The revolution of photon-counting CT towards new horizons of diagnostic imaging

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KEYWORDS:

Computed tomography; CT Spectral imaging; photon-counting detectors; clinical applications; Diagnostic imaging

ABSTRACT

Photon-counting CT (PCCT) is a new computed tomography detection technology that uses photon-counting detectors to convert individual X-ray photons directly into an electrical signal and has the potential to overcome limitations of previous CT systems, such as limited spatial resolution, or lack of spectral information. The upcoming development in PCCT technology promises to enhance image resolution, contrast, and diagnostic accuracy while reducing radiation doses to patients. In this review article we aim to evaluate the basic principles and potential clinical benefits of PCCT, with particular attention to the constantly evolving recent literature and the changes that this method will meticulously bring to the world of cardiovascular and neuroradiological diagnostic imaging.

INTRODUCTION

Computed tomography (CT) underwent significant advances in imaging hardware and applications since its initial introduction in 1972. While previous technical developments were mainly driven by increased detector rows, improved power of X-ray tubes and increased rotation speed, the recent progress of CT has completely revolutionized the operation and application of this method. Today, in fact, we are talking about NAEOTOM Alpha (Siemens Healthineers) with Quantum technology which is the first CT in the world with Photon-Counting technology, which represents a total revolution in computed tomography. For instance, Photon counting detectors (PCDs) in photon counting computed tomography (PCCT) work fundamentally differently from conventional energy integrating detectors (EIDs) used in traditional CT scanners. PCDs are designed to count individual X-ray photons and measure their specific energies as they interact with the detector, offering several significant advantages in imaging performance and diagnostic precision.

The two main components of every CT scanner are the X-ray tube and the detectors. The detector determines both the image quality and the radiation dose. The X-ray tube rotates around the patient at speeds of up to four rotations per second, capturing about a thousand projections per rotation, meaning a single projection takes 250,000 nanoseconds. Within that projection, around 30,000 photons arrive at a single detector, meaning there are only 8 nanoseconds to collect and measure the intensity of each photon before the next impact. Today even the fastest detectors can't collect all these photons simultaneously so traditionally we measure all 30,000 photons together. The intensity of the light produced is proportional to the energy of the X-rays. This light is collected by photodiodes and subsequently converted into electrical signals for further processing. The electric current is integrated over the measurement time of each frame and results in a cumulative signal of all pulses during this time, while the energy information of the incident X-rays is not preserved (Withers et al. 2021). At the heart of PCD technology is the direct conversion material, typically made from semiconductors like cadmium telluride (CdTe) or cadmium zinc telluride (CZT). When X-ray photons enter the detector, they interact with the semiconductor material, creating electronhole pairs proportional to the energy of the incident photons. This process is known as direct conversion, as it directly converts the X-ray photon energy into an electrical signal without the intermediate step of light conversion required in EIDs (Figure 1).

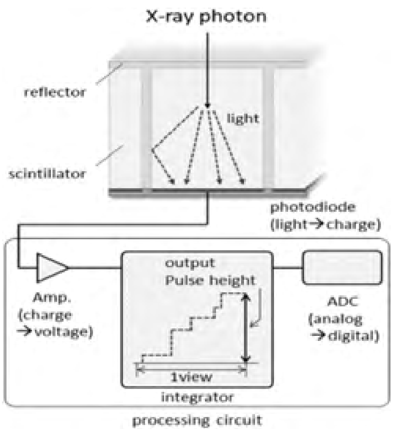

Figure 1.
Schematic drawing of energy-integrating detector (EID)

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JAHC 6:2 2024

Received: 03/04/2024
Revised: 10/04/2024
Accepted: 18/04/2024
Published: 19/04/2024

The electrical signal is then quantified to count the number of photons and measure their energies, allowing for precise energy resolution (Taguchi and Iwanczyk, 2013).

One of the key features of PCDs is their ability to discriminate between photon energies, enabling spectral imaging. This capability allows for the differentiation and quantification of materials based on their specific attenuation characteristics at different energies. For instance, iodinated contrast media and calcium can be distinguished in vascular and bone imaging applications, improving the detection and characterization of lesions, plaques, and other pathologies (Schlomka et al., 2008).

Moreover, PCDs can significantly reduce image noise and artifacts commonly associated with conventional CT imaging. By accurately counting photons and eliminating low energy photons that contribute to noise, PCDs enhance image quality (Figure 2). This improvement in image clarity is achieved while simultaneously reducing the radiation dose required, as the efficiency of photon counting allows for lower X-ray exposure without compromising image quality (Willemink et al., 2018).

