RESEARCH PAPER

Optimizing Photon Counting Detectors for enhanced image quality and noise reduction in low dose setting: A review study

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Abstract:
Photon counting detector CT, which has shown significant advancements in recent years. PCDs detect x-rays via a direct conversion mechanism that does not require a scintillator layer Unlike energy-integrating detectors. The semiconductor detector material directly transforms X-ray photons into electronic signals. However, electrical noise, particularly at low doses, can impair detectors and degrade image quality. The various approaches for improving PCDs to improve image quality in low-dose imaging applications are examined in this review paper. The basic ideas of PCDs are first discussed, along with the benefits and drawbacks of this technique compared to traditional energy-integrating detectors. Additionally, we discuss the role of advanced calibration techniques in enhancing PCD performance even more. The review additionally highlights the present limitations and future directions in the development of photon-counting technology.

Keywords: Photon Counting Detectors, Image quality, electronic noise

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Introduction

Since its introduction in 1972, CT has been extensively utilized in both diagnostic and therapeutic medicine due to its rapid scanning capabilities, excellent spatial resolution, and wide accessibility [1]. Currently, the majority of existing CT systems utilize solid-state energy-integrating detectors (EIDs) that feature third-generation rotate–rotate designs to transform X-rays into electrical signals. The indirect conversion method used by EIDs relies on a scintillator layer that changes X-ray photons into visible light, which is later detected by a photodiode layer and transformed into an electric output signal [2]

However, a significant drawback of these EIDs systems arises from the indirect measurement of X-ray photon energy through a scintillator, which converts incoming X-ray photons into visible light before the signal is transformed into an electrical current. Additionally, the detected signal represents a collective assessment of the energy of all incoming X-ray photons and lacks details regarding their total count and individual energy levels. The photon-counting detectors (PCDs) developed has the ability to address these challenges [3]. PCDs use a direct conversion method for x-ray detection that eliminates the need for a scintillator layer, unlike EIDs. The semiconductor material in the detector directly transforms x-ray photons into electron-hole pairs when a bias voltage is applied across the semiconductor, electrons move towards the anode and are collected to produce electronic signals [4,5,6]. The primary semiconductor materials utilized in PCDs are cadmium telluride or cadmium zinc telluride however, other materials like silicon and gallium arsenide have also been used. PCDs have the ability to enhance dose efficiency by merging higher geometric efficiency, reduced sensitivity to electronic noise, and ideal signal weighting, achieving greater spatial resolution, and providing superior spectral imaging [7]. However, in PCDs lower photon counts can result in higher noise levels, especially in low-dose applications, which can degrade image quality. This review article explores different approaches to optimizing PCDs in order to improve image quality and minimize noise in low-dose imaging scenarios**.** We begin by exploring the basic principles of photon counting, highlighting the benefits and drawbacks of this technology in contrast to traditional energy-integrating detectors. This review paper explores the various strategies for optimizing PCDs to enhance image quality in low-dose imaging applications Furthermore, we examine the significance of advanced calibration techniques in both clinical and research environments. The review also identifies the current obstacles and future paths in the evolution of photon counting technology.

Principle of PCDs

PCDs represent a new technology in computed tomography (CT) and X-ray imaging that it contains semiconductor material (zinc cadmium telluride and cadmium telluride) which converts each individual X-ray photon directly into electrical signals, (see fig 1) providing energy-resolved information with high spatial resolution [8,9]. The fundamental design of a PCD consists of a pixelated detector that captures individual X-ray photons and assesses their energy levels. When an X-ray photon interacts with the detector material, it creates electron-hole pairs that are later gathered by electrodes to generate an electrical signal. The electronics within the detector analyse this signal to identify the energy of the photon and categorize it into a designated energy bin [10,11]

2) Advantages of PCDs over conventional energy integrating detectors (EID-CT)

1. Weighing of photons:

An Energy-Integrated Detector (EID) weighs each detected photon according to its energy, thus giving higher importance to high-energy photons, which typically exhibit lower contrast. Furthermore, the uneven weighting of photons contributes to a decrease in the Signal-to-Noise Ratio (SNR). The decrease in SNR for an EID due to photon weighting is often referred to as the Swank factor. PCDs weigh all photons equally (one photon, one count). As a result, counting photons emphasizes low-energy photons more than energy integration does, leading to increased contrast, especially low absorbing materials. PCDs also eliminate the adverse effects of the Swank factor. Furthermore, spectrally resolving PCDs enable different weighting for photons based on their energy during signal processing, and this weighting can be adjusted, for instance, to enhance the contrast-to-noise ratio (CNR) [12].

