Review

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Photon-counting Detector CT in Vascular Imaging

Chiara Zanon * , Filippo Cademartiri , Alessandro Toniolo , Costanza Bini , Alberto Clemente , Elda Chiara Colacchio , Giulio Cabrelle , Florinda Mastro , Michele Antonello , Emilio Quaia , Alessia Pepe

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Keywords: Vascular; Photon-counting; CT Angiography; Dose Exposure; Contrast Agents; EVAR; Aorta; Endoleaks

Review

Photon-counting Detector CT in Vascular Imaging

Chiara Zanon [1], Filippo Cademartiri [2], Alessandro Toniolo [1], Costanza Bini [1], Alberto Clemente [2], Elda Chiara Colacchio [3], Giulio Cabrelle [1], Florinda Mastro [4], Michele Antonello [3], Emilio Quaia [1] and Alessia Pepe [1]

[1] Department of Radiology, University of Padua, Padua, Italy.
[2] Department of Radiology, Fondazione Toscana Gabriele Monasterio, Pisa, Italy
[3] Vascular and Endovascular Surgery Section, Department of Cardiac, Thoracic, Vascular Sciences and Public Health, University of Padova, Padova, Italy.
[4] Division of Cardiac Surgery, University of Padova, Padova, Italy.

Abstract: Photon-counting Computed Tomography (PCCT) is a promising cardiovascular-imaging technique. Using detectors that count the number and energy of photons in multiple bins, PCCT offers several advantages over conventional CT, including a higher image quality, reduced contrast agent volume, radiation doses, and artifacts. Although PCCT is well established for cardiac imaging in assessing coronary artery disease, its application in vascular imaging remains limited. This review summarizes the available literature and provides an overview of the current use of PCCT for the diagnosis of vascular conditions. Of the 13 records selected in the initial search, 7 articles were included in the present review: 6 cohort studies and 1 case report. This review synthesized the available literature on PCCT in vascular imaging, focusing mainly on endoleaks detection and characterization after endovascular aneurysm repair (EVAR), contrast dose volume, and radiation exposure reduction, particularly in patients with chronic kidney disease and in those requiring follow-up CT.

Keywords: Vascular; photon-counting; CT angiography; dose exposure; contrast agents; EVAR; aorta; endoleaks

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1. Introduction

Photon-counting CT (PCCT) is an innovative technology that delivers a high image quality and enhanced spatial resolution [1]. Using detectors that count the number and energy of photons in multiple bins, PCCT offers several advantages over conventional CT, including higher spatial and contrast resolutions, reduced artifacts, and lower radiation doses [2]. PCCT has been a well-established technique used in cardiac imaging [3] to assess coronary artery disease (CAD) since its introduction in 2021 [4]. Rajagopal et al. demonstrated that PCCT exhibited superior accuracy in detecting plaque composition in coronary phantoms, compared to standard CT [5]. Although high-resolution PCCT produces higher noise levels, it is less affected by artifacts and blooming caused by stents[5]. However, the application of PCCT to vascular imaging remains limited.

Recent studies have demonstrated the potential of PCCT for detecting and characterizing endoleaks (ELs) after EVAR. PCCT shows endoleak detection capabilities comparable to those of traditional CT, reducing radiation exposure [6,7]. Bicolor K-edge imaging and dual-contrast agent protocols in PCCT allowed accurate characterization of ELs within the thoracic aorta. Furthermore, PCCT low-volume contrast protocols have shown promising results in reducing contrast agent volume without compromising image quality [8]. This is particularly relevant for patients with chronic kidney disease or those requiring frequent follow-up imaging. Virtual monoenergetic images (VMI) reconstructed at optimal energy levels demonstrated improved contrast-to-noise ratios compared with energy-integrating detector (EID) CT, highlighting the potential of PCCT in achieving higher image quality while minimizing contrast-related risks[9]. This review aimed to synthesize the available literature and provide an overview of the current use of PCCT in diagnosing vascular conditions. (Table 1)

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Table 1. Study selected from our research. **Abbreviations:** PCCT, PCCT; VNI = Virtual Non-iodine; TNC =True Non-contrast; CTA, computed tomography angiography; AAA, abdominal aortic aneurysm ; EID = Energy-Integrating Detector; CNR = Contrast to Noise Ratio ; ATVS = Automatic Tube Voltage Selection.

