



Photon-Counting Detector CT: Key Points Radiologists Should Know

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Photon-counting detector (PCD) CT is a new CT technology utilizing a direct conversion X-ray detector, where incident X-ray photon energies are directly recorded as electronic signals. The design of the photon-counting detector itself facilitates improvements in spatial resolution (via smaller detector pixel design) and iodine signal (via count weighting) while still permitting multi-energy imaging. PCD-CT can eliminate electronic noise and reduce artifacts due to the use of energy thresholds. Improved dose efficiency is important for low dose CT and pediatric imaging. The ultra-high spatial resolution of PCD-CT design permits lower dose scanning for all body regions and is particularly helpful in identifying important imaging findings in thoracic and musculoskeletal CT. Improved iodine signal may be helpful for low contrast tasks in abdominal imaging. Virtual monoenergetic images and material classification will assist with numerous diagnostic tasks in abdominal, musculoskeletal, and cardiovascular imaging. Dual-source PCD-CT permits multi-energy CT images of the heart and coronary arteries at high temporal resolution. In this special review article, we review the clinical benefits of this technology across a wide variety of radiological subspecialties.

Keywords: *Clinical applications; Photon counting X-ray detectors; Spectral tomography; Computed tomography; Diagnostic imaging*

INTRODUCTION

Photon-counting detector computed tomography (PCD-CT) is a new CT technology approved by the United States Food and Drug Administration that overcomes many of the limitations of conventional energy-integrated detectors (EIDs). It utilizes semiconductor materials to generate electronic signals from incident X-ray photons. In this special review article, we review the clinical benefits of this technology across a wide variety of radiological subspecialties.

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Key Technical Characteristics of PCD-CT

Figure 1 shows a schematic representation of energy integrating and photon-counting detectors. PCDs directly convert deposited X-ray energy to an electronic signal, as a large voltage is applied across the semiconductor, creating electron hole pairs when a photon hits the detector. All other CT scanners use scintillator-based EIDs that emit visible light when X-rays hit them. This light requires the use of reflective septa within the conventional X-ray detector to channel the light toward the optical photon sensor [1]. Because PCDs do not require such septa, the use of PCDs permits a significant reduction of detector pixel size without compromising geometric detection efficiency (fill factor). This makes PCDs capable of ultra-high-resolution imaging and has been leveraged to increase the spatial resolution of *in vivo* CT imaging, for both large and small body regions [2-6]. A secondary clinical benefit of the smaller pixel size has been the ability to obtain routine imaging at lower radiation doses.

Conventional EIDs emit light and generate a signal

Key Points on Photon Counting CT

proportional to the sum of the energies of all detected X-rays. PCDs uniformly weigh detected X-rays of different energies, providing more signal to lower energy photons that may contribute to important parts of a CT image (as lower energy X-rays are more likely to be attenuated by iodine and other biologic tissues) [7]. This energy discriminating ability of PCDs arises as the electrical signal deposited by each X-ray is proportional to its energy and can be used in two key ways. Firstly, it allows the application of energy-specific thresholding to remove low-energy photons that are part of electronic noise. Eliminating electronic noise facilitates the development of ultra-low-

dose CT protocols for adults and children [3]. Secondly, the energy discriminating ability of PCDs permits evaluation of spectral information using a single X-ray tube, as one or more energy thresholds can be used to separate detected X-ray photons into bins based on their deposited energy. Multi-energy CT information can be displayed and analyzed similar to dual-energy CT, but using photons in different energy bins, rather than two exposures from different X-ray tubes (each with its own polychromatic X-ray tube potentials, or kV). For dual-source PCD-CT systems, this implies that both X-ray tubes can operate at the same kV and both produce dual-energy datasets, which is beneficial

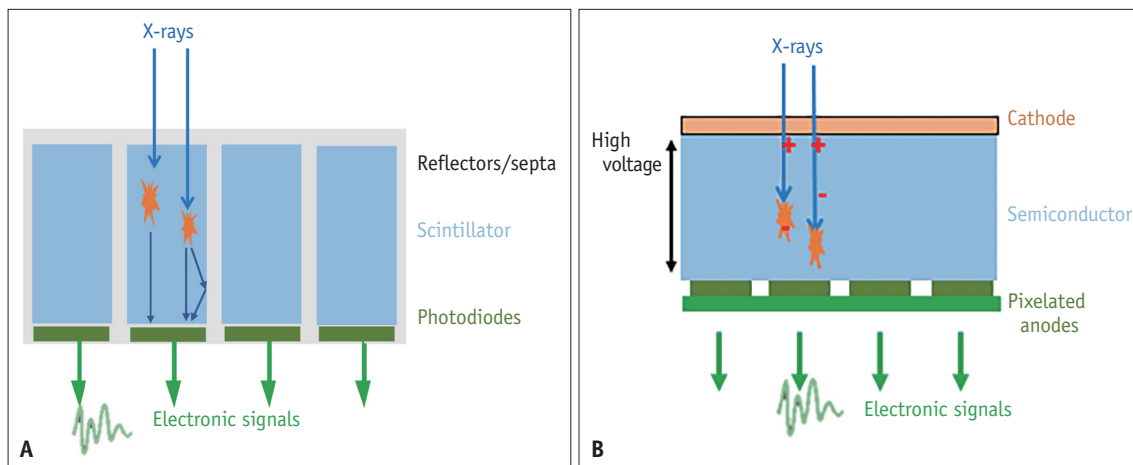


Fig. 1. Schematic comparison of conventional EIDs and PCDs.

