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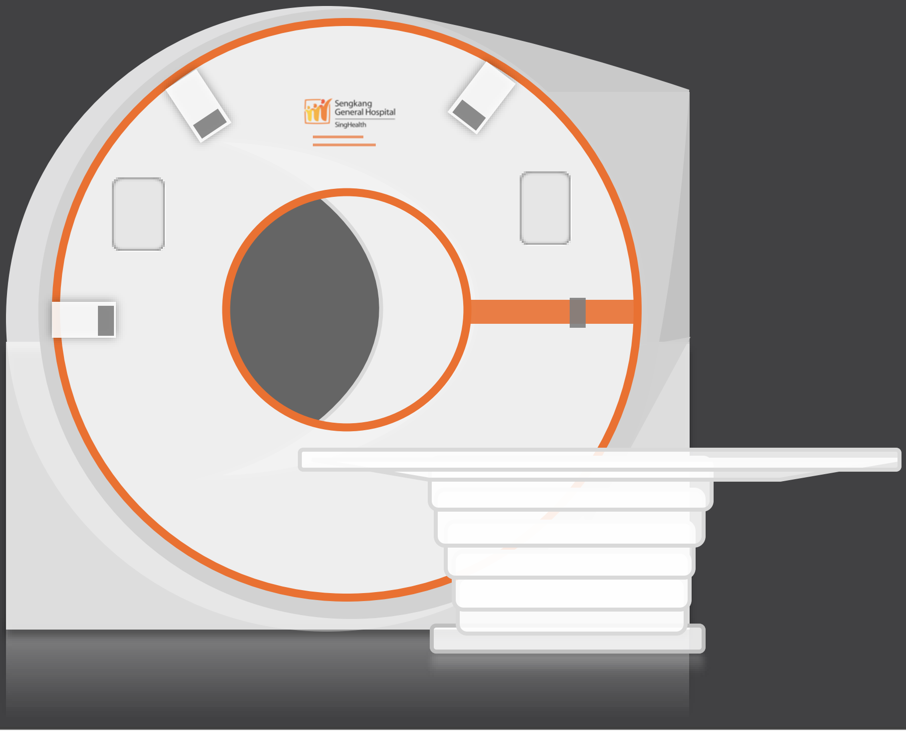
Defining Tomorrow's Medicine

RSNA 2024
Building Intelligent Connections

Photon Counting Computed Tomography (CT)

What Do We Know and What Can We Expect?



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Non-Disclosure

All authors declare that they have no financial relationships.

Teaching Points

1. Explain the **technology** underpinning Photon Counting CT and discuss the **differences** compared to currently available CT technology.

2. Discuss the **advantages** and **clinical applications** of Photon Counting CT scanners.

3. Discuss **potential challenges** to consider before obtaining a Photon Counting CT scanner.

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Learning Objectives

1. Overview of Photon Counting CT technology
2. Differences compared to current CT technology
3. Advantages and Clinical applications
4. Potential Challenges of a Photon Counting CT scanner

Learning Objectives

1. **Overview of Photon Counting CT technology**
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Evolution of CT Scanner Technology

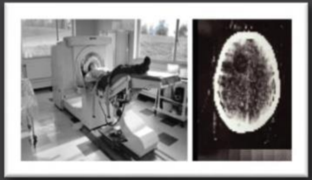
1. **Overview of PCT**
2. Comparison with current CT
3. Advantages & applications
4. Potential Challenges

Discovery of X rays by Wilhelm Conrad Roentgen[i]

1895

Invention of the first CT scanner by Dr Godfrey Hounsfield[ii]

1967



Installation of the first commercial CT scanner in Atkinson Morley's Hospital, London[iii]

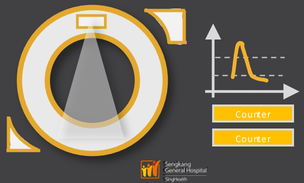
1971

Introduction of Helical CT

1980s

Creation of Dual Energy CT

2010s



Introduction of first photon counting CT by Siemens Healthineers, obtaining FDA* clearance in 2021

