Photon-counting computed tomography – clinical application in oncological, cardiovascular, and pediatric radiology

Photon-Counting Computertomographie – klinische Anwendungen in der onkologischen, kardiovaskulären und pädiatrischen Radiologie

Authors
Florian Hagen[1], Martin Soschynski[2], Meike Weis[3], Muhammad Taha Hagar[2], Patrick Krumm[1], Isabelle Ayx[3], Jana Taron[2], Tobias Krauss[2], Manuel Hein[4], Philipp Ruile[4], Constantin von zur Muehlen[4], Christopher L. Schlett[2], Jakob Neubauer[2], Ilias Tsiflikas[1], Maximilian Frederik Russe[2], Philipp Arnold[2], Sebastian Faby[5], Matthias F. Froelich[3], Jakob Weiß[2], Thomas Stein[2], Daniel Overhoff[3], Malte Bongers[1], Konstantin Nikolaou[1], Stefan O. Schönberg[3], Fabian Bamberg[2], Marius Horger[1]

Affiliations
1 Department of Diagnostic and Interventional Radiology, University Hospital Tübingen, Tübingen, Germany
2 Department of Diagnostic and Interventional Radiology, Medical Center – University of Freiburg, Faculty of Medicine, University of Freiburg, Freiburg, Germany
3 Department of Radiology and Nuclear Medicine, University Medical Center Mannheim, Medical Faculty Mannheim, University of Heidelberg, Mannheim, Germany
4 Department of Cardiology & Angiology, University Heart Center Freiburg – Bad Krozingen, University Hospital Freiburg, Faculty of medicine, 79106 Freiburg, Germany
5 Computed Tomography, Siemens Healthcare GmbH, Forchheim, Germany

Key words
photon-counting, computed tomography, diagnostic imaging, photon-counting detector, spectral computed tomography, energy-integrating detector

received 03.04.2023
accepted 04.06.2023
published online 04.10.2023

Bibliography
Fortschr Röntgenstr 2024; 196: 25–34
DOI 10.1055/a-2119-5802
ISSN 1438-9029

Georg Thieme Verlag KG, Rüdigerstraße 14, 70469 Stuttgart, Germany

Correspondence
Herr Dr. Florian Hagen
Department of Diagnostic and Interventional Radiology, University Hospital of Tübingen, Hoppe-Seyler-Straße 3, 72076 Tübingen, Germany
Tel.: +49/70 71/2 96 86 22
florian.hagen@med.uni-tuebingen.de

ABSTRACT

Background Photon-counting detector computed tomography (PCD-CT) is a promising new technology with the potential to fundamentally change workflows in the daily routine and provide new quantitative imaging information to improve clinical decision-making and patient management.

Method The contents of this review are based on an unrestricted literature search of PubMed and Google Scholar using the search terms "photon-counting CT", "photon-counting detector", "spectral CT", "computed tomography" as well as on the authors' own experience.

Results The fundamental difference with respect to the currently established energy-integrating CT detectors is that PCD-CT allows for the counting of every single photon at the detector level. Based on the identified literature, PCD-CT phantom measurements and initial clinical studies have demonstrated that the new technology allows for improved spatial resolution, reduced image noise, and new possibilities for advanced quantitative image postprocessing.

Conclusion For clinical practice, the potential benefits include fewer beam hardening artifacts, a radiation dose reduction, and the use of new or combinations of contrast agents. In particular, critical patient groups such as oncological, cardiovascular, lung, and head & neck as well as pediatric patient collectives benefit from the clinical advantages.

Key Points:
- Photon-counting computed tomography (PCD-CT) is being used for the first time in routine clinical practice, enabling a significant dose reduction in critical patient populations such as oncology, cardiology, and pediatrics.
- Compared to conventional CT, PCD-CT enables a reduction in electronic image noise.
- Due to the spectral data sets, PCD-CT enables fully comprehensive post-processing applications.

Citation Format

- Hagen F, Soschynski M, Weis M et al. Photon-counting computed tomography – clinical application in oncological, cardiovascular, and pediatric radiology. Fortschr Röntgenstr 2024; 196: 25–34

ZUSAMMENFASSUNG

Hintergrund Die Technologie der photonenzählenden Computertomografie (PCD-CT) hat Einzug in die klinische Praxis gehalten und wird erstmals in der klinischen Routine eingesetzt. Während die ersten Erfahrungen mit diesem Verfahren in bestimmten Patientengruppen gemacht werden, hat die Technologie das Potenzial, bestehende Arbeitsabläufe zu verändern und neue Möglichkeiten in der diagnostischen Bildgebung zu öffnen.

Methode Der Inhalt dieser Übersicht basiert auf einer uneingeschränkten Literaturrecherche in den Datenbanken PubMed und Google Scholar unter der Verwendung der Suchwörter „Photon-Counting CT", „Photon-Counting detector", „spectral CT", „Computed Tomography" sowie auf den Erfahrungen der Autoren.

Ergebnisse Der grundlegende Unterschied zu den derzeit etablierten energieintegrierenden CT-Detektoren besteht darin, dass die PCD-CT die Zählung jedes einzelnen Photons auf Detektorebene ermöglicht. Basierend auf der identifizierten Literatur haben PCD-CT-Phantommessungen und erste klinische Studien gezeigt, dass die neue Technologie eine verbesserte räumliche Auflösung, ein reduziertes Bildrauschen, Potenzial zur erheblichen Dosisreduktion und neue Möglichkeiten für quantitative Bildnachbearbeitung ermöglicht.

Schlussfolgerung PCD-CT ist eine neuartige, innovative Technologie mit dem Potenzial, viele der derzeitigen Einschränkungen der CT-Bildgebung in der klinischen Praxis zu überwinden. Insbesondere kritische Patientengruppen, wie onkologische, kardiovaskuläre, pneumologische als auch pädiatrische Patientenkollektive profitieren von den klinischen Vorteilen.