A. EIDs use a scintillator to generate visible light when an incident X-ray photon hits them, then the light is recorded by a photodiode with reflective septa in between detector elements to reduce crosstalk. **B.** While PCD-CT uses a semiconductor to directly generate positive and negative charges, with negative charges going to pixelated anodes to record each individual photon and its energy. EID = energy integrating detector, PCD = photon-counting detector

Table 1. Unique Properties of Photon-Counting Detectors and Impact on CT Images in Clinical Practice

Photon-Counting Detector Property	Impact on Clinical Images
A. Direct conversion of X-ray coincidence to signal that is proportional to photon energy	- Increased iodine signal as there is no down weighting of lower energy photons - Ability to obtain multi-energy information with a single X-ray tube voltage: virtual monoenergetic images, virtual non-contrast, virtual non-calcium, and iodine maps routinely available
B. Smaller detector pixel size	- Improved spatial resolution
C. Reflective septae are not required for each detector element, which contributes to geometric dose inefficiency with conventional energy-integrated detectors	- Radiation dose reduction improved spatial resolution
B and C	- Ultra-high spatial resolution does not require attenuating filters that increase radiation dose - Ultra-high spatial resolution no longer has a radiation dose penalty and can be performed in larger body regions
D. Elimination of electronic noise	- Only quantum noise is present
E. Shaping of the X-ray beam with tin filters, energy thresholds, and tube potential selection	- Reduction of metal and blooming artifact - Reduced radiation dose

for cardiac and high pitch clinical applications [8-10]. The technical advantages of PCD-CT over conventional energy-integrating detectors and their potential clinical benefits are summarized in Table 1 [11-13].

Benefits of Photon-Counting Detectors and Effect on Clinical Applications

Higher/Improved Spatial Resolution

Many diagnostic tasks in lung and musculoskeletal imaging rely on the ability of CT to scan large body regions while simultaneously displaying small structures. The improved spatial resolution of PCD-CT may consequently assist with many diagnostic tasks in pulmonary and musculoskeletal imaging. For example, PCD-CT demonstrates detailed and subtle imaging findings associated with interstitial lung disease owing to its higher spatial resolution. Inoue et al. [14] recently demonstrated that in patients with known or suspected usual interstitial pneumonia, PCD-CT increases readers' confidence in key imaging findings such as ground-glass opacity, reticulations, and mosaic pattern (Fig. 2). PCD-CT also improves the visualization of higher-order bronchi and bronchial walls [2]. For both pulmonary and musculoskeletal applications, the improved visualization of smaller structures is achieved by using higher resolution reconstruction kernels, and often by using thinner slices.

The inherently higher spatial resolution of PCDs relative to EIDs is also beneficial for low dose musculoskeletal CT imaging. For instance, low-dose CT scans are frequently performed during the workup of multiple myeloma to

identify lytic bone lesions and sequelae of myeloma such as pathologic fractures. At similar scanning dose levels, PCD-CT images can be acquired using an ultra-high-resolution mode. Ultra-high resolution requires the use of comb filters with conventional CT imaging, which increase radiation dose, so low-dose, high-resolution whole body CT cannot be performed with conventional EIDs. At whole body low dose PCD-CT, small osteolytic lesions (which are characteristics of myeloma) are seen more clearly on the PCD-CT images (Fig. 3) [15]. The smaller detector pixel size and higher geometric dose efficiency of PCD-CT facilitates substantial radiation dose reduction for ultra-high-resolution imaging of small joints, which can be beneficial in trauma and degenerative disease. It also permits ultra-high spatial resolution imaging of large joints like the shoulder and hip, which is not possible with most conventional CT systems [16].

Renal stone detection, delineation, and characterization is another area where high-resolution PCD-CT can be advantageous. PCD-CT images reconstructed with sharper kernels and thinner slices have improved spatial resolution yielding an improved display of smaller renal calculi. Accurate display and characterization of small renal calculi is one of the challenges with dual-energy CT due to limitations in spectral separation and spatial resolution. It has been shown that PCDs are able to display and characterize more small renal stones 3 mm or less in size compared to conventional energy-integrating-based dual-energy CT techniques [17]. In this way the improved spatial resolution of the PCD-CT enables the spectral characterization of smaller objects such as a very small

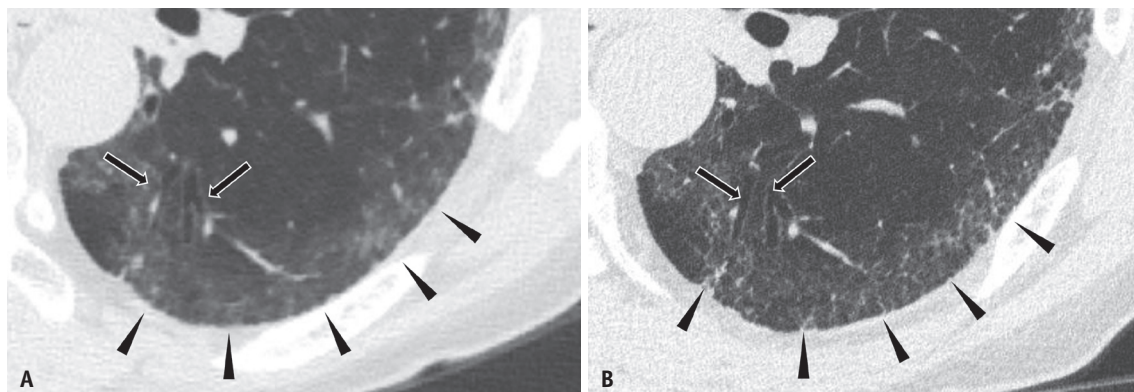


Fig. 2. A 74-year-old male clinically diagnosed with idiopathic non-specific interstitial pneumonia was scanned on conventional energy-integrating detector CT (A) and investigational PCD-CT (B) using a clinical routine protocol.

A, B. PCD-CT demonstrates fine reticulations (arrowheads, B) in the right subpleural right lower lobe, compared to conventional CT, which appears to show ground glass opacities in this region (arrowheads, A). PCD-CT more sharply displays traction bronchiectasis than conventional CT (arrows). PCD = photon-counting detector

kidney stones.

Another area of interest where spatial resolution plays a very important role is in the imaging of small bony structures, specifically the temporal bone [3,5]. Benson et al. [18] showed that the improved spatial resolution of PCD in this setting provides improved visualization of critical

anatomic structures (such as the incudostapedial joint), prostheses, and pathology (Fig. 4).

