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REVOLUTIONIZING IMPACT OF PHOTON COUNTING COMPUTED TOMOGRAPHY IN RADIOLOGICAL IMAGING TECHNIQUES

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Abstract
Conventional Computed Tomography (CT) systems utilize Energy-Integrating Detectors that aggregate the energy of incoming X-ray photons, which often results in limited spatial resolution and diminished contrast in soft tissues, causing difficulties in material differentiation. By counting individual photons and detecting their energy levels, Photon Counting Computed Tomography (PCCT) has become a revolutionary imaging method intended to get beyond these restrictions. PCCT measures photon energy using semiconductor-based photon-counting detectors, usually based on cadmium telluride or cadmium zinc telluride, which directly transform X-ray photons into electrical signals. Compared to traditional CT systems, PCCT offers better tissue characterisation, lower radiation doses, and higher image quality, making it a major breakthrough in medical imaging technology. Superior spatial resolution, a higher contrast-to-noise ratio, and multi-energy imaging capabilities are made possible by this, enabling specialised diagnostic applications like material decomposition, plaque characterisation, and better tiny lesion detection. Furthermore, PCCT has the potential to improve soft tissue visualisation and lessen artifacts, which would help with more precise diagnosis and personalised patient treatment. With its increased diagnostic precision, dose-reduction benefits for patient safety, and potential for personalised imaging procedures, PCCT is a significant milestone in medical imaging. It is anticipated that its uses in musculoskeletal imaging, cardiovascular evaluation, oncology, and early illness detection would revolutionise radiology research and clinical practice.

Keywords: Energy Integrating Detectors, Spatial resolution, Contrast-to-Noise Ratio, Artifacts, Photon Counting Computed Tomography.

Introduction
Photon Counting Computed Tomography (PCCT) is a recent advancement in medical imaging technology. On 29th September 2021, Naeotom Alpha became the world's first photon counting CT scanner (Courtesy: Siemens healthineers). A conventional CT scan or computed tomography scan is a non-invasive medical imaging procedure that uses x rays to create cross sectional images of the internal organs. These images, also called tomographic images or slices, can be stacked together to create a 3D image. The scintillator and photodiode layers make up the detector's two layers.

Scintillator layer transforms absorbed x-ray photons into visual light photons, whereas the photodiode layer transforms the light photons into electrical signals. **(Stein et al., 2022)**

FIG.1 Photon Counting Computed Tomography (PCCT), (Naeotom Alpha) (Courtesy: Siemens healthineers)

Conventional Computed Tomography consists of Energy Integrated Detector (EID). It uses Scintillator and Photodiode:

1. Scintillator {e.g. Cesium Iodide} converts x-rays into a visible light.
2. In scintillating materials, light spreads out into a sphere once X-ray energy is deposited into the scintillator.
3. To ensure that the light produced by scintillators is retained only in the incident detector element and prevent crosstalk, each detector pixel is physically shielded from others by optically reflecting septa (TiO2 based reflector).
4. Photodiode receives the light signal and converts it into electrical signal. **(Horst et al., 2023)**

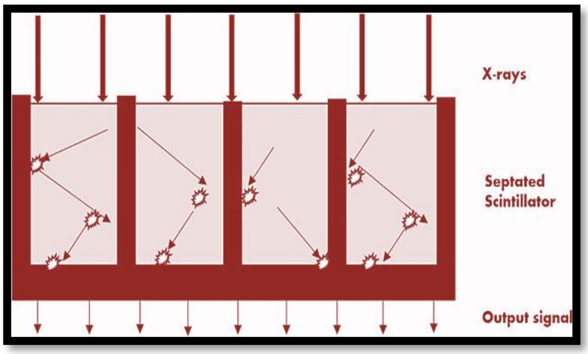

FIG.2 Conventional Energy-Integrated Detector (EID) (Horst et al., 2023)

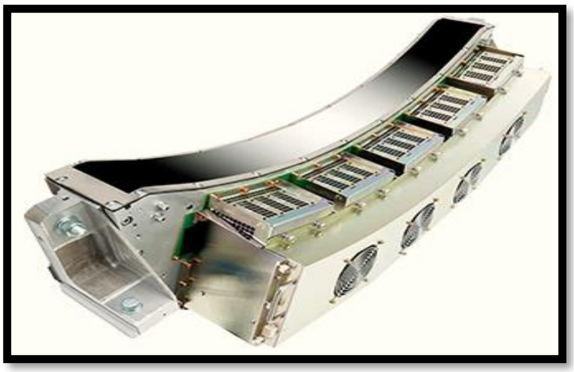

FIG.3 Three Dimensional Image of Detector (Horst et al., 2023)

