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Signal and noise characteristics of a CdTe-based photon counting detector: Cascaded systems analysis and experimental studies

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Abstract

Recent advances in single photon counting detectors (PCDs) are opening up new opportunities in medical imaging. However, the performance of PCDs is not flawless. Problems such as charge sharing may deteriorate the performance of PCD. This work studied the dependence of the signal and noise properties of a cadmium telluride (CdTe)-based PCD on the charge sharing effect and the anti-charge sharing (ACS) capability offered by the PCD. Through both serial and parallel cascaded systems analysis, a theoretical model was developed to trace the origin of charge sharing in CdTe-based PCD, which is primarily related to remote k-fluorescence re-absorption and spatial spreading of charge cloud. The ACS process was modeled as a sub-imaging state prior to the energy thresholding stage, and its impact on the noise power spectrum (NPS) of PCD can be qualitatively determined by the theoretical model. To validate the theoretical model, experimental studies with a CdTe-based PCD system (XC-FLITE X1, XCounter AB) was performed. Two x-ray radiation conditions, including an RQA-5 beam and a 40 kVp beam, were used for the NPS measurements. Both theoretical predictions and experimental results showed that ACS makes the NPS of the CdTe-based PCD flatter, which corresponds to reduced noise correlation length. The flatness of the NPS is further boosted by increasing the energy threshold or reducing the x-ray energy, both of which reduce the likelihood of registering multiple counts from the same incident x-ray photon.

Keywords

X-ray detector; photon counting detector; noise power spectrum; cascaded systems analysis; charge sharing; anti charge sharing; CdTe; x-ray imaging

1. INTRODUCTION

Recent advances in single photon counting detector (PCD) technology are opening up new opportunities in x-ray and CT imaging.¹ Cadmium telluride (CdTe) is one of the most popular options for the x-ray conversion layer of PCD. Compared with silicon (Si), CdTe has several attractive features, including a relatively large bandgap that permits room temperature operation, and relatively high atomic number that offers higher x-ray stopping

power. Meanwhile, CdTe-based PCD is a relatively new technology. Therefore, many aspects of this detector technology need to be further improved, and its pros and cons for each specific x-ray imaging application need to be thoroughly investigated.

In this work, a cascaded systems model for a CdTe-based PCD was developed to facilitate our understanding about its signal and noise properties, particularly their dependence on the charge sharing effect and the anti-charge sharing (ACS) capability offered by the detector. Experimental studies have been performed to validate the cascaded systems model and demonstrate how the noise power spectrum (NPS) of CdTe-based PCD depends on ACS and other system conditions such as x-ray energy.

2. MATERIALS AND METHODS

2.1 Theoretical method: Cascaded systems analysis

Unlike the serial cascade model developed for Si-based PCD,² both serial³ and parallel cascade models^{4,5} need to be used for CdTe-based PCD due to the high K-fluorescence yield (denoted as ω) of CdTe (86%) and the relative high energy of K-fluorescence photons of CdTe (> 23 keV). If a single x-ray photon interacts with the CdTe layer, it will experience either path A (no K-fluorescence), path B (K-fluorescence emission and K-fluorescence reabsorption in CdTe), or path C (K-fluorescence emission but no K-fluorescence reabsorption). The effective gain and stochastic spreading are different in these paths. Sub-stages similar to those of the direct conversion energy integrating detector (EID) are not discussed in detail. This paper focuses primarily on those stages that are unique to CdTe-based PCD. An overview of the cascaded noise transfer model is provided in Fig. 1.

2.1.1 Stage 0: Incident of individual x-ray photon—Different from EID, PCD is capable of treating the incidence of each individual photon as an independent event, except in the case of pulse pileup. As two consecutive x-ray photons incident on a detector pixel are mutually independent, so are the subsequent quanta generated by the two photons. Therefore, if there is any noise correlation in PCD, it should be caused by the spreading of secondary quanta generated by each individual photon. The modeling of noise correlation in PCD need to trace the transfer process of an individual photon instead of a collection of x-ray photons or “quanta”. This is fundamentally different from the noise transfer model of EID.

2.1.2 Stage 1: Interaction of x-ray photon with photoconductor—X-ray photons may interact with the CdTe photoconductor when they incident onto the detector. The probability of an x-ray photon to interact with the CdTe layer is given by $\bar{g}_1 = 1 - \exp(-\mu L)$, where L and μ denote the thickness and the attenuation coefficient of CdTe, respectively. The variance of the gain is given by $\sigma_{g_1}^2 = \bar{g}_1(1 - \bar{g}_1)$.

Due to the high probability to have K-fluorescence, a photon interacting with CdTe may follow either path A (without K-fluorescence), path B (with K-fluorescence and K-fluorescence reabsorbed) or path C (K-fluorescence escapes). For path B, sub-paths B1 (photoelectron) and B2 (K-fluorescence) will always occur in pair. Path C is similar to Path

A in the sense that it can be treated as a photon with lower energy interacting with CdTe without K-fluorescence.