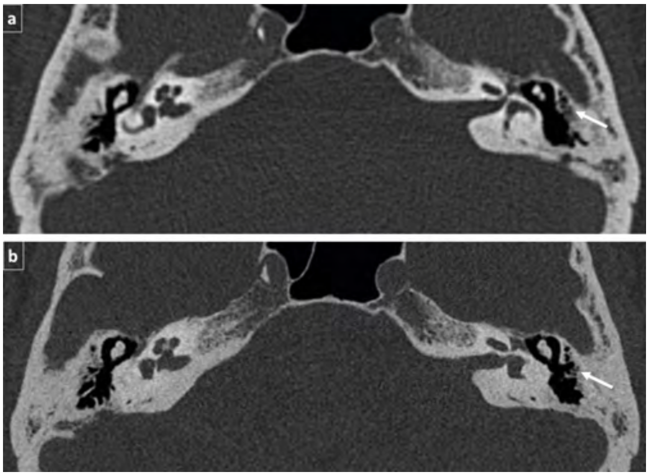
Introduction

Computed tomography (CT) remains one of the most commonly used imaging modalities in the examination of oncological, pneumological, skeletal, and cardiovascular diseases, and is also specifically used in certain pediatric clinical pictures. However, a major limitation of CT imaging remains the associated radiation exposure, which particularly affects the following three subgroups: first, oncological patients who are repeatedly referred for CT follow-up; second, cardiovascular patients at a younger age who receive coronary CT angiography to screen for coronary heart disease, especially using retrospective gating; and third, pediatric patients who are more sensitive to the effects of ionizing radiation as their bodies undergo rapid cell division [1–3]. With the introduction of the photon counting detector (PCD) CT, it should now be possible to significantly reduce the dose while maintaining comparable or even improved image quality. [4, 5] Other significant technical advantages over conventional energy-integrating detectors (EID) are the improved spatial resolution and the ability to record the energy of individual photons, thus performing a CT by means of a "multi-energy" technique. These technical advantages result directly from the new detector technology. A PCD is based on a semiconductor material (usually cadmium telluride) that directly converts each incoming X-ray photon into an electrical signal, whereby the level of the current pulse generated by the X-ray photon is proportional to the energy of the same [6]. Therefore, the PCD is also referred to as a direct-converting detector. This bypasses the intermediate step of conversion required for EID, in which X-ray photons must first be converted into visible light in a scintillator and then into an electrical signal in a photodiode [6]. Therefore, the otherwise necessary reflective "septa" between the individual detector cells are also obsolete, since no light photons need to be bundled onto a detector cell. This achieves a higher resolution in the PCD CT because, on the one hand, a higher cell density on the PCD is possible and, on the other hand, the energy proportion that would otherwise reach the septa and thus lack information is lost [6, 7]. In addition, a flatter design of the photon counting detector is also possible. Another advantage of photon counting is the elimination of electron noise, as only integers of photons are read. The resulting specific advantages are discussed below in the subsections on oncology, cardiovascular radiology, and pediatric radiology.

Oncological imaging

Head and neck area

The challenge with CT of the head/neck region is to achieve an optimal balance between the applied radiation dose (to minimize radiation exposure of the radiation-sensitive organs in the midface) and the detailed image quality to be achieved. [8] Fine structures, such as the paranasal sinuses or the skull base, in particular, benefit from the higher image resolution of the PCD CT, as this enables better visualization of both traumatic complications of the inner/middle ear and subtle bone infiltration caused by inflammation or tumors (see ▶ **Fig. 1**) [8]. This high image resolution is also crucial for tumors of the larynx and (nasal) pharynx, which are sometimes difficult to visualize. In particular, the assessment of whether there is infiltration of the laryngeal cartilage, tongue bone, or even the skull base is crucial here, and is made easier by the higher spatial resolution of the PCD CT [9]. Also, the combination of the higher resolution of the PCD CT with already validated bone subtraction algorithms allows for the assessment of the possible involvement of the skull base [10]. In addition, the potential connection to the cervical vessels, which are superimposed, for example, by high-contrast artifacts in the form of dental implants, can be minimized. As with the Dual-Energy EID CT, the calculation of virtually monoenergetic (VMI) image

