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

Hanbeean Youn\textsuperscript{a}, Jong Chul Han\textsuperscript{a}, Soohwa Kam\textsuperscript{a}, Seungman Yun\textsuperscript{a}, Ho Kyung Kim\textsuperscript{a,b,*}

\textsuperscript{a} School of Mechanical Engineering, Pusan National University, Busan 609-735, Republic of Korea
\textsuperscript{b} Center for Advanced Medical Engineering Research, Pusan National University, Busan 609-735, Republic of Korea

\textbf{A R T I C L E   I N F O}

Article history:
Received 10 December 2013
Received in revised form 23 May 2014
Accepted 23 May 2014
Available online 2 June 2014

Keywords:
Photon counting
Pixel detector
Energy calibration
Image quality
Spectral x-ray imaging

\textbf{A B S T R A C T}

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 × 128 pixels 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 \textasciitilde5 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.

\textcopyright 2014 Elsevier B.V. All rights reserved.

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 \cite{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 \cite{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 \cite{4}, thereby misallocating pulse counts in channels of a pixel for photons with the same energy \cite{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 pixilated detector, every pixel should be calibrated. In general, monoenergetic photons with known energies from various sources are used for irradiation of the pixel detector.
The monoenergetic photons include x-rays and γ-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 × 2 arrangement. Each modular detector featured a 0.35 mm-sized pixel arranged in a 32 × 64 format; hence, the ERPCD produced an active area of about 45 × 45 mm² with 128 × 128 pixels. 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 × 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 (Epeak, ADU)] data in each pixel element, we applied linear least-squares regression analysis. Hence, we obtained the slope a (in 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.
To identify the main peak energies, the spectra were measured by replacing the ERPCD with an x-ray spectrometer (X-123, Amptek Inc., MA, USA), which employed a CdTe diode with a thickness of 1 mm, as shown in Fig. 1(b). Two pinhole disks were incorporated for the beam collimation.

When the pulse processing time of a detector is not shorter than the time interval in which two or more x-ray photons arrive at the detector, those photons are recorded as a single count in an incorrect energy channel [19,20]. Therefore, this pulse pile-up effect distorts the recorded spectrum, and it becomes more severe at high counting rates. For a nonparalyzable detector having a true count rate of \( n \) and a deadtime of \( \tau \), the probability of an \( m \)-th order pulse pile-up event follows Poisson statistics and can be given as [19]

\[
\Pr(m) = \frac{(nt)^m e^{-nt}}{m!}
\]

which describes the Poisson probability of having \( m \) events during time \( t \), given the mean number of counts \( nt \). We estimated \( \tau \) of the ERPCD used in this study to be \( 8 \times 10^{-4} \) s from the manufacturer’s data, which claimed that the speed of the ERPCD is 1 kHz mm\(^{-2}\). To reduce the pulse pile-up effect (\( m = 1 \)) in this study, we set the source-to-detector distance, \( d_{SD} \), to be \( 10^3 \) mm in our optical bench geometry, as shown in Fig. 1(a).

The x-ray fluence \( \Phi \) (in photons mm\(^{-2}\)) can be estimated using the exposure \( X \) (in mR) measured at the detector input times the x-ray fluence per unit exposure \( \Phi/x \) (in photons mm\(^{-2}\) mR\(^{-1}\)) for a particular spectrum such that [21]

\[
\Phi = \frac{X}{x(E)} = \frac{X}{\int_0^\infty \Phi(E) dE} \int_0^\infty \Phi(E)x^{-1}(E) dE
\]

where \( x(E) = 5.43 \times 10^6 / (\mu_{m/e}/\rho)_{\text{air}} \) is the mass energy-absorption coefficient (in cm\(^2\) g\(^{-1}\)) for air and \( \rho \) denotes the physical density. We measured the exposure as a function of \( d_{SD} \) with a calibrated ionization chamber (Piranha R&F/M 605, RTI Electronics AB, Sweden). We then calculated the x-ray fluence using Eq. (2) with \( \Phi(x) \) that was estimated from the measured half-value layer (HVL) of the considered x-ray beam and x-ray spectrum simulator [22]. Then, the true count rate \( n \) per pixel was estimated with the known pixel size and readout time. From these analyses, we obtained \( m = 1 \) at \( d_{SD} = 10^3 \) mm.

2.4. Validation

The calibration curves obtained by using the proposed method were validated with the known energy of 59.6 keV from \(^{241}\text{Am}\). We defined the relative calibration error of a detector pixel element located at \((i, j)\) coordinates in the pixel arrays as

\[
ev(i,j) = \frac{59.6 - E(i,j)}{59.6} \times 100\%
\]

where \( E(i,j) \) denotes the energy measured with pixel \((i, j)\) for 59.6 keV from \(^{241}\text{Am}\). Then, the averaged relative error for all the pixel elements is given by

\[
(\varepsilon) = \frac{1}{IJ} \sum_{i,j} e(i,j)
\]

where \( I \) and \( J \) denote the number of rows and columns in the pixel arrays, respectively.

