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Spectroscopy with a CdTe-based photon-counting imaging detector (PCD) having charge sharing correction capability

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Abstract

The spectroscopic capabilities of a newly upgraded version of a prototype imaging photon counting detector (PCD) was investigated. The XCounter Actaeon has four acquisition modes in which signal processing is varied including one mode having a charge sharing correction so that neighboring pixels that share a detected event will not be erroneously counted twice, hence it is designated the Anti-Coincidence Circuit On or ACC On mode. Since this CdTe-based direct conversion PCD has 100 μm pixels, such charge sharing may frequently occur for typical medical x-ray energies. Each pixel of this PCD has two scalers and two energy discriminators that enable counting without instrumentation noise of events above each threshold level; hence, a spectrum can be obtained by sequentially moving the thresholds of both discriminators. It became evident from the spectra for the various acquisition modes that only those obtained with the charge sharing correction enabled, compared favorably with theoretically predicted spectra. After verifying the energy calibration using the mono-energetic emissions from an Am-241 source, spectra at various kVps from a standard medical x-ray generator were obtained. The spectra generated by ACC On mode for 70 kVp and 110 kVp were the closest match to the theoretical spectra generated by SpekCal. For dual energy applications, ACC On mode with charge sharing correction circuitry would be the best choice among various acquisition modes. Also investigated was the dual energy imaging capability of the Actaeon PCD with ACC On mode to separate Aluminum and Iodine while imaging an artery stenosis phantom.

Keywords

Photon Counting Detectors (PCD); Spectroscopy; Anti-Charge Sharing Correction; Dual Energy Imaging; Material Separation

INTRODUCTION

Imaging during neurovascular interventions requires detectors which can provide utmost details of structures like stents and coils. Spatial resolution translates to discerning finite size of structures and contrast resolution manifests in differentiating material. Small Region of Interest (ROI) detectors with smaller pixel size (35 – 100 μm) have been focus of research for the past decade whereas the current trend is towards photon counting detectors that could provide both higher spatial resolution and material decomposition. By means of a thresholding circuitry PCDs are able to count individual photons and do direct detection with materials such as CdTe and CZT resulting in overall improved image quality. We explore such a PCD, XCounter's Actaeon for its energy calibration and spectroscopic

abilities and test its ability to do dual energy material separation. For any potential dual energy application including material decomposition, accurate thresholding and spectrum measurements are prerequisites. Also simulated is a dual energy imaging scenario with aluminum and iodine to be discerned at two thresholds.

MATERIALS AND METHODS

Actaeon PCD has 100 μm pixel size which makes it a good candidate for ROI imaging, even though the field of view is small ($1'' \times 1''$, 256×256 pixels). The CdTe active layer which makes direct detection possible for the Actaeon is 0.75 mm thick. Through a custom built ASIC circuitry the Actaeon is able to threshold the signal generated from interactions, count the events whose signal is above the threshold and in turn convert the number counted in each pixel into grayscale values. The sharing of charges between neighboring pixels results in misdirected allotment of events to inaccurate pixels, thereby losing resolution. One of the acquisition modes within Actaeon has a circuitry which, when turned on, could do 8 next-nearest-neighbor correction for the signal and locate events to the pixel with the maximum signal, based on the assumption that the pixel with the maximum signal is the primary site of interaction. This mode is named High Sensitivity with Anti Coincidence (ACC On). The other three modes include: High Sensitivity without Anti-Coincidence (ACC Off), which turns off the charge sharing correction, thereby enabling faster counting; High Flux (HF) mode which is designed for situations involving higher flux rates; and High Power (HP) mode which is the default photon counting mode.