Improved Iodine Signal

PCD-CT allows for improved iodine contrast at the same tube potential compared to EID CT, with the added benefits

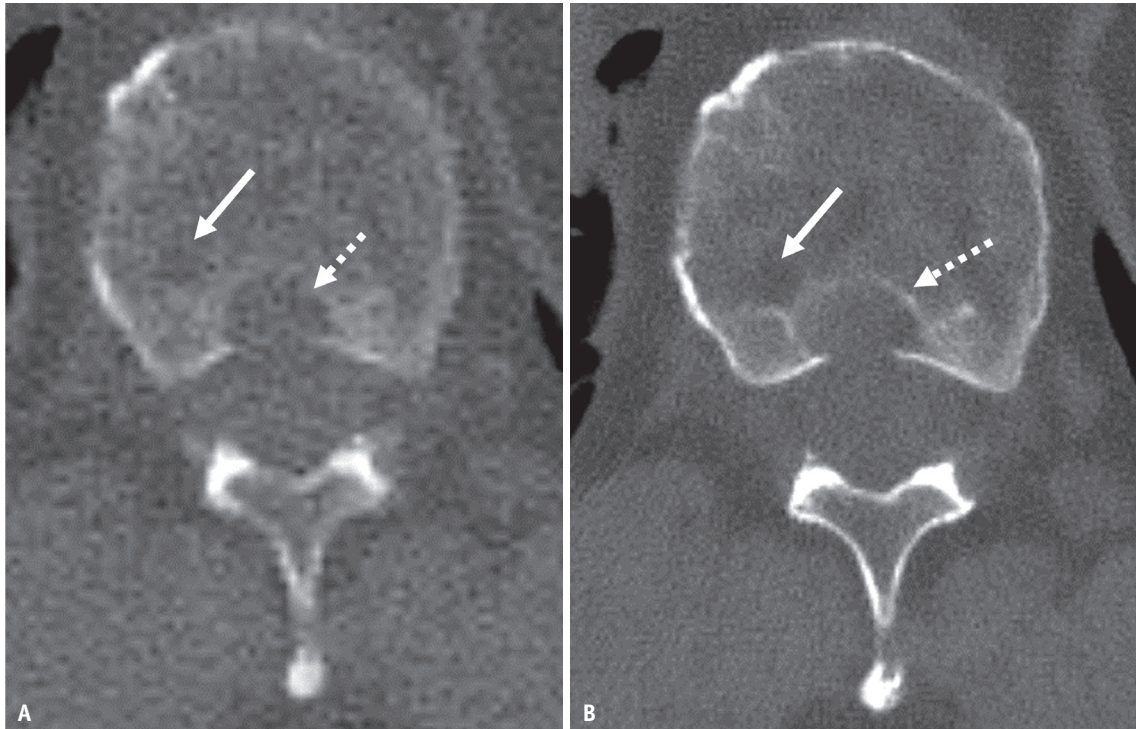


Fig. 3. A 56-year-old male with multiple myeloma.

A, B. Axial energy integrating detector-CT (**A**) and PCD-CT (**B**) slices through the thoracic spine. Lytic lesions in the thoracic spine are more clearly seen on the PCD-CT image. A lytic lesion in the posterior aspect of the vertebral body with breach of the posterior cortex is more clearly delineated (dashed arrows). A smaller lytic lesion in the vertebral body (arrows) is more conspicuous on the PCD-CT image. PCD = photon-counting detector

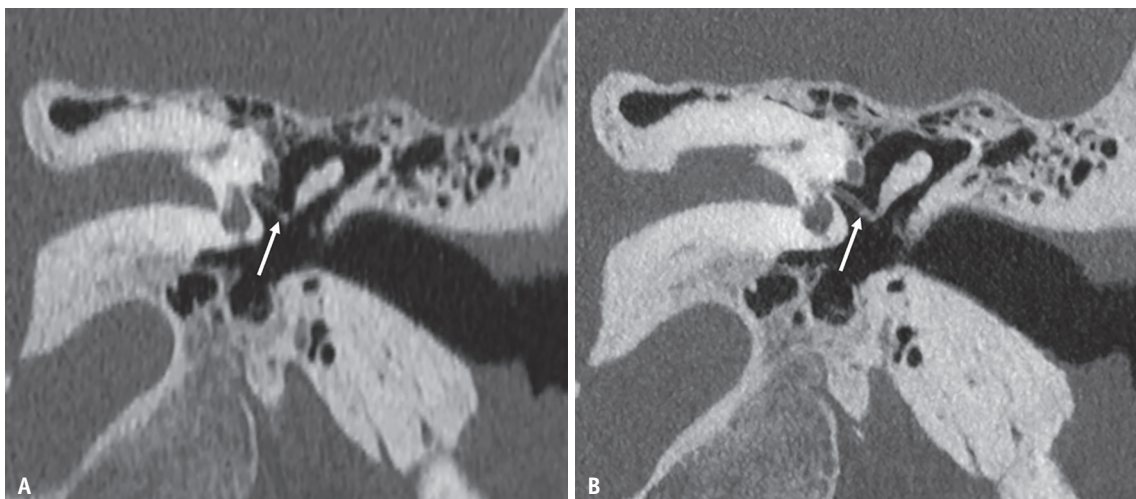


Fig. 4. The incudostapedial joint (arrows), shown on energy integrating detector-CT (A) and PCD-CT (B) images. The joint was one of several anatomic structures specifically graded using a 5-point Likert score, with higher scores favoring the quality of the PCD-CT images. Adapted from Benson et al. *AJNR Am J Neuroradiol* 2022;43:579-584 [18]. PCD = photon-counting detector

of multi-energy display and material decomposition. PCD-CT improves iodine signal due to the lack of the down-weighting of low-energy photons that occurs using EID X-ray detectors [7]. For instance, polychromatic 120 kV PCD-CT images yield image contrast characteristics resembling lower tube potential (kV) settings with increased contrast differences (Fig. 5). This increased iodine contrast extends the benefits of low kV imaging, mainly dose reduction for low contrast detection tasks in the abdomen for larger patients, where conventional low kV imaging is limited by available tube current. These benefits can be further expanded through the reconstruction of virtual monoenergetic images (VMIs) with the radiologist selecting the most appropriate kiloelectronvolt (keV) energy level for the diagnostic task, in addition to virtual non-contrast images and iodine maps.