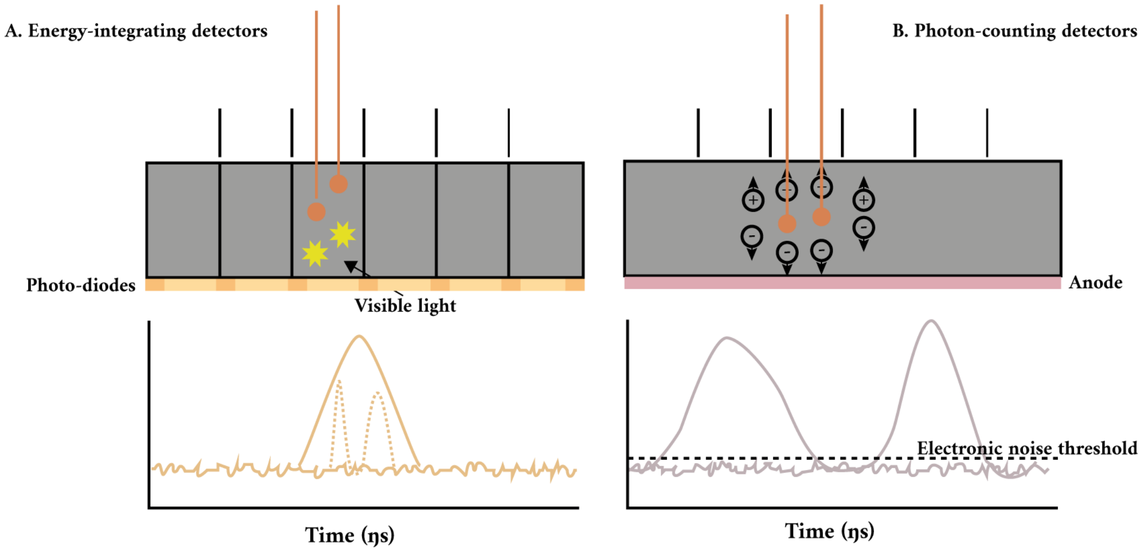

Figure 2. *Schematic representation of an energy integrating detector and of a photon-counting detector directly converting X-rays into an electrical signal*

This review aims to emphasize how PCCT can change the world of diagnostic imaging, analyzing its various fields of application. The goals of this review are (a) to examine recent findings that employ PCCT to investigate in details pathologies in several anatomical districts, (b) gain insight into technical protocols to optimize radiation dose and iodine contrast dose. NAEOTOM Alpha allows us to obtain high resolution images at low dose and also allows you to have spectral information at each scan, improving contrast and reducing noise. There are numerous clinical applications to benefit from, which translate into safer clinical decision making processes, more accurate diagnoses and the possibility to examine patients previously excluded by CT.

MATERIALS AND METHODS

The articles listed in references and included in this review were found using the PubMed and Mendeley electronic database from 2020 to 2024 using the following keywords: photon counting, CT Spectral imaging (5 articles), photon counting clinical application (4 articles), PCCT angiography, Cardio-CT, applications of PCCT, advantages of PCCT, advantages in neurovascular imaging with PCCT. Preclinical studies and studies reporting only phantom acquisition were not considered. Original articles were selected. A final sample of 27 articles was reviewed.

From these 27 articles, 9 introduce and validate the use of photon counting in terms of improvements in the dose/noise ratio, the other 18 were related to clinical use, indeed 10 focus on the application of photon counting in cardiovascular studies and the remaining 8 in the application and advantages in the neuroradiological field.

DISCUSSION

Technical challenges of PCCT

In addition to the overall amount of X-ray intensity, photon counting detectors allow the measurement of each incoming X-ray photon individually through a direct conversion technology using a fast semiconductor sensor with high stopping power, such as cadmium (CdTe) or cadmium-zinc-telluride (CZT). Other materials have also been used, such as silicon and gallium arsenide. Electrical circuits transform current pulses into voltage pulses with the height of the resulting voltage pulse (and therefore the number of electrons) proportional to the photon energy of the absorbed X-rays. This translates into the ability to "count" each pulse produced and discriminate each energy level of the X-ray photons, thus providing multispectral images.