2) Improved Iodine Contrast-to-Noise Ratio and Radiation Dose Efficiency:

In a conventional EID CT system, the detector's signal corresponds to the cumulative energy of all x-ray photons detected as a result, lower-energy photons have a lesser impact on the detector's signal compared to higher-energy photons, which carry more significant information from materials with high atomic numbers like iodine. This reduced significance of lower-energy photons degrades the contrast-to-noise ratio of the iodine signal within an EID CT system. In contrast, PCD CT systems count each photon individually without regard to its energy level. Thus, low-energy photons enhance the image contrast in PCD CT more effectively than in EID CT, leading to improved image contrast and a better contrast-to-noise ratio for iodine contrast agents [1,4].

3) Improved spatial resolution

The PCD detector has the capability to enhance spatial resolution by up to two times compared to existing detectors. Since 1990, there has been little improvement in spatial resolution. This is why PCD detectors generate considerable excitement, as they provide a notable enhancement in resolution with only a slight increase in radiation exposure. The absence of a scintillation layer in these detectors significantly contributes to the improvement in spatial resolution and the more effective application of Ultra Hard Resolution (UHR) imaging while maintaining a low radiation dose. Moreover, the lack of septa, or partitions, between individual detector units further boosts the geometric resolution of the PCD detector. The smaller pixel size eliminates the necessity for comb filters and grids, thereby enhancing the dose utilization rate. The spatial resolution of the PCD detector ranges from 2.81 to 4.00 lp/mm, in contrast to the EID detector, which has a resolution of approximately 2.08 lp/mm [4,14].

4) Radiation dose reduction:

Numerous characteristics of the PCD detector play a vital role in minimizing the radiation exposure, particularly in the imaging of pediatric patients. Enhanced spatial resolution and improved CNR enhance the visibility of anatomical features in children while reducing the radiation exposure they receive. Using the UHR mode can lead to a dose reduction of 20-30% without compromising image quality. Tin filters are employed to eliminate low-energy photons, such as scattered radiation. Reducing the radiation exposure is also beneficial for conducting repeated imaging on young patients suffering from chronic illnesses. For instance, low-dose lung imaging excels in delivering a clear depiction of anatomical and pathological details with minimal radiation, thus lessening the long-term risks associated with repeated imaging [4,13,14]

Disadvantages of PCDs

The performance of PCDs at high photon fluxes is one of their primary challenges. The detector response function may be impacted and spectral distortions may result from pulse pile-up, which happens when several photons reach the detector in a brief period of time. In high-flux situations, this restriction may affect the precision of material decomposition and energy discrimination. Another drawback of PCDs is their comparatively small pixel size, which may cause neighbouring pixels to share charges. The detector's spatial and energy resolution may be weakened by this effect [15]. Furthermore, compared to traditional photomultiplier tubes (PMTs), PCDs usually have higher dark count rates, which can be problematic in low-light applications [16]

various approaches for optimizing PCDs to enhance image quality in low-dose imaging applications

1) **Energy discrimination:**

In PCDs, energy discrimination is an advanced approach aimed to improve image quality and minimize noise in imaging systems. Photon counting detectors in such systems count the number of photons that strike them. However, there are a number of benefits to being able to discriminate between photons that have different energies, including better material differentiation, increased contrast in images, and decreased noise [12]. Unlike conventional energy-integrating detectors, which gradually accumulate the total energy deposited by photons, photon counting detectors were developed directly to detect and count individual photons. Photon counting detectors provide more precise data for imaging, resulting in higher image fidelity and more accurate diagnoses by differentiating between photons according to their energy. Arranging photons into different energy bins according to their energy levels is the basic principle of energy discrimination (see fig 2). By understanding how different tissue types, materials, or structures interact with X-rays at different energies, this makes it possible to differentiate them more accurately in the imaged area. Energy thresholding, that divides photons above a specific energy threshold into separate channels, is one of the fundamental processes behind energy discrimination. In order to distinguish between soft and hard X-rays and improve material differentiation, more advanced systems are able to discriminate photons across multiple energy bands. Another method is pulse height analysis, in which the energy of each photon is represented by the amplitude of the pulse that is produced in the detector. This enables the system to examine and classify the photons according to their energy [17]

2) Use of High-Quantum Efficiency (QE) Materials:

In photon counting detectors, high-quantum efficiency (QE) materials are essential for enhancing image quality and reducing noise. These substances improve the detector's overall performance by improving its capacity to transform incoming photons into detectable electrical signals. The advantages of high-QE materials in photon counting detectors have been shown in numerous investigations. For example, at wavelengths of 543 nm, visible light photon counters (VLPCs) have demonstrated remarkable QE values of up to 85% (18). A single-photon counting system that used VLPCs is even more impressive; it produced a corrected QE of 88.2% ± 5% at 694 nm, which is thought to be the highest value ever recorded for a single-photon detector (19). Interestingly, a variety of materials and technologies have been created to attain high QE in a number of spectral regions. Silicon detectors augmented using molecular beam epitaxy for superlattice and delta doping have shown QE > 50% in the 100-300 nm region in the ultraviolet (UV) spectrum. When sophisticated antireflection coatings are applied, QE reaches about 80% at ~206 nm (20). When used at 2.0 K, nanostructured superconducting single-photon detectors (SSPDs) have demonstrated QE of up to 17% for 1.55-µm photons and over 30% for 1.3-µm photons for infrared detection [21]. For photon-counting CT, silicon (Si), cadmium telluride (CdTe), and cadmium zinc telluride (CZT) are the most commonly considered detector materials [22]

3) **Hybrid pixel detector:**

In photon counting mode, hybrid pixel detectors (HPD) showed a great deal of potential for enhancing image quality and minimizing noise in X-ray imaging applications. These detectors provide energy discrimination and single photon counting by combining the benefits of direct conversion sensors with modern readout electronics, silicon is the most widely used semiconductor sensor material for hybrid pixel detectors Due to its extensive research, affordability, and large-scale availability. However, due to its low atomic number, silicon is inappropriate for X-ray imaging applications where photon energy exceeds 30 keV. Therefore, in such X-ray imaging systems with photon energies up to 100 keV, heavier substitutes for silicon, such as gallium arsenide and cadmium telluride, are being used more and more as sensor materials for hybrid pixel detectors [23,24] Compared to traditional energy-integrating detectors, the photon counting capacity enables higher material specificity, contrast resolution, and reduced image noise [25]. Interestingly, HPDs can saturate at high rates even though they work excellently at low to medium X-ray fluxes. Some researchers have suggested hybrid detectors that combine counting and integrating modes in order to overcome this drawback. This allows for a greater dynamic range and the calculation of the mean energy of the detected X-ray spectrum [26]. A reduction in detection performance and a loss of registered hits may also arise from charge sharing between neighbouring pixels caused by the tiny pixel sizes of HPDs [27]. To sum up, HPDs operating in photon counting mode have shown significant improvements in image quality, especially when it comes to contrast-to-noise ratio and gray-white matter differentiation [28]. However, to balance spatial resolution, energy discrimination, and detection efficiency, their performance must be optimized by carefully evaluating parameters such pixel size, sensor material, and readout electronics [29].

4) **Optimizing readout electronics:**

Enhanced image quality and reduced noise in computed tomography (CT) imaging depend on optimized readout electronics in photon counting detectors (PCDs). The single photon time resolution (SPTR) of silicon photomultipliers (SiPMs) has been significant factor influencing PCD performance. SPTR for large area, analog SiPMs can be greatly enhanced by reducing electronic noise by front-end readout circuit optimization, with this adjustment, SPTR measurements for some SiPM models have been as low as 100 ps FWHM, which is closer to the performance of single avalanche photodiodes [30]. Interestingly, the possible SPTR for large area, analog SiPMs is also influenced by other parameters, even if electronic noise reduction is crucial. These include the reabsorption of characteristic/scatter photons and depth-dependent charge collection, which can broaden photopeaks and possibly exaggerate the detective quantum efficiency (DQE) [31]

5) Optimization of Pixel Size and Pitch:

In photon counting detectors, pixel size and pitch optimization is essential for enhancing image quality and lowering noise. Smaller pixels have been demonstrated in studies to significantly increase image quality and reduce noise. According to a study that used a PCCT scanner with various detector pixel binning modes, image noise was reduced when pictures were reconstructed from measurements using smaller pixels below the system's resolution limit as opposed to bigger pixels With the same spatial resolution for a quantitative kernel, the ultra-high-resolution (UHR) mode with 0.25 mm pixel size at isocenter outperformed the macro mode with 0.5 mm pixel size by around 6% in terms of dose-normalized contrast-to-noise ratio (CNRD). A finer kernel enhanced this gain to an average of 21%. [32].Interestingly, the ability to distinguish various contrast agents can be impacted by the pixel pitch selection. Pixel pitches of 110 and 165 µm produced distinct detective quantum efficiencies and capacities to distinguish between iodine and gadolinium contrast agents, according to a study on Medipix2 MXR multi-chip assemblies with CdTe sensors. A lower minimum contrast agent concentration for material discrimination resulted from the narrower pixel pitch. Image quality and noise reduction in photon counting detectors can be greatly enhanced by adjusting pixel size and pitch. Better contrast-to-noise ratios and enhanced material identification skills can be achieved with smaller pixels, even if they are below the system's resolution limit. However, the particular application and imaging needs may determine the ideal pixel size [33].