The image contrast optimization attainable with PCD-CT has multiple potential applications in the abdomen and pelvis, including improved conspicuity and delineation of neoplasms within parenchymal backgrounds, especially so-called “low contrast” lesions, in which the CT number of the target lesion is similar to the anatomic background. For instance, PCD-CT can increase the conspicuity of liver

lesions (both hypovascular and hypervascular tumors) and pancreatic cancers by accentuating CT number differences due to small differences in iodine enhancement (Fig. 6). The improved dose efficiency of photon-counting detectors allows the use of narrower slices thicknesses at matched radiation doses, resulting in less partial volume averaging (Fig. 6). With improved iodine contrast signal using the photon-counting detector, alone or in combination with VMIs, the higher spatial resolution of PCD-CT images can improve the detectability of small objects, such as small hypoattenuating liver metastases (Fig. 7) or peritoneal implants (Fig. 8). Improvements in iodine signal with PCDs, potentially in combination with low energy VMIs, can alternatively be used to reduce the amount of iodine used to achieve similar differences in image contrast for different diagnostic tasks (Fig. 9), an approach which can be useful for patients with renal impairment or undergoing repeat endovascular procedures [1,19-21].

Multi-Energy Imaging

Multi-energy CT reconstructions pertinent to musculoskeletal imaging include the evaluation of gout (Fig. 10) and virtual non-calcium images for bone edema.

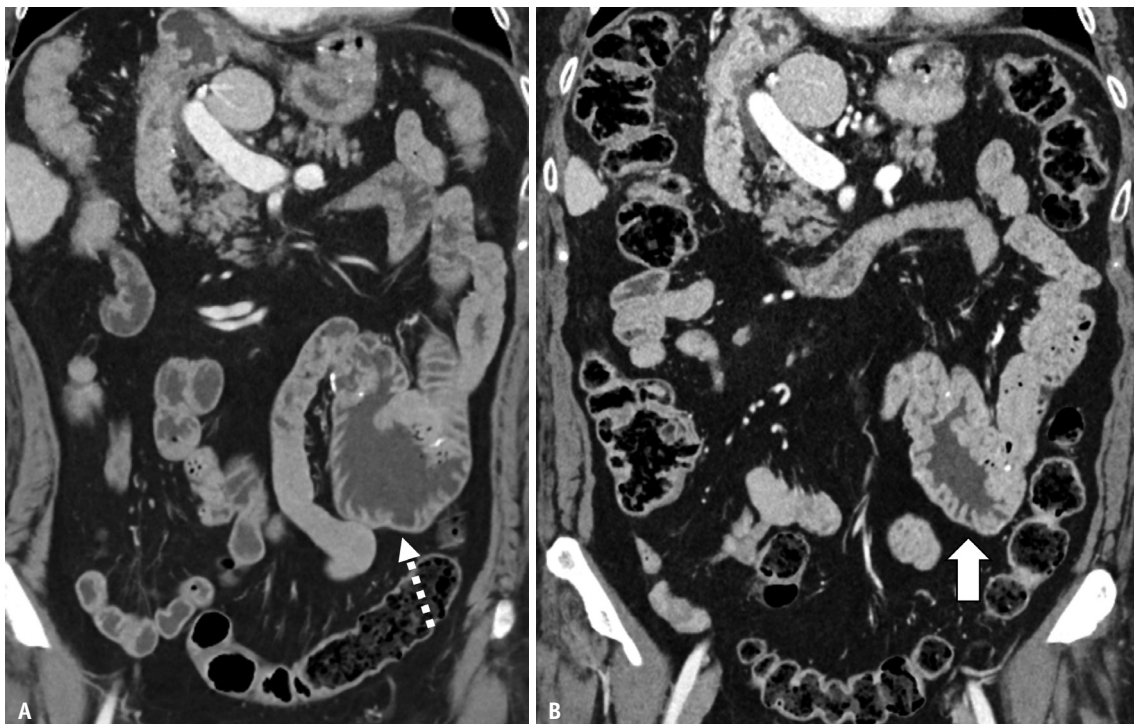


Fig. 5. A 70-year-old female with a history of resected intrahepatic cholangiocarcinoma, gastric bypass, and a side-to-side jejunojejunostomy.

A, B. Both studies were taken at a tube voltage of 120 kV. Coronal energy integrating detector-CT (**A**) shows the jejunojejunostomy (dashed arrow) but photon-counting detector-CT (**B**) improves the visualization of the contrast and the sharpness of the folds in the jejunojejunostomy (arrow).

Dense cortical bone and trabeculae make the medullary cavity of bone a challenging site to evaluate on CT. For instance, bone edema associated with traumatic injury and

focal medullary lesions of myeloma are often obscured using conventional CT images. Virtual non-calcium reconstructions from multi-energy acquisition allow radiologists to clearly