Endoleaks detection	**Gomollon** et al. *Investigative Radiology* 2023 [6]	Retrospective study (110 patients)	• PCCT Endoleak detection and image quality were comparable to biphasic CT. • Reduction of scan phases and radiation exposure.
	Cosset et al. *Diagnostic and Interventional Imaging* 2023 [8]	Phantom experimental study	• PCCT allows characterization of thoracic endoleaks (I-III) in a single acquisition with a biphasic contrast agent (gadolimiun +iodine)
	Dangelmaier et al. *European Radiology* 2018 [8]	Phantom experimental study	• PCCT may replace multiphase CT to capture endoleak dynamics. • PCCT allow distinction from intra-aneurysmatic calcifications. • Reduction of radiation exposure.
Contrast Volume Reduction	**Higashigaito** et al. *Radiology Cardiothoracic Imaging* 2023[9]	Prospective study (100 patients)	• PCCT was associated with higher CNR, low-volume contrast media protocol. • Noninferior image quality compared with EID CT at the same radiation dose.
	Rau et al. *Radiology Case Reports* 2023[10]	Case report (follow-up imaging of AAA)	• PCCT modified scan protocol allowed a significant reduction of contrast agent while preserving diagnostic confidence

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	Decker et al. *Diagnostics* 2022[11]	Retrospective study (20 patients) after EVAR	• PCCT have high image quality and should reduce cumulative radiation dose in patients post-EVAR.
Radiation Dose Reduction	**Euler** et al. *Investigative Radiology* 2022[12]	Prospective study (40 patients)	• High-pitch PCCT with VMI at 40 and 45 keV resulted in increased CNR compared with EID-CT with ATVS at matched radiation dose. • CNR gain of PCCT increased in overweight patients.

2. Photon-Counting Detector – Technical Considerations

Photon-counting Detector (PCD) directly measures the energy of each photon and converts it into an electrical signal. PCD quantifies the number of photons and divides the X-ray energy spectrum into multiple bins. This technology offers several advantages over conventional CT, including improved spatial and contrast resolution, reduced image noise and artifacts, lower radiation exposure, and the ability to perform multi-energy/multiparametric imaging based on the atomic properties of the tissues. This enables the use of different contrast agents and enhances quantitative imaging. [13]PCCT also provides the capability to differentiate between materials based on the energy of incoming photons. Conventional CT uses energy-integrating detectors (EID) with scintillator elements that convert X-rays into visible light, which are then detected by a photodiode[11]. The photodiode indirectly measured the energy of the X-ray photons. Instead, PCCT directly converts X-ray photons into an electrical signal by applying a high voltage to a semiconductor sensor between the cathode and pixelated anode[14]. Each X-ray photon is promptly converted into electron-hole pairs, which move toward the anode under an applied voltage [Fig. 1]. The charge carriers collected by the pixels generate a second electrical signal proportional to the incoming X-ray photons. By setting energy thresholds, PCCT can separate photons that exceed a certain level, thereby reducing the electronic noise[15–17].

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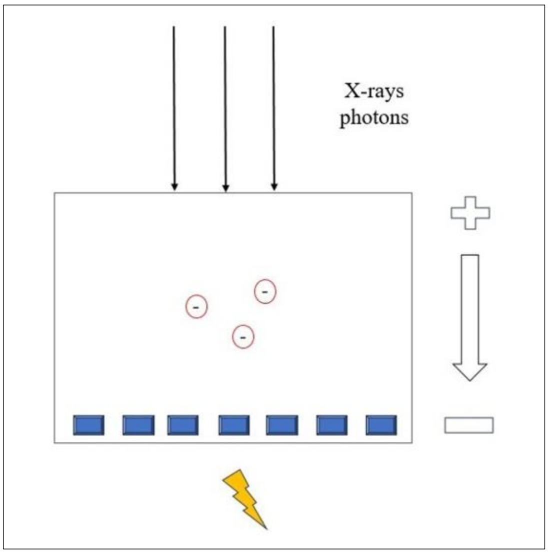

Figure 1. Physical principle of the Photon-counting Detector CT.

