier with a pulse-width extender.

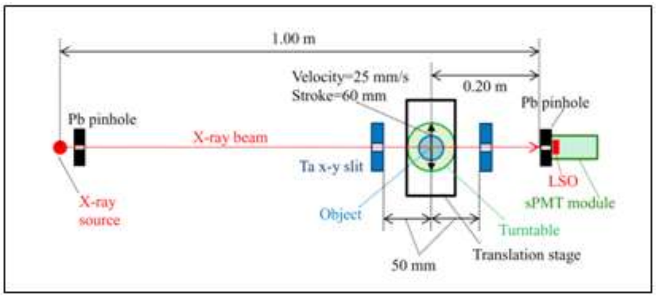

Figure 3: Experimental setup of the main components in the DE-CT scanner. The DE-CT is performed by repeated translations using the LSO-sPMT detector and rotations of the object.

3. Results

3.1 X-Ray Dose Rate

Figure 4 shows the X-ray dose rate with changes in the tube voltage at 1.0 m from the source. At a constant tube current of 1.0 mA, the X-ray dose rate increased with increasing tube voltage. At a tube voltage of 60 kV for DE-CT, the X-ray dose rate was 45.5 μGy/s at 1.0 m.

3.2 X-Ray Spectra Using CdTe

X-ray spectra with changes in the tube voltage using the CdTe detector are shown in Figure 5. I-K-edge energy is shown for reference to perform K-edge CT. Both the maximum-photon and bremsstrahlung-maximum-count energies increased with increasing tube voltage. At a tube voltage of 100 kV, sharp W-K lines were observed.

3.3 X-Ray Spectra Using LSO-sPMT

Figure 6 shows X-ray spectra at a tube current of 0.10 mA. Both the maximum and bremsstrahlung-maximum-count energies increased with increasing tube voltage. Compared with spectra in Figure 5, the maximum-count energy at a tube voltage of 60 kV was almost equal, and the maximum-count energy shifted to high energy owing to the K-photon irradiation at a tube voltage of 100 kV. The energy resolution was approximately 20% at 59.5 keV without the pinhole, and it was easy to increase the count rate for DE-CT. The maximum energies did not correspond to the tube voltages owing to low energy resolution.

Figure 7 shows selected X-ray spectra for DE-CT, and the photons with energies ranging from 35 to 60 keV are useful for performing I-K-edge CT because these photons with energies beyond I-K-edge are absorbed effectively by I atoms. On the contrary, photons at a range of 12-31 keV are useful for carrying out soft CT.

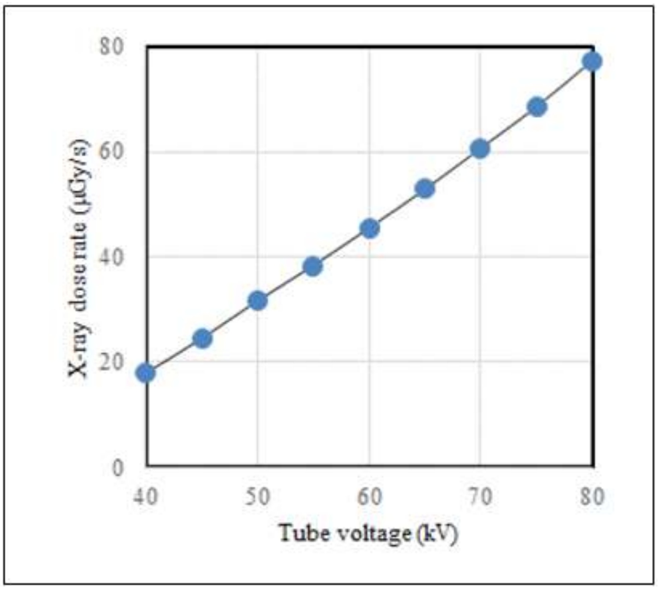

Figure 4: X-ray dose rate with changes in the tube voltage at 1.0 m from the source and a tube current of 1.0 mA.