Rate of projection in conventional Computed Tomography

Generally Computed Tomography consists of X-ray tubes and detectors and they undergo typically 4 rotations per second, 1000 projections per rotation, and take up to 250000 milliseconds for an individual projection time. Within one projection approx. 30000 X-ray photons arrive at single detector. So, there are only 8 nanoseconds to collect and measure the intensity of each photon before the next impact. **(Tortora et al., 2022)**

Limitations of scintillator detector

There are several limitations of scintillator detector which are mentioned below:-

a) **Energy Integrating:** Different energies have different weights, the detector's output is proportional to the total energy of incoming photons, not the number of individual photons.
b) **Limited spatial resolution:** Use of optical separations (TiO2 based reflector) that is septa between detector elements result in formation of dead spaces or dead zones which affects the spatial resolution of image.
c) **Limited contrast resolution:** EID integrates the energy of all photons, regardless of their energy. This down weights the contribution of lower energy photons, which carry more information about subtle contrast differences.
d) **Electronic noise:** EIDs can experience increased noise levels at low radiation doses thus reduces signal to noise ratio.
e) **Spectral imaging:** Dual layer, dual detector or switching between low and high kvp levels (140 and 70 kvp). **(Meloni et al., 2024)**

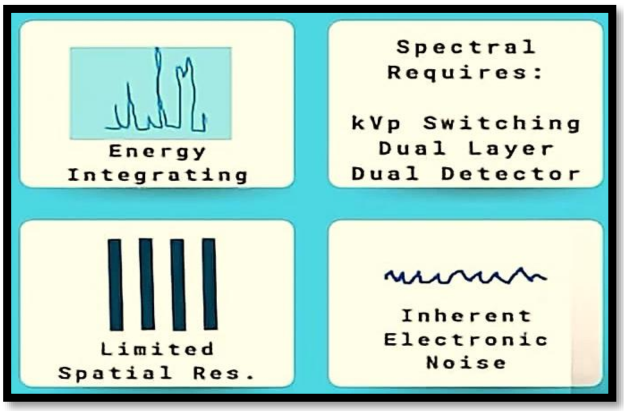

FIG.4 Limitations of EID (Meloni et al., 2024)

Photon Counting Computed Tomography

Photon Counting Detector is used in PCCT, a form of X-ray CT, to record the interactions of individual X-ray photons without turning them into light signals. On 29th September 2021, **Naeotom Alpha** became the world's first photon counting CT scanner. (Courtesy: Siemens healthineers).

Photon counting detector

By using a crystal semiconductor material instead of a conventional ceramic scintillator, the intermediate light-producing process that is typically necessary for X-ray detector materials used in CT imaging is eliminated. With semiconductors, the optical separations known as septa are no longer required in between each pixel in the QuantaMax detectors. By establishing that there is no "dead space" between individual pixels in the detector grid, this increases the active area of photon detection and improves detector efficiency, enabling dosage reduction without diminishing quality. **(Meloni et al., 2023)**

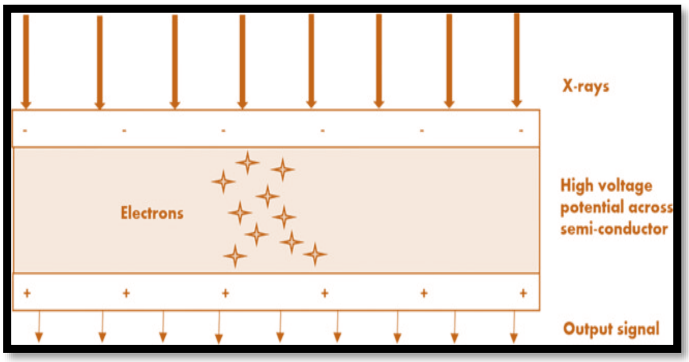

FIG.5 Photon Counting Detector (Wehrse et al., 2021)

Working of Photon Counting Detector (PCD)

