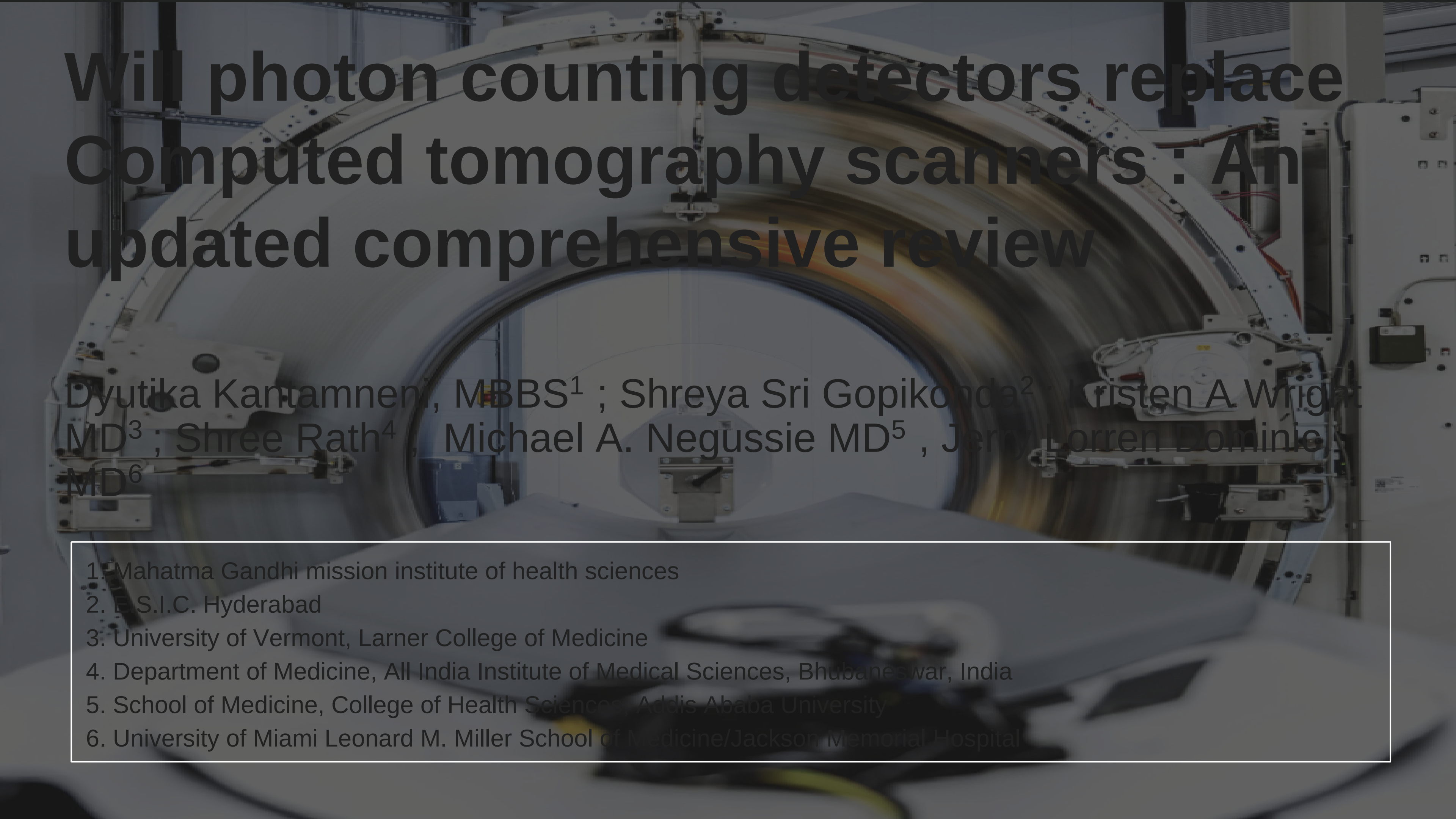


Will photon counting detectors replace Computed tomography scanners : An updated comprehensive review