Spectrum measurements were carried out with two sources. The first source was a Toshiba Rotanode GRX T744GFS tube within an Infinix biplane system. The second one was a 5.6 μCi Am-241 rod from Eckert and Zeigler. For the x-ray spectrum measurements, we used two sets of X-Ray generator parameters. Both acquisitions were done in dual energy (DE) mode with two simultaneous thresholds operative and moved together to increasing energies yet with the energy separation constant. The first set was fixed at 70 kVp, 160 mA, 10 ms and 150 frames were acquired at 10 fps. The thresholds were separated by 2 keV and moved from 20 keV to 70 keV for all four modes of Actaeon. An RQA5 attenuator was placed in the beam and the exposure at the detector was found to be 141 $\mu\text{R/frame}$. The second set of measurements were taken at 110 kVp, 100mA, 10 ms at 5 keV intervals over a larger range from 20 keV to 110 keV. Again 150 frames were acquired in dual energy mode with pulse duration trigger. The detector exposure was found to be 800 $\mu\text{R/frame}$ with an RQA5 attenuator in the beam. Differential counts were obtained to plot the spectrum. SpekCal² was used to generate theoretical spectra for 70 kVp and 110 kVp and then compared with the measured spectra. For gamma ray spectroscopy with Am-241, 750 frames were acquired at 10 fps. The energy intervals were varied in increments of 2 keV from 40 to 70 keV in dual energy mode.

For dual energy imaging experiments, a 76–700 Digital Subtraction Angiography Phantom with iodine contrast arteries from Nuclear Associates was used. The artery used for imaging was 4 mm thick and had a concentration of 6 mg iodine/ cm^2 . The acrylic slab (2.5 cm thick) was placed on a Unistrut metal framing platform, on top of which a 3 mm thick aluminum slab was placed over half the field, followed by the Actaeon detector. Iodine and aluminum

were used to simulate contrast media and bone attenuation in interventional procedures. The technique parameters were fixed at 120 kVp, 250 mA and 10 ms and 150 frames were acquired at 10 fps with pulse duration triggering for the Actaeon. A voltage of 120 kVp was chosen so that the spectrum would have sufficient separation in counts between the low and high energy windows. Dual Energy was used for imaging, with the lower energy threshold fixed at 20 keV. The higher energy threshold was varied from 40 to 70 keV in increments of 5 keV. The stack of 150 images were flat field corrected to get images for processing. Two central pixel rows and two outer pixel rows were avoided to remove hot pixels from the merging of the two ASIC modules and darker pixels in the outer row, respectively.

For processing images, the 20 keV image was subtracted from all higher energy acquisitions so as to remove any background noise. For example, if during an acquisition the lower energy window was fixed at 20 keV and higher at 70 keV, the subtracted energy window would represent information between 20 and 70 keV. This image would be termed as “Lower Energy Image” and the 70 keV acquisition would be termed “Higher Energy Image”. The Higher Energy Image would represent events between 70 and 120 keV. The grayscale values in the acrylic region of higher energy image were normalized to values in the same region as those for the lower energy image. After this step of background equalization, the images are weighted according to equation (1).

$$\text{Difference Image} = \ln(\text{Image}_{\text{Lower}}) - w * \ln(\text{Image}_{\text{Higher}}) \quad (1)$$

To find the ‘w’, the normalization factor for the difference image, an equivalent ROI was selected in logarithmic images, within a region of aluminum without iodine, and considered in both lower and higher energy images. The grayscale values/signal in the lower energy image and those in the higher energy image will be equalized after exponentiation because the effective attenuation of aluminum at the two thresholds are essentially made equal so that the aluminum should appear the same in both high and low energy images. The resulting modified low energy image was then divided by the higher energy image to get the final contrast image with the aluminum boundary minimized in contrast.

RESULTS

As indicated in figures 1 and 3 we can infer that High Sensitivity with Anti-Coincidence On appears to be working properly because it is supposed to attribute multiple events from 8 neighboring pixels to the central pixel or the primary site of interaction. All the modes, excluding ACC On, count multiple events from the same central pixel separately which is evidenced by an increased amount of counts registered at the lower end of the spectrum where the thresholds are lower. The increase in overall counts at higher energies for ACC On mode is due to the proper allocation of events to the appropriate energy bin. For ACC On the spectrum peaks around 58 keV as it should for these experimental conditions, as predicted by the simulations from SpekCal in Figure 2. Figure 3 shows the spectrum at 110 kVp. For the 110 kVp spectrum ACC On gives the spectrum most closely resembling the one generated with SpekCal as can be seen from Figure 4 where there is a more detailed

spectrum for the ACC On mode. There are peaks in the 110 kVp spectrum for ACC On mode at 59, 71, 79, 89 and 97 keV. The peaks are supposed to be at 59, 67 and 69 keV from SpekCal. The change in locations in the peak could be due to characteristic emission of Cd and Te around 23 keV and possible non-linear thresholding for energy bins.