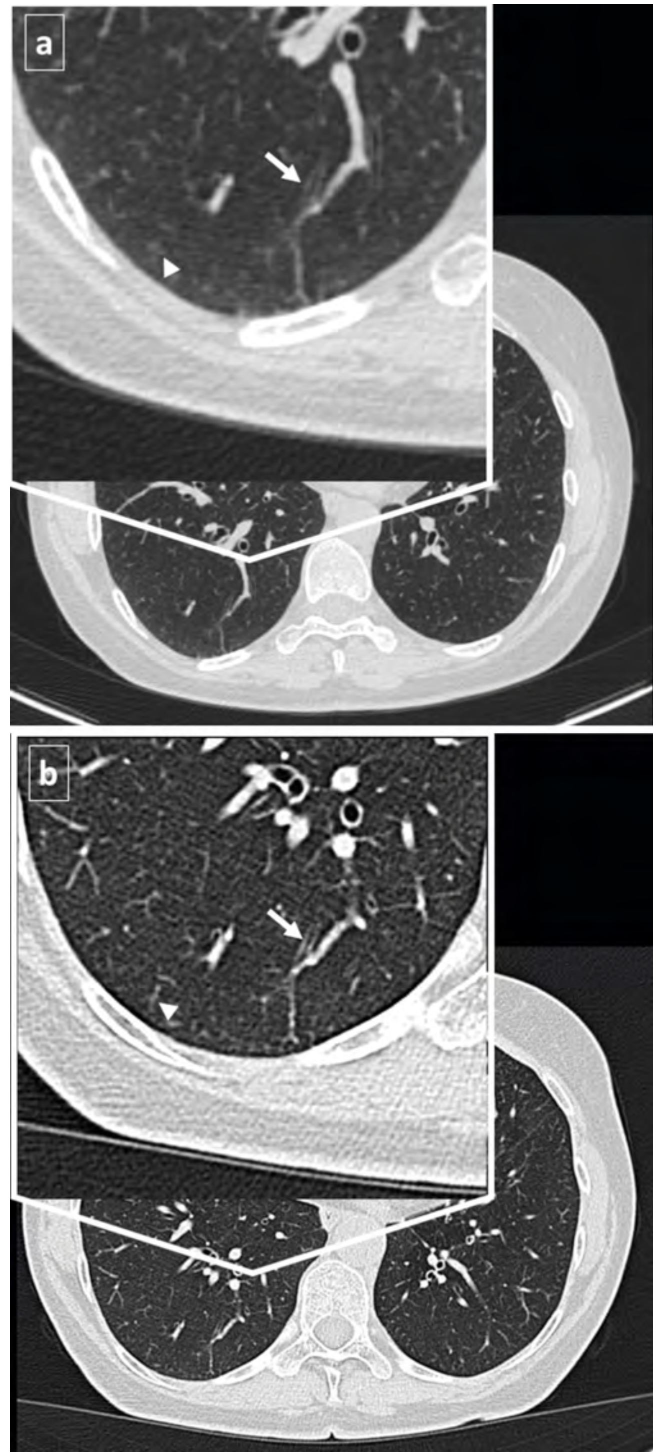


▶ **Fig. 1** 76-year-old patient, preoperative status prior to implantation of a cochlear implant. **a** Ultra-high-resolution single-source examination of the petrous bone (Siemens SOMATOM Definition AS + 120 kV); **b** Ultra-high-resolution PCD-CT scan (Siemens Naeotom Alpha 120 kV) of the petrous bone. In comparison, the lower noise of the PCD-CT images and also the higher resolution of the trabecular structures are particularly striking. Instead of a slightly blurred spongiosa architecture, highly detailed contours, e.g., in the middle ear, are seen. Window width: 3514 HU, center of the window: 927 HU.

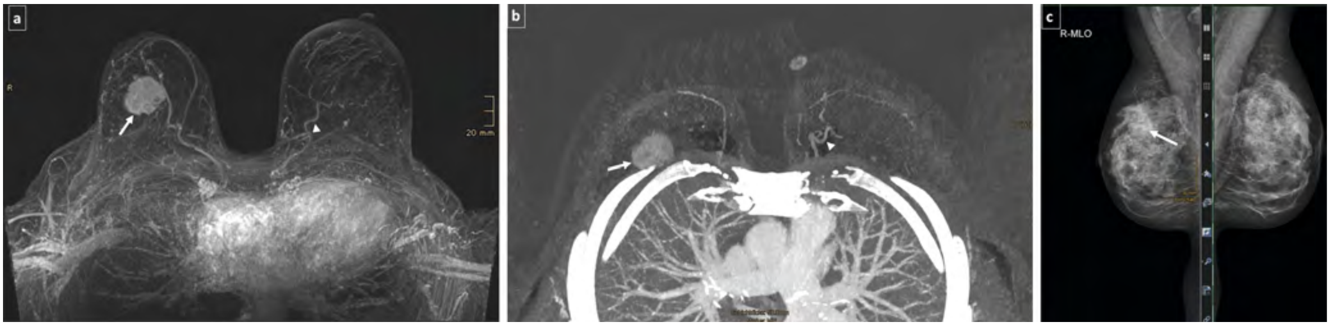
datasets allows either a high tissue contrast due to an increased iodine signal (low keV) or the reduction of beam hardening artifacts (high keV) [11]. Furthermore, the PCD CT compared to the EID CT allows a higher tissue contrast between gray and white matter, which, in combination with the reduced image noise, can be crucial, especially in the diagnosis of acute stroke (1–3 hours) [12].

Chest and breast

The spectral datasets generated by the PCD CT can be divided into different energy areas by defining different energy threshold values. Through this subdivision, the photons that reach the detector can be sorted into so-called "bins" depending on the energy level [13]. In chest diagnostics, this bundling of low-energy photons after contrast media administration allows high tissue contrast, both in the breast parenchyma [14]and in the pulmonary parenchyma [15]. This enables even small structures, such as pulmonary nodules, to be more clearly displayed in the marginal area with the high-resolution PCD CT, and, in terms of their size over time, to be more comparable [16, 17]. The overall lower noise level as well as the higher spatial resolution of the native PCD CT also lead to improved detailed visualization of peripheral lung structures, such as thickened bronchial walls (see ▶ **Fig. 2**), ground-glass-like changes, and the "tree-in-bud"/mosaic pattern, which are all crucial for the diagnosis of interstitial lung disease [18]. Milos et al. show that using a suitable reconstruction kernel (Bl64), bronchial branches in the peripheral lung regions, the lobular fissures, and also the bronchial walls can be better visualized in ultra-high-resolution (UHR) PCD CT without affecting the vascular noise and the detail acuity of pulmonary round foci [19]. To further improve pulmonary image quality, it is possible to generate virtual monoenergetic (VMI) image datasets. This, for example, makes pulmonary emphysema best visible between 60 and 70 keV [20]. In addition, the vascular contrast can be significantly



▶ **Fig. 2** 65-year-old patient with chronic bronchitis. **a** EID-CT (Siemens SOMATOM Definition AS+ 120 kV), **b** PCD-CT (Siemens Naeotom Alpha 120 kV). In particular, the bronchial walls are displayed significantly more clearly (long arrow). The branching of the peripheral vessels directly at the pleura (see arrowhead) is more detailed on PCD-CT than EID-CT. Window width: 1500 HU, center of the window: -500 HU, 1-mm slice thickness.