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The NAEOTOM Alpha hardware supports multispectral imaging with up to four energy bins. Compared to solid state scintillation detectors, Photon Counting detectors carry several advantages. Individual detector cells are defined by the strong electric field between the cathode and p (pixeled) anodes, without the need to add baffles between detector pixels to avoid optical crosstalk for scintillation detectors. The geometric dosing efficiency is therefore better than in scintillation detectors and is only reduced by the antiscatter collimator blades or grids, which are also present in scintillation detectors. Furthermore, each "macro" pixel of the detector confined by the collimator blades can be divided into smaller subpixels that are read separately in order to significantly increase the spatial resolution. With a Photon Counting detector capable of counting the charges created by individual X-ray photons and measuring the relative energy level, we will therefore have a detector equipped with intrinsic spectral sensitivity in each scan.

Advantages of photon counting-CT technology

Photon-counting technology in computed tomography offers several revolutionary advantages:

Improved Detector Efficiency with Direct Signal Conversion: The QuantaMax detector's semiconductor crystal allows for direct signal conversion, generating an electrical charge instead of light. This process improves the efficiency of the detector without compromising the radiation dose, since it does not require septa to divide the detector into cells.

Smaller Detector Pixels: Quantum Technology uses the smallest pixels ever used in a CT scan. This allows you to obtain very high resolution images with maximum dose efficiency.

Elimination of electronic noise: Photon-counting detectors directly convert X-rays into electrical charges, which are not subject to decay and afterglow. This allows you to clearly distinguish between signal and electronic noise, allowing the elimination of the latter. The inherent advantage of a PCD system for electronic noise exclusion can be particularly useful for examinations with low detector signal intensity, such as those on pathologically obese patients and those performed with a low radiation dose. In these scenarios, electronic noise can reduce image uniformity and cause noticeable artifacts on images acquired with an EID CT system compared to images from a PCD CT system, which have showed to be more immune to the effect of electronic noise. This rejection of electronic noise in a PCD CT system can be used to reduce overall image noise and improve diagnostic image quality for lowdose examinations.

Better image quality: Photon counting tomography has significantly higher image quality than traditional tomography. This happens because, for the same dose used, there is an almost total absence of electrical noise, and also because low energy photons are more relevant than traditional tomography. These two aspects greatly increase the quality of the images and also allow a notable step forward at a clinical level. In particular, you will have images that define the anatomical details much more precisely, allowing radiologists to make very accurate diagnoses (Figure 3).

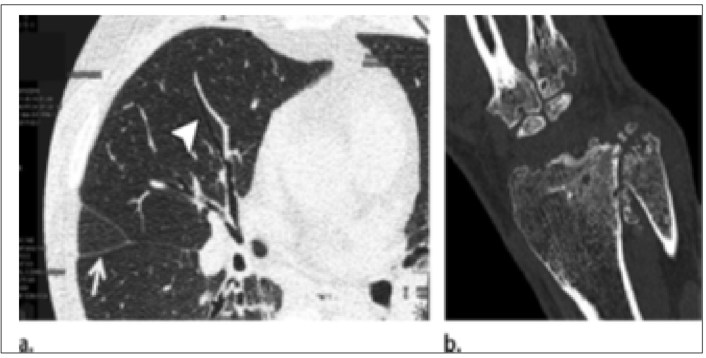

Figure 3. *CT imaging in UHR mode. In vivo axial CT image of the lung in a 69 year old woman (a) and coronal CT image of the wrist (b) show that high spatial resolution enables accurate delineation of lung fissures (arrow in a), airway walls (arrowhead in a), and trabecular bone (Leng et al.* 2019).

Intrinsic spectral sensitivity: the Photon Counting detector can have numerous applications. Furthermore, all multienergy reconstructions are calculated directly based on the available spectral information present in the raw data. The Photon Counting detector detects individual photons and measures their energy at full FoV. The resulting scans always provide multienergy data which allow, for example, real quantification of iodine even at low dose levels. PCCT detectors can measure the energy of each individual photon, allowing the acquisition of spectral data. This allows you to obtain color images, where each color represents a different energy level, unlike the monochromatic image in conventional CT (Figure 4).