Dyutika Kantamneni, MBBS[1] ; Shreya Sri Gopikonda[2] ; Kristen A Wright MD[3] ; Shree Rath[4] , Michael A. Negussie MD[5] , Jerry Lorren Dominic, MD[6]

1. Mahatma Gandhi mission institute of health sciences
2. E.S.I.C. Hyderabad
3. University of Vermont, Larner College of Medicine
4. Department of Medicine, All India Institute of Medical Sciences, Bhubaneswar, India
5. School of Medicine, College of Health Sciences, Addis Ababa University
6. University of Miami Leonard M. Miller School of Medicine/Jackson Memorial Hospital

DISCLOSURE STATEMENT…

Neither I nor my immediate family members have a financial relationship with a commercial organization that may have a direct or indirect interest in the content.

GOALS AND OBJECTIVES

- Advancements in application of photon counting detectors - computed tomography (PCD-CT) in the field of imaging various organ systems.
- Technological advancements in PCDs have improved spatial and spectral resolution, tissue contrast, and dose efficiency.
- Challenges such as photon pile-up, charge sharing, K-escape, and artifacts like beam hardening and blooming persist.
- Resolution to challenges and the future direction of use of photon counting detectors.

FUNDAMENTALS OF PCD

- PCDs eliminate the need for a scintillator layer by directly converting x-ray photons into electronic signals. This direct conversion process allows PCDs to avoid the mechanical separation between detector pixels required in conventional detectors.
- 3 main types of PCDs have emerged and each uses a unique material to maximize the benefits of direct photon detection:

1. **Single Photon Avalanche Diodes (SPADs)**

single photon avalanche diodes (SPADs) are sensors that can detect individual photons with precision. SPADs operate in Geiger mode. This mechanism provides SPADs with high photon detection efficiency (PDE) and low timing jitter

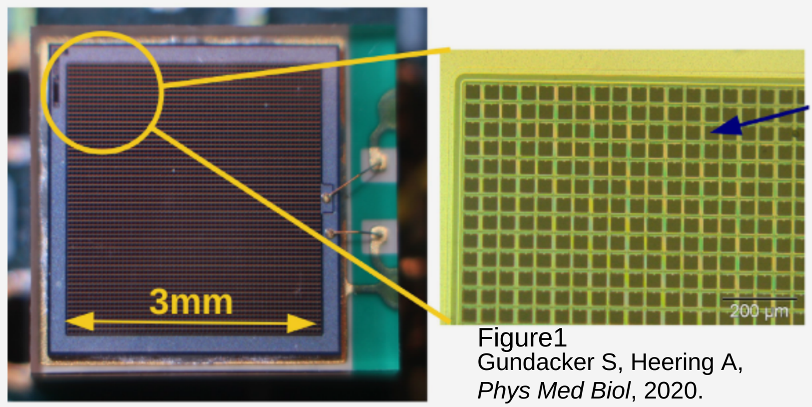


Figure1
Gundacker S, Heering A,
Phys Med Biol, 2020.

2. Silicon Photomultipliers (SiPMs) signals

Silicon photomultipliers (SiPMs) are arrays of SPADs that form a highly sensitive photodetector. These devices can operate in analog or digital modes. In analog mode, from all SPADs are summed. In digital mode, each SPAD is read out individually. SPiMs are known for their high PDE, low operating voltage, and robustness. This makes them ideal for applications requiring precise light detection . SiPMs are used in time of flight positron emission tomography (TOF-PET). This application benefits from SPADs' ability to capture very low light levels.

3. Microchannel Plates (MCPs)

A microchannel plate (MCP) is a detector with many tiny electron multipliers. These multipliers are aligned parallel and amplify signals by multiplying electrons. MCPs excel in photon counting applications. They are particularly effective in detecting low-energy photons like visible light and soft x-rays. This capability is crucial in biomedical imaging techniques. These include Fluorescence Lifetime Imaging and Förster Resonance Energy Transfer. Both are used in biological imaging and medical diagnostics.

