CARDIOVASCULAR APPLICATIONS OF PHOTON-COUNTING CT TECHNOLOGY

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SUMMARY

Photon-counting computed tomography (PCCT) is an emerging imaging technology that offers substantial advantages over conventional energy-integrating detector CT in cardiovascular imaging. By detecting individual X-ray photons with intrinsic energy discrimination, PCCT provides ultra-high spatial resolution, improved contrast-to-noise ratio, reduced blooming artifacts, and true multi-energy imaging. These features enable more accurate assessment of coronary lumen, calcifications, plaque composition, and coronary stents, particularly in complex cases with severe calcification. PCCT also allows advanced myocardial tissue characterization, including extracellular volume quantification and improved detection of myocardial fibrosis, as well as reliable evaluation of epicardial and pericoronary adipose tissue using spectral and virtual non-contrast imaging. Despite current limitations related to cost and availability, PCCT shows strong potential to improve diagnostic accuracy, refine coronary artery disease assessment, and influence clinical decision-making in cardiac imaging.

I. INTRODUCTION

Coronary computed tomography (CT) angiography plays a pivotal role in the diagnosis and treatment of patients with artery disease. However, unlike conventional CT systems, photon-counting computed tomography (PCCT) introduces substantial technological improvements, includes improved spatial and contrast resolution, energy discrimination, and reduction of various artifacts. As a result, PCCT enables superior coronary lumen and plaque evaluation, even in complex cases with severe calcification or smaller coronary stents. Beyond the coronary arteries, PCCT offers improved visualization of cardiac anatomy and myocardial tissue characterization with the potential to reduce downstream testing, improve diagnosis and treatment, and ultimately improve clinical outcomes. This review explores the technical principles of PCCT, its advantages over conventional CT, and its current and potential future applications in cardiac imaging.

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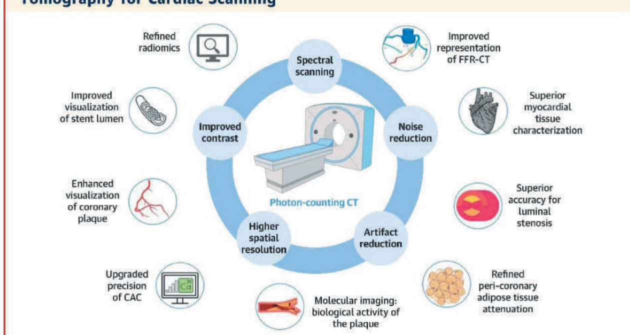
CENTRAL ILLUSTRATION: Applications of Photon-Counting Computed Tomography for Cardiac Scanning



Shiyovich A, et al. JACC Cardiovasc Imaging. 2025;10.1016/j.jcmg.2025.07.022

II. HISTORY OF PCCT

Photon-counting CT (PCCT) emerged from early detector research in the late 20th century, when semiconductor materials were first shown capable of counting individual x-ray photons. Prototype systems in the 2000s proved the feasibility of energy discrimination but were restricted by limited detector area and insufficient count-rate performance. Major advances after 2015—including high-speed, low-noise CdTe/CZT detectors—enabled robust spectral imaging and ultra-high spatial resolution. These technical breakthroughs paved the way for the first clinical whole-body PCCT scanners, which obtained regulatory approval in 2020–2021. Since then, PCCT has rapidly evolved into a powerful clinical modality, particularly in cardiovascular imaging where resolution and spectral accuracy provide clear advantages.

III. PHOTON-COUNTING DETECTOR TECHNOLOGY

Energy-integrating detectors (EIDs) are the traditional technology used in CT systems for x-ray detection, operating by converting incident photons into visible light and subsequently into an electrical signal. Because this process integrates the total energy deposited by all photons, conventional CT systems with EIDs cannot differentiate individual photon energies. In contrast, photon-counting CT (PCCT) performs true multi-energy acquisition by detecting each photon individually and measuring its energy. This capability is enabled by pulse-height analysis, which classifies photons into discrete energy bins without spectral overlap, ensuring accurate spatial and temporal registration. The resulting energy-resolved data allow precise material decomposition, generation of voxel-wise material maps, and substantially improved tissue characterization.

