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Evaluation of a new photon-counting imaging detector (PCD) with various acquisition modes

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Abstract

The prospect of improved low noise, high speed, and dual-energy imaging that may be associated with the use of photon-counting imaging detectors (PCD) has motivated this evaluation of a newly upgraded version of a prototype PCD. The XCounter Actaeon was evaluated in its four acquisition modes each based upon varying signal processing firmware including a mode with charge sharing correction that enables neighboring pixels that share the energy from one incident x-ray photon detection to be counted only once at the proper summed energy in the pixel with the largest charge deposition. Since this PCD is a CdTe-based direct detector with 100 μm pixels, such charge sharing for typical medical x-ray energy photons may occur frequently and must be corrected to achieve more accurate counts. This charge sharing correction is achieved with an Anti-Coincidence Circuit (ACC) which prevents double pixel counting from one event as well as prevents counting from either event if they are below a preset threshold. Various physical parameters of the PCD were evaluated including linearity, sensitivity, pulse pile-up effects, dark noise, spatial resolution, noise power spectrum, and detective quantum efficiency.

Keywords

Photon Counting Detectors (PCD); Modulation Transfer Function (MTF); Noise Power Spectrum (NPS); Detector Quantum Efficiency (DQE)

INTRODUCTION

Current state-of-the-art medical diagnostic detectors are mostly indirect-conversion energy integrating detectors. Using a scintillator layer such as CsI, x-rays are converted to light photons which results in the production of signals proportional to the energy of incident x-rays. A photon counting direct detector¹, on the other hand generates charge by the interaction of x-rays with a semiconductor material such as Cadmium Telluride (CdTe), and the resulting signal then passes through a discriminator/thresholding circuit producing a count. The number of counts collected is proportional to the number of incident photons detected. Some of these detectors are capable of high frame rate imaging and dual energy acquisition. This work is intended to characterize such a photon counting direct detector, the Actaeon, from XCounter AB with the most recent firmware updates. Linearity, sensitivity, pulse pile-up effects, dark noise, spatial resolution (MTF), noise characteristics (NPS) and detector efficiency (DQE) have been explored in this study. In this work we include an evaluation of the detector using standard image quality metrics.

MATERIALS AND METHODS

The XCounter Actaeon PCD used in this study has a 0.75 mm thick CdTe converter layer. The pixel pitch is 100 μm , with an active area of 1" x 1" and 256x256 pixel readout. The detector is capable of dual energy acquisition by the use of two independent thresholds for each pixel and is capable of high frame-rate imaging exceeding 1000 fps. Although photon counting detectors (PCDs) have the potentials for increased spatial resolution and higher signal to noise ratio, they also have been associated with unique problems. The major ones being pulse pile up and charge sharing. Pulse pileup occurs when signals are clustered together at a rate faster than the resolution time of the detector. This leads to two or multiple events being treated as one single signal with their combined amplitude and this results in lower overall counts. This can be evidenced in the non-linearity of the plot of counts versus exposure. For larger exposures the curve may tend to flatten or even saturate indicating a change from linearity resulting from pulse pileup effects. Charge sharing or cross talk happens when one single event in a pixel can produce a cascade of events in the neighboring pixels either through the creation of fluorescent x-rays or diffusion of charge. These resultant shared charges in multiple pixels may produce signals which are separately below the set threshold, leading to decreased overall counts. The penalty associated would be lower signal to noise ratio and contrast resolution.

There are four imaging modes available in this Actaeon detector. They are i) High Sensitivity with Anti Coincidence On (ACC On) ii) High Sensitivity with Anti Coincidence Off (ACC Off) iii) High Flux without Anti Coincidence (HF) iv) High Power-Legacy (HP). ACC On mode is the most interesting mode among the four because of its ability to allocate charges resulting from multiple adjacent pixel detections of one single x-ray absorption event to the primary pixel. This results in an overall increase in the number of counts in comparison to other modes when the threshold is set higher. ACC Off mode on the other hand does not have this anti charge sharing circuitry and leads to faster counting. HF mode is further optimized for larger flux rates, with compromised sensitivity for higher thresholds. HP mode is the default settings of the detector.