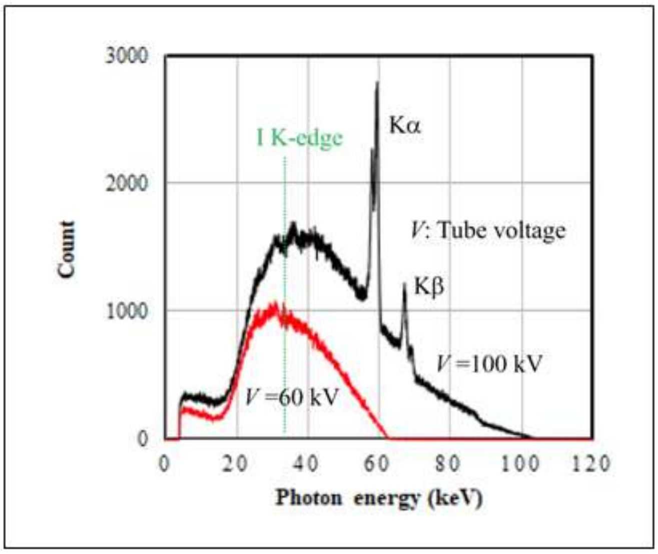

Figure 5: X-ray spectra measured using the CdTe detector with changes in the tube voltage at a tube current of 5 μA.

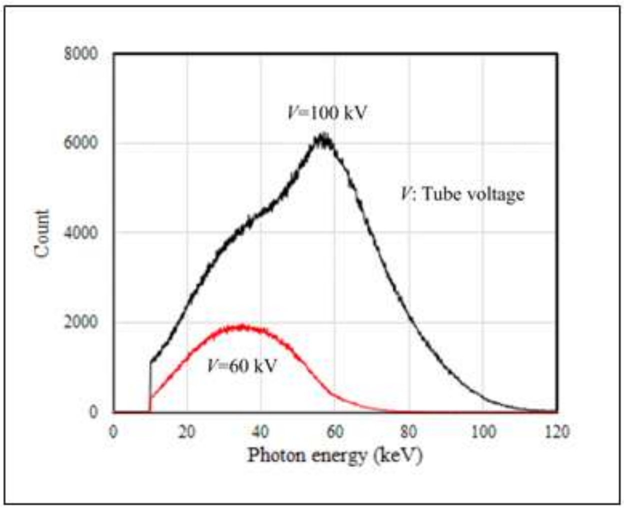

Figure 6: X-ray spectra measured using the LSO-sPMT detector with changes in the tube voltage at a tube current of 0.10 mA.

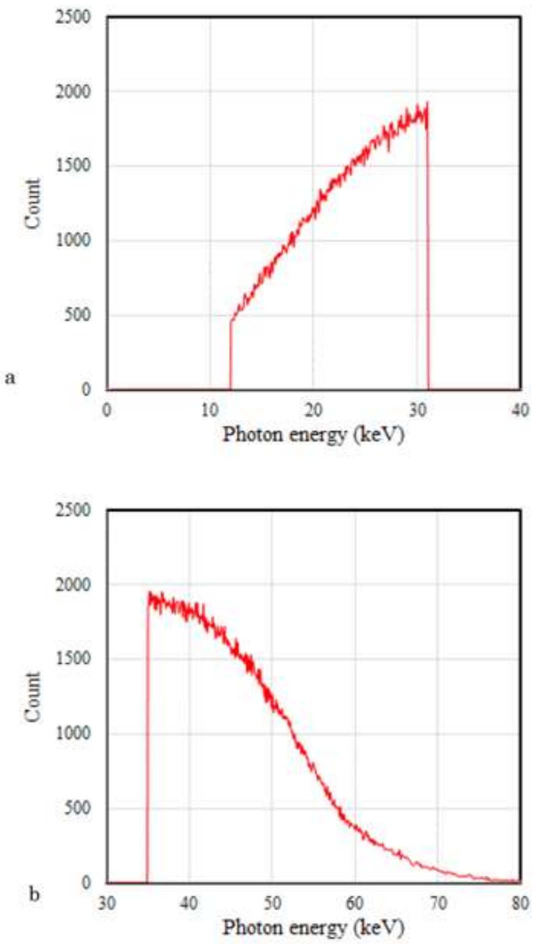

Figure 7: Selected X-ray spectra for DE-CT at a tube voltage of 60 kV. (a) X-ray photons at an energy range of 12-31 keV for soft CT and (b) photons at a range of 35-60 keV for I-K-edge CT; the maximum energy corresponds to the tube voltage

3.4 DE-CT

Tomography was performed at a constant tube voltage of 60 kV and a tube current of 1.0 mA. Tomograms are obtained as JPEG files, and the maximum and minimum gray-value densities are defined as white (255) and black (0), respectively.

Tomograms of two glass vials filled with I (iopamidol) medium of two-different densities of 15 and 30 mg/ml are shown in Figure 8, and the density analysis of the tomograms using the Image J image processing software is shown in the same figure. Using soft CT at an energy range of 12-31 keV, the glass walls were observed at high contrasts, and the densities of I media were quite lower than those of glass walls. Utilizing I-K-edge CT at an energy range of 35-60 keV, the I densities increased, and the density difference between the two media slightly increased.

