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High-sensitivity X-ray computed tomography using a ceramic-substrate silicon diode and a current-voltage amplifier module

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Abstract

The computed tomography (CT) system with a tube current of 1.0 mA was developed using a silicon X-ray diode (Si-XD). The Si-XD is a high-sensitivity Si photodiode selected for detecting X-ray photons and is connected to an X-ray-detecting module using a 5.0-m-length coaxial cable. X-ray photons are directly detected using the Si-XD without a scintillator, and the photocurrent from the diode is amplified using current-voltage and voltage-voltage amplifiers in an X-ray-detecting module. Tomography is accomplished by repeated linear scans and rotations of an object, and projection curves of the object are obtained by the linear scanning. The exposure time for obtaining a tomogram was 10 min at a scan step of 0.5mm and a rotation step of 1.0°. The tube current and voltage were 1.0 mA and 70 kV, respectively, and CT was carried out using iodine-based contrast media.

Keywords: Si X-ray diode, direct conversion, high-sensitivity detector, X-ray CT

1. Introduction

To perform enhanced K-edge imaging using iodine (I) and gadolinium (Gd) contrast media, we have developed several photon-counting energy-dispersive X-ray computed tomography (ED-CT) systems [1−5]. In particular, X-ray photons with energies just beyond I-K-edge energy 33.2 keV are absorbed effectively by I atoms, and coronary arteries of a dog-heart phantom are observed at high contrast.

Recently, we found a high-sensitivity silicon X-ray diode (Si-XD), and high-sensitivity X-ray CT was carried out [6]. In addition, we developed a dual-energy Si-XD consisting of two Si-XDs and a 0.2-mm-thick copper filter and performed energy subtraction [7].

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In our former research, the Si-XD was connected to an X-ray-detecting module using a 5.0-m-length coaxial cable and was used to measure low-dose-rate X-rays. Therefore, we constructed a high-sensitivity X-ray CT system using a linear X-ray scanner with a Si-XD.

2. Experimental methods

2.1. Low-dose-rate X-ray detection

Figure 1 shows a block diagram for detecting low-dose-rate X-rays using a Si-XD (S 1087-01, Hamamatsu). Using the Si-XD detector, X-ray photons are detected directly by the light receiving surface of 1.3×1.3 mm^2, and the detector is shielded using an aluminum (Al) case with a 25-μm-thick Al window and a BNC connector. Subsequently, the detector is connected to an X-ray detecting module through a 5.0-m-length coaxial cable.

2.2. X-ray CT system

The experimental setup of the main components in the high-sensitivity X-ray CT system using the Si-XD is shown in Fig. 2. 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

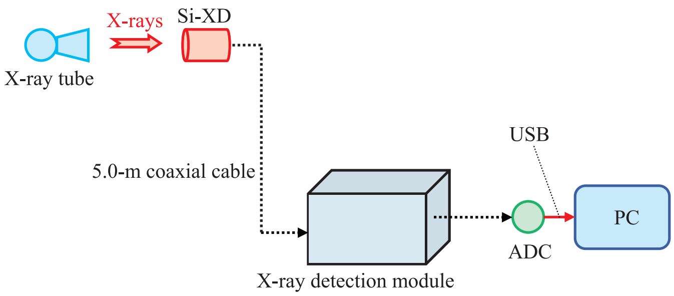

Fig. 1. Block diagram for detecting low-dose-rate X-rays using a Si-XD. The Si-XD is connected to an X-ray-detecting module using a 5.0-m-length coaxial cable.

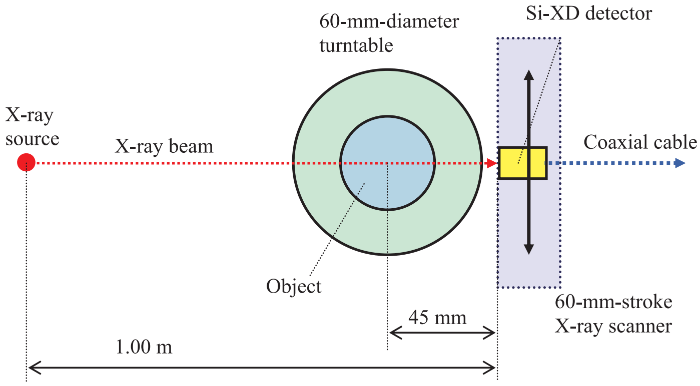

Fig. 2. Experimental setup of the main components in the high-sensitivity X-ray CT system. The CT is performed by repeated linear scans and rotations of the object.