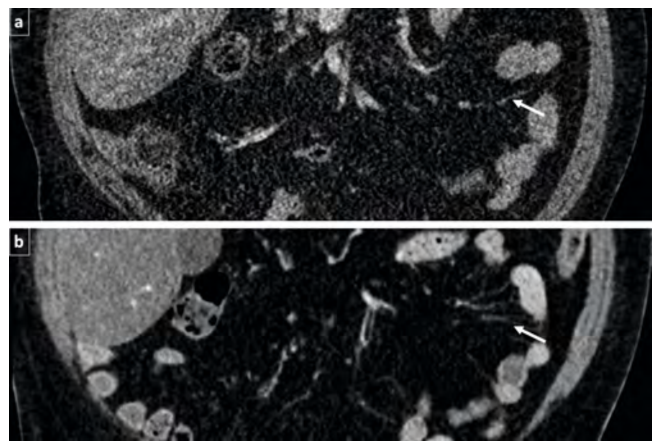
▶ **Fig. 3** Initial diagnosis of a mass suspicious for malignancy in the upper inner and upper outer quadrants of the right breast (arrows **a-c**). MIP of an MRI scan showing the suspicious mass (**a**). Corresponding 5-mm MIP of the PCD-CT scan (**b**). Note the fine vascular structures that are visible both on the MRI scan and the PCD-CT scan of the upper inner quadrant of the left breast (arrowhead).

increased at less than 60 keV in the contrast-enhanced chest PCD CT, but this carries the disadvantage of higher noise levels [20, 21]. The generation of VMI image datasets also significantly reduces beam hardening and metal artifacts at 90 keV [22]and thus allows a better assessment of tumor manifestations and metastases near the artifacts. In addition, it is possible to reduce the radiation dose by 66 % compared to the EID CT without compromising image quality and diagnostic certainty, which is important, for example, in the assessment of interstitial lung disease (ILD) [23, 24]. Another advantage is the ability to create virtual contrast media-free images (VNC), which allows better quantification of pulmonary emphysema, as the higher parenchymal density in contrast-enhanced CT can lead to underestimation of the emphysema [25].

Imaging of the female breast also significantly benefits from PCD CT. Due to the higher spatial resolution, it is possible to image focal findings [14] and vascular structures in good quality (see ▶ **Fig. 3**). In addition, by post-processing the image data, iodine maps could be reconstructed, which allow conclusions to be drawn about contrast media uptake within the mammary gland tissue. In this way, breast carcinomas can be better recognized, assessed, and characterized in terms of their extent, similar to what has already been reported for the Dual-Energy EID CT [14, 26, 27]. Finally, no compression of the breast is required compared to mammography and, accordingly, a significantly higher level of patient comfort is provided [28]. Even though mammography is still recognized as the standard diagnosis in breast imaging, PCD CT still offers promising new possibilities (e. g., in staging examinations) that should be evaluated in further clinical trials.

Abdomen and pelvis

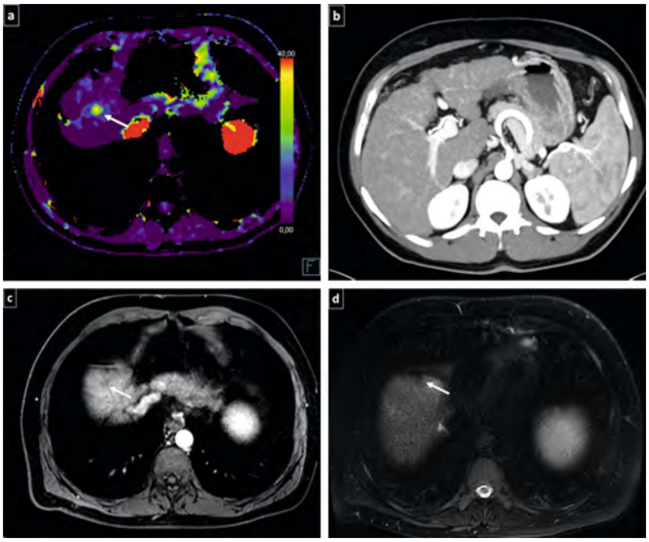
Abdominopelvic imaging is largely influenced by the higher fat percentage in this area of the body, which is often constitution-related, as this requires an increased radiation dose. The PCD scanner improves image quality while reducing image noise and photon starvation artifacts, especially in obese patients. Several studies have reported that with increasing BMI, the signal-to-noise ratio of various abdominal structures decreases less strongly in PCD CT, and noise increases less strongly than in EID CT (see ▶ **Fig. 4**) [4, 29, 30]. Further potential improvement with regard to image quality lies in the various iterative reconstruction stages



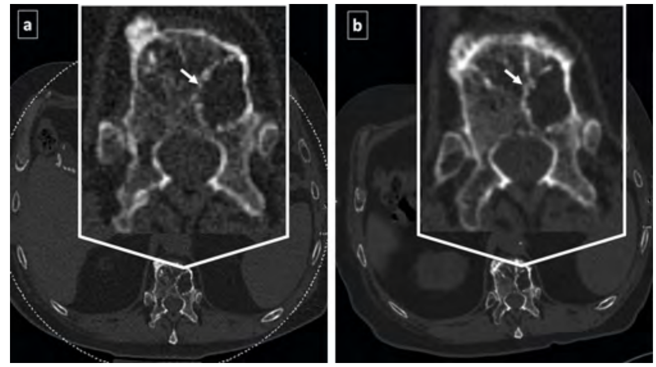
▶ **Fig. 4** 69-year-old patient with a BMI of 43. **a** Single-source EID-CT with low contrast and reduced visualization of the mesenteric veins (white arrows). **b** PCD-CT with high contrast and improved visualization of the mesenteric veins. Observe the lower image noise of the PCD-CT images and the higher vascular contrast. Window width: 342 HU, center of the window: 56 HU.