The fundamental difference in PCCT and conventional CT is that PCCT detects individual x-ray photons and measures their energy levels. The **purest cadmium telluride crystal or cadmium zinc telluride** is used as PCD. Working of PCD includes following steps:-

a. High voltage is applied from bottom to top of semiconductor.
b. X-rays are converted to an electron cloud that moves across a high voltage within the semiconductor.
c. Material is relatively thinner than scintillator, so they generate electron hole pairs.
d. Positive ions move towards the cathode and negative ions move towards the anode.
e. Negative ions are getting measured at the pixelated anodes (anode is separated in small rectangles).
f. The detected photons are grouped into **multiple energy bins** based on their energy.
g. Thus spectral imaging is achieved as it allows different tissues or materials (for example fat, iodine or calcium) to be differentiated more distinctly. **(Flohr and Schmidt, 2023)**

Application-Specific Integrated Circuit (ASIC)

An Application-specific integrated circuit (ASIC) is used in photon-counting CT (PCD-CT) to process the charge signal that is converted from incident X-rays by a semiconductor detector. ASIC converts electrical signals into digital signals.

1. Faster read outs and energy classifications.
2. Reducing signal pile-up as ASICs can help prevent signal pile-up by using high counting rate.
3. Improving contrast to noise ratio as it differentiates the charge signal with multiple thresholds.

Images are reconstructed in PCCT by QIR **(Quantum Iterative Reconstruction)** algorithms and DLR **(Deep Learning Reconstruction) (Alves et al., 2024)**

Reconstruction techniques in PCCT;

A. Features of **QIR (Quantum Iterative Reconstruction)**

- Purpose: Improves image quality by reducing noise and improving Contrast to Noise Ratio (CNR).
- Working: Performs statistical optimization of spectral data and corrects for geometric cone beam artifacts.
- Strength levels: QIR has four strength levels (QIR-1 to QIR-4), these are noise reduction levels.

B. Features of **DLR (Deep Learning Reconstruction)**

- Higher-quality data is available with photon-counting CT scanners
- DLR uses artificial intelligence to reconstruct high-quality images from lower-dose CT **(Alves et al., 2024)**

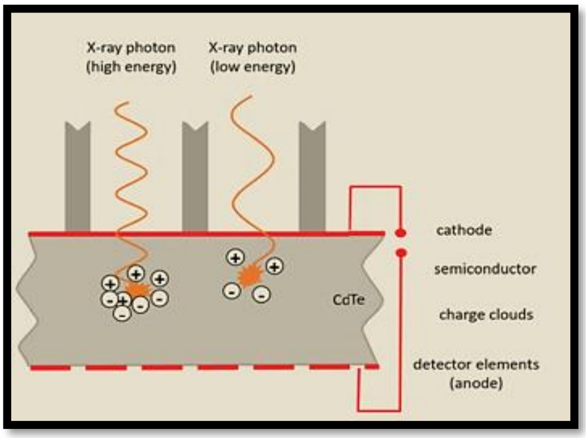

FIG.6 Photon Counting Detector (Wehrse et al., 2021)

Comparison of construction in Energy Integrated Detector (EID) and Photon Counting Detector (PCD) with the use of images

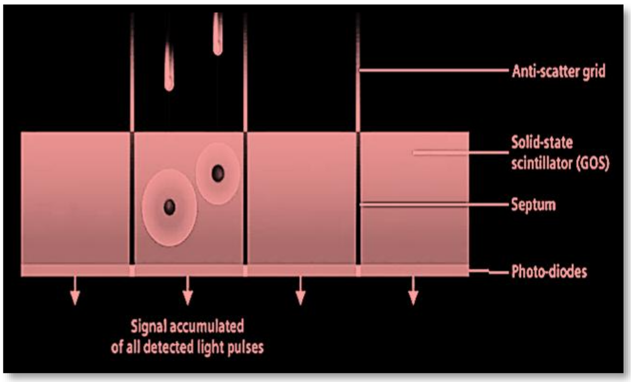

FIG.7 Energy Integrated Detector (Mese et al., 2024)

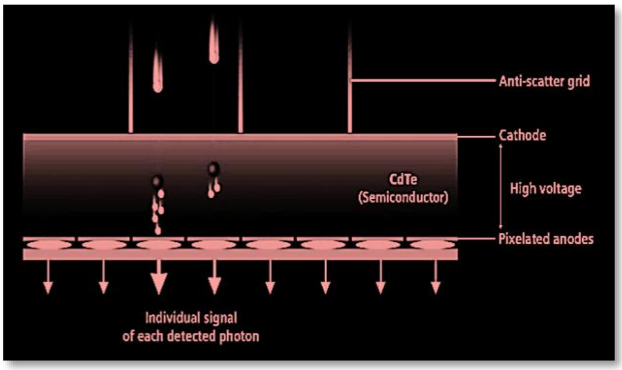

FIG.8 Photon Counting Detector (Mese et al., 2024)