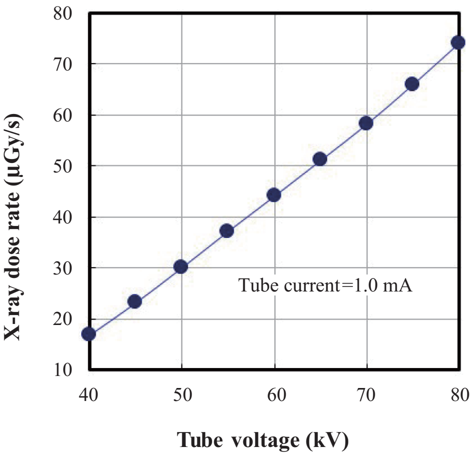

Fig. 3. X-ray dose rate measured at 1.0 m from the X-ray source and a tube current of 1.0 mA.

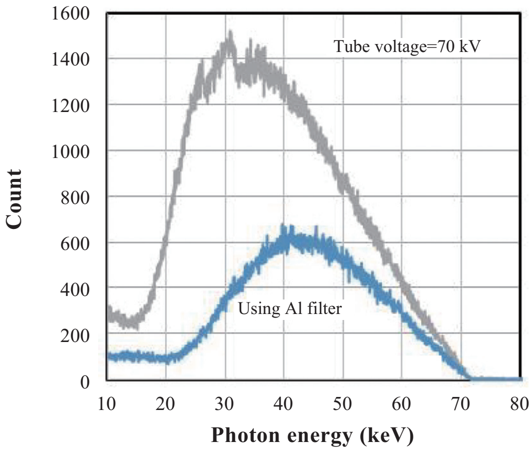

Fig. 4. The X-ray spectra measured using the CdTe detector at a tube voltage of 70 kV.

object. Only the Si-XD detector 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 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 1.0 mA without filtration. At a constant tube current, the X-ray dose rate increased with increasing tube voltage (Fig. 3). At a tube voltage of 70 kV, the X-ray dose rate was 58.2 μGy/s.

3.2. X-ray spectra

To measure X-ray spectra, we used the CdTe detector in the quasi-monochromatic ED-CT system (Fig. 4). In the entire spectra with energies ranging from 10 to 70 keV, the bremsstrahlung peak energy was 32 keV. According to the insertion of a 5.0-mm-thick aluminum filter, low-energy photons were absorbed by the filter, and the bremsstrahlung peak shifted to 42 keV.

3.3. Tomography

Tomography was performed at a tube voltage of 70 kV and a tube current of 1.0 mA, 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

