Applied Radiation and Isotopes 130 (2017) 54–59

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Investigation of quad-energy high-rate photon counting for X-ray computed tomography using a cadmium telluride detector

Hiroshi Matsukiyo[a], Eiichi Sato[b,*], Yasuyuki Oda[b], Satoshi Yamaguchi[c], Yuichi Sato[d], Osahiko Hagiwara[a], Toshiyuki Enomoto[a], Manabu Watanabe[a], Shinya Kusachi[a]

[a] Department of Surgery, Toho University Ohashi Medical Center, 2-17-6 Ohashi, Meguro, Tokyo 153-8515, Japan
[b] Department of Physics, Iwate Medical University, 2-1-1Nishitokuta, Yahaba, Iwate 028-3694, Japan
[c] Department of Radiology, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka, Iwate 020-0023, Japan
[d] Central Radiation Department, Iwate Medical University Hospital, 19-1 Uchimaru, Morioka, Iwate 020-0023, Japan

HIGHLIGHTS

- X-ray counter based on quad-energy-range selection has been constructed.
- Counter is realized by four-sets of comparators and microcomputers.
- Photon energy determination was carried out online using microcomputers.
- CT was performed for four X-ray energy ranges with high count rates.
- Iodine and gadolinium K-edge CT was accomplished simultaneously.

ARTICLE INFO

Keywords:
X-ray photon counting
CdTe detector
Energy-selection electronics
Quad-energy CT
Penetrating-count regulation

ABSTRACT

To obtain four kinds of tomograms at four different X-ray energy ranges simultaneously, we have constructed a quad-energy (QE) X-ray photon counter with a cadmium telluride (CdTe) detector and four sets of comparators and microcomputers (MCs). X-ray photons are detected using the CdTe detector, and the event pulses produced using amplifiers are sent to four comparators simultaneously to regulate four threshold energies of 20, 33, 50 and 65 keV. Using this counter, the energy ranges are 20–33, 33–50, 50–65 and 65–100 keV; the maximum energy corresponds to the tube voltage. We performed QE computed tomography (QE-CT) at a tube voltage of 100 kV. Using a 0.5-mm-diam lead pinhole, four tomograms were obtained simultaneously at four energy ranges. K-edge CT using iodine and gadolinium media was carried out utilizing two energy ranges of 33–50 and 50–65 keV, respectively. At a tube voltage of 100 kV and a current of 60 µA, the count rate was 15.2 kilocounts per second (kcps), and the minimum count rates after penetrating objects in QE-CT were regulated to approximately 2 kcps by the tube current.

1. Introduction

Quasi-monochromatic X-ray imaging can be performed using K-series characteristic rays (K-rays) (Sato et al., 2008) or narrow-energy-width bremsstrahlung rays (Enomoto et al., 2006). In particular, iodine (I) K-edge imaging was performed using cerium K-rays (Sato et al., 2004), and fine blood vessels were clearly observed. In addition, extremely clean monochromatic parallel beams (Mori et al., 1996; Hyodo et al., 1998) formed using silicon crystals with energies of approximately 35 keV are quite useful to image fine coronary arteries below 100 µm in diameter.

To perform K-edge computed tomography (CT), we constructed several first-generation energy-dispersive CT (ED-CT) scanners (Matsukiyo et al., 2011; Sato et al., 2012a; Hagiwara et al., 2014), and K-edge CT using I and gadolinium (Gd) contrast media has been performed using a CdTe detector with an energy resolution of approximately 1% at 122 keV. First, the photon energy range was determined using a multichannel analyzer (MCA). Subsequently, the range has been selected by photon-count energy subtraction using a dual-energy comparator and a computer program. Lately, we have developed an energy-range selecting device (ESD) (Watanabe et al., 2015) with two comparators and a microcomputer (MC) to perform quasi-monochromatic

* Corresponding author.
E-mail address: dresato@iwate-med.ac.jp (E. Sato).

http://dx.doi.org/10.1016/j.apradiso.2017.09.011
Received 7 April 2017; Received in revised form 27 June 2017; Accepted 7 September 2017
Available online 10 September 2017
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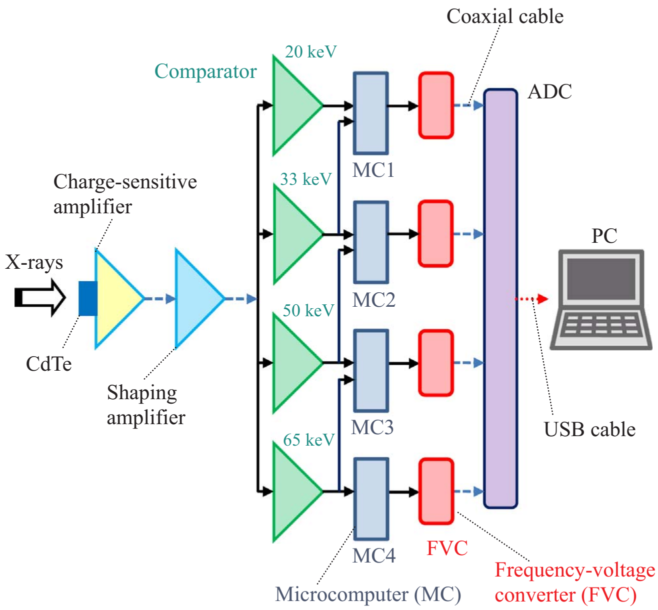

Fig. 1. Block diagram of QE photon counting using a CdTe detector and four sets of comparators and MCs. The MC performs photon-count energy subtraction at the photon-energy range between two threshold energies.

