

Review Article

Photon-counting computed tomography: a next-generation imaging technology and its clinical impact

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ABSTRACT

Photon-counting computed tomography (PCCT) is the radically new technology in the X-ray imager that makes it possible to directly detect and energy-discriminate a photon. PCCT, in contrast to traditional energy-integrating detector (EID) CT systems, uses semiconductor-based detectors that transform X-ray photons directly into electrical signals, which means that it has better spatial resolution and lower electronic noise, sufficient contrast-to-noise ratio, and improved dose efficiency. The main benefit of PCCT is that it has intrinsic spectral imaging capacity that enables it to obtain multi-energy data during a single scan, enabling a material to be decomposed accurately, better tissue characterization and beam-hardening and metal artifact reduction. Recent clinical and preclinical trials have shown that PCCT also has a broad diagnostic potential in a broad spectrum of uses such as neuroimaging, cardiovascular imaging, thoracic imaging, musculoskeletal examination and oncologic imaging. The enhanced spatial resolution allows the visualization of small structures of the anatomy to be better and the spectral information is possible to support quantitative imaging and the characterization of the lesion. These abilities can lead to the earlier detection of a disease, the increased confidence of the diagnostic results, and the optimal management of the patients. Though this has been advantageous, the common clinical use of PCCT is still hampered by issues of high costs of the systems, large volume of data, computational requirement and limited accessibility. However, these limitations are set to be overcome by the ongoing improvement in detector technology, image reconstruction algorithms and clinical validation studies. The review gives a summary of the principles underlying photon-counting CT as well as the comparison that has been given between PCCT and conventional CT technology, limitation of PCCT, and its future in diagnostic imaging.

Keywords: Photon-counting computed tomography, Spectral CT, Energy-resolved imaging, Detector technology, Advanced CT imaging, Medical Imaging

INTRODUCTION

Computed Tomography (CT) has become an indispensable imaging modality in modern medicine because of its rapid acquisition, high spatial resolution and its extensive clinical utility.¹ Conventional CT scanners use energy-integrating detectors (EIDs), which measure the total deposited energy of incident X-ray photons but are limited by electronic noise, limited spectral information and poor

dose efficiency.^{2,3} In order to overcome these limitations and obtain improved image quality, advanced detector technologies have been developed. Photon-Counting Computed Tomography (PCCT) is an emerging CT technology based on photon counting detectors (PCDs) which can count and measure the energy of the incoming X-ray photons individually, thus providing intrinsic spectral imaging and enhanced quantitative evaluation.⁴ By minimizing electronic noise and allowing energy

discrimination, PCCT offers improved spatial resolution, contrast-to-noise performance and material differentiation compared to the performance of conventional CT.^{4,5}

In addition, multi-energy data are acquired by PCCT in a single scan without the requirement of dual-energy modes, leading to increased artifact reduction and the ability to pursue quantitative imaging.^{4,5} Early clinical evaluations suggest that PCCT is capable of achieving diagnostic image quality for a lower dose of radiation while providing further spectral parameters that could potentially aid in characterization of lesions and detection of disease.⁶ These advances in technology have made PCCT a revolutionary imaging modality with tremendous potential impact in various areas of clinical medicine, including cardiovascular, neuro, thoracic, musculoskeletal and oncologic imaging.^{4,6}

PRINCIPLES AND DETECTOR TECHNOLOGY OF PHOTON-COUNTING COMPUTED TOMOGRAPHY

Energy-integrating detectors versus photon-counting detectors

Conventional CT systems are based on energy-integrating detectors (EIDs), in which incoming X-ray photons are first converted into visible light using a scintillator and then integrated in time to produce an electrical signal.² In this method all photons have equal contribution to the total detected energy and thus the spectral information is lost as well as the dose efficiency. Furthermore, EID-based

systems are also prone to electronic noise especially for low radiation doses, which can impair image quality.^{2,3}