3. Photon-Counting CT - Endoleaks Detection

Abdominal aortic aneurysm (AAA) is a bulging of the abdominal aorta with a diameter ≥ 3 cm, affecting 1.6-7.2% of people and occurring in 0.4-0.7% per year in the Western population[18].

The current criteria for elective treatment of AAAs are based on aortic diameter. European Society for Vascular Surgery (ESVS) guidelines suggest elective repair for AAAs ≥ 5.5 cm in men (5 cm in women) or if they show rapid growth (greater than 1 cm/year). Elective repair is also recommended for asymptomatic fusiform AAAs of 5.5 cm in men and 5.0 cm in women.[19]

Endovascular aneurysm repair (EVAR) is a common treatment that involves insertion of a covered stent graft inside the aneurysm[20]. However, EVAR can lead to endoleaks (ELs), which are the persistence of blood flow outside the graft into the aneurysm sac[21], posing the risk of growth and rupture (Table 2). ELs were the most common complication (53% of all complications), with an incidence of 11.7%[22]. Detecting and managing ELs is challenging, and lifelong follow-up is essential, involving regular contrast-enhanced CT scans at specific intervals, including 1, 6, and 12 months after EVAR and yearly thereafter[23,24]. Traditional CT protocols include unenhanced, arterial-phase, and venous/delayed-phase scans to assess the blood vessels and stent grafts[25–27]. However, the drawback of repeated CT scans exposes patients to high radiation doses and kidney toxicity, necessitating the exploration of advanced imaging techniques to mitigate this concern[28].

Table 2. Endoleak classification.

Type 1 Endoleak (EL1)	5-10%	**EL1a**: leakage from proximal attachment site of the graft[29]
		EL1b: leakage from distal attachment site of the graft
		EL1c: leakage from back filling due to an incomplete common iliac arterial occlusion

Type 2 Endoleak (EL2)	10-40%	Backflow of collateral arteries into the aneurysm sac [30]
Type 3 Endoleak (EL3)	2-4%	Stent graft component separation or EL due to a fabric tear [31]
Type 4 Endoleak (EL4)	Almost never seen with new generation grafts	Leakage due to porosity of the graft[32]
Type 5 Endoleak (EL5), *also known as* ***"endotension"***	Diagnosis of exclusion	Expansion of the sac without an apparent EL on imaging[33]

Photon-counting CT (PCCT) has emerged as a promising advanced imaging modality aimed at reducing radiation exposure while improving endoleak detection accuracy. Gomollon et al. [6]conducted a comparative study to evaluate the image quality and endoleak detection between traditional triphasic CT and virtual non-iodine (VNI) images on PCCT in 110 patients after EVAR. Their results demonstrated comparable endoleak detection between the two readout sets with high sensitivity and specificity. This study demonstrated the feasibility and potential of using virtual non-iodine image PCCT as a valuable tool to reduce radiation exposure during endoleak detection. Cosset et al. [8] has explored the potential of bicolor K-edge PCCT in endoleak analysis by employing a dynamic thoracic aorta phantom and creating three types of thoracic endoleaks using iodinated and gadolinium contrast agents. This imaging technique allowed the characterization of endoleaks within the thoracic aorta in a single acquisition combined with a biphasic contrast agent injection. The authors underscored the potential of SPCCT to accurately characterize endoleaks and offer valuable insights for improved diagnosis and management. Dangelmaier et al.[7] explored the feasibility of PCCT with two contrast agents to detect endoleaks following EVAR. Using a specialized abdominal aortic aneurysm phantom filled with a mixture of iodine, gadolinium, and calcium chloride, they were able to differentiate the distribution of these agents, enabling reliable detection of endoleaks. The authors suggested that PCCT has the potential to replace multiphase CT scans, thereby reducing radiation exposure while maintaining the diagnostic accuracy. [Fig 2, 3]