2.5. Imaging tests

We obtained phantom images with the ERPCD. The phantoms included an aluminum step wedge, a home-made contrast phantom consisting of an acrylic cylinder in which four different materials (water, Teflon, iodine, and nylon) were implanted along the radial direction, and a finger phantom consisting of artificial bones encased in acrylic, as shown in Fig. 2(a), (b), and (c). We compared the images obtained before and after the application of the energy calibration procedures.

3. Results

As shown in Fig. 3, the peak energies were determined to be 46, 49, 51, and 64 keV, respectively, for the measured spectra of 50, 55, 60, and 70 kVp beam setups for energy calibration. In the measured spectra, we also observed small broad peaks due to escaping fluorescence x-rays from the CdTe spectrometer. The most probable energies of the escape peaks could be estimated from the differences between the main peak energies (i.e., 46, 49, 51, and 64 keV) of the spectra and the K-edge energies of the Cd (26.7 keV) and Te (31.8 keV) elements [23]. As the peak widened with increasing kVp, the escape peak correspondingly broadened in the Al-filtered spectra. In addition, we note that the estimated spectra generated by the x-ray spectrum simulator [22] were in good agreement with the measured spectra. The averaged relative difference between the measured and simulated spectra was about 1.2%.

Fig. 4 demonstrates the peak-channel detection procedure in a flood-field spectral image obtained using the ERPCD for the 60 kVp beam setup as an example. A raw spectrum measured with the pixel element located at coordinates (32, 32) is shown in Fig. 4(a). The spectral shape was similar to the spectrum measured from the x-ray spectrometer [see Fig. 3(c)], but was more asymmetric and broader. This is probably due to charge-sharing [24] and hole trapping effects [25] in the ERPCD. The spectrum was then smoothed with an averaging kernel with a size of three channels, as shown in Fig. 4(b). Then, the peak channel was determined by the zero-derivative method as shown in Fig. 4(c). Fig. 4(d) shows

Fig. 2. Phantoms used for imaging tests of the ERPCD. (a) Aluminum step wedge, (b) home-made contrast phantom and (c) finger phantom.
the smoothed spectra measured at pixel coordinates (32, 32) for the four beam setups.

For flood-field spectral images obtained for four different beam setups with the known main peak energies, we determined the corresponding peak ADUs at all the pixel elements following the procedure shown in Fig. 4. Then, we applied linear least-squares regression analysis to the \((E_{\text{peak}}, \text{ADU})\) data of each pixel in order to obtain linear calibration curves. Fig. 5(a) and (b) shows the calibration maps, which describe the slopes and intercepts, respectively, of the ERPCD, in 2-D representations. The maps are

Fig. 3. Measured spectra for (a) 50, (b) 55, (c) 60, and (d) 70 kVp beam setups by using the CdTe x-ray spectrometer. The solid lines describe the calculated spectra generated from the spectrum simulator using the measured HVLs for the considered x-ray beams.

Fig. 4. Demonstration of peak-channel detection in the flood-field spectral image: (a) raw, (b) smoothed, and (c) differential spectra for the 60 kVp beam irradiation. Smoothed spectra for four different beam setups are shown in (d). For brevity, we cut off the counts at ADU levels less than that corresponding to the electronic noise floor in the 70 kVp spectrum. All the spectra were measured with the pixel located at (32, 32) coordinates.
shown with the level of their mean value $\mu$ and a window of two times their standard deviation $\sigma$. The results show that the slope is $0.31^{+0.07}_{-0.04}$ keV ADU$^{-1}$ and the intercept is $16.73^{+7.07}_{-10.38}$ keV. Hence, the coefficient-of-variation ($\sigma/\mu$) values, which quantify the spread of data, are 0.13 and 0.62, respectively. Although the overall nonuniformities are small, Fig. 5 indicates that the deviations in the calibration curves are mainly governed by the readout electronics rather than by the CdTe sensor material, since the spatial patterns are visible at the edges of modules. The slopes of calibration curves were less variable (with respect to the location of pixel elements) than the intercept, which can be seen more clearly in Fig. 6.

Fig. 6 shows 2-D distributions of the slope-and-intercept value of each pixel. The values describing slope $a$ and intercept $b$ were normalized by their mean values $\bar{a}$ and $\bar{b}$, respectively. The distributions are separately plotted for each detector module to investigate the uniformity of the responses among modules—the nonuniformity in responses among modules is negligible. Fig. 6 clearly shows that variations in the intercept values are more pronounced than those in the slope values, which may imply small variations in amplifier gains but large variations in voltage settings by DACs. In addition, we observe a weak linear correlation between $a$ and $b$: $b$ decreases as $a$ increases.