In comparison, PCDs in PCCT count the individual X-ray photons and measure their energy separately.⁴ Each detected photon with an energy greater than a predefined level is counted as an individual event, allowing the true energy discrimination. This fundamental difference enables PCCT to have improved contrast-to-noise ratio, higher spatial resolution and intrinsic spectral imaging capability as compared with conventional CT systems.^{4,5}

Photon-counting detector design and working principle

Photon counting detectors are usually composed of direct conversion semiconductor materials such as cadmium telluride (CdTe) or cadmium zinc telluride (CZT) which directly convert incident X-ray photons into electrical charge without an intermediate scintillation step.¹¹ When an X-ray photon interacts with the detector, electron-hole pairs are created depending on the energy of the X-ray photon and are collected by dedicated readout electronics for signal processing.⁷⁻¹¹

A unique feature of PCD technology is the use of multiple energy thresholds, permitting photons to be separated into different energy bins. This allows the decomposition of material, better tissue contrast and quantitative spectral imaging from a single acquisition.⁵⁻⁷ By rejecting electronic noise at the set energy threshold, PCCT allows to improve the quality of the image, especially in a low-dose situation.^{5,6}

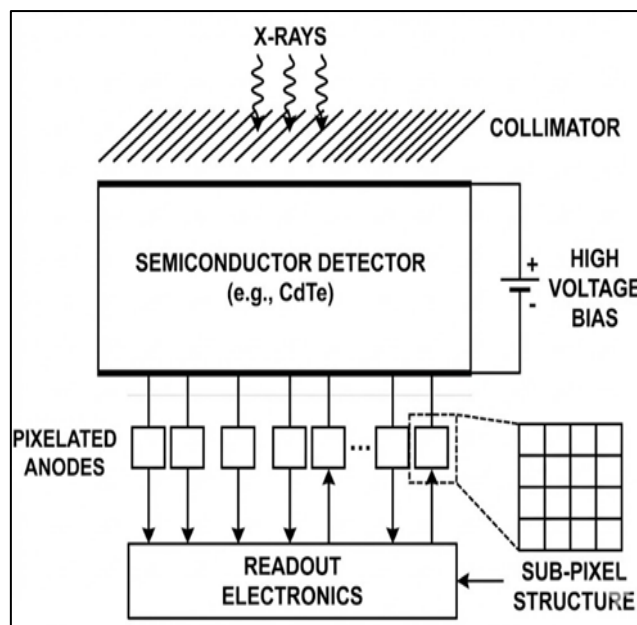


Figure 1: Schematic illustration of a photon-counting detector used in photon-counting computed tomography (PCCT). Incident X-ray photons are collimated and directly converted into electrical charge within a semiconductor detector material (e.g., CdTe) under a high-voltage bias. The generated charge is collected by pixelated anodes and processed by dedicated readout electronics. The inset highlights the sub-pixel structure, which enables improved spatial resolution and energy discrimination.

Data acquisition and image reconstruction in PCCT

Photon counting CT offers intrinsic multi-energy acquisition during a single scan, obviating the need for separate dual-energy imaging modes.⁵ This capability provides the ability for simultaneous high-resolution anatomical imaging and spectral analysis, leading to less beam hardening artifacts and better quantitative accuracy.⁵⁻⁹ Advanced reconstruction algorithms make use of energy-resolved data to produce material-specific images, such as iodine maps and virtual monoenergetic reconstructions.⁹ Additionally, better efficiency of doses allows for high quality imaging using less doses of radiation, which makes PCCT especially useful in paediatrics, follow-up studies and for high resolution applications.^{5,6} These principles of detectors and reconstruction are the technological basis for the growing

clinical role of photon counting CT.

COMPARISON OF PHOTON-COUNTING CT AND CONVENTIONAL CT

Photon-counting computed tomography (PCCT) differs fundamentally from conventional CT systems that use energy-integrating detectors (EIDs), particularly in detector design, data acquisition, image quality, and spectral capabilities. While EID-based CT integrates the total energy deposited by incoming photons, PCCT counts individual photons and records their energy, resulting in significant improvements in spatial resolution, contrast differentiation, and dose efficiency.^{4,5} These differences translate into both technical and clinical advantages, as summarized below.