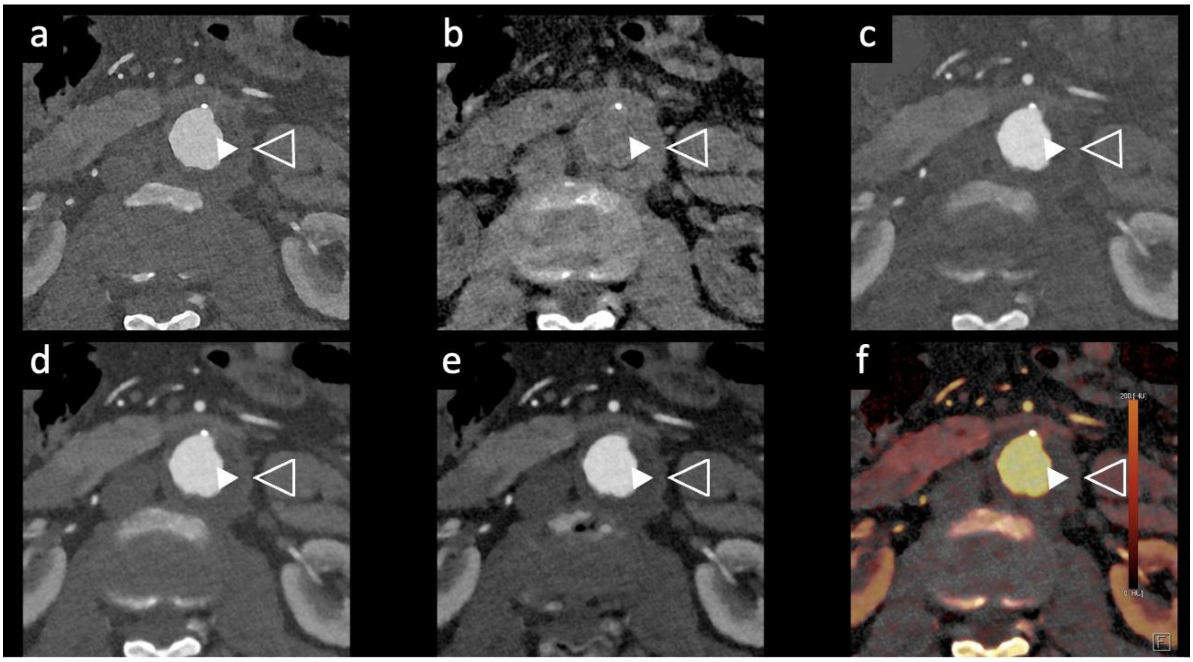

Figure 2. Comparison of image quality of an abdominal aortic aneurysm evaluated with photon-counting CT and standard contrast media (axial images). A thickened aortic wall related to aortitis (between solid and empty arrowhead) and intraluminal thrombotic stratification are visible at the level of the abdominal aortic aneurysm. High Resolution evaluation (Matrix 1024 x 1024) (a); Virtual Non-Contrast VCN (b); Iodine Map (c); 55keV reconstruction (d); Pure Lumen reconstruction (e); Spectral Dual Energy Reconstruction (f).