6) Deep learning and AI based techniques:

In photon-counting detector (PCD) CT images, deep learning and AI-based methods showed promising results in terms of noise reduction and image quality enhancement. These techniques have a lot to offer over conventional methods, especially when working with low-dose and ultra-high-resolution images. The effectiveness of deep learning-based denoising techniques for PCD-CT images has been shown in numerous researches. Photon counting CT images have been successfully denoised using the Noise2Noise framework, with results that are comparable with traditional Noise2Clean training methods. This method is helpful in clinical settings where it might be challenging to produce paired low-dose and high-quality images (34) Lesion detection and spatial resolution have also improved with deep learning approaches. PCD CT using convolutional neural network denoising showed better visibility of lesions and pathological abnormalities in a study comparing it to energy-integrating detector (EID) CT for multiple myeloma imaging [35]. This demonstrates how AI-enhanced PCD CT can increase diagnostic precision. It's interesting to note that some research has found discrepancies in the demonstrated improved performance of deep learning techniques. The majority of deep learning-based techniques for low-dose CT image denoising exhibit statistically comparable performance, with slight advancements in recent years, according to a thorough assessment conducted using a standardized benchmark setting. This emphasizes the necessity of a rigorous and open assessment of the innovative deep learning-based approach [36]. In PCD CT, deep learning and AI-based methods present effective techniques to increase picture quality and reduce noise. Significant noise reduction has been demonstrated by techniques like the prior-information-enabled neural network (Pie-Net) and the prior knowledge-aware iterative denoising neural network (PKAID-Net), which maintain the spectral and spatial characteristics of high-resolution virtual monoenergetic images in a number of clinical applications [37].

7) Advanced Reconstruction techniques:

In photon-counting CT, model-based iterative reconstruction (MBIR) approaches have demonstrated potential for enhancing picture quality. These techniques have an advantage over conventional two-step methods in that they can directly recreate material-specific pictures from spectral CT data. MBIR methods have proven to be effective in improving spatial resolution, lowering noise, and correcting beam-hardening errors, especially in low-dose imaging situations. These methods can outperform filtered back projection, particularly for extremely noisy data, by combining statistical noise features and accurate forward models. [38]. MBIR methods have shown promise in enhancing spatial resolution, minimizing noise, and resolving beam-hardening variations, especially in low-dose imaging situations. MBIR techniques have shown effective in a number of therapeutic settings, such as material classification, brain imaging, and breast cancer diagnosis. Recent investigations have demonstrated the promise of photon-counting CT in conjunction with MBIR techniques for low-dose imaging and enhanced material characterisation [39]

Various advanced calibration methods in further improving the performance of PCDs.

1) Multi material calibration phantoms:

Multi-material calibration phantoms are used in photon-counting CT (PCCT) systems to aid in precise material decomposition and quantification. In order to calibrate the system's response across a range of energy levels, these phantoms usually contain a variety of materials with established compositions and concentrations. The maximum likelihood estimation (MLE) approach for material decomposition was calibrated using a calibration phantom with pure material compositions. This calibration revealed a good correlation between known concentrations in the phantom and measured x-ray attenuation in each energy bin [40]. Similarly, a prototype photon-counting silicon detector for unconstrained three-material breakdown is calibrated using a multi-material calibration phantom [41]

2) Gain energy calibration:

An important beginning in the calibration of PCDs is threshold energy calibration. The linear pixel-by-pixel relationship between the input photon energy and the PCD's output voltage is established by this method. For photon-counting CT systems to operate at their best and produce correct spectrum imaging, calibration is necessary. For threshold energy calibration, three distinct approaches have been used, each with unique needs and results. These techniques include the use of a PCD response model, an X-ray source in combination with K-edge materials, or a normal X-ray source alone. Remarkably, the calibration technique that produces superior pixel uniformity in air projections and fits a detector response model to polyenergetic observations had the best spectrum accuracy when predicting monoenergetic peaks. Although threshold energy calibration is essential for spectral accuracy and pixel homogeneity, it might not have as much of an effect on traditional CT image quality metrics like noise power spectrum (NPS) and ring artifact assessment [42]. This means that spectral imaging applications, as opposed to traditional CT imaging, may benefit more from accurate threshold calibration. For photon-counting CT systems to be optimized for their special energy-resolved imaging capabilities, enhanced contrast-to-noise ratio, and potential for quantitative imaging, threshold energy calibration is still an essential step [43].