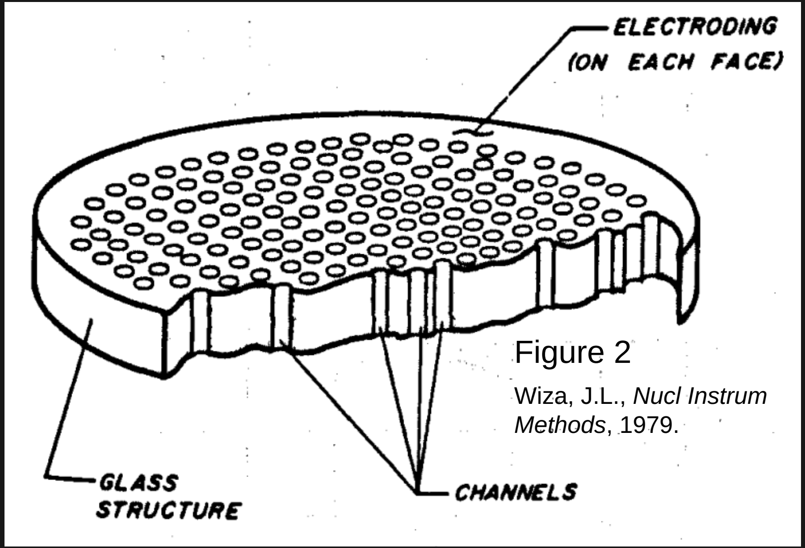


Figure 2

Wiza, J.L., *Nucl Instrum Methods*, 1979.