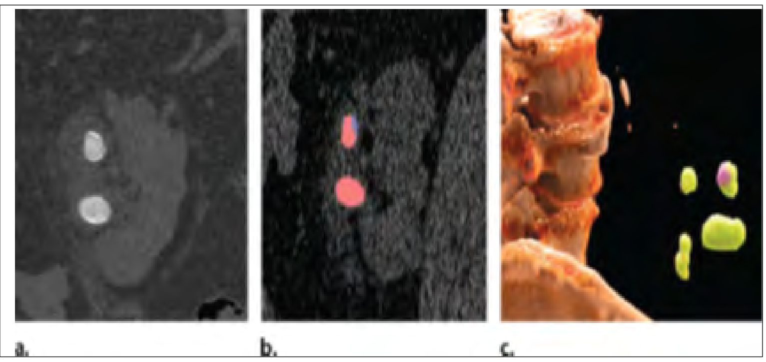

Figure 4. *Renal stones. (a) High-resolution single-energy PCCT image shows the morphologic features of the stones. (b) Dual-energy image shows the stone composition. (c) Cinematic threedimensional volume-rendered image enhances the visualization of stone morphology and composition (Leng et al.* 2019).

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***Simultaneous multi-energy acquisition*:** One of the major driving forces behind the development of PCD CT is that it enables the acquisition of simultaneous multienergy CT images. PCD CT intrinsically allows dual-energy or multienergy (>2) acquisitions on a single X-ray tube potential thanks to its energy discrimination capability.

This unique feature enables single source, single tube, single acquisition, single detector layer, single filter multienergy CT imaging with perfect temporal and spatial registration in the acquired multienergy data, thus eliminating many sources of artifact. User defined energy threshold selection offers the freedom to select the correct energy thresholds tailored to the specific diagnostic task. This activity based energy threshold selection helps resolve different tissue types or contrast agents with optimal imaging settings to achieve the best image quality or lowest radiation dose. Furthermore, the K-Edge imaging capability of PCD CT has provided the opportunity for the development of new types of contrast agents and imaging techniques such as nanoparticle based blood pool imaging or targeted imaging with multimedia multiphase imaging of contrast. However, these are primarily research methods that have yet to be translated into mainstream clinical practice. Multienergy PCD CT offers opportunities for advanced data processing, such as the creation of virtual monoenergetic images, virtual non contrast images, and images with automated bone removal.

***Artifact Reduction*:** Artifacts are commonly seen in clinical CT and can simulate or obscure true pathology. Beam hardening artifacts occur when the X-ray beam passing through an object is attenuated more by high density materials than by low density (soft tissue) materials. This uneven attenuation causes distortion of the reconstructed CT images, resulting in resulting in streaking or shadowing artifacts. In PCDs, constant weighting allows these attenuation measurements to be normalized at different energy levels, reducing beam hardening artifacts. In this context, the use of high energy thresholds that act as an advantageous filter is particularly useful. These artifacts are significantly mitigated in PCDs due to improved spatial resolution and consequent decrease in partial volume effects and thanks to improved material decomposition that allows accurate separation of high density materials (such as metals) from surrounding soft tissues. PCCT's faster acquisition times dramatically reduce the duration of scans, also reducing the possibility of artifacts caused by patient motion (Figure 5).

Limits

Unfortunately, Photon – Counting detectors also have some imperfections. When X-ray photons arrive near the boundary between two pixels, the electron cloud produced by the photon can be partially detected by both pixels. This phenomenon, known as charge sharing, can cause a single incident X-ray photon to be detected twice. Charge sharing can also occur through the emission of a characteristic photon. Another problem is that two independent photons can arrive at the same pixel in very rapid succession. The resulting signals will "accumulate" and will be interpreted by the processing electronics as a single photon.

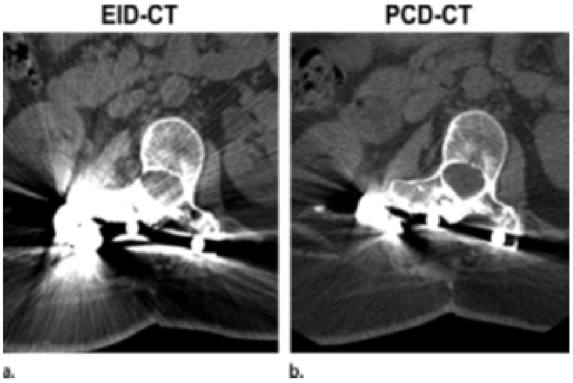

Figure 5. *Reduction of metal artifacts at PCD CT. Axial EID (a) and PCD (b) CT images of a fused lumbar spine show that the reduction of metal artifacts arising from the posterior metallic hardware enables visualization of the spinal canal, which was obscured by the metal artifacts on (a) (Leng et al.* 2019).