Figure 9 shows tomography of a polymethyl methacrylate (PMMA) phantom with two holes filled with I medium of two different densities of 15 and 30 mg/ml. When the energy-range level was increased, the PMMA body density decreased, and I media were observed at high contrasts.

The tomography of a dog-heart phantom is shown in Figure 10. Coronary arteries are filled with I-based microspheres 15 μm in diameter. Utilizing I-K-edge CT, the muscle density decreased, and the arteries were visible.

4. Discussion

Various specifications of the DE-CT scanner are shown in Table 1. In the DE-CT with an LSO-sPMT detector, the maximum count rate was 75 kcps at a tube voltage of 60 kV and a tube current of 1.0 mA, and the maximum count per measuring point was approximately 1.5 kilocounts at a scan step of 0.5 mm and a scan velocity of 25 mm/s.

The DE counter has the energy-range and -region selectors, and the two energy widths for DE-CT can be selected corresponding to the objectives. Generally, the count rate increases with increases in the width, and sufficient count rates for DE-CT are obtained.

The image granulation was substantially improved by increasing the count rate and by reducing the scattering photon count using a 0.5×0.5-mm^2-size Ta back slit. In particular, using the slit, the outlines of the objects were clearly visible, and the artifact slightly improved.

The pixel sizes 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 0.5 mm, and the spatial resolutions were approximately 0.5×0.5 mm^2.

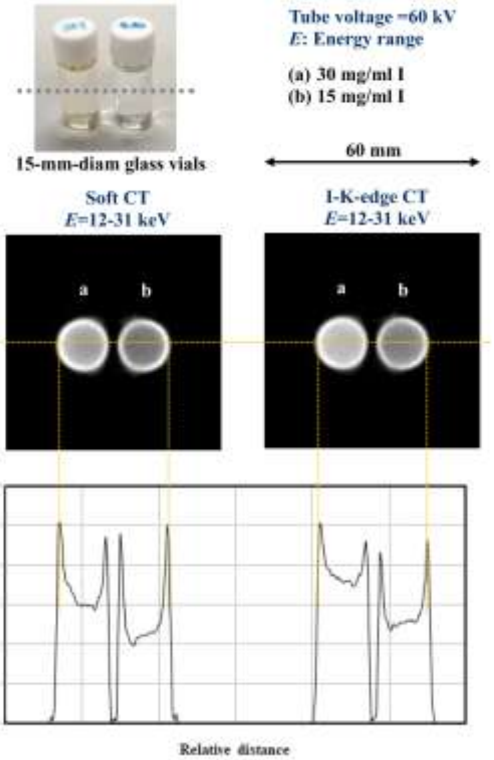

Figure 8: Tomography of two glass vials filled with two-different-density I media of 15 and 30 mg/ml. Using I-K-edge CT at a range of 35-60 keV, the I densities substantially increased, and the density difference between the two media slightly increased.

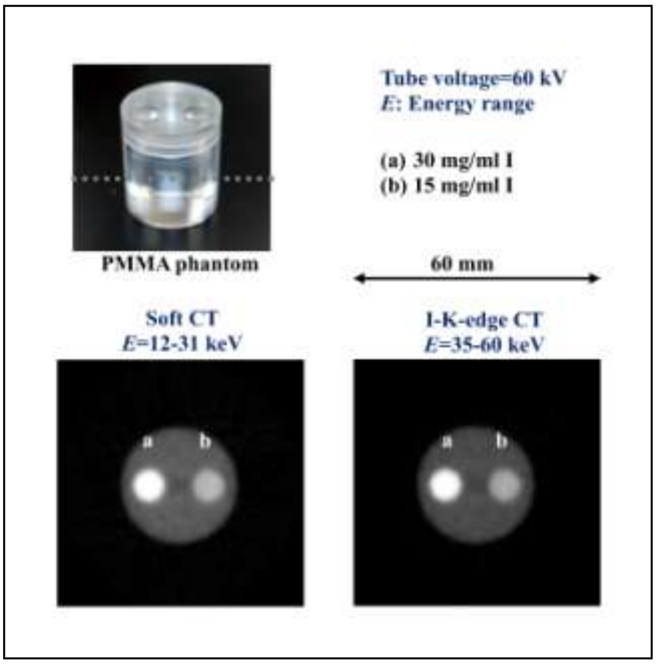

Figure 9: Tomography of a PMMA phantom with two holes filled with two different density I media of 15 and 30 mg/ml. Utilizing the I-K-edge CT, the PMMA body density decreased, and I media were observed at high contrasts.