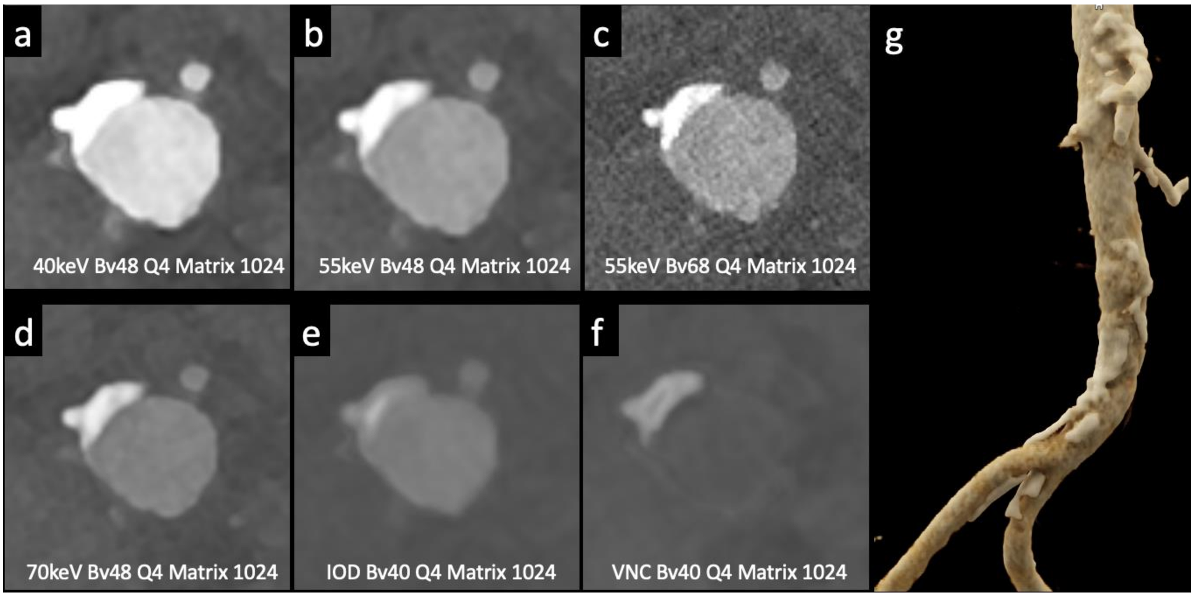

Figure 3. Comparison of image quality with photon-counting CT and standard contrast media. Abdominal aortic lumen with wall calcification axial images. High Resolution images (Matrix 1024 x 1024) with different reconstruction kernels (window level W2000, C700): 40keV Kernel Bv48, Q4 (a); 55keV Kernel Bv48, Q4 (b); 55keV Kernel Bv68, Q4 (c); 70keV Kernel Bv48, Q4 (d); Iodine map reconstruction, kernel Bv40, Q4 (e); Virtual Non-Contrast VCN reconstruction (f); 3D-Cinematic Rendering of the abdominal aorta (g).

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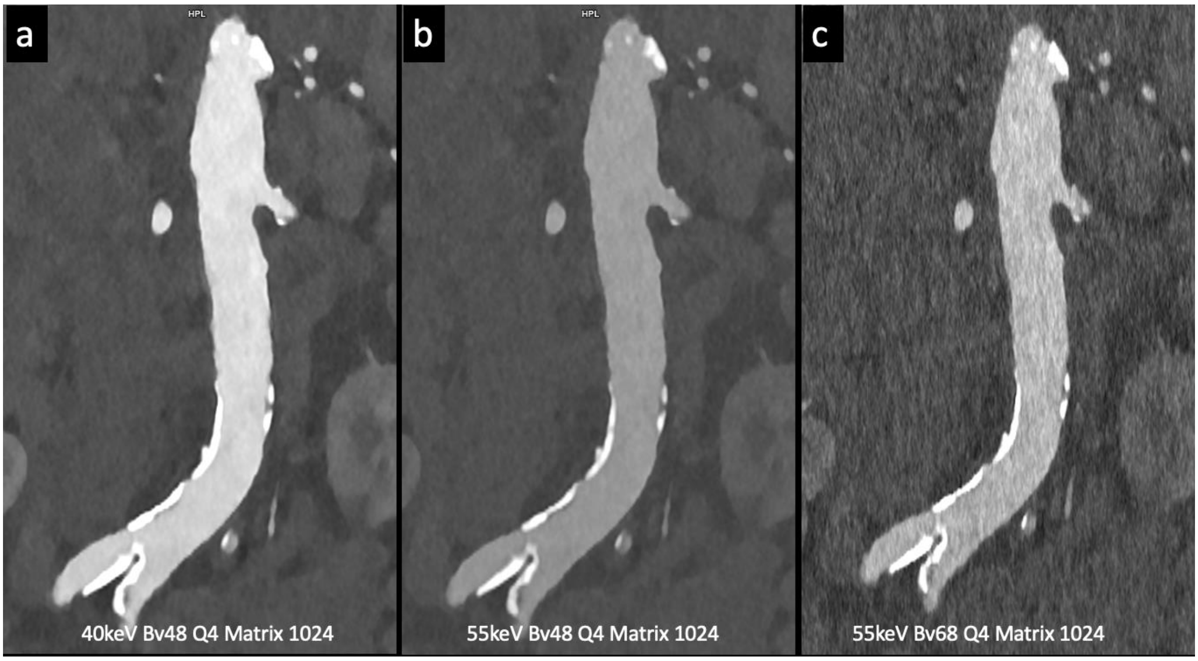
Overall, these studies highlight ongoing advancements in endoleak detection in patients with AAAs undergoing EVAR. photon counting CT hold promise in revolutionizing the management of ELs by reducing radiation exposure while enhancing accuracy.

