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Energy calibration of a CdZnTe photon-counting linear-array detector with various x-ray spectra

Okla Joe, Hanbean Youn, Ho Kyung Kim*
School of Mechanical Engineering, Pusan National University, Busan 609-735, South Korea
**Corresponding author: hokyung@pusan.ac.kr*

1. Introduction

Recently medical imaging area has focused in reduction of radiation exposure to patient. As reduction of radiation exposure causes the noise in image, low noise imaging systems such as photon-counting detector can be considered as a candidate. Whereas conventional flat-panel detector integrates charges from incident x-ray energy flux during integration time, photon-counting detector counts each photon with energy. Thus photon-counting imaging application can reduce the radiation exposure and also discriminate materials in object. To discriminate materials by energy, each threshold voltage has to be converted to energy. In this study, with a CdZnTe single-channel photon-counting linear-array detector, we calibrated the threshold voltage to energy using various x-ray spectra. Although photon-counting detector has a single-channel, we can measure spectra by scanning the signals with changing threshold voltages.

2. Methods and Results

As each threshold voltage has linear relation with an energy, we can calibrate the threshold voltage to energy using monochromatic x-ray spectrum. Although fluorescence x-ray system can be used as monochromatic source, the photon flux of the system is very low and it is hard to be equipped in the lab. Gamma rays from radioisotopes can also be used as monochromatic sources. But the availability energies corresponding to diagnostic imaging and low activity may restrict the use of radioisotope source.

In this regard, we propose a simple method to calibrate the threshold voltage of the photon-counting detector using x-rays from a conventional tube/generator. Various x-ray spectra, which have different peak energies can be used to calibrate the threshold voltage.

In this study, we calibrate a CdZnTe linear-array detector (eV-2000, eV-Product, PA 16056, USA) which has 64 pixels with a dimension of 0.8×0.8×3.0 mm. Although the detector has a single-channel, x-ray spectrum can be measured by changing threshold voltage during x-ray irradiation. Ideally, the measured spectrum should be the same as the incident x-ray spectrum, but it can be distorted by charge trapping, charge sharing, and pulse pile-up, caused by detector material properties and electronics. However, a large pixel compound semiconductor detector with the bias voltage enough for a high charge collection efficiency can measure the incident spectrum relatively precise. Then we can say the peak voltage of the measured spectra and the peak energy of incident spectra are same. With various incident x-ray spectra, each threshold voltage can be calibrated to energy by linear fitting using peak information of two spectra at least.

2.1 Gain-offset correction

The variation in exposure response of an individual detector element of x-ray detector requires gain-offset correction. The offset correction is used to account for the dark current effects, while the gain correction for the nonuniform response of individual pixels. The conventional method to correct a raw image (W_i) is

$$W_{i,\mathrm{GOC}} = \frac{W_i - \overline{D}}{\overline{W} - \overline{D}} \times \overline{\overline{W} - \overline{D}} \tag{1}$$

where W_{GOC} is the corrected image, $\overline{D}$ is the averaged offset image, $\overline{W}$ is the averaged gain image, and $\overline{\overline{W} - \overline{D}}$ is the mean pixel value of the gain-offset corrected image. The subscript i denotes the number of image to be analyzed. We took 5 images at each threshold voltage for gain-offset correction.

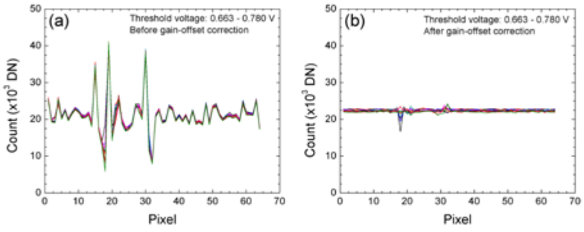

Fig. 1. 64 pixel values of detector with respect to various threshold voltages (a) before gain-offset correction, (b) after gain-offset correction. As some pixels from module 2 have abnormal properties with respect to the time, they did not be corrected properly.

