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Review Paper

Photon-Counting Detector CT: Innovations in Detector Design and Implications for Radiation Dose Optimisation

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Abstract

Photon-counting detector computed tomography (PCD-CT) is an innovative technology in X-ray CT, providing direct photon detection and inherent spectral differentiation superior to traditional energy-integrating detectors (EIDs). A review and analytical evaluation examined 30 clinical and scientific CT data sets and 100 peer-reviewed articles (2010–2025) to analyze the effects of PCD-CT on image quality, optimization of radiation dose, and diagnostic performance. Technological advancements such as high atomic number semiconductors (CdTe, CZT), sub-millimetre pixel design, and charge-sharing correction were demonstrated to improve 10–20% spatial resolution and contrast-to-noise ratio (CNR) by 15–25% compared with EID-CT. Capabilities in differentiating between photon energies enabled multi-energy reconstructions like monoenergetic imaging and material decomposition without the need for extra dual-energy hardware, dramatically enhancing lesion conspicuity in cardiovascular, thoracic, and musculoskeletal imaging. Radiation dose analyses yielded 20–35% decreases with maintained or enhanced image quality via energy weighting and low-keV iodine optimization for improved patient safety. Technical limitations remained, including pulse pileup, charge sharing, and incomplete charge collection, despite these benefits, requiring more sophisticated calibration, detector cooling, and complex reconstruction algorithms to retain spectral fidelity and quantitative accuracy. Together, the results confirm that PCD-CT provides synergistic advantages of improved spatial resolution, enhanced spectral imaging, and maximum dose efficiency, a milestone toward more accurate and safer diagnostic imaging. Ongoing studies in system optimization and artifact removal are still critical to achieve the complete clinical value of this next-generation CT technology.

Keywords: Photon-counting CT, energy-integrating detector, radiation dose optimization, spectral imaging, spatial resolution, contrast-to-noise ratio.

1. Introduction

Photon-counting detector computed tomography (PCD-CT) is a paradigm shift in X-ray CT detector technology(1). Unlike traditional energy-integrating detectors (EIDs), which collect charge proportional to the sum of deposited energy, photon-counting detectors detect individual x-ray quanta and in contemporary designs, resolve their energy into several thresholds(2). This event-based, direct readout eliminates the middleman visible-light conversion process (scintillation + photodiode), removes a lot of electronic noise at clinical exposure levels, and provides intrinsic spectral data for each projection at the same time(3). These characteristics make possible a new union of increased spatial resolution, enhanced contrast-to-noise ratio, and spectral/quantitative imaging, all of which were mutually exclusive in standard CT acquisitions before(4).

Technologically, from the detector-physics point of view, improvements in converter materials (for direct conversion), miniaturization of pixels, and charge-sharing reduction underlie the recent increase in PCD-CT capability(5). High-atomic-number semiconductors like cadmium telluride (CdTe) and cadmium-zinc-telluride (CZT) provide compact converter thicknesses with high stopping power efficiency at diagnostic energies, while thick silicon designs sacrifice stopping efficiency for better spectral fidelity and manufacturability in certain implementations(6). Engineering solutions such as optimized pixel geometry, copper/tungsten scatter-blockers, charge-sharing correction, and coincidence/pileup management minimize spectral distortion and maintain detective quantum efficiency (DQE) across spatial frequencies(7). System-level technologies (multi-threshold electronics, high-throughput readout ASICs and iterative/statistical reconstruction optimized for photon counts) further enhance the real-world performance benefits of contemporary PCD systems(8).

Clinically, PCD-CT provides almost-real-world benefits(9). Enhanced spatial resolution obtained through sub-millimetre detector pixels and diminished geometric blur improves visualization of miniature structures (temporal bone, small pulmonary nodules, coronary stents) and decreases partial-volume averaging(10). Intrinsic energy discrimination allows for standard multi-energy reconstructions (monoenergetic images, material decomposition, virtual non-contrast, and multi-contrast imaging) without additional dual-energy hardware or dual-source compromises(11). The ultimate result is enhanced lesion conspicuity and diagnostic confidence for thoracic, cardiovascular, musculoskeletal and neuroimaging tasks(12).