(quantum iterative reconstruction, QIR), which can be selected in stages 1 to 4 and achieve increasing noise suppression with increasing stages, used for optimal detection of liver lesions [31].

In addition to the absolute dose reduction per scan due to higher dose efficiency, PCD CT offers the theoretical possibility of reducing the required number of total scans per examination by simultaneous application of several contrast media [9]. Several promising studies have shown that it is possible to separate two fundamentally different contrast media, which were administered with a certain delay or in different ways, in one scan [32–34]. For example, in an ex vivo phantom, the simultaneous use of rectal and intravenous contrast media enabled the differentiation between simple polyps and bowel contents [35]. In addition, an animal model study using gadolinium-based and iodine-containing contrast media to differentiate hepatic arteries and veins in a biphasic single scan using PCD CT shows promising results and paves the way for correct differentiation of hepatic lesions based on their characteristic contrast uptake and washout at each phase [33, 36]. Another technique for characterizing liver lesions is so-called volume perfusion CT (VP CT). This is already used as an



▶ **Fig. 5** 63-year-old man with an HCC. **a** Volume perfusion PCD-CT scan showing a hyperarterialized liver lesion in segment 8 (white arrows). **b** Dynamic perfusion PCD-CT scan with visualization of the arterial and venous vessels in an MIP using 3D-angio post-processing software. **c, d** Corresponding MRI images show the liver lesion with less contrast enhancement (C = T1 Vibe DIXON DCE arterial phase axial, d T2 Blade FS axial).



▶ **Fig. 6** 73-year-old patient with stable multiple myeloma with pronounced lytic changes of the entire axial skeleton. **a** DSCT Siemens Somatom Definition Flash. **b**) PCD-CT Siemens Naeotom Alpha. Note the significantly lower noise on the PCD-CT scan and the significantly better edge definition of the lytic bone structure in L5. The PCD-CT scan allowed a dose reduction of 27% (CTDIvol 11,37mGy vs. 8,19mGy). Window width: 1500 HU, center of the window: 450 HU.

alternative to liver MRI on EID CT, as it enables the degree of arterialization of hepatocellular carcinomas (HCCs) and other tumors to be quantified [37]. Volume perfusion CT of the liver combined with the higher resolution and lower radiation exposure of PCD CT promise encouraging results and may possibly lead to changes in the guidelines (see ▶ **Fig. 5**). In addition, PCD CT makes it easier to assess the liver parenchyma, as the spectral information can be used to generate VNC images that come very close to the true contrast media-free (native) datasets. In this way, hepatic steatosis can be detected with a sensitivity of 94 % from VNC images on the PCD CT [38].

With regard to the kidneys, on the one hand, the energy discrimination between the grouped photon energies provides information about the elementary composition of particularly small (< 3 mm) renal stones. On the other hand, compared to EID CT, PCD CT also enables better detection of such small concretions [39].

Bone and bone marrow

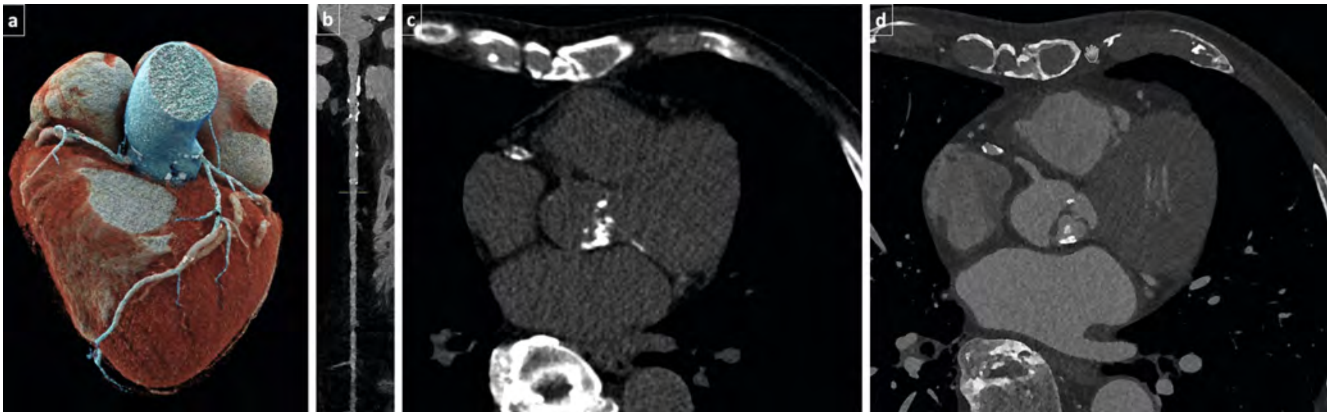
PCD CT provides a much better representation of the trabecular bone microstructure, which is also a primary effect of the improved spatial resolution. On the one hand, osteoporotic patients benefit from this, since bone strength can be determined via bone mineral density and fractures can also be better visualized [40]. On the other hand, cancer patients benefit from this, since osseous metastases and their courses can be presented in much more detail (see ▶ **Fig. 6**). As in other parts of the body, noise reduction is achieved by using ultra-high-resolution PCD CT image datasets [40], which enables more detailed visualization of bony structures and thus better detection of metastases and fractures [41–43]. In addition, the improved visualization is also associated with a significant reduction in radiation dose in PCD CT examinations of the extremities of up to 49 % in the wrist structures [44, 45]. Promising results have already been achieved with visualization of cartilage in patients with knee osteoarthritis, which have the potential to improve the diagnostic significance of PCT CT in joint diseases [46]. PCD CT also makes it possible to distinguish between calcium pyrophosphate and hydroxylapatite deposits in the joint cartilage. This could provide new insights into the pathogenesis of rheumatic diseases with crystal deposits [47]. In addition, multi-energy post-processing allows the quantification of gout deposits and the creation of virtual non-calcium images (VNCa) to visualize bone marrow edema [48]. Similar to Dual-Energy EID CT, visualization of bone marrow edema is intended to make it easier to detect subtle fractures and to assess the fracture value [49].