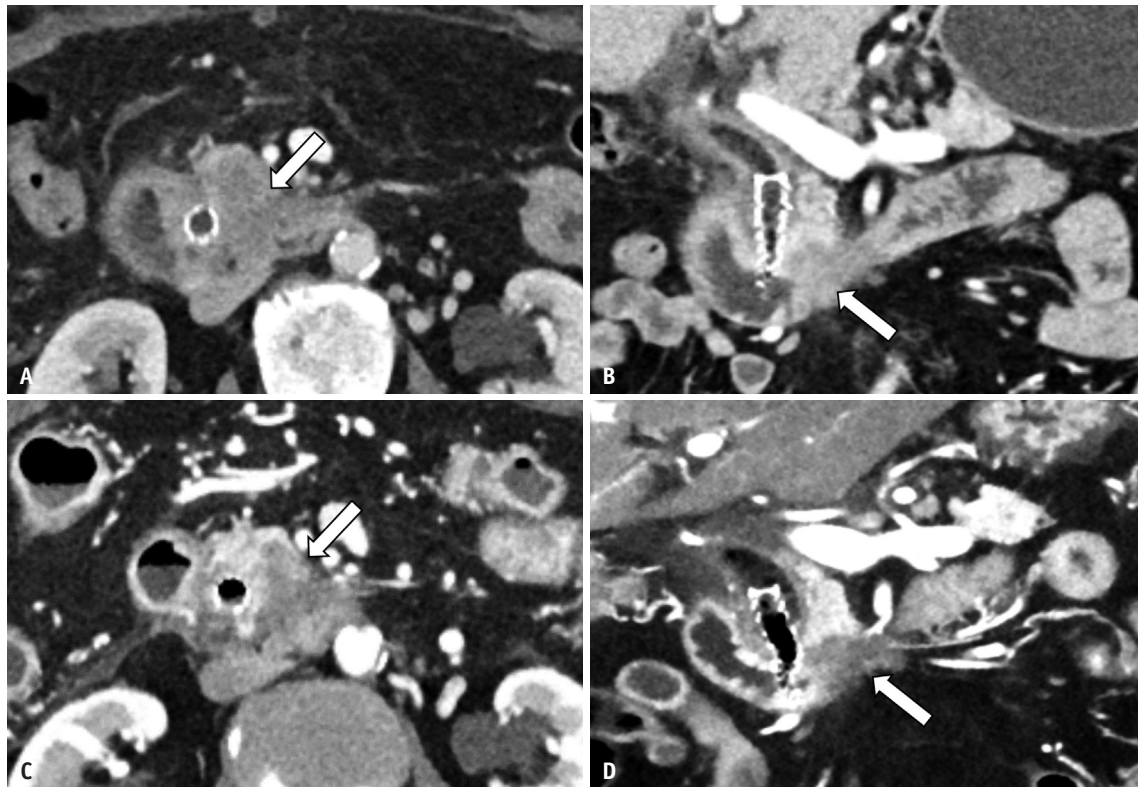


Fig. 6. A 67-year-old female with pancreatic adenocarcinoma.

A-D. Compared with axial and coronal 2-mm images acquired with energy integrating detector-CT (**A, B**), axial and coronal 1-mm images acquired with PCD-CT (**C, D**) provide better visualization of the hypodense tumor in the uncinate owing to the ability of PCD-CT to highlight iodine contrast; also in these images, the ability of PCD-CT to display thinner slices without substantial increase in image noise is demonstrated. Thinner slices reduce partial volume averaging for small structures and pathologies. PCD = photon-counting detector

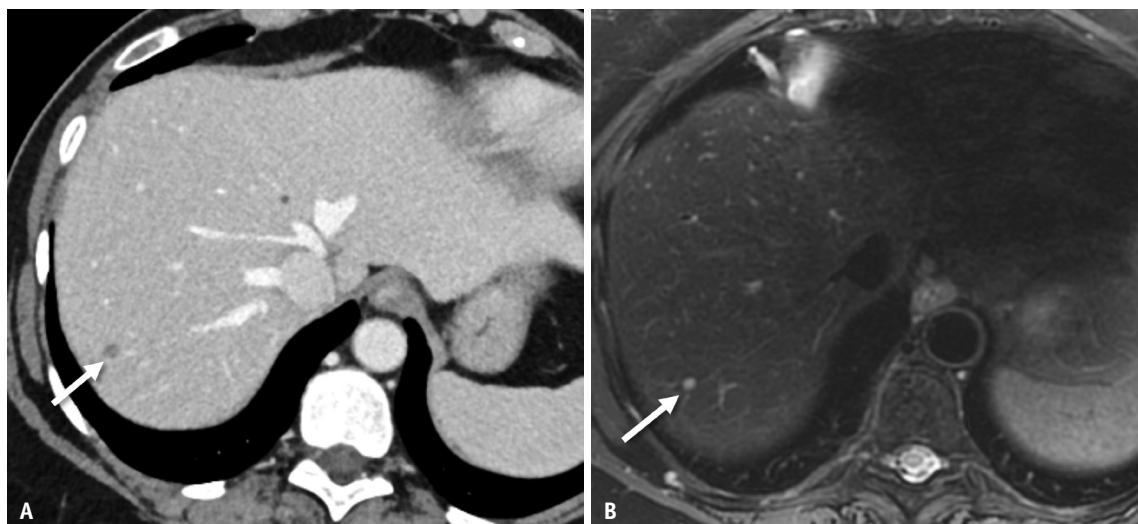


Fig. 7. A 64-year-old patient with metastatic pancreatic cancer.

A, B. Photon-counting detector-CT image (**A**) shows a very small liver metastasis in the right posterior section (arrows) confirmed on subsequent MRI (**B**).

visualize the medullary cavity to identify bone marrow edema due to trauma or neoplasm, and can be created with PCD similar to their creation at dual-energy CT.