The calibrated pixel responses of the ERPCD were validated using the known energy from the $^{241}$Am radioisotope. The relative error map calculated using Eq. (3) is shown in Fig. 7, and $\langle \varepsilon \rangle = 0.56^{+0.09}_{-0.09}\%$. Fig. 7. Relative error map of the calibrated pixel responses of the ERPCD for the $^{241}$Am radioisotope. The averaged relative error is $0.56\%$ (level $= \mu$ and window $= \pm 2\sigma$). To emphasize the modular detector boundaries, we intentionally inserted dummy gaps among modules, and the gap size corresponds to the pixel pitch.

Fig. 8 compares the images obtained with the ERPCD for the aluminum step wedge, contrast, and finger phantoms (see Fig. 2) at 50, 50, and 80 kVp, respectively. The images in the upper row were obtained without energy calibration, whereas those in the lower row were obtained after the application of energy
calibration. We note that energy calibration greatly enhanced the image quality with respect to viewing with the naked eye. For a quantitative evaluation of image quality, the signal-to-noise ratio (SNR) was calculated for some regions of interest (ROIs) as designated by dotted boxes in the step-wedge phantom images shown in Fig. 8. The calculated SNR values were 10.16 and 12.94, respectively, for ROIs 1 and 2 in the image without energy calibration, and were 56.76 and 62.38 in the image with energy calibration. Therefore, the energy calibration improved the SNR by a factor of ~5. On the other hand, an improvement in the contrast-to-noise ratio between the ROIs due to energy calibration was about three.

4. Discussion

For pixelated electrode geometries such as the CdTe ERPCD used in this study, charge sharing can shift photopeaks to lower energies depending on the pixel size, bias voltage, and photon energy. Therefore, charge sharing could introduce nonlinearities into the calibration curves. However, Koenig et al. [26] reported a peak shift of only 0.6 keV due to the charge-sharing effect in a CdTe Medipix2 Hexa detector with a pixel pitch of 0.165 mm for the $^{241}$Am radioisotope. In this study, we neglected nonlinearity due to charge sharing and used a linear relationship for detector calibration.

We used four spectra from the W target operated at the x-ray tube voltage setups ranging from 50 to 70 kVp for energy calibration. Although we could further lower the kVp value, we selected the 50 kVp as the lowest setup because the most pixels in the ERPCD measured the corresponding spectra with well-defined main peaks that were clearly distinguished from the electronic noise peaks as shown in Fig. 4(a). On the other hand, we could not use the spectra generated at the tube voltages greater than 75 kVp, since the W-anode characteristic peaks contaminated the main peaks. The lowest and highest kVp setups should be carefully determined accounting for the electronic noise floor, and detectable maximum energy and energy resolution of a detector to be investigated. We also note that the use of peak energies that are closely spaced to one another could be prone to yield errors in the resultant calibration curves.

For the determination of peak energies from a calibration probe such as the polyenergetic x-ray beams described in this paper, we directly measured the photon spectra using a spectrometer. This implies that additional apparatus is needed and costs are incurred when implementing our approach for detector calibration. As shown in Fig. 3, however, we note that the simulated photon spectra well describe the main peaks in the measured spectra. X-ray spectrum simulators are available [22,27–29]; hence, we can use them for peak detection instead of the direct measurement of spectra.

In order to analyze robustness of the peak-channel detection routine used in this study, we performed simple numerical simulations by using a unimodal distribution:

$$f(x) = g(x) + c \times \text{randn}(0, 1) \times g(x)$$

where $g(x)$ is the Gaussian distribution with a known peak position. “$\text{randn}(0, 1)$” is normally-distributed pseudorandom numbers and $c$ is a constant ranging from 0 to 1. We applied the peak-channel detection routine to Eq. (4), and the number of iterations performed for each $c$ was $10^4$. The averaged relative error between the true and detected peak positions was negligible when $c < 0.1$, and then it gradually increased with increasing $c$. We note that the averaged relative error was about 19% when $c = 1$.

5. Conclusion

We successfully demonstrated the energy calibration of an energy-resolved CdTe photon-counting pixel detector in a pixel-by-pixel way by using conventional polychromatic x-ray beams. The imprecision of the proposed method was estimated to be less than 0.60% for the 59.6 keV photons from $^{241}$Am. Using the proposed energy calibration method, we obtained, approximately, a five-fold improvement in image quality (i.e. SNR). We believe that the proposed method will be useful for the energy calibration of photon-counting detectors without concerns regarding the flux, field of view, accessibility, and cost compared to conventional methods.

Acknowledgment

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea.
(NRF) funded by the Ministry of Education, Science and Technology (2011-0009769).

References