Advantages of Photon Counting Detector in Photon Counting Computed Tomography
There are several advantages of using PCD which gives PCCT an upper hand than conventional CT which uses Energy Integrated Detector (EID). Some of the advantages are discussed below:-

1. Smaller detector pixels -- high spatial resolution:-
Designed with the smallest pixels ever used in a whole-body CT, Quantum Technology can deliver ultra-high-resolution images at full dose efficiency. **(Ruetters et al., 2022)**

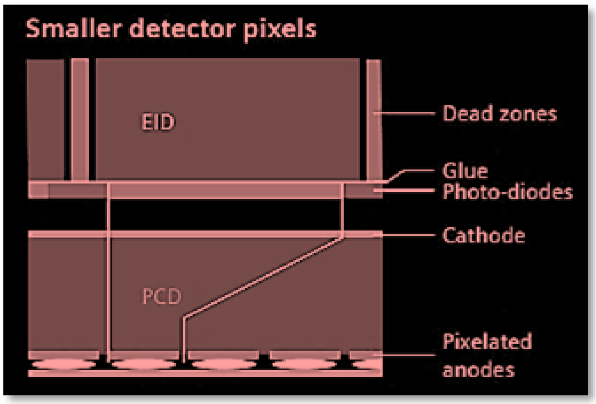

FIG.9 Smaller detector pixels (Mese et al., 2024)

2. Elimination of electronic noise -- lower radiation dose:-

As photon-counting detectors directly convert X-rays into electric charges which are not subject to decay and afterglow, this technology allows a clear distinction between signal and electronic noise which allows the elimination of the latter. A threshold can be applied digitally to the pulse height on analysis then electronic noise can subsequently be removed from the detection process. The threshold is typically set at around 20 keV. **(Heismann, Kreisler and Fasbender, 2025)**

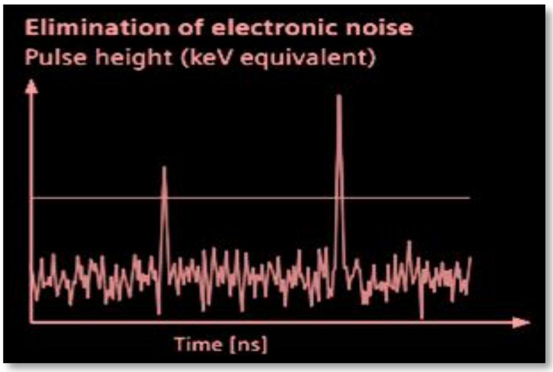

FIG.10 Elimination of electronic noise (Mese et al., 2024)

3. Equal contribution of lower energy Quanta -- improved image contrast:-

There is no down-weighting of low-energy photons in photon-counting detectors because each X-ray's energy is measured, resulting in optimum image contrast. This allows for lower iodine contrast dose in contrast based studies, without sacrificing enhancement or image quality. **(Heismann, Kreisler and Fasbender, 2025)**

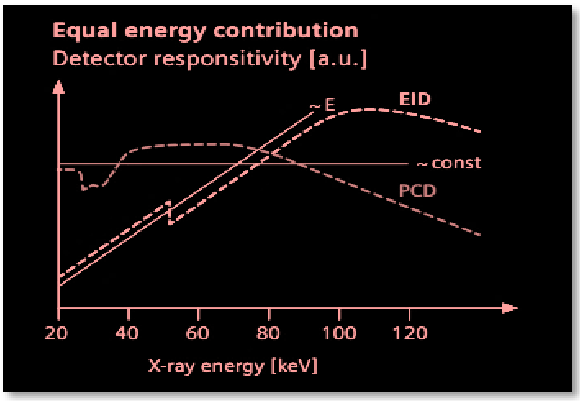

FIG.11 Equal Energy Contribution (Mese et al., 2024)

4. Intrinsic spectral sensitivity -- multi energy information:-

Measuring discrete photon energy levels in up to four energy bins means that the spectral information is captured for every exam. QuantaMax detector registers a current pulse that exceeds the threshold for electronic noise. It is sorted into one of four energy bins—according to the measured pulse height in keV. The detector thereby always acquires a spectrally resolved signal regardless of scan speed or temporal resolution. **(Feng et al., 2020)**