Linearity

For checking linearity of the detector, two sets of measurements were carried out. Part of an artery/stenosis phantom from Nuclear Associates (76–700) was imaged (Figure 1 Left) with all four modes of the Actaeon. The technique parameters were set at 70 kVp and the tube current was continuous (not pulsed) and a software acquisition sequence was used to capture 150 frames at 10 fps. The tube current was varied from 1 – 4 mA in increments of 0.5 mA. For the second set with higher exposure for the same 70kVp, pulsed exposure was used with tube current being varied from 50 – 400 mA and the pulse duration was set at 10 ms. An RQA5 attenuator was in the beam and the exposure to the detector ranged from 13 $\mu\text{R}/\text{frame}$ to 520 $\mu\text{R}/\text{frame}$. The thresholds were set at 20 keV and 32 keV for both sets of acquisitions. The average of 150 frames was used to find the mean signal using ImageJ, to plot against exposure. Linear fits were made to the curves of mean signal vs exposure to find the slope and correlation coefficients (R).

Dark field

To check for the thresholds above which the instrumentation noise became negligible, dark field measurements were carried out under three conditions. The first was using a software acquisition sequence (internal triggering of detector) with no source near the detector. The second acquisition was using a software acquisition with an X-Ray Source On and shielded to prevent exposure to the detector. The third acquisition was using a pulse duration acquisition (external triggering of detector) with an X-Ray Source On and shielded. For all three acquisition sequences, 250 frames were captured. The log dark field counts were plotted against threshold values in keV for an averaged frame.

Single/Dual energy acquisitions and noise ratios

Measurements with the Actaeon can be done in two ways, single window acquisition and dual energy acquisition. In this section we discuss the decrease in noise with an image formed by subtracting (either manual or through software) a dual energy acquisition compared to an image with two separate single energy acquisition.

Let N_1 and N_2 be the counts registered with two thresholds of acquisition, assuming quantum limited performance the signal to noise ratio for dual energy (simultaneous) acquisition is given by

$$SNR_D = \frac{N_2 - N_1}{\sqrt{N_2 - N_1}} = \sqrt{N_2 - N_1}$$

With the single window acquisition (two separate acquisitions) this expression is modified, as the errors add up in quadrature.

$$SNR_S = \frac{N_2 - N_1}{\sqrt{N_2 + N_1}}$$

Relative signal to noise ratio improvement, R is given by the equation below

$$R = \frac{SNR_D}{SNR_S} = \frac{\sqrt{N_2 - N_1}}{N_2 - N_1} * \sqrt{N_2 + N_1} = \frac{\sqrt{N_2 + N_1}}{\sqrt{N_2 - N_1}}$$

If both window counts are altered by a factor of “m” for example when the overall x-ray intensity is changed, the R value is given by

$$R^m = \frac{SNR_D^m}{SNR_S^m} = \frac{\sqrt{m} * \sqrt{N_2 + N_1}}{\sqrt{m} * \sqrt{N_2 - N_1}} = R$$

This means that for the same spectrum irrespective of the changes in technique parameters including ms, and mA, or other variations, the relative SNR remains the same. The dual energy acquisition with two independent thresholds will always have an advantage over single energy acquisition as indicated.

Standard linear systems metrics

Spatial resolution capabilities will vary with various modes. Using a slanted edge,² the MTF was measured for the various modes of the Actaeon. The exposure conditions were set at 70 kVp, 160 mA, 10ms and with an RQA5 attenuator in the beam, for an exposure of 204 μ R/frame. A total of 150 frames were captured at 10 fps and an averaged flat-field corrected frame was used to measure the MTF of the detector. The thresholds were kept at 20 keV and 32 keV and the acquisition was carried out in dual energy mode. Weiner spectra were measured for the same exposure conditions; 400 frames were acquired at 10 fps with triggering in synchronization with X-ray pulses from Toshiba's Infinix 8000 Biplane system under an Angio Protocol. Normalized Noise Power Spectrum was measured as suggested by Dobbins et. al,³. Detective Quantum Efficiency (DQE) was found from the expression

$$DQE(u) = \frac{MTF^2(u)}{NNPS * \phi}$$

where ϕ is the exposure per frame.

RESULTS

Linearity & Dark Field Measurements

As indicated in the Figure 2, at the 20 keV threshold, there is no substantial difference between any of the modes (upper four curves). However, at the 32 keV threshold the curve representing ACC On is significantly higher than all other modes. This translates to better charge tracking in physical reality hence better sensitivity. All the plots have correlation values greater than 0.9996 indicating a linear behavior and furthermore no evidence of pileup in any of the modes up to an exposure of 520 μ R/frame. The values of the slopes are as indicated in Table 1 below.