4. Photon Counting CT Aortic Imaging: Radiation Dose and Contrast Volume Reduction

PCCT has shown significant promise, particularly in patients with chronic kidney disease (CKD) or those requiring follow-up imaging. Several recent studies have demonstrated the potential benefits of PCCT, including excellent image quality, reduced contrast agent volume, and improved contrast-to-noise ratio (CNR). Higashigaito et al. [9] explored a low-volume contrast medium protocol for thoracoabdominal CT angiography using PCCT. This study compared PCCT with previous energy-integrating detector (EID) CT at equal radiation doses. Virtual monoenergetic images (VMI) at 50 keV exhibited the best trade-off between objective and subjective image quality, with a 25% higher CNR than that of EID CT. The low-volume contrast media protocol also reduced the volume of the contrast medium by 25%. These findings suggest that PCCT with a low-volume contrast media protocol achieves superior CNR while maintaining non-inferior image quality compared to EID CT. (Fig 4a-e)



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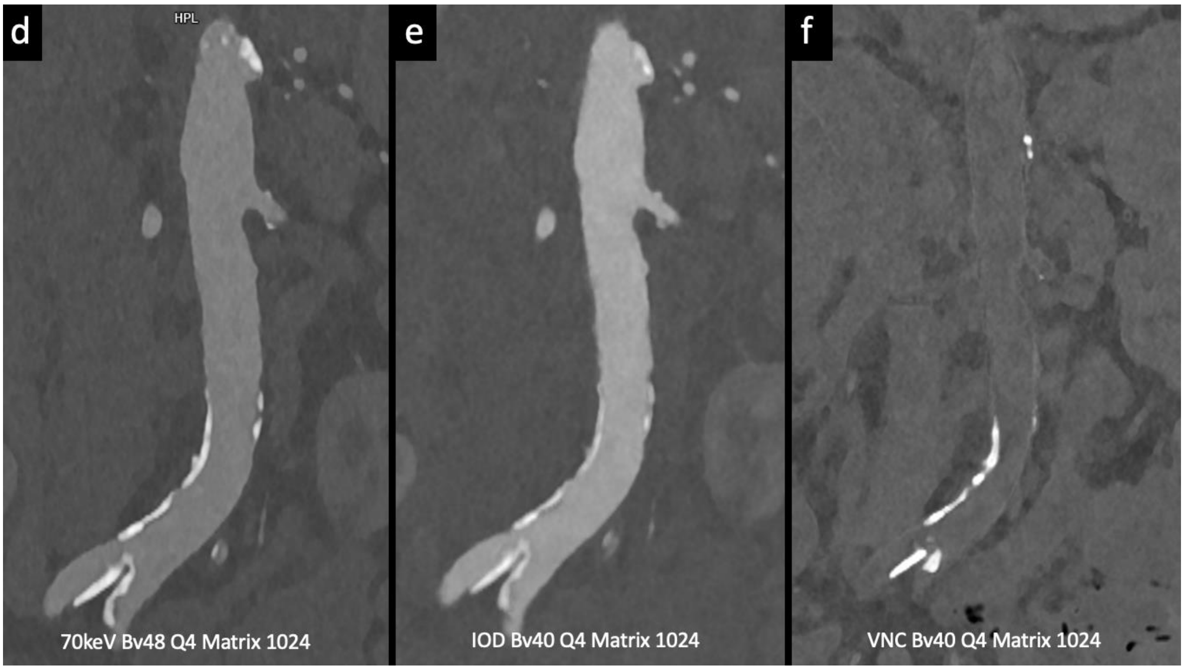