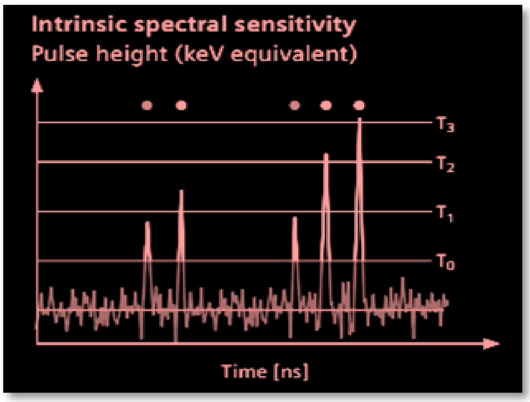

FIG.12 Intrinsic Spectral Sensitivity (Mese et al., 2024)

Limitations with PCCT

There are few limitations of using this new innovative technology which are mentioned below:-

1. **Pulse Pile up**: One x- ray come in then very quickly before the signal can get read another x-ray comes in that causes pulse pile up. (Difficult to assign individual energies) (Alves et al., 2024)
2. **Charge sharing**: If x-rays interact right in between the middle of two anodes, charge splits. (Degrades image quality) **(Alves et al., 2024)**

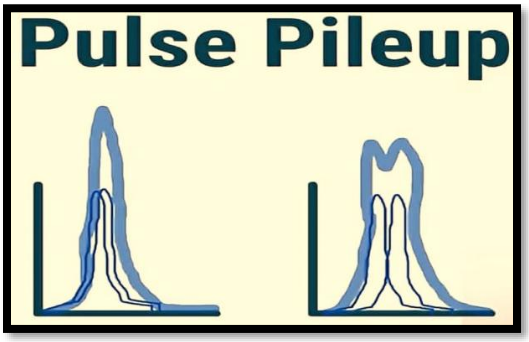

FIG.13 Pulse Pileup (Alves et al., 2024)

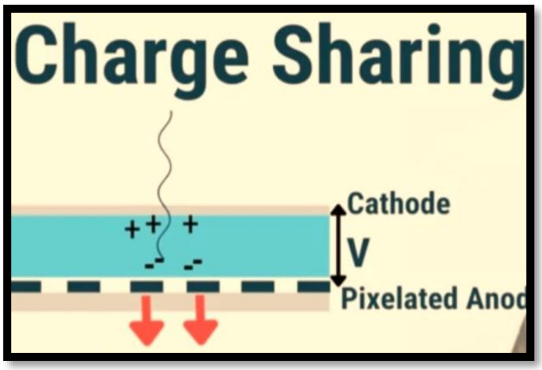

FIG.14 Charge Sharing (Alves et al., 2024)

To overcome these challenges,

1. For Pulse pileup	small detector size used
2. For Charge sharing	large detector size used

Silicon sensors

Another material used for photon counting is Silicon, deep silicon detector is used which is much thicker, approx. 10 times.

- Different depth segments allow us higher count rates.
- It makes Fast read outs thus shorter collection times. **(Aly et al., 2023)**

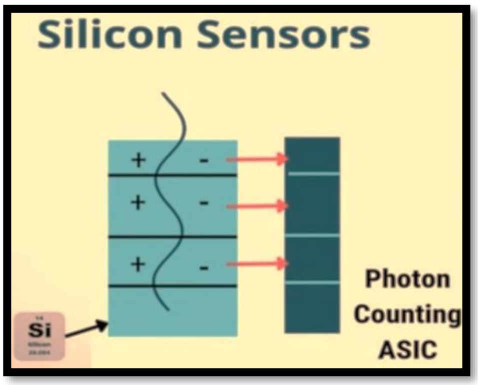

FIG.15 Silicon Sensors (Aly et al., 2023)

Clinical applications of PCCT

PCCT provides advantages in clinical cardiac, vascular, thoracic, musculoskeletal applications and clear visualization of temporal bone.

Primary factors of PCCT include;

a. Improved spatial resolution
b. Reduced noise and artefacts
c. Improved detection of smaller structures and subtle abnormalities.
d. Reduced radiation dose as well as contrast dose.
e. Cinematic rendering is done for more advanced view.