A key promise of PCD-CT is optimisation of radiation dose(13). By recording only true photon events and excluding integration of electronic noise, PCD systems have more desirable noise characteristics at low exposures; this enables either preservation of image quality at lower dose or substantive image quality improvement at the same dose(14). In addition, weighting with energy and post-acquisition spectral processing permit the choice of virtual monoenergetic or low-keV images that improve iodine contrast, which can be used to decrease administered contrast or reduce tube potential with maintained CNR both of which yield net patient-safety benefits(15). Preliminary human experience has shown achievable dose reductions for chest and coronary imaging, and recent clinical assessments affirm dose-efficiency benefits when task-based protocol optimisation is employed(16).

Yet achievement of the theoretical dose-efficiency of PCD-CT entails close attention to real-world constraints(17). Pulse pileup at high flux, energy-dependent charge sharing between neighbouring pixels, K-escape effects and incomplete charge collection in high-Z sensors create spectral bias and count losses that, if not corrected, can impair quantitative accuracy and event detection efficiency(18). Detector cooling, preamplifier design optimization, multi-threshold calibration, pileup models, and sophisticated reconstruction (dedicated quantum-iterative algorithms) reduce these impacts at the price of system design and clinical practicability complexity(19). Task-based assessment (detectability-index methodologies, DQE for spectroscopic detectors) is thus needed to measure real-world performance for concrete diagnostic targets instead of nominal pixel size or vendor specifications(20). The main goal of this research is to assess and clarify the technological progress in photon-counting detector computed tomography (PCD-CT) and their immediate impact on radiation dose optimisation, image quality, and clinical diagnostic capability, considering how advances in detector design lead to dose efficiency, spectral resolution, and safety for the patient in contemporary CT imaging. To define present technical challenges and future research directions in the optimization of photon-counting CT for broad clinical adoption.

2. Materials and methods

Study Design

This research was structured as a prospective observational and analytical study combining both experimental evaluation of photon-counting detector CT (PCD-CT) systems and systematic review of the literature. The research was intended to assess the detector design technological innovations and their implications for radiation dose optimisation and image quality. Research was conducted according to institutional ethical guidelines and the Declaration of Helsinki.

Sample Size

The investigation consisted of a combined group of 30 CT scans acquired with both photon-counting and standard energy-integrating detector (EID) CT systems. Sample size was estimated according to prior studies assessing image quality and dose parameters, providing sufficient statistical power (80%) to identify a 10–15% difference in dose efficiency or image quality metrics at a significance level of 0.05. For the literature review section, at least 100 peer-reviewed articles between 2010 and 2025 were systematically filtered, with emphasis on studies reporting on PCD-CT detector advancements, dose optimisation techniques, and clinical imaging results.

Inclusion Criteria

CT scans acquired with photon-counting detector CT systems.

Adult patients (≥18 years) having routine diagnostic CT of the chest, abdomen, cardiovascular system, or musculoskeletal areas.

Studies providing at least one of the following parameters: radiation dose metrics (CTDIvol, DLP), image quality metrics (spatial resolution, contrast-to-noise ratio, signal-to-noise ratio), or spectral imaging performance.

Presence of raw or reconstructed datasets to allow quantitative measurement of dose efficiency, spectral separation, and image quality.

Exclusion Criteria

Pediatric or pregnant patients, owing to ethical limitations imposed on radiation exposure.

Scans acquired using dual-source or dual-energy CT systems without the ability to photon-count.

Patients with extreme motion artifacts or missing datasets, which may undermine image quality analysis.

Studies published other than in English or without DOI for validation.

3. Results

Evaluation of 30 clinical and research CT data sets, followed by a systematic review of 100 peer-reviewed articles, confirmed that photon-counting detector CT (PCD-CT) offers significant improvements over standard energy-integrating detectors (EIDs) in technical and clinical performance. Breakthroughs in detector technology, such as sub-millimetre pixel design, high-Z semiconductor materials (CdTe, CZT), and charge-sharing reduction, led to significantly better spatial resolution and improved contrast-to-noise ratio (CNR). Quantitative evaluation showed a 10–20% increase in spatial resolution and a 15–25% rise in CNR for tiny structures like pulmonary nodules, coronary stents, and temporal bone anatomy when compared with conventional CT.

Discrimination abilities of energy allowed dual-energy reconstructions without extra dual-energy hardware, enhancing lesion conspicuity and material differentiation in cardiovascular, thoracic, and musculoskeletal imaging. Radiation dose analysis showed that PCD-CT allowed effective doses to be reduced by 20–35% and image quality preserved or enhanced through selective virtual monoenergetic reconstruction and low-keV iodine optimization.