Mitigation of pileup and charge sharing is being researched. Some PCDs apply analysis mechanisms that can resist both pileup and charge sharing.

Clinical Application

The intrinsic characteristics of PHOTON COUNTING CT allow the development of new low dose radiation protocols, the aim of which is to protect patients from high dose exposures but at the same time maintain good image quality.

In summary, Photon Counting CT technology offers a wide range of advantages in diagnostic imaging, enabling more precise diagnosis, reduced radiation dose to patients and improved management of cardiovascular, neurological and oncological diseases.

CARDIOLOGY

PCCT is set to revolutionize cardiological diagnostics with its exceptional image clarity and advanced material discrimination capabilities. In cardiology, accurate visualization of coronary arteries, cardiac tissues, and associated abnormalities is crucial. PCCT, with its high resolution imaging and ability to perform spectral imaging, significantly enhances the detection and characterization of coronary artery disease by providing detailed views of calcified plaques and differentiating them from iodinated contrast material. This ability improves the assessment of stenosis severity and aids in the planning of interventional procedures (Symons et al., 2019).

Moreover, PCT's capacity for lower dose imaging is particularly beneficial in cardiology, where patients often undergo repeated scans for monitoring. By reducing the radiation exposure without compromising image quality, PCCT ensures safer long term patient follow-up. Additionally, the technolo-

gy's spectral imaging features allow for better characterization of myocardial perfusion, potentially improving the detection and management of ischemic heart disease by mapping blood flow variations within the myocardium (Willemink et al., 2018).
Coronary heart disease kills more people every year than any other disease and the numbers are increasing. Noninvasive cardiovascular diagnostic procedures save time and reduce risk by providing rapid results that help study disease and guide treatment decisions (Gibilaro 2023). NAEOTOM Alpha with Quantum Technology, dual source photon counting CT, provides Quantum HD cardiac images with 0.2 mm slice thickness. This displays previously undetectable details in the heart without dose penalty. Additionally, spectral information is automatically available in each scan with a direct conversion process that transforms individual X-ray photons into an electrical signal to create the image. Quantum technology allows for better diagnostic evaluation of coronary vessels in CT. According to a recent study, NAEOTOM Alpha and Quantum HD Cardiac could have helped reduce the need for invasive coronary angiography for 54% of patients in the detection of coronary artery disease in a high risk population. Numerous studies have demonstrated the utility of PCCT in improving measurements of plaque volume and stenosis severity, due to increased spatial resolution, improved soft tissue contrast, and significantly reduced image noise (Figure 6-7).