Cardiovascular Imaging:

- **Enhanced Visualization of Vascular Anatomy:** PCCT's superior spatial resolution and reduced noise allow for clearer depiction of small vessels, arterial walls, and stent structures, leading to more accurate assessment of coronary artery disease and stent performance.
- **Improved Stent Evaluation:** PCCT can help identify calcifications, assess stent strut dimensions, and reduce blooming artifacts, leading to a more accurate evaluation of intra-stent stenosis.
- **K-Edge Imaging:** PCCT's spectral capabilities allow for K-edge imaging, enabling the visualization of specific materials like titanium in stents, potentially aiding in differentiating them from calcifications. **(Michael et al., 2023)**

Thoracic Imaging:

- **Improved Detection of Pulmonary Lesions:** PCCT's high spatial resolution can facilitate the detection of small lung nodules, bronchiolar abnormalities, and vascular anomalies, improving the accuracy of diagnosis and staging.
- **Reduced Radiation Dose and Contrast Material Usage:** PCCT's improved dose efficiency can reduce radiation exposure for patients, making it a potentially more suitable option for paediatric and repeat scans. **(Symons et al., 2018)**

Abdominal Imaging:

- **Differentiating Renal Masses:** PCCT may improve the differentiation between simple cysts, complex cysts, and solid tumours in the kidneys, potentially enhancing accuracy in renal mass characterization.
- **Improved Evaluation of Abdominal Aortic Aneurysms:** PCCT's high spatial resolution can help visualize the aneurysm sac, assess plaque characteristics, and evaluate the extent of the aneurysm. **(Flores et al., 2025)**

Other Potential Applications:

- **Cancer Staging and Treatment Planning:**

PCCT's improved spatial resolution and contrast sensitivity could enhance the accuracy of cancer staging, tumour characterization, and treatment planning. **(Shah et al., 2025)**

- **Paediatric Imaging:**

PCCT's reduced radiation dose and improved image quality make it a promising option for paediatric imaging, where radiation exposure is a major concern. **(Stålhammar et al., 2024)**

- **Quantitative Imaging:**

PCCT's spectral capabilities and low noise levels enable the quantification of tissue properties, potentially leading to new diagnostic and therapeutic approaches.

CASE STUDY

Case I: This case presents a low-dose temporal bone CT scan in a paediatric patient, demonstrating the capability of ultra-high-resolution (UHR) imaging in visualizing minute anatomical structures. Despite the lower radiation dose (as shown by the DLP), the scan clearly reveals the stapes, one of the smallest bones in the human body. This highlights the diagnostic value of photon-counting CT (PCCT) or advanced CT systems in paediatric imaging, where minimizing radiation exposure is important. It Provides detailed temporal bone anatomy while ensuring patient safety through low-dose protocols. And High-resolution visualization of middle ear ossicles, including the stapes.

FIG.16 Low dose pediatric temporal scan (DLP) showing stapes (arrow) in ultra-high resolution (Rao et al., 2024)

Case II: An 85-year-old male underwent ultrahigh-resolution (UHR) coronary CT angiography (CCTA) using a photon-counting CT (PCCT) scanner. Despite a high Agatston score (4,162) and presence of a coronary stent, the imaging successfully provided diagnostic clarity of the coronary arteries**.** The 0.2-mm axial slices enabled detailed assessment of the coronary lumen, even in regions with heavy calcification. No significant obstructive coronary artery disease was identified. UHR CCTA offers excellent spatial resolution, overcoming calcification and stent-related artifacts, especially in elderly patients.

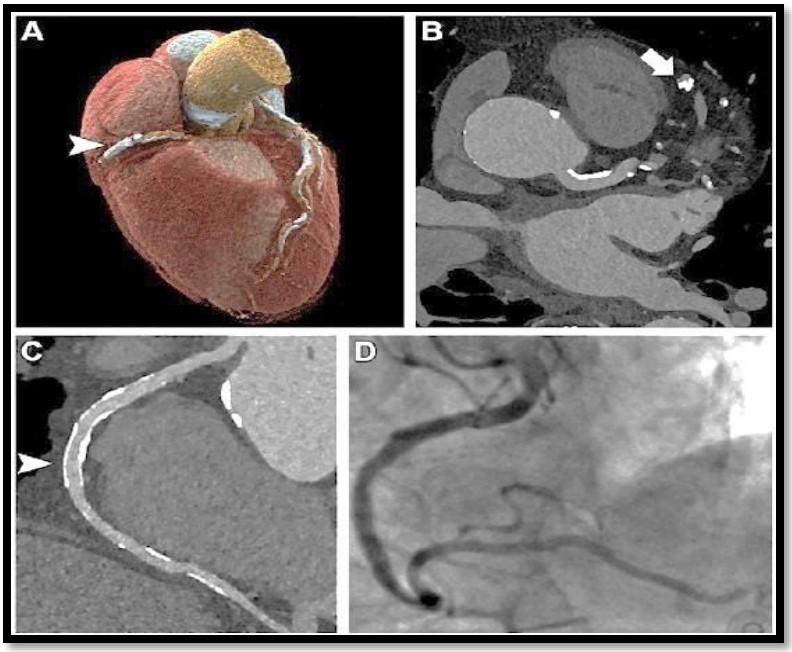

FIG.17 (Michael et al., 2023)