2.1.3 Stage 2 - 6: Generation, spreading and collection of secondary quanta; additive noise

Stage 2-6 is similar to those of EIDs. Secondary quanta (electron-hole pairs) are generated from the interactions between x-ray photons and CdTe. The number of quanta is determined by how the absorbed x-ray energy E_a is distributed among electron-hole pairs with a creation energy (W) of CdTe. Due to diffusion and Coulomb repulsive force, the quanta spread laterally, and a fraction of them are collected at the electrodes. Integration within each pixel is performed, and noise from the readout electronic is added.

2.1.4 Stage 7: Anti-charge sharing (ACS)

ACS can be turned on or off and is optional. The basic idea of ACS is to put an adding node at each pixel, which adds charges collected in several (e.g., 2×2) neighboring pixels. As an example, Figure 2 shows that, the charge adding node in pixel E may add coincident charges at pixel G, H, I when ACS is on. The summed charge in E (denoted as q_7^E) will not only be compared with the threshold qT (discussed in stage 8), but also be compared with the charges collected in A, B, D. If summed charges in E is the largest, the count register of E will add one, otherwise it does nothing. ACS helps to decrease the likelihood of registering two concurrent counts at two neighboring pixels thus the likelihood of noise correlation.

2.1.5 Stage 8: Energy thresholding

The energy thresholding process is unique to PCD, which compares the charges collected in a pixel with a given threshold qT . For CdTe-based PCDs, this stage almost completely eliminates noise correlation. Fig. 3 summarizes why this is the case.

Assuming that the photon follows path A or C, which means no K-fluorescence or the K-fluorescence photon escapes. The average range of lateral spreading due to charge carrier drift and Coulomb force is limited. If the interaction happens at the center of pixel m [Fig. 3(a)], the collected charges are unlikely to exceed the threshold qT except at the pixel m . Therefore, no noise correlation is introduced between m and adjacent pixels.

For those photons that follow path B and are incident on the center of a pixel [Fig. 3(b)], the K-fluorescence x-ray may create a charge cloud in adjacent pixels. In case of low input x-ray energy E , the remaining energy ($E - E_k$) in pixel m is relatively small and is unlikely to exceed the minimal threshold qT and generate an output. When E is high enough, the locally deposited energy ($E - E_k$) may exceed the minimal qT . There is a small but non-zero probability to generate two counts in neighboring pixels for one single photon, which will result in noise correlation. Similar analysis can be applied to photons that are incident on the edge of a pixel following path A, B or C [Figs. 3(c)-(d)]. For low energy photons (< 40 keV), it is almost impossible to generate more than one count for a single photon. As the energy of the photons increases, the likelihood that two or more counts are registered for one incoming photon increases.

2.1.6 Summary of the cascaded model

The number of incoming photons for a single pixel is given by

$$\bar{q}_0 = a^2 \Delta t \bar{\psi}_0 \quad (1)$$

where a is the linear dimension of the pixel, t is the exposure time, $\bar{\psi}_0$ is the mean fluence rate. As described in stage 1, a g_1 fraction of the incoming photons will interact with CdTe layer. The expected number of interacted photons per pixel is given by

$$q_1 = \bar{g}_1 \bar{q}_0 = a^2 \Delta t \bar{\psi}_0 \bar{g}_1. \quad (2)$$

The variance is given by

$$\sigma_{q_1}^2 = \bar{g}_1^2 \sigma_{q_0}^2 + \bar{q}_0 \sigma_{g_1}^2 = \bar{q}_1. \quad (3)$$

Stages 2-8 describe how an interacted single photons may lead to a detector count. The gain can be summarized as $g_{2:8}$. The expected PCD output, the variance of the output and the NPS can be theoretically derived as

$$\begin{aligned} \bar{q}_{\text{PCD}} &= \bar{q}_1 \bar{g}_{2:8} = a^2 \Delta t \bar{\psi}_0 \bar{g}_1 \bar{g}_{2:8}; \\ \sigma_{\text{PCD}}^2 &= \bar{q}_{\text{PCD}}; \\ \text{NPS}_{\text{PCD}}(f) &= a^2 \sigma_{\text{PCD}}^2 = a^4 \Delta t \bar{\psi}_0 \bar{g}_1 \bar{g}_{2:8}. \end{aligned} \quad (4)$$

$\bar{g}_{2:8}$ is related to the detector material, the energy of the x-ray photon, the anti-charge sharing process and the threshold. The relationship between the variance σ_{PCD}^2 and $\text{NPS}_{\text{PCD}}(f)$ is based on the approximation that the NPS is flat.