Unlike dual-source dual-energy CT systems, PCDs do not restrict the scan field of view for use of multi-energy applications, extending the benefits of multi-energy CT

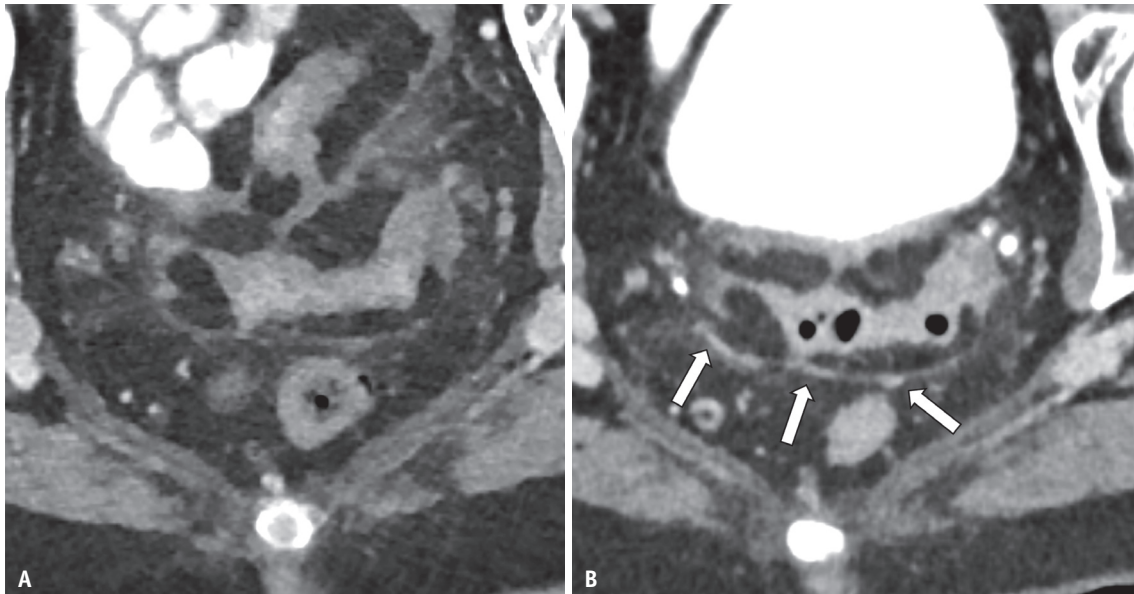


Fig. 8. A 73-year-old female with peritoneal dissemination of ovarian cancer.

A. Energy integrating detector-CT demonstrates irregularity of the serosa of the sigmoid colon and questionable nodularity along the anterior peritoneal reflection. **B.** Photon-counting detector-CT clearly demonstrates small tumor implants causing irregular and nodular-like thickening of the anterior peritoneal reflection (arrows).

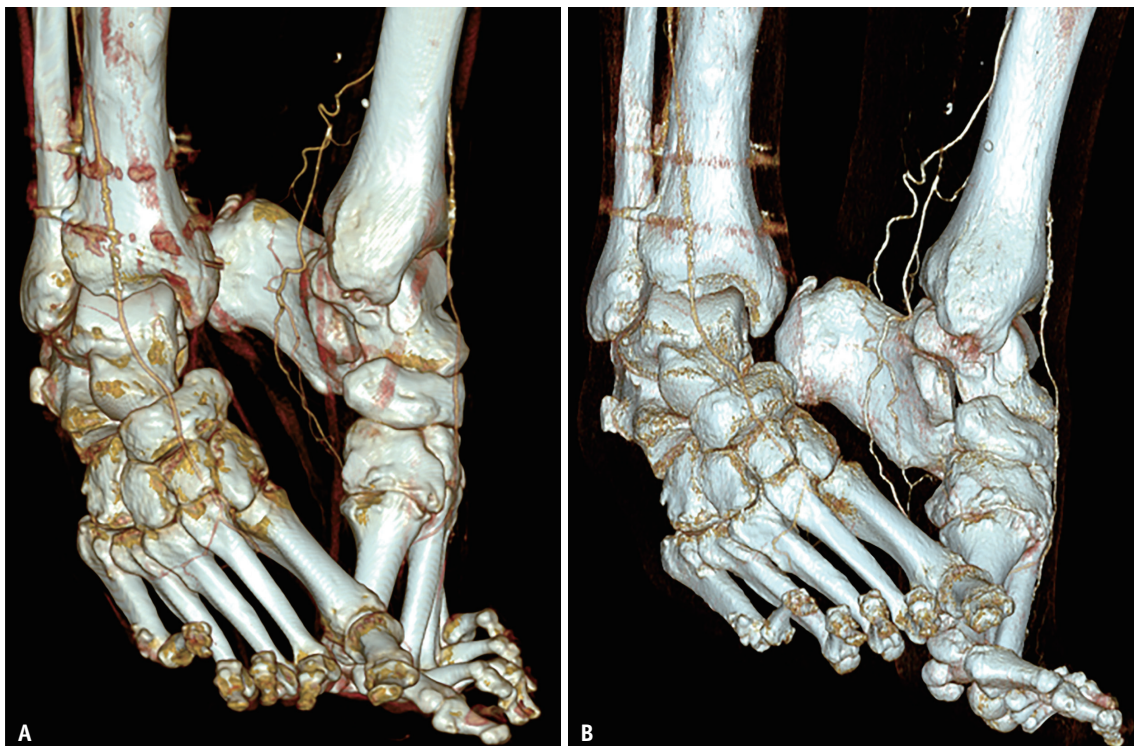


Fig. 9. A 69-year-old female patient with known peripheral arterial disease.

A, B. 3-dimensional reconstruction images reconstructed from energy integrating detector-CT angiography (**A**) and 145 mL of iodinated contrast appear similar to PCD-CT angiography images (**B**) using only 55 mL of the same iodinated contrast agent. This example illustrates the ability to leverage improved iodine signal from PCD-CT for reduced need for iodine contrast. PCD = photon-counting detector



Fig. 10. A 36-year-old male patient with gout arthritis with tophi.

A-D. Images obtained using PCD-CT with subsequent material classification show monosodium urate deposition in green at the great toe interphalangeal joint.

imaging to larger patients. While PCD will evolve with new software versions designed to permit visual and quantitative display of multi-energy data, PCD-CT multi-energy capabilities will “always be on” and at full field of view, allowing, e.g., display of a foot fracture with simultaneous display of bone marrow edema and gout in a single scan, but requiring multiple reconstructions for each imaging task. Finally, the combination of improved iodine signal, multi-energy-based discrimination, and material separation can help expand the clinical potential of quantification tasks, for focal lesions (e.g., discrimination of iodine in renal cysts versus solid renal masses) or parenchymal organs, such as liver fat quantification. Further studies are

needed to determine the clinical use of PCD-CT in these clinical contexts.