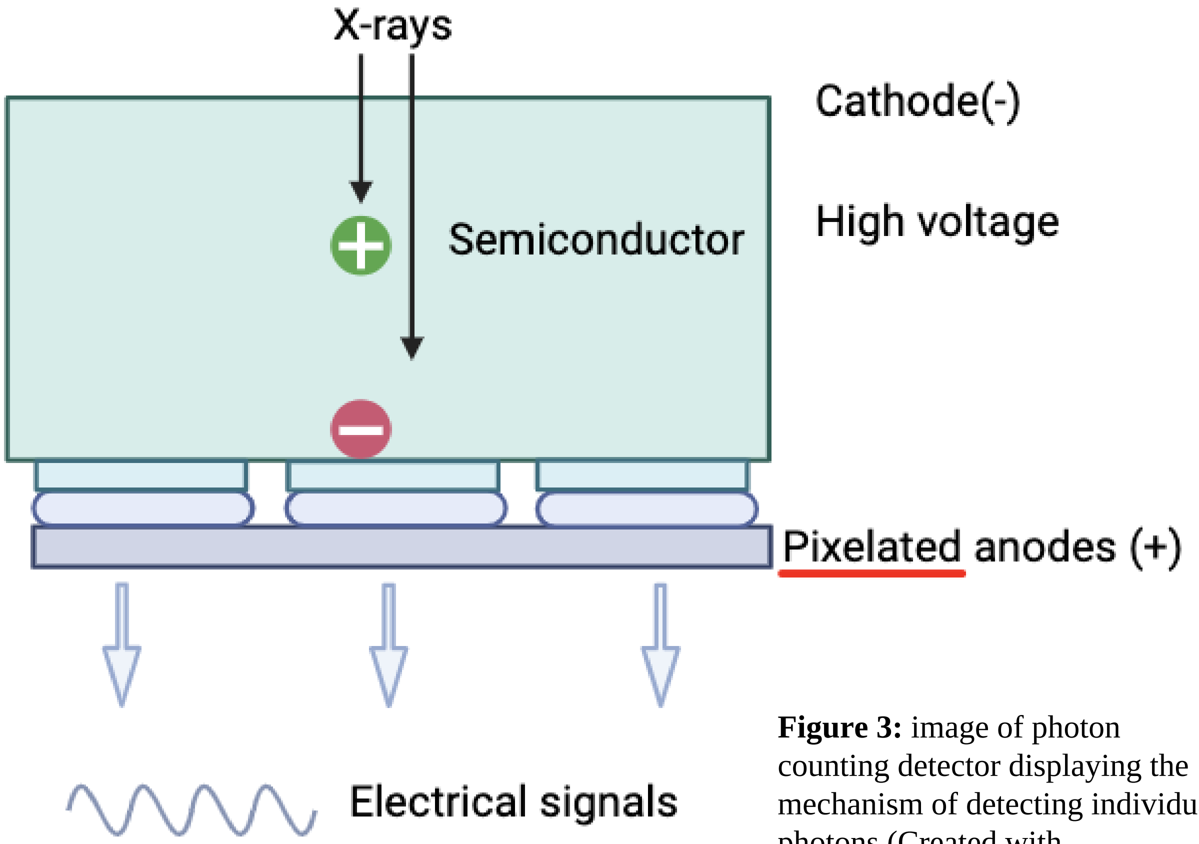


Figure 3: image of photon counting detector displaying the mechanism of detecting individual photons.(Created with BioRender.com.)

APPLICATIONS AND TRIALS

1. Photon Counting Detectors (PCDs) represent a transformative advancement in radiological imaging, significantly enhancing image quality and radiation dose management across various clinical scenarios.
2. The incorporation of spectral imaging and photon-counting detectors into computed tomography (CT) has notably propelled diagnostic radiology forward.

CARDIOVASCULAR IMAGING

1. Notably high-resolution images of cardiovascular structures at reduced radiation doses, reduction of blooming artifacts from calcified plaques in coronary artery imaging across multiple studies
2. McCollough et al. demonstrated that the CAC volume and Agatston scores of dual source PET-CT were significantly higher than EID-CT
3. Sharma et al. evaluates the accuracy of virtual non- contrast (VNC) and virtual non iodine (VNI) reconstructions in photon-counting CT (PCCT) for CAC scoring, using true non-contrast (TNC) images as the reference. Conventional VNC was seen to underestimate TNC scores when assessing aortic valve calcium scoring by 74%, whereas in calcium preserving VNC (VNC$_{\text{pc}}$) with 0.4 mm sliced, Br36 kernel and QIR 4 the results were comparable showing promise to replace TNC.

Figure 4. PCD-CT coronary without (A) and with multi-energy post-processing (B) using an algorithm that performs material decomposition and removes calcium signal. The post-processed image (B) shows the patent lumen adjacent to the heavily calcified plaque (arrowhead). [8]

4. The study demonstrated that optimal quality for coronary plaque characterization and vessel lumen delineation can be achieved using a Bv64 kernel, with a field of view (FOV) of 200 × 200 mm², and a matrix size of 512 × 512 pixels
5. On comparing the calcium scoring, mitral annular calcium scores, aortic valve calcium scores between a 66 ms using dual source information and 125ms using a single source information, the lower temporal resolution had increased motion artifacts leading to overestimation of patient risk.
6. After coronary angioplasty with stent placement, ultra-high resolution (UHR) reduced blooming artifacts, improving the lumen visualization, which is essential to rule out restenosis
7. In a retrospective study of patients with suspected coronary artery disease (CAD) underwent coronary CT angiography (CCTA) with either PCD-CT or EID-CT, the rate of invasive coronary angiography (ICA) was lower with PCD-CT

ONCOLOGY IMAGING

1. PCDs are particularly effective in identifying and characterizing small tumors, with studies showing improved detection rates in pancreatic and liver cancers. This capability is instrumental in staging cancer and planning appropriate treatment strategies. PCDs have been shown to improve the differentiation and quantification of different tissue types.