Table 1: Comparison between conventional CT vs photon-counting CT.

Parameter	Conventional CT (EID)	Photon-counting CT (PCCT)
Detector principle	Energy integration	Individual photon counting
Signal conversion	Indirect (via scintillator)	Direct semiconductor conversion
Electronic noise	Present	Minimal / threshold-based rejection
Spatial resolution	Moderate	High (smaller pixel size)
Spectral imaging	Dual-energy required	Intrinsic multi-energy
Material differentiation	Limited	Improved
Beam-hardening artifacts	More common	Reduced
Dose efficiency	Standard	Improved

This table shows the key differences between conventional energy-integrating detector CT and photon-counting CT in terms of detector design, image quality, spectral capability, and dose efficiency.

Detector technology and signal processing

Conventional CT detectors use an indirect conversion based on the conversion of X-ray photons first into visible light by a scintillator and then to an electrical signal. This multi-step process causes electron noise and loss of spectral information especially at low doses of radiation.^{2,3} In contrast, PCCT uses direct conversion semiconductor detectors which eliminate the intermediate light conversion, hence reducing noise and increasing signal fidelity.^{4,11}

Spatial resolution and image quality

PCCT systems use smaller detector pixel sizes than EID-based CT, allowing for higher intrinsic spatial resolution. This feature is especially useful in imaging of the following fine anatomical structures: coronary arteries, intracranial vessels, and trabecular bone.⁵⁻¹⁰

Moreover, by rejecting the electronic noise below predefined energy thresholds, PCCT offers superior contrast-to-noise ratio, in particular in low-dose imaging scenarios.⁶

Spectral imaging capability

Spectral imaging in conventional CT generally requires dual-energy techniques, which include either dual source scanners or rapid kVp switching. These approaches are linked with an increase in system complexity and a potential temporal misregistration.¹¹ In contrast, PCCT inherently gives multi-energy data from a single acquisition by energy binning, making it possible to perform accurate material decomposition and quantitative imaging, without any additional hardware or scan protocols.⁵

Radiation dose efficiency

Several experimental and initial clinical studies have shown that PCCT can provide the same or better image quality with lower radiation doses than conventional CT.⁶ This increased dose efficiency makes PCCT especially useful in paediatric imaging, screening programs, and follow-up examinations in which repeated scans are needed.

BENEFITS OF PHOTON COUNTING COMPUTED TOMOGRAPHY

Compared with traditional energy-integrating detector CT systems, photon-counting computed tomography (PCCT) has a number of obvious advantages, foremost of which is

its ability to count individual photons and to resolve the energy information. These benefits lead to greater spectral imaging capability, radiation dose efficiency, and image quality, which enhances diagnostic performance in a number of clinical applications.^{4,5}

Improved spatial resolution

PCCT systems utilize smaller detector pixel sizes compared with conventional CT, enabling higher intrinsic spatial resolution.

This allows improved visualization of fine anatomical structures, such as small vessels, coronary arteries, and trabecular bone, which may not be adequately resolved with energy-integrating detector CT.⁵⁻⁹

Reduced electronic noise and improved image quality

PCCT can enhance the contrast-to-noise ratio by a large margin (especially in low-dose imaging situations), by selecting energy thresholds that discard low-energy electronic noise. This is particularly advantageous in imaging of children and where follow-up examinations must be repeated, and minimization of radiation dose is of paramount importance.⁶

Intrinsic spectral imaging capability

In contrast to traditional CT that uses dual-energy-specific acquisition methods necessary to obtain spectral data, PCCT intrinsically offers multi-energy data in a single acquisition. This inherent spectral sensitivity provides better material differentiation, quantitative imaging, and produces virtual monoenergetic images without extra complexity of the scan.⁵⁻⁸