Figure 4. *Comparison of image quality with photon-counting CT and standard contrast media.* Abdominal aortic lumen with wall calcification coronal images. High Resolution images (Matrix 1024 x 1024) with different reconstruction kernels (window level W2000, C700): 40keV Kernel Bv48, Q4 (a); 55keV Kernel Bv48, Q4 (b); 55keV Kernel Bv68, Q4 (c). 70keV Kernel Bv48, Q4 (d); Iodine map reconstruction, kernel Bv40, Q4 (e); Virtual Non Contrast VCN reconstruction (f).

Decker et al. [11]evaluated the potential of virtual non-contrast reconstructions using a calcium-preserving algorithm (VNCPC) compared with the standard algorithm (VNCConv) in patients after EVAR. This study demonstrated that VNCPC reconstructions exhibit excellent image quality with complete contrast removal and minimal erroneous subtractions, making them a potential alternative to true non-contrast acquisitions. Euler et al. [12] compared the image quality of high-pitch PCCT angiography with that of conventional CT at equal radiation doses. PCCT with virtual monoenergetic images (VMI) at 40 keV and 45 keV demonstrated a significantly increased CNR compared to traditional CT at matched radiation doses. Subjective image quality ratings revealed slightly higher subjective noise for VMI at 40 keV and 45 keV. However, this study suggests that VMI at 45–50 keV offers a favorable balance between the objective and subjective image quality.

Rau et al. [10]presented a case study of a patient with incipient chronic renal failure who required contrast-enhanced aortoiliac CT angiography for follow-up imaging of an asymptomatic abdominal aortic aneurysm (AAA) Utilizing a PCCT protocol with dual-source spectral image acquisition and dynamic monochromatic reconstruction near the K-edge of iodine, this study demonstrated a significantly reduced required contrast agent while preserving the diagnostic confidence. (Fig 5)