2.2 Incident spectrum calculation

We used two x-ray tube such as XTF5011 (Oxford instruments, CA 95066, USA) for energy ranges under 50 kVp and EXG6 (Vatech Humanray, Gyeonggi-do, Korea) for over 50 kVp. Additional tube filtration was applied to reduce an uncertainty from low energy.

The photon fluence was estimated based on the measured half-value layer (HVL) and the lab-made X-ray spectrum simulator [1].

Table I: One example of spectrum simulation results

	Actual condition	Simulation
Target	Tungsten	Tungsten
Inherent filter	0.125 mmBe	0.100 mmBe
Additional filter	0.5 mmCu	0.48 mmCu
Tube voltage	40 kVp	39 kVp
HVL	3.21 mm	3.283 mm

2.3 Measurement of spectra

Using the single-channel photon-counting detector, we obtained S-curve first by scanning the threshold voltage during x-ray irradiation. The differentiation of S-curve provides the measured spectrum with respect to the threshold voltage. As mentioned above, the measured spectrum can be distorted by charge trapping. Thus the measured spectrum which was obtained from the differentiation of S-curve shows high counts in the low energy range. To denoise the spectrum some investigators have fitted S-curve with a model such as the error function and then differentiated it [2]. Since only the peak information of the measured spectrum is important, we can approximate the steep region of the S-curve to the error function:

$$\operatorname{erf}(x) = \tfrac{2}{\sqrt{\pi}} \int_0^{\infty} e^{-t^2} dt \tag{2}$$

The error function for estimating the peak region in S-curve was slightly modified to fit the data using regression analysis.

From the approximated S-curve, we can derive the measured spectrum (M) by differentiating it by using central difference method [3],

$$\mathrm{M}_k = \frac{\mathrm{S}_{k-1} - \mathrm{S}_{k+1}}{2\Delta \mathrm{V}} \tag{3}$$

where S is the approximated (fitted) S-curve, ΔV is a bin of threshold voltage, and the subscript *k* denotes the increase of threshold voltage.

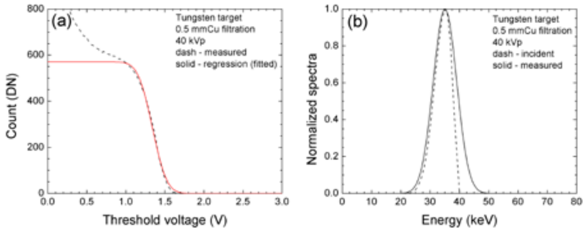

Fig. 2. (a) The dashed line shows the measured S-curve and the solid line shows the estimated S-curve using the error function. The region of interest in the measured data makes good agreement with the fitted data. (b) Comparison of incident spectrum and the measured spectrum. The agreement is reasonable.

2.4 Energy calibration and verification

From the incident and measured spectra, we can obtain the peak information of energy and threshold voltage, respectively. Assuming the linear relation between the threshold voltage and energy, we can obtain the linear equation for energy calibration. The method can be verified by measuring exactly known spectrum using radioisotopes. As shown in Fig. 3. The calibrated energy channel well describes the measured radioisotope spectrum.

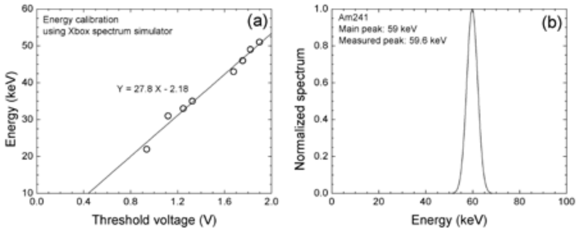

Fig. 3. (a) Energy calibration result of CdZnTe from peak information using various x-ray spectra. (b) Verification of the energy calibration method. The peak energy of measured spectrum using Am^{241} shows 59.6 keV and it shows good agreement with actual peak energy within error of lower than 1%.

3. Conclusions

Although the incident spectrum simulation shows a slight difference from the exact spectrum due to the insufficient tube filtration and the approximation for calculating photon fluence, the result of energy calibration shows good agreement with known gamma-ray spectrum. The proposed method in this study is simple and can be used conveniently in lab environment.

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