IV. Cardiovascular Applications of PCCT

1. Calcifications and Coronary Artery Calcium and Assessment Coronary Plaque Characterization

Compared with energy-integrating detector (EID) CT, the estimated volume of calcifications on photon-counting CT (PCCT) is closer to the actual volume of an anthropomorphic phantom. This improvement is primarily attributed to enhanced spatial resolution and the reduction of blooming artifacts. In addition, PCCT enables the detection of smaller (as small as 0.2-0.5 mm) and less-dense calcifications, demonstrates an increased contrast-to-noise ratio (CNR), and allows visualization of dense calcifications at lower radiation doses compared with EID CT.

Considering plaque type in addition to plaque burden may enhance atherosclerosis imaging and risk prediction. PCCT outperforms conventional CT in visualizing and differentiating calcified, fibrous, and lipid-rich plaques, with ultra-high-resolution mode reducing blooming artifacts and improving depiction of non-calcified elements. Molecular PCCT using K-edge imaging with gold nanoparticles enables simultaneous assessment of lumen stenosis, plaque composition, vulnerability, and macrophage infiltration, with stronger correlations to histology than conventional CT.

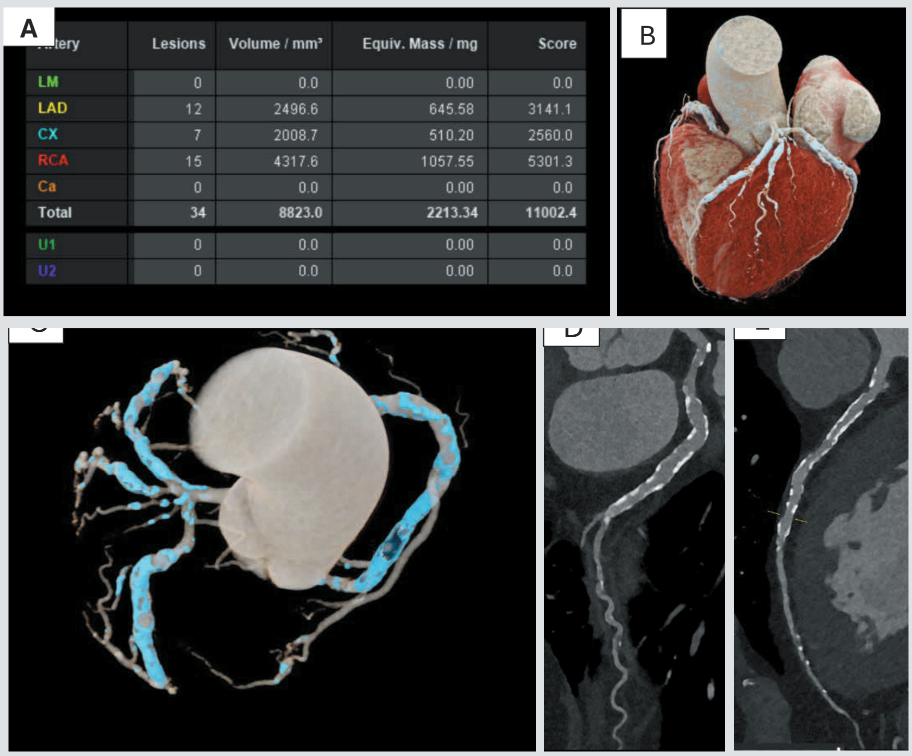


Figure 1. Images from **(A-E)** coronary photon-counting CT (PCCT) in a 69-year-old man. Volume-rendered PCCT image **(B)** depict long, thick, concentric calcifications (Calcium Score over 11000) **(A)** in total coronary arteries, but there is clear improvement in the depiction of distal coronary arteries with MPR on PCCT. **(C,D,E)** Curved coronary arteries LAD1-3 show long calcifications and mild stenosis (<30%).

2. Coronary Artery Stenting

Coronary stents have been imaged with PCCT in vitro in different experimental settings. Compared with EID CT, PCCT depicted the structure of the stent better, estimated strut dimensions closer to the true dimensions, enabled easier detection of calcifications adjacent to the stent, and reduced the artifacts inside the stent, allowing for improved assessment of intrastent stenosis. K-edge imaging with PCCT allows for improved stent structure evaluation and distinction from very dense calcifications.

