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## Energy calibration of energy-resolved photon-counting pixel detectors using laboratory polychromatic x-ray beams

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## ABSTRACT

Recently, photon-counting detectors capable of resolving incident x-ray photon energies have been considered for use in spectral x-ray imaging applications. For reliable use of energy-resolved photon-counting detectors (ERPCDs), energy calibration is an essential procedure prior to their use because variations in responses from each pixel of the ERPCD for incident photons, even at the same energy, are inevitable. Energy calibration can be performed using a variety of methods. In all of these methods, the photon spectra with well-defined peak energies are recorded. Every pixel should be calibrated on its own. In this study, we suggest the use of a conventional polychromatic x-ray source (that is typically used in laboratories) for energy calibration. The energy calibration procedure mainly includes the determination of the peak energies in the spectra, flood-field irradiation, determination of peak channels, and determination of calibration curves (i.e., the slopes and intercepts of linear polynomials). We applied a calibration algorithm to a CdTe ERPCD comprised of  $128 \times 128$  pixels<sup>2</sup> with a pitch of 0.35 mm using highly attenuated polychromatic x-ray beams to reduce the pulse pile-up effect, and to obtain a narrow-shaped spectrum due to beam hardening. The averaged relative error in calibration curves obtained from 16,384 pixels was about 0.56% for 59.6 keV photons from an Americium radioisotope. This pixel-by-pixel energy calibration enhanced the signal- and contrast-to-noise ratios in images, respectively, by a factor of  $\sim 5$  and 3 due to improvement in image homogeneity, compared to those obtained without energy calibration. One secondary finding of this study was that the x-ray photon spectra obtained using a common algorithm for computing x-ray spectra reasonably described the peaks in the measured spectra, which implies easier peak detection without the direct measurement of spectra using a separate spectrometer. The proposed method will be a useful alternative to conventional approaches using radioisotopes, a synchrotron, or specialized x-ray sources (e.g., characteristic or fluorescent x-rays) by reducing concerns over the beam flux, the irradiation field of view, accessibility, and cost.

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### 1. Introduction

A two-dimensional (2-D) photon-counting pixel detector for spectral x-ray imaging, a so-called energy-resolved photon-counting pixel detector (ERPCD), is typically composed of two layers: a sensor material layer for converting x-rays into electronic charges and a readout pixel array layer for converting current to voltage, thus measuring the voltage amplitude and registering it as a count [1]. The readout pixel array is an electronic chip, each pixel of which contains many analog/digital circuits for signal processing and pulse counting. The pixel electrodes of the readout pixel array are electrically connected to the pixel electrodes patterned on the bottom surface of

the sensor layer through indium bump bonds [2,3]. This hybrid detector system design readily enables the use of different semiconductor sensing materials that are relevant to specific imaging applications.

During fabrication of the readout pixel array, small variations in the electrical performance of microelectronic devices (for example, dispersions in threshold-voltage levels in transistors), which constitute the pixel circuits, are unavoidable [4], thereby misallocating pulse counts in channels of a pixel for photons with the same energy [5]. Therefore, for reliable use of photon-counting pixel detectors for spectral x-ray imaging, precise calibration in terms of energy is essential.

Energy calibration can be carried out using a variety of methods. In all of these methods, photon spectra with well-defined peak energies are recorded. In the case of a pixelated detector, every pixel should be calibrated. In general, monoenergetic photons with known energies from various sources are used for irradiation of the pixel detector.

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The monoenergetic photons include x-rays and  $\gamma$ -rays from radioisotopes [6–9], fluorescence x-rays from x-ray tubes or targets excited by radioisotopes [10–13], bremsstrahlung x-rays from a synchrotron facility [14–16], or combinations thereof. To some degree, all of the conventional calibration approaches have disadvantages in their applications. The use of radioisotopes may suffer from a small irradiation area and weak beam flux, which makes the calibration procedure time-consuming. The use of a fluorescence x-ray tube requires additional materials: a K-edge target and filter materials, for example [17]. More importantly, given the rather coarse energy resolution of ERPCDs, the overlap of various fluorescence peaks makes it difficult to assign a well-defined energy to the resulting single peak, which introduces errors into the calibration process. The use of a synchrotron is limited by extent of its beam; hence, a scanning approach might be needed for calibration of all pixel elements in the detectors [14]. In addition, most users have difficulty accessing synchrotron facilities.

As an alternative, we propose the use of polyenergetic beams from general x-ray tubes, which are usually installed in laboratories, without any alterations in the imaging setup so that we can reduce concerns over beam flux, the irradiation field of view, accessibility, and cost.