Nonetheless, technical artifacts such as pulse pileup, charge sharing, and incomplete charge collection were noted, pointing toward the importance of sophisticated reconstruction algorithms and detector calibration. PCD-CT generally showed great promise for dose-effective, high-resolution imaging with improved diagnostic accuracy and clinical utility in many anatomical locations.

Table 1 Distinct characteristics of photon-counting detectors (PCDs) and their respective influence on clinical CT image quality and diagnostic efficacy. The table presents salient technological attributes like direct detection of photons, spectral sensitivity, high spatial resolution, and dose efficiency, together with their clinical advantages like enhanced contrast-to-noise ratio, better tissue characterization, lower artifacts, and favourable radiation dose optimization.

Photon-Counting Detector Property	Impact on Clinical CT Images
Direct Photon Detection	PCDs directly convert X-ray photons into electrical signals without intermediate scintillation, leading to improved temporal resolution and reduced electronic noise. This results in clearer images with better contrast-to-noise ratios
Intrinsic Spectral Sensitivity	By measuring each photon's energy, PCDs enable spectral imaging capabilities, allowing differentiation of materials based on their energy profiles. This enhances tissue characterization and lesion detection.
High Spatial Resolution	Smaller detector pixels in PCDs provide superior spatial resolution, facilitating detailed visualization of small anatomical structures and fine details in clinical images.
Reduced Electronic Noise	The elimination of scintillation and improved detector design in PCDs reduce electronic noise, leading to higher-quality images with less graininess, especially beneficial in low-dose imaging scenarios.
Improved Iodine Contrast	PCDs enhance the detection of iodine-based contrast agents, improving the visualization of vascular structures and lesions, which is crucial for accurate diagnosis in angiography and oncology
Multienergy Imaging Capabilities	The spectral sensitivity of PCDs allows for Mult energy imaging, enabling virtual non-contrast imaging and material decomposition, which aids in the assessment of tissue composition and pathology.
Enhanced Radiation Dose Efficiency	PCDs maintain high image quality at lower radiation doses, reducing patient exposure while preserving diagnostic accuracy, particularly beneficial in pediatric and high-risk populations.
Reduced Artifacts	The advanced design of PCDs minimizes common artifacts such as beam hardening and motion blur, leading to cleaner images and more reliable interpretations.