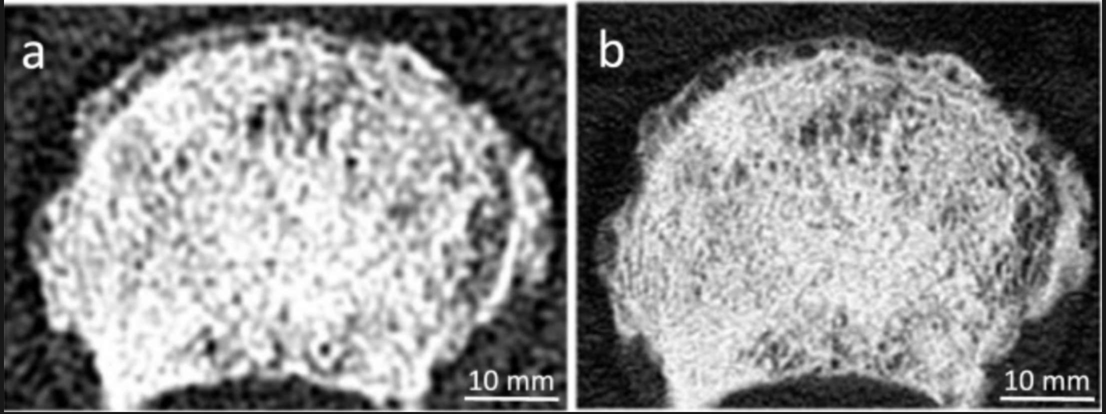


Figure 5. Images of osteoplastic metastasis of 5th lumbar vertebra, visualized by conventional CT (a) and PCD-CT(b).
Source: Wehrse E, Sawall S, Klein L, et al. Potential of ultra-high-resolution photon-counting CT of bone metastases: initial experiences in breast cancer patients. Npj Breast Cancer. 2021;7(1). doi:10.1038/s41523-020-00207-3

Proton radiation therapy is one the new booming treatment modality whose accuracy and precision of targeting cancerous tissue is dependent on Bragg's peak of protons. CT image data plays an important role in determining proton stopping power ratio that is essential to concentrate high dose beams to the tumor. These images were used as input for a deep learning based neural network model to evaluate SPR maps and assess the root mean square of errors (RMSE) which are found to have been significantly reduced in comparison with dual energy CT (DECT). This can essentially pave a new path to assess the beam range uncertainty improving specificity toward tumor emphasizing the fact that proton radiation therapy is a common indication for tumors involving the Central nervous system involving delicate and important organs making specificity of paramount importance .

NEUROIMAGING

1. Klempka et al. describe using PCCT with spectral imaging to differentiate between arterial and venous circulation based on the attenuation of the cavernous sinus (CS) and carotid artery(CA) confluence. At 67keV and other phases of imaging, CS had a higher attenuation than CA. This can enhance our ability to diagnose conditions like hemorrhages and extravasation and improve the management of neurovascular conditions.
2. The role of PCD-CT myelography in improving the detection of CSf-venous fistulas.
3. Pituitary adenomas that are resected surgically according to image findings and PCD-CT can better demarcate the adenomas, which can be missed in up to half of patients when read with conventional MR imaging.
4. In an RCT on phantom aneurysms were clipped and assessed with PCD-CT and qualitatively evaluated the outcomes and location of clip placement, which is crucial in assessing post-surgical outcomes in complex neurosurgical procedures. The reduction of artifacts in PCD-CT is a key factor that allows for improved visualization of the surgical results, enhancing the overall effectiveness of the surgical technique.

EAR, NOSE, THROAT

1. Congenital anomalies of the ossicular chain, ossicular chain dislocation, tympanosclerosis, and cholesteatoma are essential causes of hearing loss, and these minute structures are visualized with PCD-CT, especially in 3D images. During visualizing pediatric temporal bones, PCD CT decreased the radiation dose by 43% compared to EID-CT, with almost 70% reduction in subgroups of children under six years, and improved structure visualization .