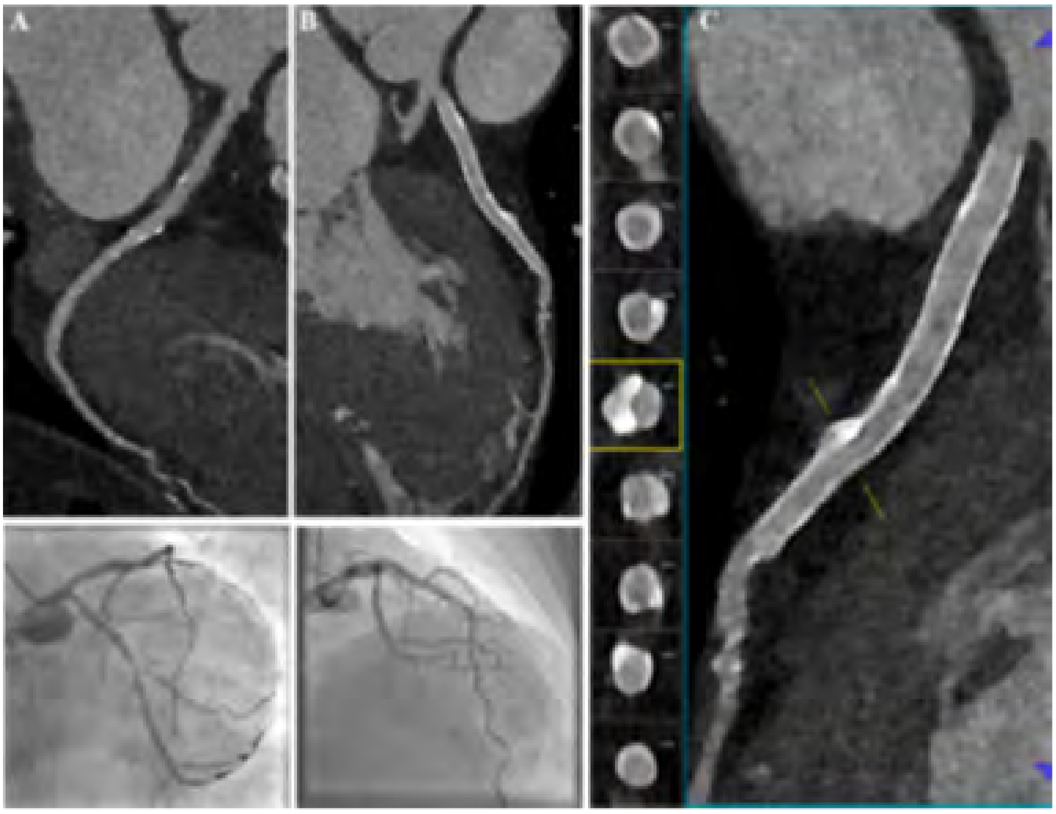

Figure 6. *Dual-source ultra-high resolution PCCT scans in a suspected of obstructive coronary ar-tery disease A. Demonstrate calcifications in circumflex coronary artery with no significant steno-sis as confirmed by angiography. B/C. Depiction of a stent in the left anterior descending with cal-cification outside of the stent is compressing the lumen. Mid-LAD a suspected stenosis was ob-served (van der Bie et al. 2023).*

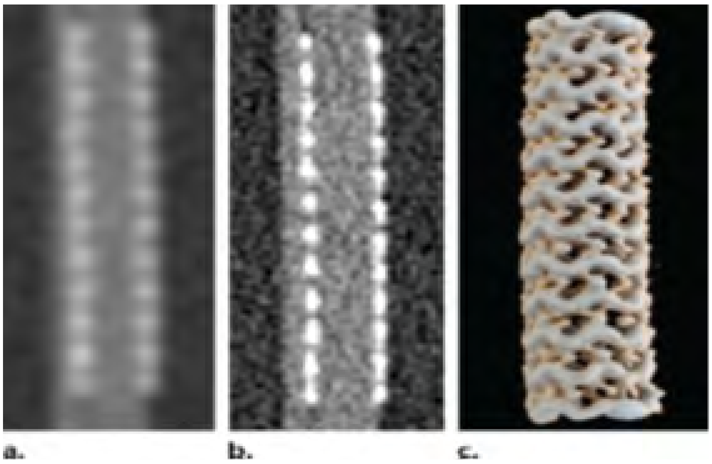

Figure 7.
Coronal EID (a) and PCCT images acquired in UHR mode (b) show examples of a coronary stent. The PCCT image clearly shows the individual struts, which are evident on the corresponding three-dimensional rendering (c) of the PCCT image.

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PNEUMOLOGY

PCCT presents transformative opportunities in pneumology, particularly enhancing the di-agnosis and management of pulmonary diseases. The technology’s high-resolution imaging and spectral capabilities make it ideal for detailed visualization of lung structures, facilitating early detection and accurate characterization of pulmonary nodules, fibrosis, and other parenchymal abnormalities. PCCT’s ability to discriminate between different materials at multiple energy levels allows for better contrast in lung tissue imaging, potentially improving the assessment of airway diseases and pulmonary vascular conditions (Pourmorteza et al., 2017).
Moreover, the enhanced contrast resolution provided by PCCT can significantly benefit the evaluation of lung cancer, offering improved detection of small lesions and providing critical in-formation on tumor boundaries and the involvement of adjacent structures. This precision is vital for staging cancer and planning treatments, including surgical interventions and radiation thera-py. The ability of PCCT to perform detailed material decomposition also aids in distinguishing be-tween types of tissues and pathologies, which is particularly useful in differentiating benign from malignant nodules (Symons et al., 2019). In addition, PCT’s reduced radiation dose is of particular importance in pneumology, where patients, especially those with chronic respiratory conditions, might require frequent imaging. By minimizing radiation exposure, PCCT provides a safer option for longitudinal studies and routine follow-ups, ensuring high-quality imaging is accessible for ongoing patient management without the associated risks of high radiation doses.
NAEOTOM Alpha with Quantum Technology marks the beginning of a revolutionary breakthrough in the diagnosis of lung diseases and the advancement of pulmonology. With Quantum HD resolu-tion with 0.2mm slice thickness, improved CNR, and inherent spectral information in every scan, this technology allows doctors to see the lung like they’ve never seen before. It offers complete understanding and access to properly represented and optimized details, from gratings to hon-eycombing. The high spectral resolution and image quality support safe decision making by providing meaningful answers, potentially sparing patients from unnecessary radiation exposure and enabling more targeted decisions in patient management, including treatment modification and pre- and post-operative. Quantum technology has the potential to transform the field of pulmonology, paving the way for better treatments and outcomes for patients (Figure 8).