Cardiovascular imaging

Cardiovascular imaging benefits from PCD CT due to three major technical advantages over traditional EID CT: Firstly, an improved spatial resolution, secondly, an improved signal-to-noise ratio, and thirdly, the ability to record all the spectral information of the photons.

Improved spatial resolution of cardiovascular structures

The segmentation and characterization of coronary plaques and the vascular lumen is limited by the spatial triggering of the current conventional EID CT [50–53]. In particular, the quantification of coronary stenosis in calcified plaques is limited by blooming artifacts of coronary alkaline deposits, which depend primarily on spatial resolution [54]. For this reason, coronary stenosis is often overestimated in clinical practice [52]. In phantom studies, it has already been confirmed that the improved spatial resolution of PCD CT compared to EID CT particularly depicts non-calcified and lipid-rich plaques more accurately [55, 56]. Similarly, compar-



▶ **Fig. 7** Ultra-high-resolution (UHR) PDC-CT scan (Siemens Naeotom Alpha 120 kV) of an 88-year-old patient for planning prior to transcatheter aortic valve implantation (TAVI). In addition to visualization of the aortic valve, diagnostic visualization of the coronary arteries and thus exclusion of an obstructive coronary artery disease is possible in spite of pronounced coronary calcifications with an Agatston score of 1281. **a** Three-dimensional visualization with the cinematic rendering technique; **b** Stretched MPR of the left anterior descending artery; **c** Non-contrast coronary calcification CT, axial 2.0-mm slices and reconstruction using soft-tissue kernel (Qr36); **d** UHR-CT with contrast agent, axial 0.2-mm slices and reconstruction using vascular kernel (Bv56, Q4).

ed to EID scanners, the high-resolution PCD CT improves the visualization of the vascular lumen in the stent and thus the assessment of relevant in-stent stenoses [57–59].

In this context, it is worth highlighting the "ultra-high-resolution" CT coronary angiography on PCD CTs that has recently become available, as this also allows the reduction of blooming artifacts in calcified plaques [60]. An initial study showed very good imaging of the vascular lumen and coronary plaques in UHR mode, especially in the case of reconstruction with hard pliable nuclei [61]. ▶ **Fig. 7a–d** show a CT coronary angiography in UHR mode with very good visualization of the lumen on a PCD scanner. It should be emphasized here that UHR acquisition with the same target acuity (same convolution kernel, etc.) as "normal" acquisition does not a priori require an additional dose, but nevertheless allows the benefits of intoxication reduction. Only the combined use of very sharp kernels and noise minimization is associated with an increased radiation dose. However, the gain in information justifies the use of a higher radiation dose, particularly in patients with a higher pre-test probability of stenosing coronary disease.

In theory, the CT-based fractional flow reserve (CT FFR) should also benefit from the higher spatial resolution [62], as the accuracy depends on the precise segmentation of the coronary vessels.

Improved signal-to-noise ratio of cardiovascular structures

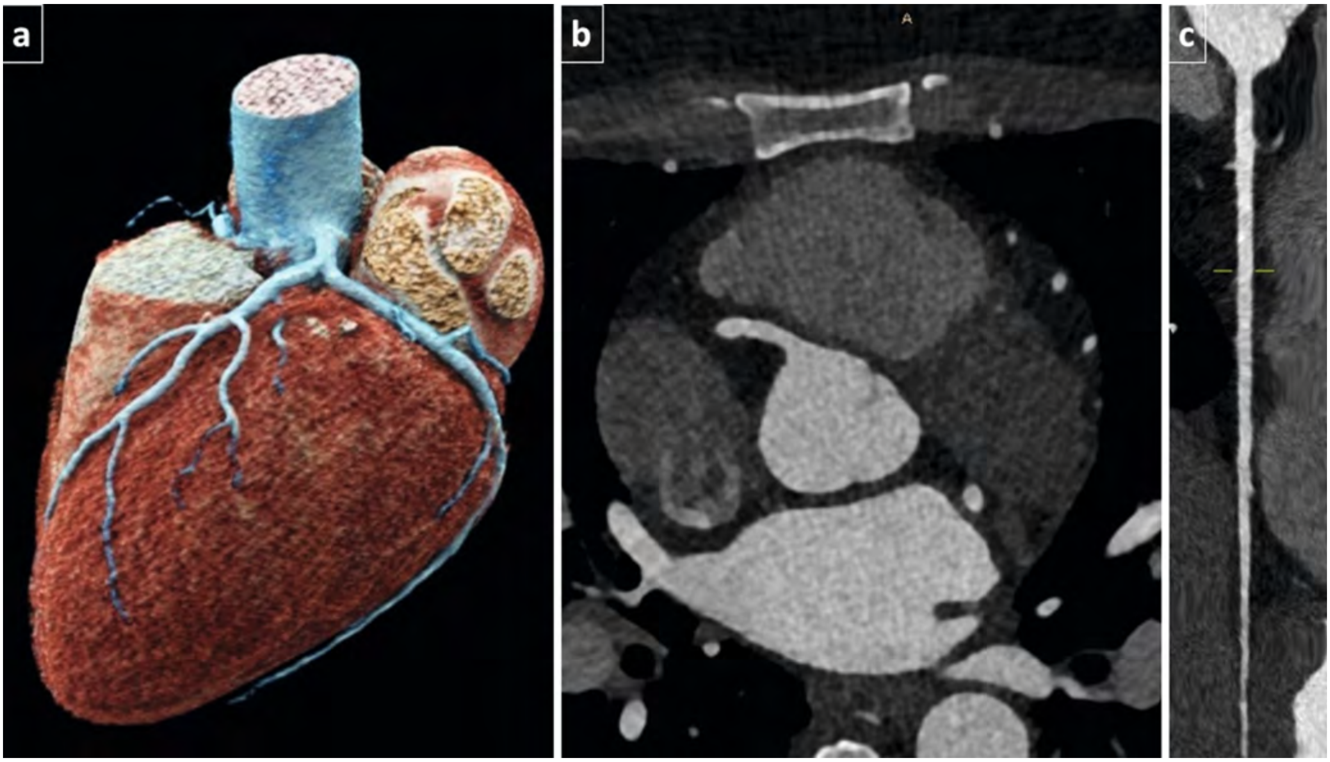
The optimized signal-to-noise (SNR) ratio leads to two major advantages in assessing coronary stenoses: On the one hand, the detector-enhanced SNR can compensate for the tougher convolution kernel, which is used to reduce blooming artifacts with a constant radiation dose [63]. On the other hand, in the case of constant SNR, the radiation dose can be reduced, which particularly benefits patients during follow-up (e. g., Marfan syndrome) [64]. ▶ **Fig. 8** shows a CT coronary angiography on a PCD CT using a high-pitch spiral technique with a low radiation dose in a young patient. Detector-based elevated SNR can be used to reduce the contrast media dose in patients with renal insufficiency. For example, a study of 100 patients with an indication for follow-up PCD CT aortography showed a 25 % reduction in contrast media compared to EID CT, while maintaining the same image quality [65].