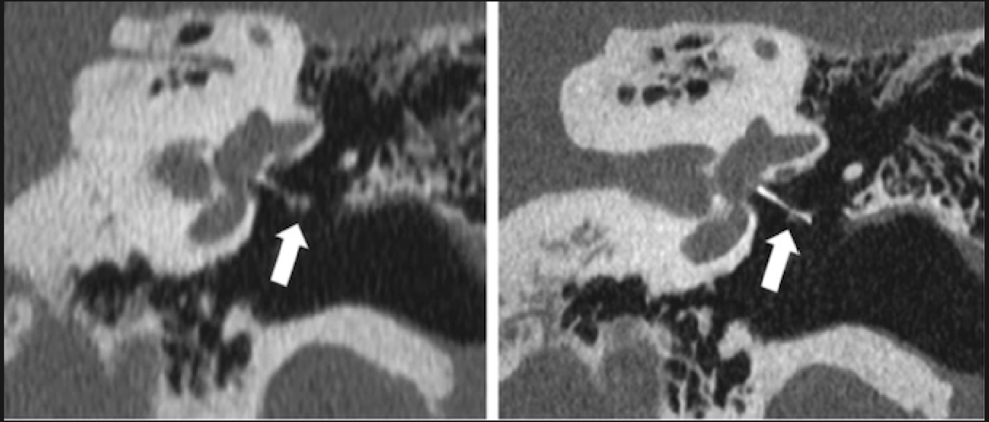


Figure 6. Temporal bone imaging at EID-C (A) and PCD-C (120kV PCD image comprising 20-120 keV photons, B), a stapes prosthesis (solid white arrow) is much better delineated on online coronal images using PCD with 0.2-mm slice thickness (B) than EID -C with 05 mm slice thickness(B); the radiation dose was lower for PCD than EID (36 vs 56 mGy, respectively).[8] [[5]

PULMONARY IMAGING

Reduced iodinated contrast in computed tomography pulmonary angiography (CTPA) and PCCT can be visualized, and the reduced doses did not affect the image quality. It was equally good, with no effects on the mean attenuation between different doses of reduced contrast .

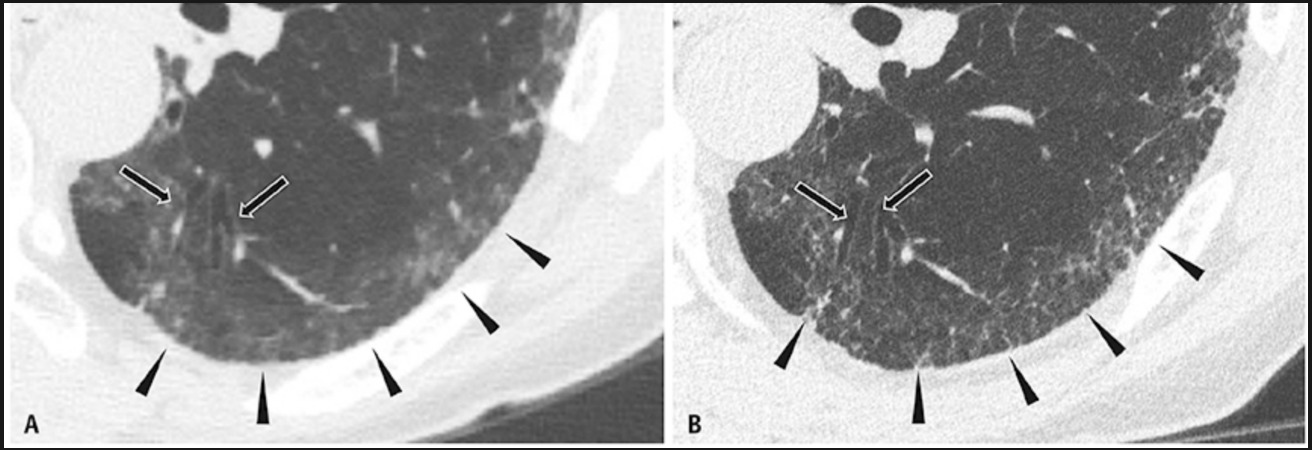


Figure 7. idiopathic non-specific interstitial pneumonia was scanned on conventional energy-integrating detector CT **(A)** and investigational PCD-CT **(B)** . **A, B.** PCD-CT demonstrates fine reticulations (arrowheads, **B**) in the right subpleural right lower lobe, compared to conventional CT, which appears to show ground glass opacities in this region (arrowheads, **A**). PCD-CT more sharply displays traction bronchiectasis than conventional CT (arrows). [8]

SOFT TISSUE

1. Diagnosed breast cancer had a better higher inter-reader reliability, and the number of tumor masses and diagnostic accuracy of T-classification was higher with PCD-CT, thus providing higher diagnostic precision and aiding in patient management. Degenerative changes and rupture of silicone breast implants and distinct contrast properties are better visualized in thoracic PCCT.
2. In a retrospective analysis by Jungblut et al., photon counting detectors showed significant promise in enhancing the diagnostic accuracy of pleural empyema, a serious infection in the pleural space with a high morbidity rate. Through the use of low monoenergetic image (VMI) energies and iodine maps, PCD-CT markedly improved the differentiation between pleural empyema and non-infectious pleural effusion. This differentiation allows for implementation of early intervention and informs treatment decisions, allowing the prevention of extensive and invasive surgeries.
3. By providing higher contrast-to-noise ratios at lower VMI energies, PCDs enable clearer and more detailed images, which are essential for accurately diagnosing and effectively managing various soft tissue disorders.