3) Temporal calibration:

Recent studies highlight the advancements in temporal calibration for photon-counting computed tomography, highlighting the complexity of threshold energy calibration in PCDs. The evaluation of three calibration methods reveals that a model-based approach produced the best spectral accuracy and pixel homogeneity, but it did not significantly improve noise power spectrum metrics [42]. show that PCDs, which have a 31% lower radiation dose than energy-integrating detectors, offer better spatial resolution and visibility of important structures in temporal bone imaging [44]. Provide a calibration model that takes into consideration non-linear flux dependency, which is essential for quantitative imaging since it improves spectral sensitivity at high photon flux levels [45]

4) Phantom based calibration:

A key component of PCCT system performance optimization is phantom-based calibration multiple studies have shown how well this method works to enhance both quantitative accuracy and image quality. To evaluate and adjust for different distortions and artifacts in PCCT, phantom calibration is utilized. states, for example, how to calibrate a CZT photon-counting detector with five energy thresholds using BR12 phantoms of varying thicknesses. In this calibration procedure, simulated and measured spectra were correlated by fitting a nonlinear function, which was subsequently utilized to rectify raw pictures. Effective attenuation coefficient estimates and output count relative RMS errors were greatly decreased by the technique [46] Phantom-based calibration extends beyond technical performance to further optimize clinical protocols. illustrates the use of a paediatric phantom to establish guidelines for children's ultra-low dose chest CT exams before going into clinical use, this method allowed researchers to balance radiation dose and image quality [47]. Phantom-based calibration is essential because it allows precise material decomposition, enhanced spatial resolution, and clinical protocol optimization. It enables quantitative imaging of various contrast agents and tissues and aids in addressing difficulties like spectral aberrations. Robust calibration techniques will continue to be essential for achieving PCCT technology's full promise in diagnostic imaging as it moves closer to wider clinical application [46].

Current challenges:

Although PCCT technology has the potential to completely transform clinical CT imaging, it still faces a number of challenges. The existing photon-counting detectors' restricted count rate capability is one of the main problems, as it might result in spectrum distortion and pulse pile-up at high photon flux rates. This restriction may have an impact on spectral accuracy and image quality, especially in areas with high densities or when large tube currents are being used [48]. Charge sharing and K-escape events, which may affect energy resolution and cause errors in multi-energy pictures, are another major problem with semiconductor-based detectors. The precision of quantitative imaging and material decomposition applications may be compromised by these effects. Furthermore, these problems may be made severe by the tiny pixel size needed for high spatial resolution, which forces a trade-off between energy and spatial resolution [49]

Future directions:

Enhancing image quality and spatial resolution is one of the main areas of advancement. With resolutions of about 0.25 mm, PCD-CT already provides better spatial resolution than traditional CT. Future developments might push this limit further, making it possible to see even tiny structures and complicated diseases PCD-CT creates new opportunities for imaging methods and contrast agent development. K-edge imaging is made possible by the technology, and when coupled with innovative contrast agents, it may open up new possibilities for future use [50] Additionally, multiparametric imaging may be made possible by PCD-CT's spectrum capabilities, which might extract many kinds of information from a single dataset, including quantitative data that could work as replacement for functional information [51]

Conclusions:

The significant advancements and ongoing efforts to optimize PCDs to improve image quality and lower noise in low-dose imaging applications are highlighted in this study. In order to overcome the difficulties of low-dose imaging, such as noise reduction and image accuracy, the approaches that have been discussed energy discrimination, high-quantum efficiency materials, hybrid pixel detectors, optimizing readout electronics, pixel size and pitch adjustments, and advanced reconstruction techniques are essential. PCDs offers a lot of opportunity to enhance image quality and lower noise, particularly in low-dose imaging environments. Furthermore, combining deep learning and AI-based techniques enhances image quality even more, indicating their potential to improve clinical results and diagnostic precision. In order to optimize PCD performance for more accurate material breakdown and enhanced spatial resolution, calibration techniques such multi-material, gain energy, temporal, and phantom-based calibrations have proven essential. PCDs are becoming more and more successful in overcoming the difficulties presented by low-dose imaging. PCDs are an essential tool for medical imaging in the future because of these developments, which not only open the door to more precise diagnosis but also reduce radiation exposure for patients to fully realize their promise in clinical practice, however, more research and development is necessary to make sure they are universally relevant, affordable, and easily accessible. The future generation of imaging equipment will probably be highly dependent on PCD technology's ongoing development, which will enhance patient outcomes and treatment

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