For the dark noise measurement in Figure 3, thresholds at the lower energy were incremented by 1 keV up to 20 keV. For the range of thresholds from 20 to 70 keV, thresholds were incremented by 5 keV. For thresholds above 20 keV, there is negligible instrumentation noise with the software triggering and no source present nearby. As shown in Figure 3 for the other two acquisitions with the sources on and shielded, and with hardware/x-ray pulse triggering, we do see an increase in log dark field counts; however, they are on the average less than 5 counts per frame and potentially due to leakage x-rays.

At the lower threshold of 20 keV, there is no significant change in spatial resolution with the various modes (Figure 4). However, at 32 keV (Figure 5) we can see that there is no degradation in MTF with ACC On mode, whereas there is improvement in MTF for all other modes. As shown earlier in the linearity plot (Figure 2) at 32 keV, threshold ACC On does a

better job in conservation of charges, but may be attributing signal to the pixel with the maximum energy of interaction, which may not necessarily be the preliminary site of interaction. Whereas, for all the other modes both primary and secondary pixels are avoided and only those pixels where the entire energy stays in the pixel, and above 32 keV are counted. Therefore, such modes exhibit no loss in resolution.

The noise performance of all modes is shown in Figure 6 at the lower energy threshold of 20 keV. The ACC On mode with charge conservation results in larger overall counts, which, with normalization of the NPS, reduces the NNPS. However, at higher frequencies there is a crossing over between ACC On and Off modes. The 32 keV threshold demonstrates (Figure 7) that at higher threshold, noise is essentially white noise and is lower with the ACC On mode.

The DQE measurements for Actaeon at the above mentioned thresholds of 20 and 32 keV are shown in Figures 8 and 9, respectively for the various modes.

For the 20 keV threshold the DQE(0) or Quantum Detection Efficiency for 0.75 mm CdTe is theoretically predicted to be 100%; however, the experimentally derived value was 72% for ACC On mode, which also is the highest among the modes. Anti-charge sharing circuitry may include separate pixel values below the threshold and attribute them to a single event newly counted, resulting in a net increased detection of events and increased DQE.

At higher thresholds we see a degradation in performance for all modes with the least degradation occurring for the ACC On mode. As shown earlier, the degraded MTF and increased NNPS for all modes, results in degraded DQE.

CONCLUSIONS

The Actaeon photon counting detector shows linear behavior for all practical ranges of exposures in the radiography/fluoroscopy domain. There was no saturation or bending over from linearity implying negligible pulse pileup effect. The ACC On mode with charge sharing correction outperforms other modes in conserving charges at higher thresholds. For thresholds above 20 keV, instrumentation noise was negligible with less than 1 count per whole frame on average. The spatial resolution capabilities of the detector were explored, indicating that the ACC On mode demonstrates poorer performance in comparison with the other modes. Noise correlation increases with threshold for all modes but minimally for the ACC On mode. With the increased signal due to anti-charge sharing circuitry the ACC On mode outperforms other modes with regard to NNPS with resulting superiority in DQE.

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Figure 1.

Left. Optical Image of the Artery-Stenosis phantom used for imaging. Right. X-ray image of a section of the phantom with ACC On mode from Actaeon at 20 kev threshold. The artefactual line in the image stems from two separate rectangular ASIC modules within the detector.

Figure 2.

The linearity for the Actaeon in various modes including High Sensitivity with Anti Coincidence On (ACC On), High Sensitivity with Anti Coincidence Off (ACC Off), High Flux (HF) and High Power (HP). Thresholds of 20 and 32 keV were used as indicated in the legend.

Figure 3.
Shows the log of dark field counts per frame vs energy threshold.

Figure 4.
MTF at 20 keV threshold for Actaeon with various modes of acquisition.

Figure 5.
MTF at 32 keV threshold for Actaeon

Figure 6.
Normalized Noise Power Spectrum at 20 keV.

Figure 7.
Normalized Noise Power Spectrum at 32 keV.

Figure 8.
DQE at 20 keV threshold.

Figure 9.
DQE at 32 keV threshold.

Table 1

Slopes for various modes at thresholds of 20 and 32 keV.

Mode	Slope (20 kev)	Slope (32 keV)
ACC On	1.36	1.15
ACC Off	1.35	0.70
High Flux	1.34	0.60
High Power	1.28	0.70