ABDOMEN AND PELVIS IMAGING

1. A virtual non-contrast reconstruction for adrenal lesions on a dual source PCD-CT by Stefanie et al. successfully differentiated the adrenal metastasis and adenomas by adjusting the attenuation thresholds. The dose of contrast was reduced in abdominal images acquired in the portal venous phase to compare the quality of images produced by PCD-CT and EID-CT.
2. The response of Rectal cancers(RC) with neoadjuvant radiochemotherapy (NARC) is quantified using iodine concentration (IC) on PCCT. Tumors that have increased lymphovascular invasion had higher normalized iodine concentration (NIC). IC may indicate tumor microvascular density and permeability. Thus, NIC can also help predict treatment response and be an imaging biomarker in RC.

4. Our comparison of various parameters of abdominal arteries using 50 and 70 keV virtual monoenergetic images (VMI) on PCCT revealed a significant finding . The visibility of more distal branches and collaterals was markedly improved, and the SNR and CNR of the arteries were found to be enhanced with low keV . This discovery underscores the potential of low keV to revolutionize vascular imaging and delineation of vessels for managing surgeries, masses, and transarterial chemoembolization.

5. Haag et al. highlight the potential of photon-counting computed tomography (PCCT)-derived virtual non-contrast (VNC) reconstructions as a substitute for true non-contrast (TNC) sequences in abdominal imaging, particularly in scenarios where TNC sequences are unavailable . While VNC images can approximate the density values of TNC images in various tissues, including parenchymal organs and muscles, there are limitations, especially in evaluating adipose and calcified structures.

6. PCDs excel in K-edge imaging, which significantly improves the visualization of contrast agents in abdominal studies. By exploiting discontinuities at specific energy levels of the X-ray spectrum, PCDs precisely localize and quantify high-Z element-based contrast agents like iodine.

MUSCULOSKELETAL IMAGING

1. The revolution of PCD-CT also triggered a challenge on its imaging capabilities concerning in-vivo quantification of trabecular microstructure of human bone.
2. G. Shi et al. worked to assess PCD-CT’s which supports the possibility of using PCCT for microstructural evaluation in lumbar spine and hip, which at present are inaccessible via in-vivo high resolution bone imaging technologies,which can help in determining prognosis of osteoporosis.

TECHNOLOGICAL ADVANCEMENTS

1. Photon-coupling spectral CCT improves spatial resolution, spectral resolution, tissue contrast, and dose efficiency.

2. The ability of PC-CT in material decomposition allows its use in multi-contrast enhanced studies and anatomical and even cellular imaging.

3. Contradictory to multiple studies showing potential use of different contrast agents like gadolinium like use of SPCCT in atherosclerotic rabbits for visualization of arteries, Baubeta E et al. displayed that no K-edge potential was offered by gadolinium contrast over iodine at levels approved for human use.