Radiation Dose Reduction

Several PCD-CT applications are particularly advantageous to pediatric patients. The higher spatial resolution and contrast-to-noise ratio improve the visibility of anatomic structures in smaller patients but with increased dose efficiency, facilitating further dose reduction. With the high-resolution mode of PCD-CT, radiation dose can be decreased by 20%–30% without sacrificing image quality. In addition, similar to its use in some conventional EID CT systems, a tin filter can be used to shape the polychromatic

X-ray tube energy spectrum, removing low-energy photons so that a greater proportion of photons pass through the patient, and facilitating substantial dose reduction for non-contrast diagnostic tasks [9]. These features of PCD-CT make it ideal for a wide variety of pediatric protocols, but ultra-low dose chest CT is an ideal application for patients that require repeated imaging studies from a young age, e.g., young patients with chronic airway disease such as cystic fibrosis. Figure 11 shows a non-contrast ultra-low dose CT image from a 6-year-old patient with cystic fibrosis, which was performed at a radiation dose similar to a chest radiograph.



Fig. 11. A 6-year-old female clinically diagnosed with cystic fibrosis was scanned on a PCD-CT (CT dose index: 0.05 mGy inspiration [shown] and 0.05 mGy expiration). PCD-CT demonstrates cylindrical bronchiectasis in the right middle lobe (arrow). PCD = photon-counting detector

Artifact Reduction

Another clinical benefit of PCD-CT is the reduction of common image artifacts, including but not limited to streaks, beam hardening, metal, and calcium blooming. For high attenuating body parts of large patients, streak and shading artifacts are commonly observed due to photon starvation and electronic noise [22]. As PCDs eliminate electronic noise, these artifacts can be markedly reduced [23,24]. For PCDs with multiple energy thresholds/bins, images at different energy bins represent different attenuation properties. High energy bin images in PCD-CT show less beam hardening artifacts compared to low energy bin images and standard CT images with all X-ray photons [7]. Moreover, metal artifact reduction can be achieved by combining high energy bin images with X-ray beam shaping using an external tin filter [25], or alternatively, by using high energy VMIs [22].

Blooming is an image artifact caused by partial volume averaging of attenuation values in a voxel with different tissues, making it difficult to resolve objects smaller than the voxel. Calcium blooming is a common artifact in cardiovascular exams due to limited spatial resolution of the CT system. Blooming is an important challenge in cardiovascular imaging, particularly in small vessels (e.g., coronary arteries, distal extremity arteries) with calcium or stents, as the radiologist seeks to distinguish these structures from the contrast-filled lumen. Hence, calcific plaques (as well as metallic stents) appear larger than their true size—resulting in overestimation of luminal stenosis, which can potentially lead to inappropriate

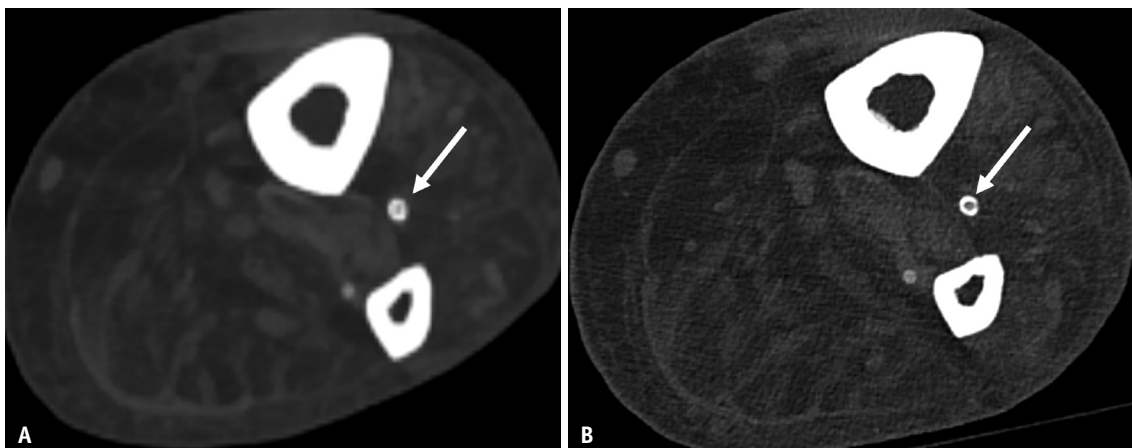


Fig. 12. A 74-year-old male patient with known peripheral arterial disease. **A, B.** Axial reconstructions in a patient with peripheral arterial disease show calcium blooming in the anterior tibial artery on energy integrating detector-CT (arrow, **A**). Compared with energy integrating detector-CT reconstruction (**A**), photon-counting detector-CT reconstruction (**B**) in the same patient at the same level shows significantly improved visualization of the calcium plaque in the anterior tibial artery (arrow, **B**) because of which the luminal caliber can be better assessed.