Improved radiation dose efficiency

Several experimental and preclinical reports have shown that PCCT is able to attain the same or better image quality at low radiation doses than traditional CT. PCCT is especially beneficial in screening tests, children and longitudinal studies in which several scans are necessary thanks to increased dose efficiency.⁶

Reduced beam-hardening and metal artifacts

The energy-resolved detection and advanced reconstruction algorithms available in PCCT contribute to reduced beam-hardening and metal artifacts. This improves image interpretability in patients with metallic implants, vascular stents, and orthopaedic hardware.⁹⁻¹²

CLINICAL APPLICATIONS OF PHOTON-COUNTING COMPUTED TOMOGRAPHY

Photon-counting computed tomography (PCCT) has had technological benefits such as better spatial resolution, intrinsic spectral imaging, and dose efficiency which have

facilitated the diversification of clinical use in various subspecialties. Results of the initial clinical studies indicate that lesions are better detected, material differentiation is enhanced, and artifacts are minimized as compared to the traditional CT systems.⁴⁻⁸

Neuroimaging

PCCT is a better visualization of small intracranial vessels and also better at differentiating between calcification and blood because of its ability to be energy resolved.^{9,10} The increased spatial resolution allows to assess better intracranial stents, aneurysms, and small vascular abnormalities. Also, the contrast-to-noise ratio is better, which strengthens the observability of the parenchymal lesions that may be minimal, and it may lead to less radiation exposure.⁸

Cardiovascular imaging

One of the most promising usages of PCCT is cardiovascular imaging. The enhanced spatial resolution enhances visualization of the lumens of the coronary arteries and the morphology of the plaque and especially in the highly calcified vessels.⁹ Less blooming artifacts enhance evaluation of coronary stents and calcifications to increase the diagnostic accuracy. Moreover, intrinsic spectral imaging also allows a better characterization of plaque and iodine mapping, which can lead to the better risk stratification of coronary artery disease.^{8,9}

Thoracic imaging

PCCT has better spatial resolution and therefore a greater ability to visualize finer lung structures in the thoracic imaging. This is especially useful when assessing interstitial lung disease and small nodules of the lungs.⁸⁻¹⁰ The spectral capabilities enhance the possibility of detecting pulmonary embolism by use of improved contrast differentiation and iodine mapping methods.⁸

Musculoskeletal imaging

PCCT also has a high level of benefits in musculoskeletal imaging since it offers a better representation of the microarchitecture of trabecular bone and small cortical fractures.⁵ Also, there are fewer metal artifacts, which positively affect the assessment of orthopaedic implants and postoperative measurements and the accuracy of the diagnosis.¹²

Oncologic imaging

PCCT is used in the oncologic imaging to characterize tumours better by quantitative mapping of iodine and spectral analysis.⁸ The material differentiation could be improved, which could make the assessment of tumour vascularity, response to treatment, and lesion conspicuity easier. Oncology patients also benefit with regards to

improved dose efficiency since they might need repeated follow-up imaging.

LIMITATIONS AND CHALLENGES OF PHOTON-COUNTING COMPUTED TOMOGRAPHY

Despite its enormous potential for technological advantages, photon-counting computed tomography (PCCT) has some drawbacks that have limited its application in clinical settings. Technical constraints of photon-counting detector physics, such as charge sharing, pulse pile-up, and count-rate limitation, particularly in high-flux imaging mode of operation, may impair energy resolution and spectral accuracy.¹⁰ In addition, one of the key obstacles to a widespread practice in clinical practice continues to be the high cost of PCCT systems, their scarcity, increased data management requirements, and further extensive clinical validation.⁴