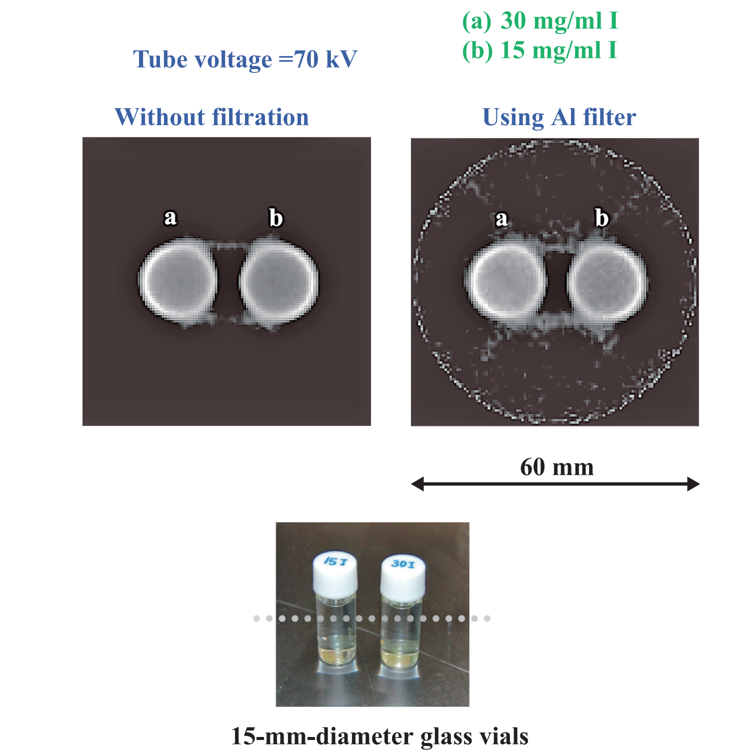

Fig. 5. Tomograms of two glass vials filled with I media of two different densities of 15 and 30 mg/ml.

gray-value densities are defined as white and black, respectively.

Tomograms of two glass vials filled with I media (iopamidol) of two different densities 15 and 30 mg/ml are shown in Fig. 5. Without the filter, it was difficult to image I media in the vials. Next, both the density and the density difference slightly increase using the filter.

The result of the tomography of a dog-heart phantom is shown in Fig. 6. Coronary arteries are filled with I-based microspheres of 15 μm in diameter. The animal operation was carried out in accordance with the animal experiment guidelines of our university. Using the filter, the image density of muscle decreased, and the image contrast of coronary arteries was high.

4. Discussion

To confirm image-contrast variations with the insertion of the Al filter, we used I media. In the X-ray CT of two glass vials filled with two different density I media, we could not observed significant contrast variations using the filter. To solve this, the tube voltage should be reduced to 60 kV because high-energy photons decreased the image contrast.

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 dimensions of X-ray-receiving surface, and the spatial resolutions were $1.3 \times 1.3\ mm^2$.

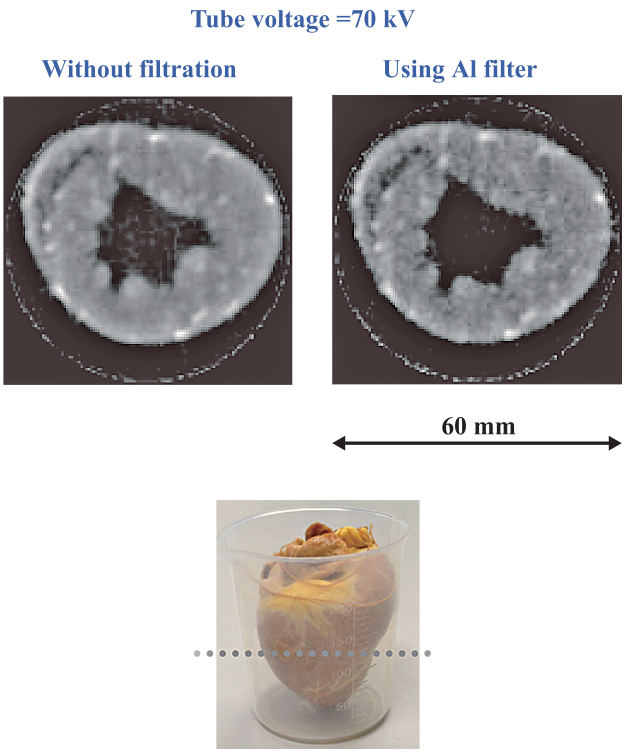

Fig. 6. Tomograms of a dog-heart phantom. Blood vessels were filled with I-based microspheres.

5. Conclusions

We performed high-sensitivity CT using a Si-XD and confirmed image-contrast variations with the insertion of a 5.0-mm-thick Al filter. Currently, although the Si-XD is connected directly to the X-ray-detecting module to reduce electric noises, a 5.0-m-length coaxial cable can be used between the Si-XD and the module. Thus, the dimensions of the X-ray linear scanner can be reduced.

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