Cardiovascular post-processing applications

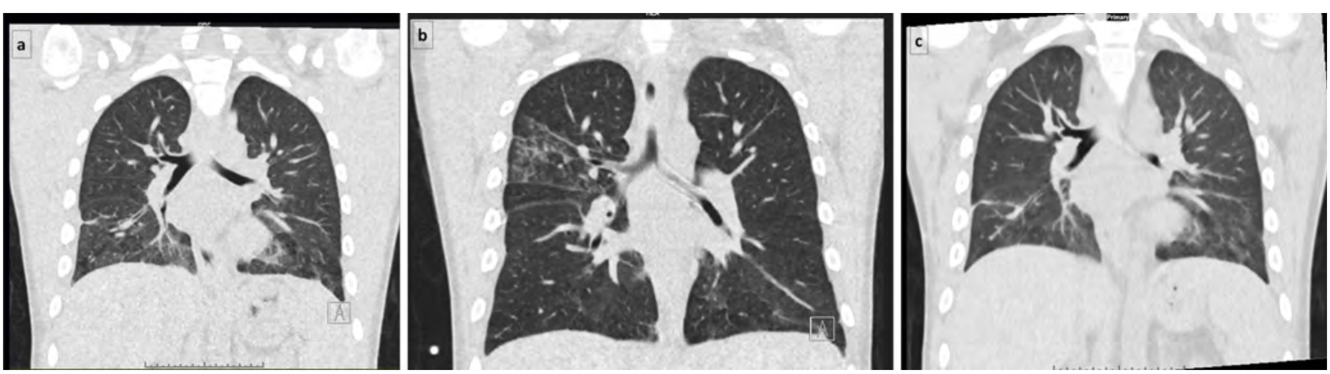
The ability of PCD CT to register the energy of individual photons and to process this as separate signals basically has the technical potential of a universal multi-energy acquisition for all scans [66]. However, in contrast to the two-layer detectors of a manufacturer of current EID scanners, which can only register two different effective photon energies, several photon energies could in principle be registered here [66]. This makes it possible to differentiate the material, enabling VNCa datasets to be generated, and thus avoiding the need for a previous native scan to quantify the coronary calcification load [67]. In addition, PCD CT allows the calculation of virtual monoenergetic images and the resulting advantages. On the one hand, it has been shown that greater weighting of the high-energy bins is helpful in reducing high-contrast artifacts, such as those from heart valves, pacemakers, or left ventricular support devices [68]. This could improve heart valve diagnostics by PCD CTs in the future. On the other hand, higher weighting of the low-energy bins can increase the iodine contrast and is therefore important for CT angiography, especially in patients with impaired renal function.

In addition, spectral image datasets can also be used to create iodine maps in the pulmonary parenchyma to visualize perfusion deficits and thus allow conclusions to be drawn about pulmonary artery embolism [69]. To date, this has only been tested on the Dual-Source EID CT; however, in view of the better intraluminal contrast of PCD CT, it should also help to better visualize small subsegmental embolisms.