CHALLENGES AND LIMITATIONS

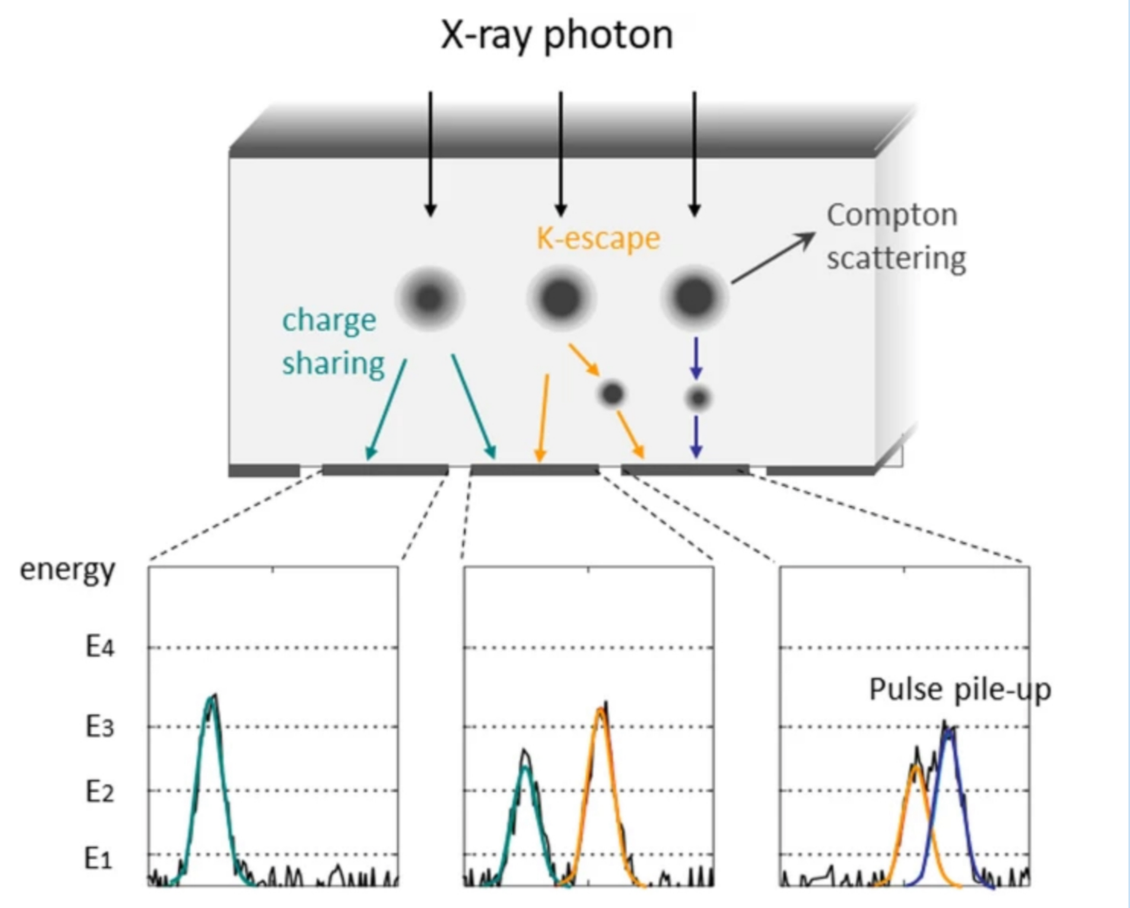
Challenges faced by current PCD systems are mainly due to cost, availability and other technical limitations and artifacts :

1. Pulse pile-up, charge sharing and K-escape form an inseparable triad of errors occurring in modern day PCD systems. While increasing pixel size can correct K-escape and charge sharing, pulse piling increases. Thus, a balance must be struck while designing these systems. On the other hand, correction models have been introduced for counteracting pulse pile up and charge sharing.

2. Streak and blooming artifacts are other limitation of PCD-CTs, especially in the domain of cardiovascular imaging, Calcification and use of iodine based contrast media contribute to these artifacts. Wolf et al proposed the use of reconstructed virtual monoenergetic imaging systems for correction of bloom artifacts.

3. Dual layer-spectral CTs are an important innovation, countering both streak and iodine artifacts. Efficacy has been demonstrated in liver CT models by Grosu et al.

4. Denoising is essential to improve image quality; integration of 2D and 3D images can help counter this and improve quality greatly (Clark et al.)


X-ray photon
K-escape
Compton scattering
charge sharing
energy
E4
E3
E2
E1
Pulse pile-up

CONCLUSION

- Introduction of Photon counting detector into medical imaging brought with it great advancements in accuracy, visualization and resolution of images.
- Its applicability and superiority to conventional systems has been proven in multiple domains of medicine
- Certain issues still prevalent in these systems include cost constraints, sensitivity and technical limitations. Future studies should strive to address these limitations, and introduce modifications to make PCD-CTs an accessible and widely utilized resource.

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