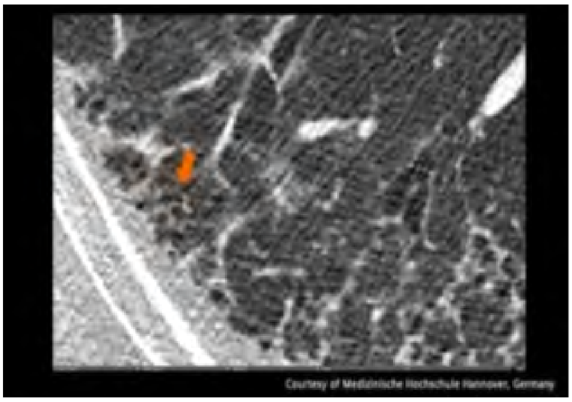
Courtesy of Medizinische Hochschule Hannover, Germany

Figure 8. *Visualizing tissue changes with much higher resolution can help classify these changes. Here, the "intralobar reticulates" that indicate pulmonary fibrosis are clearly visible even with a low-dose lung scan.*

NEUROLOGY

PCCT is particularly promising in the field of neurology, where high-resolution and con-trast-sensitive imaging are critical for accurate diagnoses. The superior spatial and energy resolu-tion of PCCT enables enhanced visualization of neuroanatomical structures, which is crucial for detecting subtle changes associated with neurological diseases. For instance, the technology’s ability to differentiate between calcifications and hemorrhages can significantly improve the as-sessment of stroke and its various types, such as ischemic versus hemorrhagic stroke. This dif-ferentiation is pivotal in determining the appropriate treatment path and can lead to more tai-lored and effective interventions (Symons et al., 2017). Additionally, the spectral imaging capabil-ities of PCCT allow for better visualization of contrast-enhanced blood vessels in the brain. This is especially beneficial in evaluating vascular pathologies, including aneurysms and arteriovenous malformations, where detailed vessel delineation can aid in surgical planning or endovascular procedures. Moreover, PCCT’s material decomposition abilities enable the identification and quantification of different substances, such as iodine in contrast agents, providing clearer images of blood flow and vessel leakage that are essential for diagnosing and monitoring conditions like brain tumors and inflammation (Pourmorteza et al., 2016).
The reduction in radiation dose offered by PCCT is also a significant advantage in neurology, where patients, particularly those with chronic conditions, may require multiple scans over time. By minimizing exposure while maintaining high image quality, PCCT addresses long-standing con-cerns about the cumulative radiation effects from repeated imaging, making it a safer option for longitudinal studies and pediatric neurology (Leng et al., 2019).
At the forefront of stroke and neurological care, photon counting computed tomography features high resolution in both axial and remaining planes to allow clinicians to evaluate subtle lesions and anatomical structures. Compared to conventional CT, PCCT offers less image noise and tends to eliminate beam hardening artifacts in the internal carotid arteries near the sur-rounding bone. The high potential of PCCT for the quantitative evaluation of atherosclerotic plaque in the carotid artery was evaluated. Compared to histopathology, used as a standard ref-erence, PCCT showed good sensitivity and excellent specificity and accuracy for the detection of necrotic core, fibrous cap, intra-plaque hemorrhage and calcifications. Furthermore, the

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correla-tion between PCCT and histopathology in terms of quantitative measurements of plaque compo-nents was excellent (Figure 9-10).

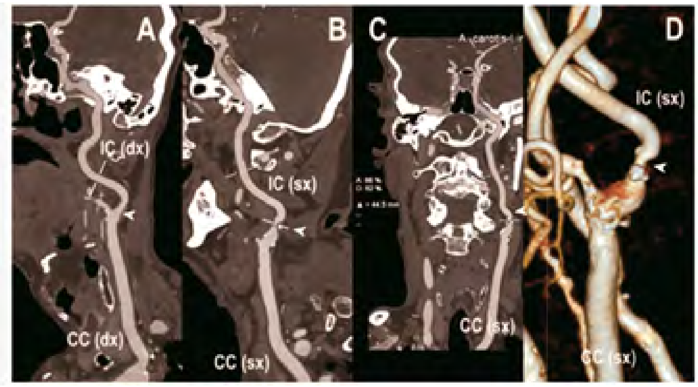

Figure 9. *Carotid CT angiography using photon count computed tomography. The figure shows advanced reconstructions of a carotid artery vascularization.*