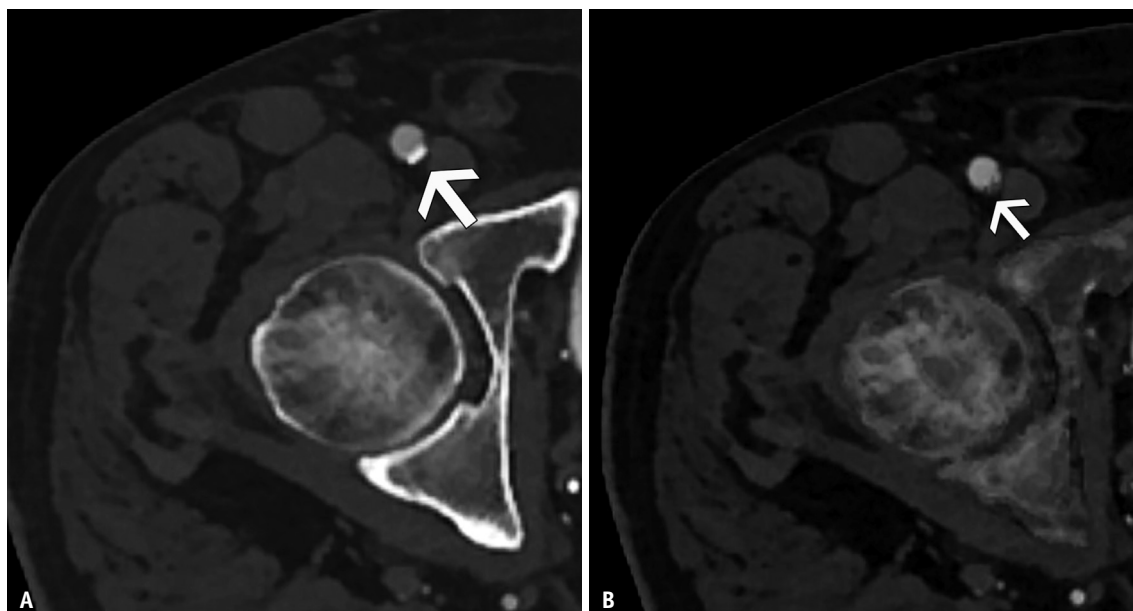


Fig. 13. Calcium separation algorithm.

A. Axial energy integrating detector-CT reconstruction in a patient with peripheral arterial disease shows a dense calcific plaque in the right common femoral artery (arrow). **B.** Axial photon-counting detector-CT reconstruction of the same patient with the use of a dedicated calcium separation algorithm shows subtraction of the calcified plaque (arrow).

clinical management. PCDs can address calcium blooming in several ways. With improved spatial resolution, calcium blooming artifact can be improved by reducing voxel size and partial voluming, increasing the accuracy of stenosis assessment in patients with dense vascular calcifications (Fig. 12) [26]. Alternatively, calcium blooming can also be reduced by decreasing the average attenuation of voxels by increasing the X-ray energy, which can be accomplished in PCD-CT utilizing high-energy VMIs [22]. Finally, calcium can be separated from the images using material decomposition algorithms, which can be created using multi-energy information, potentially providing a more accurate estimation of luminal stenosis (Fig. 13) [27].

Simultaneous Benefit of Numerous Technical Advantages in Cardiovascular Imaging

Radiologists and physicists will, of course, combine numerous technical advantages of PCDs to improve the ability to accomplish any particular diagnostic task. This may be best illustrated by considering several tasks in cardiovascular imaging. For example, visualization and characterization of small vessels (e.g., coronary arteries, peripheral run off arteries, artery of Adamkiewicz, and arterial flaps) will be facilitated by using higher spatial resolution kernels and thin slices, combined with the use of the PCD itself or by further improving visualization of

the iodine-filled lumen with the use of low energy VMIs, and further reduction of calcium bloom using high energy VMI's or algorithms designed to remove calcific plaque. The inherent high iodine contrast-to-noise ratio of PCD-CT and low-energy VMIs can be used either to lower the dose of iodinated contrast (e.g., in patients with renal dysfunction) or salvage suboptimally enhanced studies.

Since the multi-energy capability is achieved on the detector, a dual-source PCD-CT system with two X-ray tubes operating at the same tube potential can achieve high temporal resolution (66 ms) multi-energy cardiac CT, which is not feasible on conventional dual-source CT with energy integrating detectors (where the user must choose either dual energy or high temporal resolution). Dual-source PCD-CT therefore permits multi-energy CT images at high temporal resolution with substantially reduced motion artifacts, potentially detecting tiny calcifications, and identifying high-risk features such as spotty calcification and fibrous cap [28]. Multi energy material decomposition can be used to remove bones from vascular studies instead of conventional threshold-based algorithms. Iodine maps are useful in evaluation of perfusion, including that of heart and lungs, e.g., late iodine enhancement CT for myocardial scar, and myocardial extracellular volume quantification [22]. Iodine maps along with virtual non-contrast images are useful for characterization of several lesions, including

thrombus versus artifact, and high attenuation calcium versus hemorrhage versus enhancing masses.

Summary

By converting X-ray photons directly to electrical signal, PCD-CT offers several advantages over conventional EID CT systems, including: improved spatial resolution, better iodine signal with ability to exploit multi-energy imaging data, elimination of electrical noise and improved dose efficiency, simultaneous high spatial and temporal resolution combined with multi-energy energy assessment with dual-source PCD, and numerous methods to reduce calcium blooming and other troublesome image artifacts. PCD technology itself permits great flexibility in combining multiple technical advances that arise from detector design to facilitate improved image quality (and potentially diagnostic performance) across a broad range of diagnostic tasks, extending many benefits of state-of-the-art CT to larger patients, and facilitating radiation dose reduction for pediatric patients. Adaptation of this technology to different diagnostic tasks will require radiologist and physicist collaboration in selection of the most appropriate reconstruction kernels, slice thickness, VMI's and iodine maps, and other material classification algorithms and display techniques. Further study will be needed across multiple institutions to determine diagnostic tasks for which PCD-CT improves radiologists' performance and confidence, as well as to develop new diagnostic tasks for CT that will improve patient health.

Availability of Data and Material

All data generated or analyzed during the study are included in this published article.

Conflicts of Interest

Cynthia H. McCollough: Research Grant to institution, Siemens Healthcare GmbH. Joel G. Fletcher: Research Grant to institution, Siemens Healthcare GmbH.

The other authors have no relevant conflicts of interest to disclose.

Author Contributions

Conceptualization: Andrea Esquivel, Joel G. Fletcher, Andrea Ferrero. Data curation: all authors. Formal analysis: all authors. Funding acquisition: Cynthia McCollough, Joel G. Fletcher. Project administration: Andrea Esquivel, Joel G.

Fletcher. Resources: Cynthia McCollough, Joel G. Fletcher. Supervision: Joel G. Fletcher. Writing—original draft: all authors. Writing—review & editing: all authors.

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