(A) Three-dimensional cinematic rendering of the heart. The stent (arrowhead) is visible in the middle segment of the right coronary artery.
(B) UHR CCTA with 0.2-mm axial sections. The lumen (arrow) of the severely calcified distal left anterior descending artery can be assessed without artifacts.
(C) Curved multi-planar reformations of the right coronary artery with a diagnostic display of the stent lumen (arrowhead).
(D) Invasive coronary angiography enables exclusion of in-stent stenosis.

Case III: A CT angiography (CTA) of the cervical and intracranial vessels was performed with a 50% reduction in contrast dose, still enabling visualization of a high-grade stenosis in the left posterior cerebral artery**.** This case exemplifies how advanced detector technology and image post-processing can maintain diagnostic image quality even with significantly reduced contrast medium, benefiting patients with renal impairment or allergy risk. It demonstrates the effective vascular imaging with half the contrast dose, reducing risk for contrast-induced nephropathy.

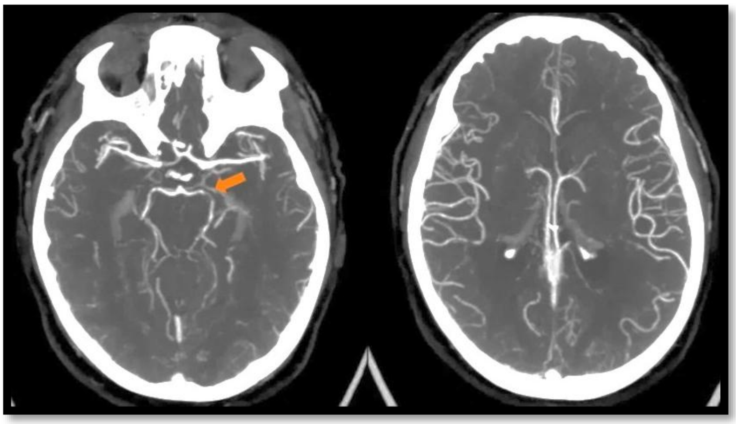

FIG.18 CT Angiography (Cademartiri et al., 2023)

Case IV: This case illustrates the power of **cinematic rendering** in **CT angiography of cervical and intracranial vessels**, producing **photorealistic 3D images** that enhance anatomical understanding and communication between radiologists, clinicians, and patients. This advanced visualization technique helps identify vascular pathologies and spatial relationships more intuitively. It offers improved perception of anatomical detail, supporting diagnostic accuracy and pre-surgical planning.

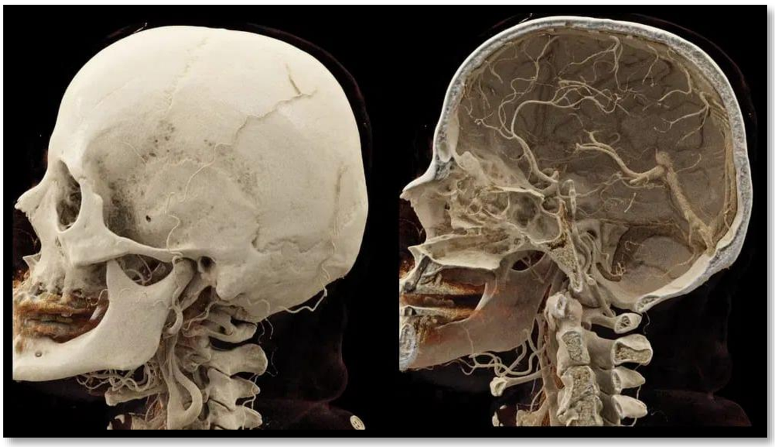

FIG.19 Cinematic rendering of CT Angiography (Cademartiri et al., 2023)