This theoretical NPS model shows the following important properties of CdTe-based PCD: Higher energy threshold and lower x-ray energy increase the flatness of NPS and therefore the “whiteness” of noise; ACS increases the flatness. The output of PCD follows the Poisson distribution, no matter whether the intermediate process follows Poisson distribution or not.

2.2 Experimental validation methods

The experimental studies were performed using a CdTe-based PCD (XC-FLITE X1, Xcounter AB), which has a pixel size of 100 μm and an active area is 15.5×1.3 cm^2 . The detector is equipped with ACS. The data were collected using a benchtop system equipped with a diagnostic tube. The acquisitions used two beam setups, including the RQA-5 beam (70 kVp) and a 40 kVp beam. The mean x-ray energy of the two beams are 54 and 29 keV, respectively. The tube currents were fixed at 5 mA. For each beam and detector configuration, an ensemble of 100 images were acquired, each with an exposure time of 0.5 s. The measurements were performed at two thresholds, which correspond to x-ray energies

of approximately 18 and 29 keV. At each threshold, measurements were performed both with and without ACS. The noise only images were achieved by subtracting the mean of the 100 acquired images and NPS was calculated by performing the Fourier transform of the noise only images. The output and NPS of an $\text{Gd}_2\text{O}_2\text{S}$ -based EID (Shad-o-Box 2048, Rad- icon Imaging Corp., Santa Clara, CA) were measured as a benchmark.

3. RESULTS

As shown in Fig. 4(a), the distribution of the measured pixel values of the PCD matched well with the Poisson distribution. To compare, the distribution of the measured pixel values of the EID did not match that of Poisson (Fig. 4(b)). As expected, the distribution of detector output of EID needs to be modeled using Gaussian distribution.

Fig. 5(a) shows the NPS measured with the 40 kVp beam. As predicted by the theoretical model, the NPS was flat and there was negligible noise spatial correlation. The effective gain $\bar{g}_{2.8}$ decreased with increasing charge threshold, leading to lower NPS magnitude. In addition, higher threshold further reduced shared charges and thus boosted the flatness of the NPS. The NPS became less flat at higher x-ray energy [Fig. 5(b)], particularly for the one measured at low threshold. Higher threshold decreased the NPS magnitude but also made it flatter. Similarly, the ACS made the NPS flatter by rejecting shared charges. All of these experimental observations were consistent with the theoretical model.

To focus on the difference in frequency distribution of the NPS between PCD and EID, each NPS was normalized by the square of the large area signal to get the NNPS (normalized noise power spectrum), which was plotted in Fig. 6. Apparently, the flatness of the NPS of PCD is more evident with this comparison. Even for the NPS acquired at high energy (70 kVp) and the lowest threshold, the slope in the NPS of the PCD was negligible compared with that of the EID. These results confirmed that there is a major difference in noise spatial correlation properties between PCD and EID.

4. CONCLUSION

In summary of the theoretical and experimental results: the image noise generated by the cadmium telluride (CdTe)-based single photon counting detector (PCD) is weakly uncorrelated across detector pixels, which corresponds to very flat noise power spectrum. This effect is primarily caused by the anti-charge sharing and energy thresholding process. Noise correlation of CdTe-based PCD increases with higher x-ray energy, lower energy threshold, or with ACS being turned off, which allows the multiple coincident counts to be recorded from the same input x-ray photon. In the absence of severe pulse pileup, the detector output of CdTe-based PCD follows Poisson statistics as a result of the binomial selection nature of the energy thresholding process. Future work will focus on developing a more quantitative relationship between ACS and the physical properties of CdTe-based PCD.

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Figure 1.

Noise propagation in CdTe-based PCD needs to be modeled using both serial cascade and parallel cascade due to the presence of K-fluorescence. Among different sub-stages, ACS is optional and actually goes across both Stage 7 and 8.

Figure 2.
The basic work flow of anti-charge sharing.

Figure 3.

An illustration on why low energy x-ray photons is almost unlikely to generate two concurrent counts at two neighboring pixels. m is the primary pixel where the incident photon interacts with CdTe. There are two extreme cases: photon incidents onto the center of m or the boundary between pixel m and $m+1$. For photons following either path A,B,C, the probability to generate two counts from a single photon is low unless the energy of the photon is high.

Figure 4.

Histogram of the pixel intensity of PCD and EID for the 40 kVp beam. The PCD used the lowest threshold without ACS. The dashed lines were given by fitting the histograms with Poisson distributions. The thick solid lines in the right column were given by Gaussian fitting.

Figure 5.

NPSs of the PCD for 40 kVp beam and RQA-5 beam are shown in (a) and (b), respectively.

(a) and (b) use the same legend.

Figure 6. Comparison of the NNPS between PCD and EID. For the PCD, the measurement was performed at the low threshold with ACS on.