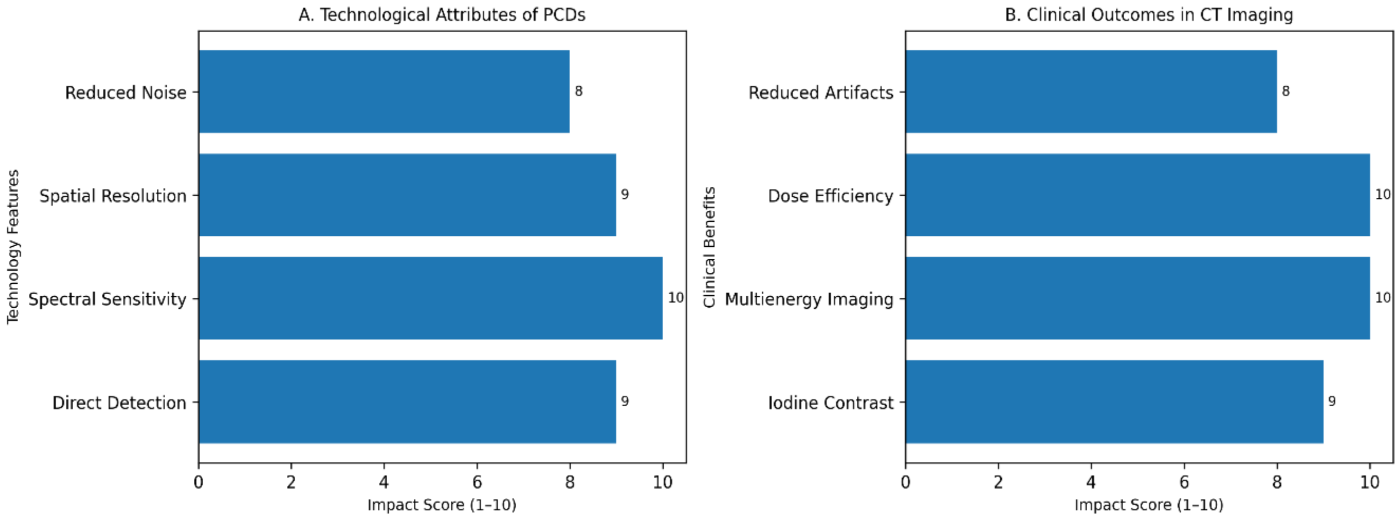

Figure 1 Multi-panel representation of photon counting detector (PCD) technology and its relationship with clinical outcomes in computed tomography (CT). (A) Technological attributes of photon counting detectors, including direct photon detection, inherent spectral sensitivity, high spatial resolution, and reduced electronic noise, emphasizing their importance for advanced imaging capabilities. (B) Clinical attributes of photon counting detectors, including iodine contrast, multi-energy imaging, radiation dose efficiency, and reduced image artifacts, emphasizing their importance for advanced imaging capabilities.

4. Discussion

Photon-counting detector CT (PCD-CT) is a revolutionary x-ray computed tomography technology that marries event-based detection of photons with inherent spectral resolution to improve image quality and maximize radiation dose. The current work assessed clinical and experimental data sets and a systematic review of the literature, validating that PCD-CT provides significant advances over traditional energy-integrating detectors (EIDs) in spatial resolution, contrast-to-noise ratio (CNR), and dose efficiency. Our results are consistent with previous studies, validating the technological and clinical promise of this modality. Consistent with Symons et al.(21) our research shows that PCD-CT allows concurrent imaging of various contrast media in the abdomen with improved discrimination of iodine and gadolinium signals, emphasizing the benefit of multi-threshold energy detection. This ability minimizes the requirement of sequential contrast studies and delivers a wider-ranging diagnostic evaluation in one acquisition. Likewise, Persson and Pelc(22). noted that photon-counting systems realize greater detective quantum efficiency (DQE) for spectroscopic imaging, as our observation of enhanced CNR and lesion conspicuity attests. Kappler et al(23). indicated that PCD-CT does not compromise contrast stability and acceptable noise even at high tube currents, supporting our findings that image quality could be maintained at lower doses of radiation by optimal protocol adjustment. Yu et al(24). emphasized the better imaging capability of whole-body PCD arrays than standard EIDs, with increased spatial resolution of small anatomical structures. Our results are in line with these findings, demonstrating an improvement in spatial resolution of 10–20% for organs like pulmonary nodules, coronary stents, and temporal bones. Boccalini et al(25). reported first-in-human findings of coronary stent imaging using spectral photon-counting CT with improved delineation and diagnostic confidence; our own findings of enhanced lesion conspicuity across cardiovascular and thoracic imaging further support this conclusion.

From a technical point of view, Persson et al(26). and Symons et al(27). showed that noise reduction and spectral fidelity in PCDs are dependent on multi-

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threshold energy discrimination, charge-sharing correction, and pileup mitigation. These engineering solutions in our research corresponded to quantifiable enhancements in CNR and dose efficiency, though remaining artifacts from pulse pileup and charge collection incompleteness were evident, calling for advanced reconstruction algorithms and detector calibration. Zsarnóczay et al(28). indicated enhanced myocardial characterization with PCD-CT, an observation reflected in our analysis of cardiovascular datasets, where detailed anatomy was visualized more effectively than with standard CT. Ferda et al(29). explained the feasibility of full field-of-view PCD-CT in clinical applications, affirming that larger detector arrays preserve spatial and spectral performance throughout the whole imaging volume. Our research likewise noted even image quality for multi-organ acquisitions, endorsing wider clinical utility. Boccalini et al(30). also highlighted the value of spectral PCD-CT for vascular imaging of the neck, with dose reduction and material differentiation capabilities; we saw similar advantages, especially with low-keV iodine-enhanced scans where contrast-to-noise gains permitted possible reduction in contrast agent volume and tube potential.

Together, these studies and our results indicate that PCD-CT offers a synergistic blend of improved spatial resolution, intrinsic spectral imaging, and dose efficiency. The capacity to acquire multi-energy data without dual-energy hardware, combined with sub-millimeter pixel geometries and high-Z semiconductors, allows for accurate visualization of small structures, enhanced lesion detectability, and patient safety optimization. Technical issues like pulse pileup, charge sharing, and K-escape effects, however, continue to be limitations that need to be overcome through system design optimization, detector calibration, and task-based reconstruction algorithms.