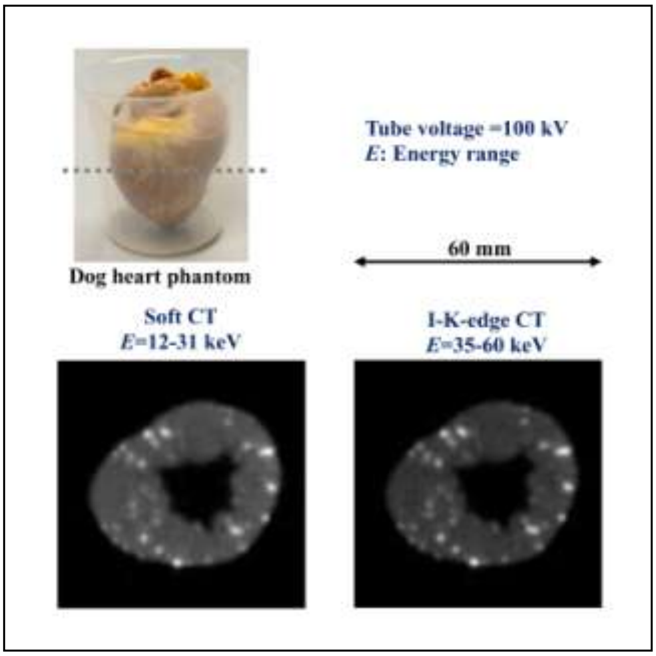

Figure 10: Tomography of a dog-heart phantom. Utilizing I-K-edge CT at a range of 35-60 keV, the muscle density decreased, and the coronary arteries were visible.

For this research, the energy range of I-K-edge CT was 35-60 keV. In addition, the I media were also observed at high contrasts utilizing soft CT at a range of 12-31 keV, since photons with energies just beyond I-L-edge energy were contained.

At 1.0 m from the X-ray source, the dose rate measured was 45.5 μGy/s at a tube voltage of 60 kV and a current of 1.0 mA. To reduce the incident dose for the object, we used a front Ta x-y slit, and the X-ray beam sizes were reduced to 0.5×0.5 mm^2. If we assume that the object is placed 1.0 m from the X-ray source, the incident dose using a 0.5-mm-width line beam is 0.91 μGy at a measuring point and a rotation step of 1.0°, since the measuring time per point is 20 ms. Thus, the incident dose at a total angle of 360° is calculated as 328 μGy.

5. Conclusions

We measured the X-ray spectra using an LSO-sPMT detector in conjunction with a simple high-speed inverse V-V amplifier with a pulse-width extender. The incident dose for an object was extremely reduced using a front Ta x-y slit, and the scattering-photon count from the object substantially decreased using a back Ta slit. The event-pulse widths were approximately 1 μs, and the energy resolution was approximately 20% at 59.5 keV. The dark-count rate from the sPMT was reduced to 0 cps by increasing the time constant of the amplifier. Thus, low-energy X-ray photons were detected, and both the soft and I-K-edge tomograms were obtained simultaneously at a maximum count rate of 75 kcps.

Table 1: Various specifications of the DE-CT scanner with the LSO-sPMT detector. The spatial resolutions were 0.5×0.5 mm^2, and the exposure time for CT was 19.6 min at a total rotation angle of 360°

Specifications	
Generation type	1st
Beam type	Line
Beam sizes (mm^2)	Approx. 0.5×0.5
Detector	LSO-sPMT
Energy resolution of detector (% at 59.5 keV)	20
Energy range for soft CT (keV)	12-31
Energy range for I-K-edge CT (keV)	35-60
Detector number	1
Maximum count rate (kcps)	75
Stroke (mm)	60
Turntable diameter (mm)	60
Pinhole diameter for X-ray source (mm)	1.5
Pinhole diameter for detector (mm)	0.5
Sizes of front x-y slit (mm^2)	Approx. 0.5×0.5
Sizes of back x-y slit (mm^2)	Approx. 0.5×0.5
Scan velocity (mm/s)	25
Scan step (mm)	0.5
Rotation step (°)	1.0
Total rotation angle (°)	360
Exposure time (min)	19.6
Reconstructed pixel sizes (mm^2)	0.5×0.5
Spatial resolution (mm^2)	0.5×0.5

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