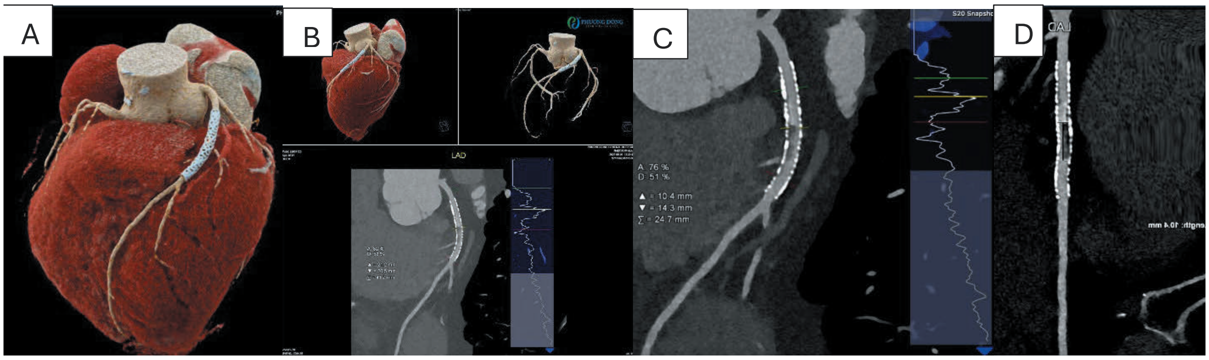


Figure 2. Images from **(A, B, C, D)** coronary photon-counting CT (PCCT) energy-integrating detector (EID) dual-layer CT (DLCT) angiography in 65-year-old man. A stent in VRT **(A, B)** with focal hypodensity in stent are better depicted with PCCT in curved MRP(**C,D**).

3. Myocardial Tissue Characterization

Myocardial disorders involve diverse changes in tissue composition, including fibrosis, edema, and infiltration by fat, iron, or amyloid. Fibrosis may present as diffuse interstitial remodeling or localized replacement scarring. Interstitial fibrosis can be quantified by measuring extracellular volume (ECV); while cardiac MRI has been the reference standard, PCCT provides accurate ECV measurements with lower radiation using either single- or dual-energy protocols. Detection of replacement fibrosis, typically arising from myocardial necrosis, is challenging with conventional CT, but PCCT's ability to differentiate contrast agents enables precise distinction between scarred and normal myocardium, validated by both histology and MRI. Overall, PCCT offers detailed myocardial tissue characterization, enhancing evaluation of cardiac pathology.

4. Epicardial and Pericoronary Adipose Tissue

Epicardial (EAT) and pericoronary (PCAT) fat are biologically active depots that contribute to local inflammation and cardiovascular regulation. CT-based evaluation often considers fat density, thickness, and overall volume, with density being the most informative measure. Recent PCCT research shows that PCAT density increases with higher X-ray energies and is only slightly influenced by contrast agents. Moreover, virtual non-contrast (VNC) images derived from PCCT provide a reliable and reproducible way to measure EAT volume, offering a practical alternative to traditional non-contrast CT scans.

5. Reclassification of Coronary Artery Disease Status Using Photon-counting CT

Ultra-high-resolution PCCT coronary angiography significantly reduces overestimation of stenosis in calcified lesions, leading to downgrading of CAD-RADS scores in many patients. In a 2024 study of 114 patients, use of PCCT with ultrahigh spatial resolution resulted in 54.4% of patients being reclassified to a lower CAD-RADS category compared with standard resolution reconstructions. In a separate intraindividual comparison, PCCT lowered percent diameter stenosis (PDS) values more consistently than conventional EID-CT, and led to CAD-RADS reclassification in 49% of patients. This improved accuracy stems from PCCT's higher spatial resolution and reduction of calcium-blooming and partial-volume artefacts, allowing clearer delineation of the true lumen. Consequently, PCCT may spare many patients from unnecessary invasive procedures or over-treatment based on overestimated stenosis severity.