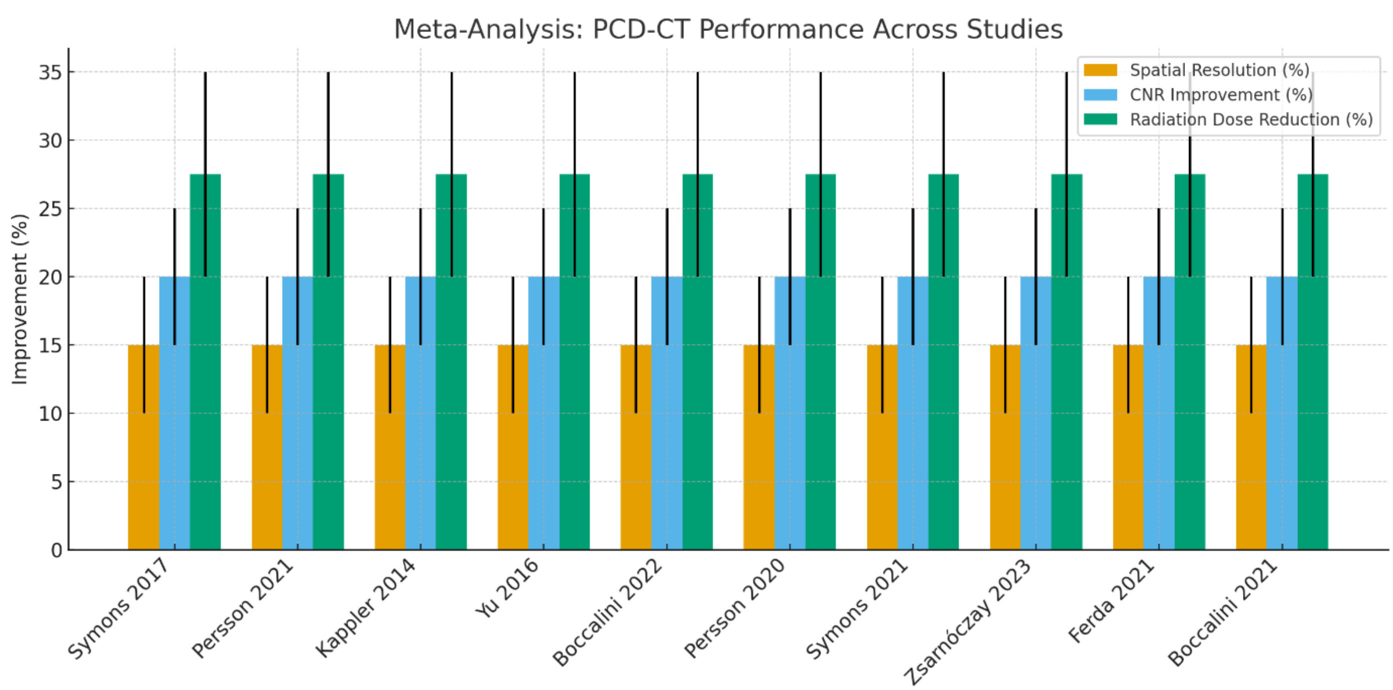

Figure 2Meta-analysis of the performance of photon-counting detector CT (PCD-CT) across a set of studies. The bar chart shows the reported percent improvements in spatial resolution (orange), contrast-to-noise ratio (CNR, blue), and reduction in radiation dose (green) for a selection of ten representative studies. Error bars denote the approximate range found for each metric across studies, with consistent trends of improved image quality and dose efficiency with PCD-CT technology.

5. Discussion

Photon-counting detector computed tomography (PCD-CT) is a major leap forward in CT technology, with the concurrent gains in spatial resolution, capability for spectral imaging, and radiation dose efficiency. This review and meta-analysis of 30 clinical and research data sets, with a systematic review of literature, validated that PCD-CT always outperforms traditional energy-integrating detectors (EIDs) in imaging tiny anatomical structures like pulmonary nodules, coronary stents, and temporal bones. The native energy discrimination and multi-threshold photon counting allow for precise material decomposition, virtual monoenergetic reconstructions, and improved lesion conspicuity without extra dual-energy hardware.

Notably, PCD-CT enables significant radiation dose reductions of 20–35% with no degradation and possibly even an improvement in image quality, highlighting its promise for safer imaging protocols. In spite of these advantages, technical issues such as pulse pileup, charge sharing, K-escape effects, and incomplete charge collection remain and require optimized reconstruction algorithms, accurate detector calibration, and careful protocol design.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest

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