Discussion

Photon Counting Computed Tomography (PCCT) has introduced a transformative approach in medical imaging by addressing the limitations of conventional Energy-Integrating Detectors (EIDs). Traditional CT scanners measure the integrated energy of all incoming x-ray photons, leading to suboptimal spatial resolution, increased image noise, and challenges in distinguishing between tissues of similar densities **(Willemink et al., 2018)**. In contrast, PCCT uses photon-counting detectors (PCDs) that not only count individual x-ray photons but also discriminate them based on energy. This direct conversion process, typically enabled by cadmium telluride (CdTe) or cadmium zinc telluride (CZT) semiconductors, eliminates intermediate signal loss and significantly enhances image quality, signal-to-noise ratio, and soft-tissue contrast. **(Si-Mohamed et al., 2021; Leng et al., 2019)**

One of the most significant clinical advantages of PCCT is its ability to acquire spectral data during a single scan. This facilitates advanced material decomposition, virtual monoenergetic imaging, and reduction of beam-hardening artifacts, which are particularly beneficial in cardiovascular imaging and oncology **(Rajendran et al., 2021)**. For instance, spectral imaging allows for improved visualization of calcified coronary plaques and stent lumens, critical in assessing coronary artery disease. Additionally, virtual non-contrast imaging and iodine mapping help in reducing contrast load in vulnerable populations, such as patients with renal impairment. **(Brendel et al., 2021)**

Furthermore, PCCT achieves higher spatial resolution than standard CT, often reaching slice thicknesses as low as 0.2 mm, enabling the detection of subtle lesions, micro-calcifications, and fine anatomical structures. This high resolution, combined with low radiation dose, offers considerable benefits in paediatric imaging and screening programs where minimizing radiation exposure is paramount **(Pourmorteza et al., 2020)**. PCCT also mitigates electronic noise and improves contrast-to-noise ratio, thereby producing clearer images at lower dose levels, which supports its application in longitudinal disease monitoring and early diagnosis. **(Symons et al., 2020)**

Despite these promising advantages, several challenges remain. The high cost of PCCT systems, increased data processing requirements, and the need for optimized reconstruction algorithms represent hurdles to widespread clinical adoption **(Willemink et al., 2018)**. Moreover, large-scale multicentre studies are needed to validate the diagnostic efficacy of PCCT in diverse clinical scenarios. As such research progresses and hardware-software integration improves, PCCT is expected to evolve from a novel innovation to a standard imaging modality, particularly in areas demanding high-resolution, multi-energy, and low-dose imaging.

In summary, PCCT addresses the core limitations of conventional CT through technological innovations that significantly improve image quality, diagnostic accuracy, and patient safety. Its integration into radiological workflows is likely to usher in a new era of precision imaging thus enabling clinicians to visualize and characterize diseases more effectively than ever before.

Conclusion

Photon Counting Computed Tomography (PCCT) marks a significant evolution in the field of diagnostic imaging. Unlike conventional energy-integrating detectors (EIDs), PCCT utilizes photon-counting detectors (PCDs) that register individual X-ray photons and measure their energy with high precision. This technology results in improved spatial resolution, reduced electronic noise, and enhanced contrast-to-noise ratio, which are critical factors in clinical imaging, especially in cases requiring high image fidelity such as cardiovascular, pulmonary, and oncological diagnostics.

One of the major strengths of PCCT lies in its ability to perform spectral imaging without the need for dual-energy systems. This enables the acquisition of multi-energy data in a single scan, facilitating material decomposition and tissue characterization. As such, it opens the door for more accurate quantification of iodine, calcium, and other elements relevant in medical imaging, which is particularly useful in identifying and characterizing lesions and vascular structures.

Additionally, PCCT offers considerable dose reduction potential. By improving detector efficiency and minimizing noise, clinically valuable images can be obtained at lower radiation doses—an advantage particularly beneficial in paediatric imaging and repeated follow-up scans. Moreover, PCCT's high temporal resolution enhances cardiac imaging by capturing fine motion details of rapidly moving structures.

However, despite its significant promise, PCCT faces several practical and technical challenges. These include issues with detector calibration, charge sharing, pulse pile-up, and the high cost of PCDs. Integration into clinical workflows is also limited by the availability of commercial systems and the need for training in interpreting PCCT images. While early clinical trials and preclinical studies are promising, larger-scale validation is necessary to demonstrate the reproducibility and cost-effectiveness of PCCT in routine practice.

In conclusion, PCCT stands as a revolutionary technology that addresses many of the inherent limitations of traditional CT systems. With on-going advancements in detector technology and increasing clinical interest, PCCT is likely to become an integral part of modern radiological practice. Future research should focus on overcoming technical barriers, expanding clinical trials, and exploring novel applications across a range of medical specialties.

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