Another area of use of the multi-energy technique is the detection of late myocardial enhancement in the CT for the diagnosis of myocardial infarction. Here, clinical trials on EID CTs have already demonstrated that multi-energy imaging improved the detection



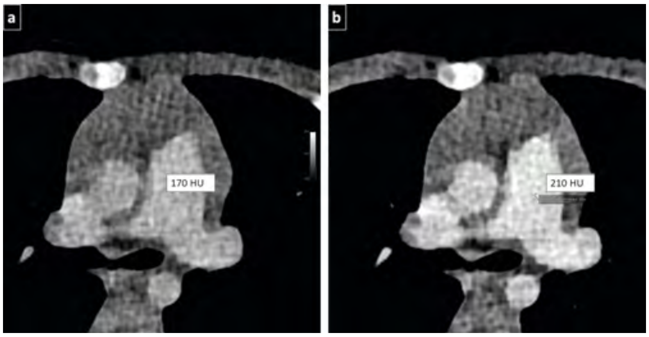
▸ **Fig. 8** Cardiac PCD-CT (Siemens Naeotom Alpha 120 kV) in a 41-year-old patient with atypical thoracic symptoms for ruling out coronary heart disease. Due to the low pretest probability for the presence of obstructive coronary heart disease and the young patient age, a low-dose high-pitch spiral examination with 90 kV was performed (CTDIvol: 2.7 mGy; DLP: 52 mGy*cm). **a** Three-dimensional visualization of the heart with the cinematic rendering technique; **b** Axial 0.6-mm slices after contrast administration and reconstruction using a vascular kernel (Bv40, Q3); **c** Stretched MPR of the right coronary artery without detection of stenoses.



▸ **Fig. 9** 16-year-old boy with infiltrates after stem cell transplantation in AML. **a, b** Third-generation dual-source CT scan (Somatom Force, Siemens Healthineers) - low-dose protocol with spectral filtering; **c** PCD-CT scan (Siemens Naeotom Alpha 120 kV) - low-dose protocol with spectral filtering. Comparable dose values and image quality for all examinations with a CTDI/DLP of 0.31mGy/10.1 mGy*cm (**a**), 0.32 mGy/9.8 mGy*cm (**b**), and 0.38mGy/12.4 mGy*cm (**c**). **a** Finding prior to treatment; b) Infiltrates in the right upper lobe; **c** Regressive infiltrates under antibiotic and antiviral therapy. Due to respiratory problems, various breathing positions were used during the examinations.

of late enhancement [70]. This has even been demonstrated on EID for late enhancement of non-ischemic causes [71]. Using late enhancement scans, it was technically possible to calculate the myocardial extracellular volume (ECV) without an additional native phase on PCD CTs in one study. However, this has not yet been compared with that of MRI, so to date only initial results have been available, and CT late enhancement cannot yet be considered an established method. [72]

Consistent with abdominal applications, the time-staged application of iodine and gadolinium – and their differentiation in phantom studies – showed promising results for the detection of Endoleaks [73]. In this way, separate detection of iodine and gadolinium could also be used in the future to simultaneously perform CT coronary angiography and detect myocardial infarction in one scan.



▶ **Fig. 10** 17-month-old girl with possible pulmonary sequestration in the case of known CPAM (congenital pulmonary airway malformation). **a, b** Comparison of contrast between the standard reconstruction at 90 kV (**a**) and the monoenergetic reconstruction at 60 kV (**b**). The monoenergetic images show an increase in the HU value of the contrast agent, which contributes to better detectability of vascular structures.

Pediatric imaging

When using ionizing radiation on children, radiation exposure considerations are particularly significant due to the increased radiation sensitivity of children, as the risk of developing malignant disease is thought to be increased after radiation exposure in childhood [74, 75]. Computed tomography in particular plays a crucial role here, as it accounts for the majority of radiation exposure in medicine. At the same time, CT, provided that the indication is correct, is of relevant importance for therapy planning and decision-making in many pediatric diseases [76].

Therefore, the greatest advantage of PCD CT in pediatric radiology is the reduction of radiation exposure [77]. The so-called "low dose" PCD CT significantly reduces the radiation dose on the one hand, but also maintains the accuracy of relevant anatomical structures and, in addition, significantly reduces image noise [78]. The effect of dose reduction occurs especially in the case of repetitive examinations (see ▶ **Fig. 9**).

Another advantage lies in the extraction of spectral information through PCD. The full spectral evaluation of the detector data requires a tube voltage of 120 kV or 140 kV, which is rarely used in pediatric patients due to the associated higher radiation dose. Therefore, in pediatric CT, the tube voltage is often reduced to 70 to 90 kV, resulting in reduced image quality due to higher noise. However, due to the spectral data of PCD CT, monoenergetic reconstruction is possible. This can, for example, increase the contrast and thus reduce the amount of contrast media (see ▶ **Fig. 10**).

Limitations and outlook

The concept of PCD CT promises numerous advances in oncological, cardiovascular, and pediatric imaging. However, CT manufacturers have faced a wide range of technical challenges to achieve excellent clinical applicability compared to EID CTs and others. In addition to improved image quality and the possibility of radiation dose reduction, the future clinical focus will presumably be on spectral image information. The different X-ray attenuating properties of different tissue types or novel contrast media make it possible to perform density quantification, which could serve as a reference for secondary diagnostic and therapeutic applications [79]. However, a few steps still need to be taken before the entire clinical spectrum is fully usable:

Firstly in oncological imaging, in which not all post-processing applications, such as the separation of different types of contrast media or bone marrow imaging in contrasting image datasets, are currently ready for use.

Furthermore, although a spatial resolution of 0.2 mm and a temporal resolution of 66 ms is currently possible in cardiac imaging, which corresponds to the currently highest temporal resolution [80], spectral information is currently not available in UHR mode.

In pediatric imaging it is hoped that spectral separation of different photon energy groups may allow multiphase images to be obtained with a single imaging technique [81]. For this purpose, in addition to the necessary contrast media, the corresponding post-processing applications are still required.

In general, increased spatial resolution and permanent spectral imaging create new practical challenges, primarily due to significantly larger image datasets, which places very high demands on the storage capacity of PACS systems and the performance of post-processing applications [66].

Funding

Ministerium für Wirtschaft, Arbeit und Tourismus, Baden Württemberg (35-4223.10/20)

Conflict of Interest

The authors declare that they have no conflict of interest.

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