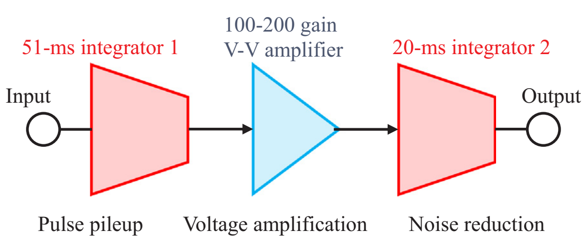

Fig. 2. Block diagram of the FVC consisting of two integrators and a V-V amplifier. Each FVC output is regulated to the maximum voltage of 5.0 V.

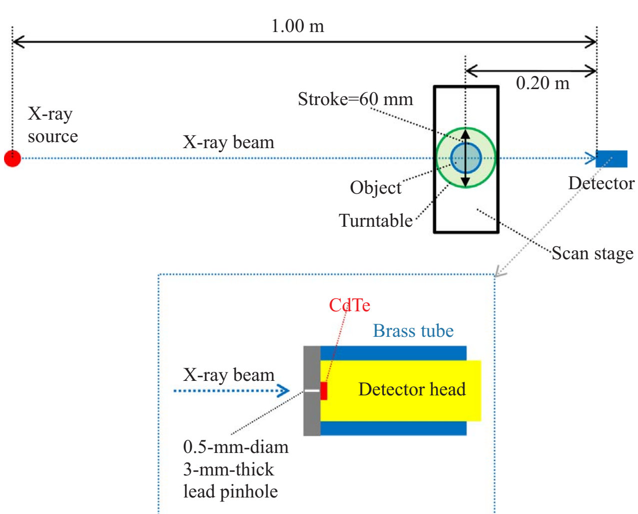

Fig. 3. Experimental setup of the main components in the QE-CT scanner. In the QE-CT, both the X-ray source and the CdTe detector are fixed, and the object on the turntable is moved by the scan stage and turned using the turntable. The tomography is performed by repeated linear scans and rotations of the object. The distance from the center of the turntable to the detector set is 0.20 m to reduce the scattering photons from the object, and a 0.5-mm-diam lead pinhole is used to improve the spatial resolution.

imaging, and dual-energy imaging (Oda et al., 2015) has also been performed using the ESD and two MCs.

To reduce exposure time for CT, we developed several high-count-

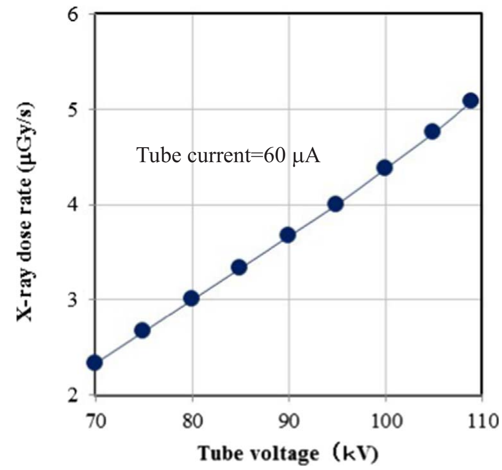

Fig. 4. X-ray dose rate measured at 1.0 m from the X-ray source and a tube current of 60 μA.

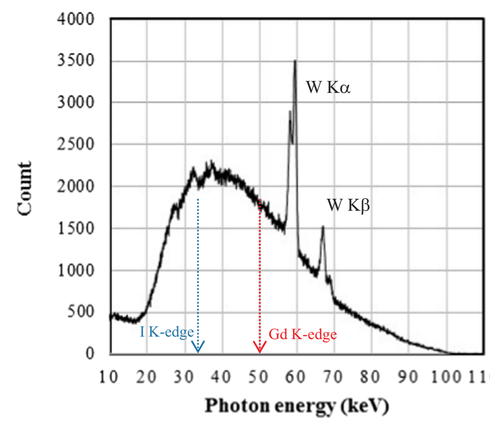

Fig. 5. Entire X-ray spectra measured using a CdTe detector in QE-CT scanner at a tube voltage of 100 kV. K-edge energies of I and Gd are shown in the same figure for reference.

rate detectors (Sato et al., 2012b), and the rate has been increased beyond 1 megacount per second (Mcps). In addition, the CdTe array detectors (Feuerlein et al., 2008; Wang et al., 2011; Ahmed et al., 2015; Taguchi, 2017) are quite useful, and preclinical ED-CT scanners have been developed to perform K-edge imaging. Therefore, we are carrying out dual-energy CT scanner using an array detector made by XCounter (Zscherpel et al., 2014).

In conjunction with the preclinical CT, the first-generation ED-CT scanner previously described is also useful for performing fundamental studies on molecular imaging including K-edge CT, since a high-energy-resolution detector can be used at a constant sensitivity. Therefore, we are also continuing studies on both the image quality improvement and the novel photon counter for the first-generation CT scanner.

In the first-generation ED-CT with plural energy ranges, the count rate at a range decreases with increasing the range number under constant tube voltage and current. Therefore, the range number should be regulated to four or below to obtain sufficient photon counts per measuring point.

Without pileup of the event pulses, the maximum count rate of a high-energy-resolution CdTe detector is approximately 5 kilocounts per second (kcps). In ED-CT, the photon count rate substantially decreases while penetrating the objects, the image quality improves with increasing the minimum count rate after penetrating the object, and the incident count rate to the object should be increased with increases in the object thickness to maintain the minimum count rate for CT.

In our research, major objectives are as follows: to develop a quad-energy (QE) counter using four comparators, to keep the minimum

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