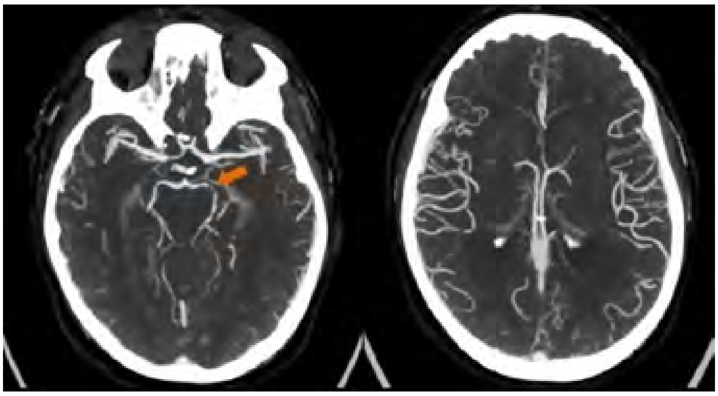

Figure 10. *CT angiography of the cervical and intracranial vessels with a 50% reduction in contrast dose in a patient with impaired renal function showing high-grade stenosis of the left posterior cerebral artery (arrow).*

CONCLUSION

The transition from EIDs to photon counting technology marks a paradigm shift in CT imaging. By accurately quantifying the energy of each detected photon, PCCT facilitates the extraction of detailed material-specific information from the scanned tissue. This capability significantly im-proves the identification and characterization of different tissue types and materials within the body, opening new avenues for more precise and targeted diagnostic applications (Schlomka et al., 2008). Moreover, photon counting CT has the potential to drastically reduce the radiation dose required for obtaining high-quality images. The technology's inherent efficiency in photon detection and energy discrimination minimizes the need for high radiation doses, thereby en-hancing patient safety—particularly beneficial for pediatric patients or individuals requiring mul-tiple scans (Willemink et al., 2018). Furthermore, the ability of PCT to perform spectral imag-ing—distinguishing between photons of different energies—enables advanced imaging applica-tions such as material decomposition and k-edge imaging. These applications have shown promise in improving the visualization of contrast agents, thereby offering new possibilities in the fields of oncology, cardiology, and neurology (Pourmorteza et al., 2016).

This review allows us to define PCCT as notable advance in the world of diagnostic imaging since spectral CT imaging is a constantly evolving field, whose new detector technology allowed the significant reduction of image noise and artifacts, improving spatial resolution and reducing radiation dose. Furthermore, K-edge imaging with material decomposition creates new possibili-ties for quantitative analyses.

However, despite its many benefits, the technology is not without its challenges. Phe-nomena such as charge sharing and pile-up can degrade image quality. Despite this, the images obtained remain far superior to those produced by traditional techniques, underlining the revo-lutionary potential of this method. To exploit the full greatness of PCCT, reliable and automated tools are needed to support data analysis and establish efficient and precise ways for data post-processing, management and storage. Looking at the future, the goal is to make this tech-nology more accessible and widespread, in order to maximize its impact in 360° diagnostic imag-ing. PCCT promises to radically change the clinical application of CT in cardiovascular, neurologi-cal and pneumological fields in the coming years. With further development and innovation, this technology has the power to radically transform the way numerous conditions are managed and diagnosed, leading to a better quality of life for the worldwide population.

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Author Contributions: *Conceptualization, E.S. and S.T.; writing—original draft preparation, E.S., S.T., V.M.; writing—review and editing, E.S., V.M., G.D.F. All authors have read and agreed to the published version of the manuscript.*
Data Availability Statement: *no new data were created to write this manuscript.*
Conflicts of Interest: *The authors declare no conflict of interest.*

JAHC | JOURNAL OF ADVANCED HEALTH CARE
OFFICIAL JOURNAL OF TSRM PSTRP
RESEARCH ARTICLE

Citation:
E. Scarfato et al.

"The revolution of photon-counting CT towards new horizons of diag-nostic imaging"

JAHC 6:2 2024

Received: 03/04/2024
Revised: 10/04/2024
Accepted: 18/04/2024
Published: 19/04/2024