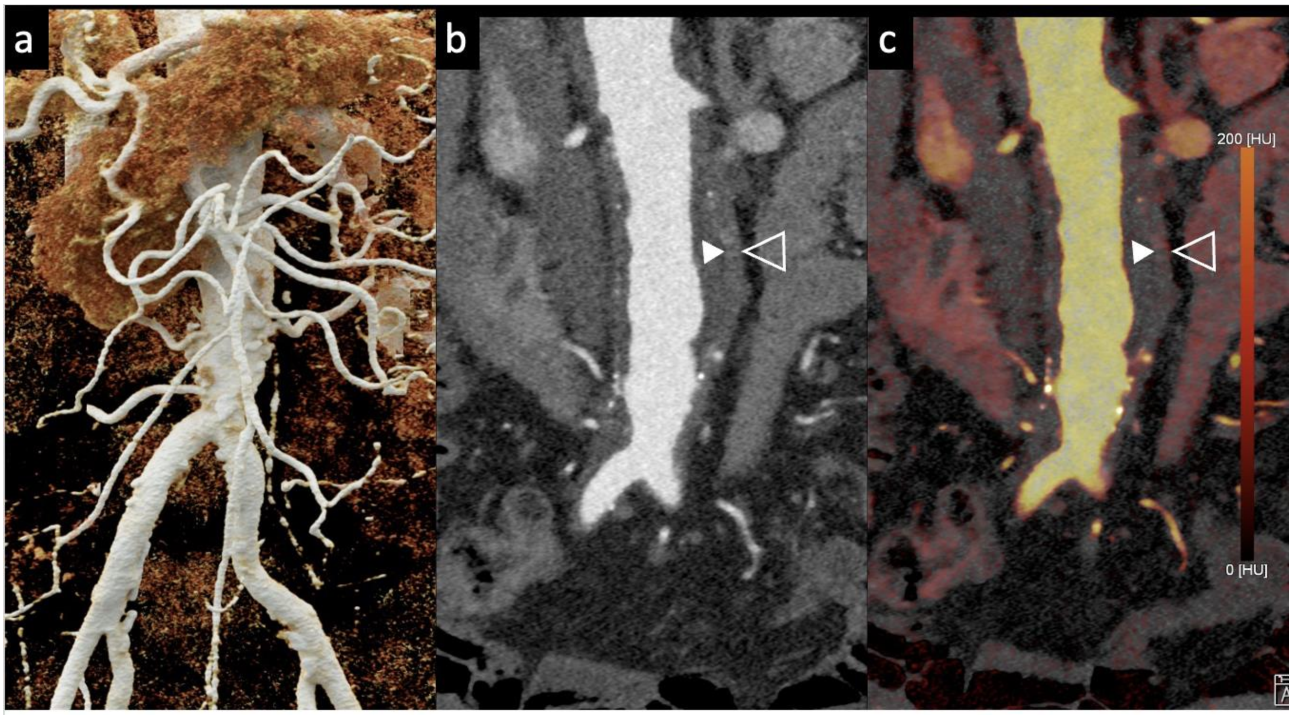

Figure 5. aortic angiographic evaluation of the abdominal aortic aneurysm evaluated with photon-counting CT and standard contrast media (the same example of Fig.1, coronal view). 3D-Volume Rendering representation (a); High Resolution coronal evaluation, 55keV, Kernel Bv68 Q4 Matrix 1024 (b); Spectral Dual Energy coronal Reconstruction (c).

In conclusion, these studies demonstrated that PCCT offers advantages such as improved CNR, reduced contrast agent volume, and enhanced image quality, making it an attractive option for patients with CDK or those requiring follow-up imaging.

5. Conclusions and Future Directions

This review demonstrates the potential of PCCT in cardiovascular imaging. PCCT presents higher spatial and contrast resolutions than conventional CT, allowing endoleak detection with less radiation after EVAR. PCCT can also characterize endoleaks in the thoracic aorta with bicolor K-edge imaging and dual-contrast agents and reduce contrast agent volumes with low-volume protocols, benefiting patients with CKD or those needing frequent CT imaging. Furthermore, PCCT can improve CNR with VIM at optimal energy levels, thereby achieving a higher image quality and lower contrast-related risks. These advancements in imaging techniques hold promise for optimizing patient care and diagnosis for the management of aortic pathologies. Further research and extensive studies are needed to confirm these results and explore the full potential of PCCT in vascular imaging.

Key Points

- Compared with conventional CT, PCCT has potential advantages in cardiovascular imaging, including improved image quality, reduced artifacts, and lower radiation doses.
- PCCT can improve endoleak detection and characterization after EVAR with reduced radiation exposure using bicolor K-edge imaging and dual contrast agents.
- Low-volume protocols in PCCT can minimize the contrast agent volume, benefiting patients with CKD and those requiring frequent CT imaging.
- Virtual monoenergetic images at optimal energy levels improve contrast-to-noise ratios, resulting in higher image quality and reduced contrast-related risk.

Glossary

AAA	abdominal aortic aneurysm
CAD	coronary artery disease
CNR	contrast-to-noise ratio
CTA	computed tomography angiography
EID	energy-integrating detector
ELs	Endoleaks
EVAR	Endovascular Aortic Repair
PCCT	Photon-Counting CT PCD = Photon-Counting Detector
TNC	True Non-Contrast; VMI =Virtual monoenergetic images
VNI	Virtual Non-Iodine image

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