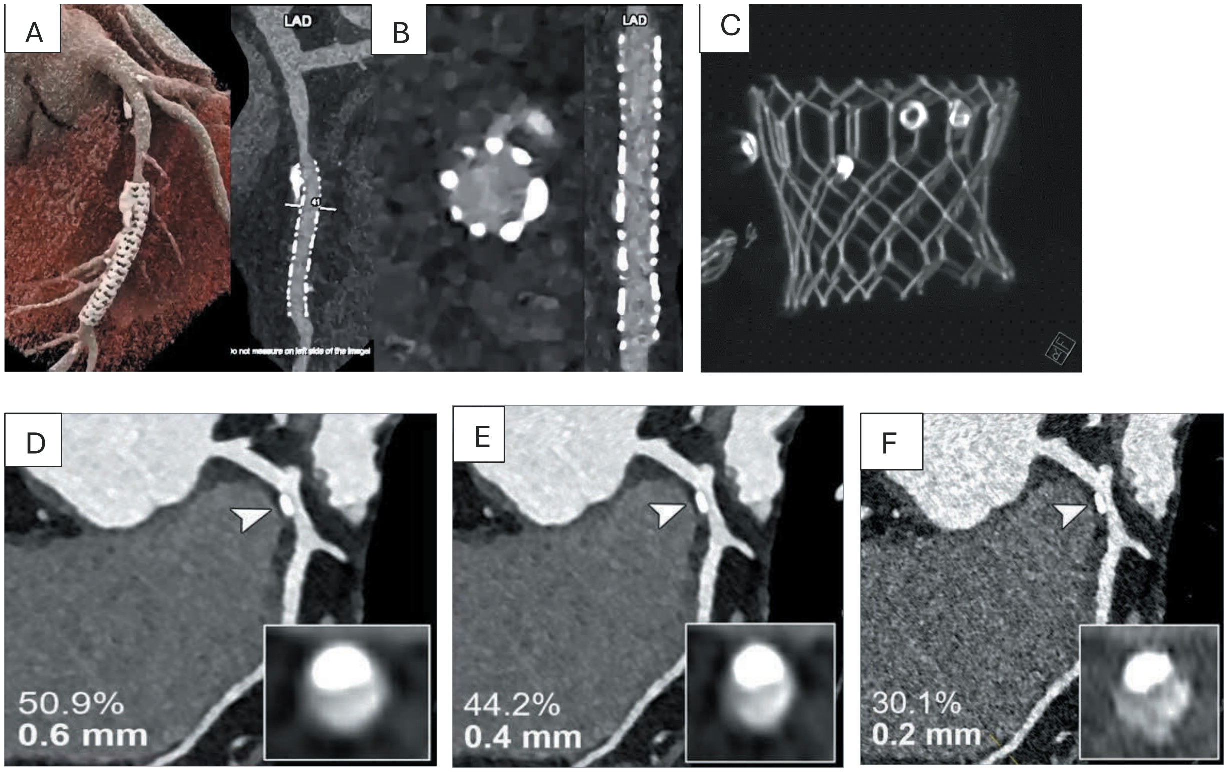


Figure3. High-spatial-resolution dual-energy photon-counting detector (PCD) improves resolution and reduces blooming. **(A,B)** Reduce artefact in stent and show in lumen of stent clearly. **(C)** Image depict structure of aorta valve implant replace without artefact. **(D,E,F)** Improve spatial resolution with reconstruction 0.6mm, 0.4mm, 0.2mm in PCCT.

V. LIMITATIONS AND CHALLENGES.

Despite its technological advancements, photon-counting CT (PCCT) has several limitations. Clinical experience remains limited, with most studies in vitro, ex vivo, or on small patient cohorts, highlighting the need for large-scale prospective trials. High cost and restricted availability of first-generation systems may limit adoption. Technical challenges such as beam-hardening, motion artifacts, and potential misregistration in dual-energy acquisitions persist. Additionally, standardized imaging protocols and post-processing workflows are not fully established, which may affect consistency and comparability across centers.

VI. CONCLUSIONS

Advances in non-invasive cardiovascular imaging over the past decades have been substantial, and the emergence of photon-counting detectors (PCDs) marks a significant leap forward. Photon-counting CT (PCCT) surpasses conventional CT in multiple aspects, offering superior spatial resolution, enhanced signal fidelity, improved contrast, lower electronic noise, reduced radiation exposure, and true multi-energy imaging. These capabilities have proven valuable for both visual characterization of coronary plaques and stents and quantitative evaluation of coronary calcium and epicardial/pericoronary fat. PCDs are poised to expand diagnostic precision, refine cardiovascular risk assessment, and inform optimized therapeutic decision-making.

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Received: 09/12/2025. Assessed: 12/12/2025. Accepted: 22/12/2025.