FUTURE PERSPECTIVES AND EMERGING TRENDS OF PHOTON-COUNTING COMPUTED TOMOGRAPHY

Future advancements in detector technology and reconstruction algorithms/techniques that continue to improve energy resolution, spatial resolution and count-rate characteristics will make photon counting computed tomography (PCCT) an increasingly important component of diagnostic imaging. Artificial intelligence and the latest methods in spectral reconstruction may potentially enhance process efficiency, image quality and quantitative accuracy. Additionally, PCCT can be accomplished in ultra-low dosage imaging, paediatric imaging, and quantitative functional imaging because of its higher dose performance and inherent spectrum sensitivity. Rather than completely replacing dual-energy CT in the near future, based on further technological advancements and further clinical validation, photon-counting CT may enhance or expand upon applications currently handled by dual-energy CT.^{13,14}

INTEGRATION OF ARTIFICIAL INTELLIGENCE AND RADIOMICS IN PHOTON-COUNTING COMPUTED TOMOGRAPHY

Spectral reconstruction, quantitative imaging, and precision diagnostics have all advanced significantly with the combination of artificial intelligence (AI) with photon-counting computed tomography (PCCT). For machine learning (ML) and deep learning (DL) techniques intended for noise reduction, artifact correction, and automatic feature extraction, the multi-energy and high-dimensional datasets produced by PCCT are especially appropriate.^{4,5,7}

AI-based image reconstruction and noise reduction

Spectral CT imaging has experienced an increase in the application of deep learning reconstruction techniques in order to improve image quality and reduce image processing overhead. In comparison to the traditional

iterative methods, the deep learning-based spectral CT reconstruction framework proposed by Wu et al using convolutional neural networks showed the improvement of structural similarity and reduction of noises.¹⁵ Similar to this, Nadkarni et al developed a deep learning denoising framework for PCCT that enhances the structural similarity index (SSIM) and peak signal-to-noise ratio (PSNR) to a great extent suggesting its potential use in clinical PCCT imaging processes.¹⁶

Furthermore, Liu et al showed enhanced noise attenuation and preservation of anatomical features at reduced radiation exposure parameters by proposing a structural prior deep learning model for low dose spectral CT reconstruction.¹⁷ These methods highlight how ultra-low-dose PCCT imaging with the aid of AI can be performed without sacrificing the diagnostic quality.

Machine learning in material decomposition and spectral processing

Additionally, machine learning techniques have been investigated to improve spectral classification and material decomposition in photon-counting CT. CNN-based spectrum distortion correction and enhanced material decomposition pipelines were among the learning-based spectral CT techniques that Bousse et al summarized in a thorough review.¹⁸

By utilizing the multi-energy information inherent in PCCT systems, data-driven algorithms may enable automated distinction of calcification, bleeding, and iodine-enhanced tissues.

Radiomics and quantitative imaging biomarkers

Radiomics is the process of characterizing disease phenotypes by extracting quantitative information from medical images. PCCT's enhanced spectral consistency and spatial resolution may increase the stability and reproducibility of radiomic features. In a scoping review of machine-learning-derived radiomic analysis in CT and PET imaging, Badesha et al showed how AI is becoming more and more important in identifying predictive imaging biomarkers for oncologic and cardiovascular applications.¹⁹ It may be possible to improve tumour characterisation, plaque evaluation, and treatment response tracking by incorporating PCCT-derived spectrum characteristics into radiomic processes.

Emerging spectral datasets for AI development

Large annotated datasets are critical for training robust AI models. Zhou et al recently introduced a cone-beam photon-counting CT dataset designed for spectral image reconstruction and deep learning research, facilitating algorithm development and benchmarking in spectral CT systems.²⁰ Such datasets are expected to accelerate the clinical translation of AI-enhanced PCCT imaging.

CONCLUSION

The introduction of photon-counting computed tomography has been one of the most significant breakthroughs in the CT technology because it allows energy-resolved imaging at better spatial resolution, lesser noise and better dose efficiency. PCCT offers intrinsic spectral image and better material differentiation compared to traditional CT, which has increased clinical applicability in various subspecialty fields. Preliminary clinical evidence shows encouraging quality of images and diagnostic confidence. Despite the present limitations, PCCT is likely to be introduced into the routine clinical procedure due to the continuous technological and clinical validation.

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