The results for gamma ray spectroscopy with various modes are shown in Figure 5 for a range of 40–70 keV. Using the information from Fig 5 above, % Energy resolution was calculated as $(FWHP/E_0) * 100$ where the Full Width at Half the Peak (FWHP) is divided by the peak energy E_0 . The Energy resolution for was thus found to be 12 keV or 20% for the 60 keV peak of Am-241 for ACC On mode, which was the best for all the modes.

The various stages involved processing images and their results are shown in Figures 6, 7 and 8. The acquisition considered here was done in dual energy mode with low energy threshold at 20 keV and higher threshold at 70 keV. Images presented are displayed with varied levels and windows through ImageJ, to maintain comparable visual perception. The artefactual horizontal line appearing in the images is due to the construction of the detector which consists of two separate rectangular modules.

Image for normalization of Higher Energy Image are marked in rectangular yellow boxes. Figure 7 Right. Image after normalization of signal in 70 keV image (Higher Energy Image) to the value in the acrylic region (ROI 1 in Fig. 7 Left) in the 20–70 keV image (Lower Energy Image).

After obtaining the final subtracted image, mean signal values were calculated for various ROIs as indicated in Figure 8b. Same ROIs were considered for the Lower Energy Image to find percent contrast (Table 1).

In addition to these values contrast between acrylic and acrylic + aluminum region was found to be 18% for the Lower Energy Image and 4.1% in the final subtracted image. The resultant image after all processing decreases the contrast between the aluminum + acrylic and acrylic region because the division does suppress the background. Some of the features, vessel on the acrylic part, appear to be subdued owing to increased noise in the final subtracted image. The origin of the increased noise requires further investigation and may be due to instability in the detector.

CONCLUSIONS

The spectroscopic abilities of the Actaeon were studied in detail. The spectrum from an Am-241 source was used to verify that the Actaeon was properly energy calibrated. The spectrum generated by ACC On mode for 70 kVp and 110 kVp was the closest available match for the theoretical spectrum generated by SpekCal. For dual energy applications, ACC On mode with charge sharing correction circuitry appears to be the best choice among various acquisition modes. Although initial results with dual energy imaging with the ACC On mode appear to enable single-shot digital subtraction angiography, increased noise in low contrast regions remains problematic.

Acknowledgments

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Figure 1.
Comparison of x-ray spectrum measured with various modes

Figure 2.

Left. Spectrum from ACC On mode. Right. Spectrum generated by SpekCal.

Fig 3.
Spectrum generated at 110 kVp by Actaeon

Figure 4.
Left. Spectrum from ACC On mode at 110 kV. Right. Spectrum generated by SpekCal

Figure 5.
Comparison of modes for gamma ray spectroscopy

Figure 6. Left. Image acquired at 20 keV threshold having all counts with energy above 20 keV. Right. Image acquired at 70 keV threshold having counts with energy above 70 keV hence designated the Higher Energy Image.

Figure 7. Left. Image after subtraction of 70 keV acquisition from 20 keV threshold hence represents events between the two thresholds (Lower Energy Image). The ROIs considered in the Lower Energy

Figure 8.

Left. Higher Energy Image after equalization for attenuation in Aluminum region (ROI 2 in Fig. 7 Left) using the weighting factor in equation 1. Right. Result of dividing Lower Energy Image (Fig. 7 Left) by the final modified Higher Energy Image (Fig. 8 Left).

Table 1

% Contrast values averaged over an ROI.

	Lower Energy Image	Final Subtracted Image
Region	% Contrast between	% Contrast between
Considered	iodinated artery and non-iodinated region	iodinated artery and non-iodinated region
Acrylic	5.6	5.3
Acrylic + Aluminum	6.1	6.8