## 2. Materials and methods

### 2.1. Energy-resolved photon-counting pixel detector

The ERPCD under investigation in this study consisted of eight modules of hybrid detectors (PID350, Oy Ajat Ltd., Finland) in a  $4 \times 2$  arrangement. Each modular detector featured a 0.35 mm-sized pixel arranged in a  $32 \times 64$  format; hence, the ERPCD produced an active area of about  $45 \times 45 \text{ mm}^2$  with  $128 \times 128$  pixels<sup>2</sup>. Each module consisted of a cadmium telluride (CdTe) crystal with a thickness of 0.75 mm bump-bonded onto a custom-designed application-specific integrated circuit (ASIC) which was made using a complementary metal-oxide-semiconductor (CMOS) process. The CMOS ASIC had 2048 readout channels arranged in the  $32 \times 64$  format, and each channel was equipped with pre- and shaping-amplifiers, a discriminator, peak/hold circuitry, and an analog-to-digital converter for digitizing the signal amplitude. To compensate for the pixel-to-pixel variations in the channel gain and offset, each channel was further equipped with two 8-bit digital-to-analog converters (DACs). The hybrid detectors were wire-bonded to readout printed circuit boards that were connected to a host personal computer through a universal serial bus interface (version 2.0). Detailed physical specifications, electrical characteristics, and details on the performance of the detector system used in this study can be found in Ref. [18].

### 2.2. Energy calibration procedure

If we assume that the analog-to-digital converted unit (ADU) or channel number in each pixel element of an ERPCD is linearly

proportional to the measured pulse height (which reflects the energy deposited due to single photon interactions), we need more than two known photon energies for energy calibration. The x-ray spectrum from a conventional laboratory x-ray tube typically consists of a single most probable peak, of which energy is characterized by the applied tube peak voltage (kVp) and filtration, as well as additional unique sharp peaks due to characteristic x-rays from the anode target material when the x-ray tube is operated at a kVp level that is greater than the K-edge energy of the target. In this case, we can use a single setup of a polyenergetic x-ray beam for energy calibration because the beam provides more than two energy peaks. If an ERPCD is not able to resolve the characteristic x-ray peaks due to poor energy resolution, at least two beam setups that provide main peaks at different energies are required. We used four different setups to check whether or not the assumption of linearity was valid. The main procedure for energy calibration includes the following:

- 1) *Determination of peak energies of the spectra.* The x-ray spectra from four different setups, which could be achieved by adjusting kVp values and thickness/material of added filter of the x-ray tube/generator system, were directly measured using a calibrated spectrometer, and the energies indicating main peaks in the spectra were determined.
- 2) *Flood-field irradiation.* Under each beam setup, the ERPCD was irradiated and all the pixel responses were recorded simultaneously. During irradiation, the distance between the x-ray source and the ERPCD was sufficient to ensure uniform irradiation over the active area of the ERPCD and to avoid the pulse pile-up effect, which can distort the peak position [19,20].
- 3) *Determination of peak channels.* We first smoothed the response function measured from each pixel element at a given beam setup by using a moving average filter, and then determined the channel number (or ADU) indicating the main peak by using the zero-derivative method.
- 4) *Determination of calibration curves.* For the pair of peak energy and ADU [or simply ( $E_{\text{peak}}$ , ADU)] data in each pixel element, we applied linear least-squares regression analysis. Hence, we obtained the slope  $a$  (in  $\text{keV ADU}^{-1}$ ) and intercept  $b$  (in KeV) describing the linear calibration curves in each pixel element.

### 2.3. Experimental

For energy calibration of all the pixel elements in the CdTe ERPCD, we used the x-ray spectra from the tungsten target (EXG6, Rayence, Korea) with 40 mm-thick added aluminum (Al) filtration operated at 50, 55, and 60 kVp, as shown in Fig. 1(a). Additionally, we employed a 70 kVp setup with a 3.5 mm-thick copper (Cu) filter. During irradiation, the beam current was fixed to 2 mA. The use of thick or strong additional filtration was intended to provide significant beam hardening as well as to reduce photon flux.

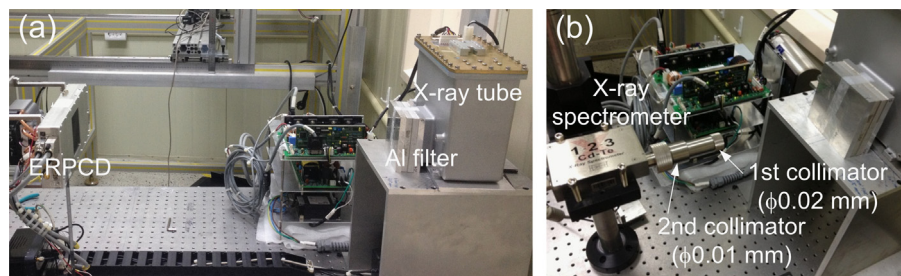


Fig. 1. (a) Experimental setup for energy calibration of the ERPCD with a laboratory polychromatic x-ray source and (b) setup for the measurements of x-ray spectra from the laboratory x-ray source by using a CdTe diode spectrometer, in front of which two pinhole collimators were equipped to reduce the x-ray beam flux.

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