2021

* USA Food and Drug Administration

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Learning Objectives

1. Overview of Photon Counting CT technology
2. **Differences compared to current CT technology**
3. Advantages and Clinical applications
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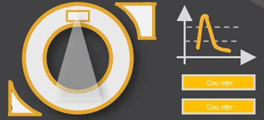
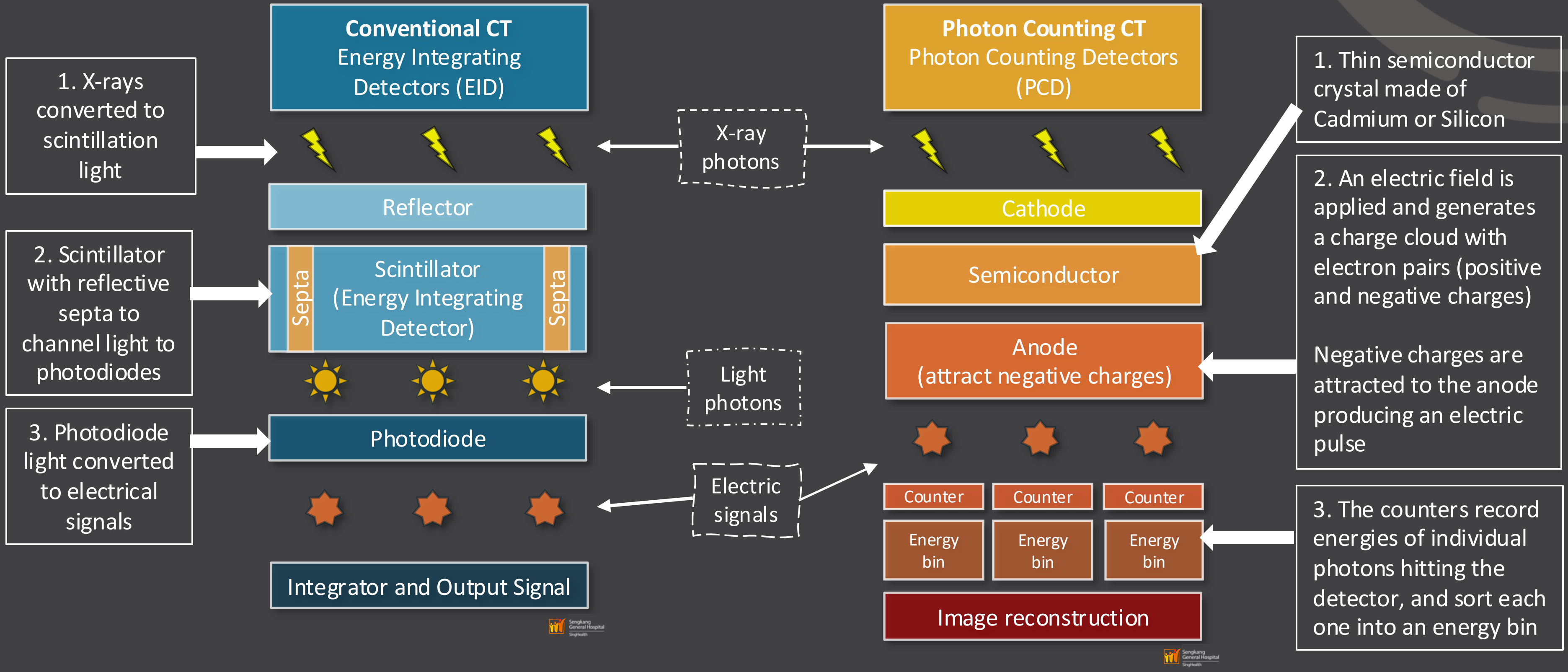
Differences between CT technology

1. Overview of PCT
2. **Comparison with current CT**
3. Advantages & applications
4. Potential Challenges

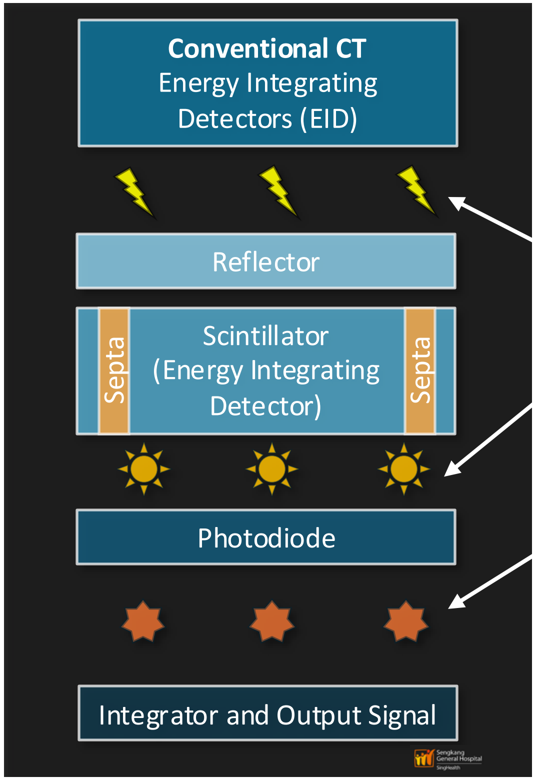
	Conventional CT 	Dual Energy CT 	Photon Counting CT 
a) Detector	Energy integrating detector (EID)	EID scans at two X-ray levels (high and low)	Detectors stratify protons by energy levels, allocating them to energy bins
b) Image	X-rays pass through different tissue densities, producing different shades/attenuation	Materials can be differentiated based on energy dependent attenuation profiles	Materials can be differentiated based on spectral signatures
c) Radiation	May require high doses with higher body mass index	May have higher dose than conventional CT	More efficient, can produce higher resolution with reduced dose

Schematic diagram for comparison

1. Overview of PCT
2. **Comparison with current CT**
3. Advantages & applications
4. Potential Challenges



Schematic diagram of *Conventional CT*



Two step process

How do current CT scanners work?

1. Current CT scanners have **energy integrating detectors (EID),** also known as **scintillators.**
2. X-rays photons go through reflectors and hit the scintillator.
3. X-rays photons are converted to **visible light photons** .
4. The **reflective septa** of scintillators channel light to **photodiodes**.
5. Photodiodes record the incoming light photons and **produce an electrical signal that is proportional** to the total energy deposited over an interval of time.
6. The image generated from the combined electrical signals.

Schematic diagram of *Photon Counting CT*

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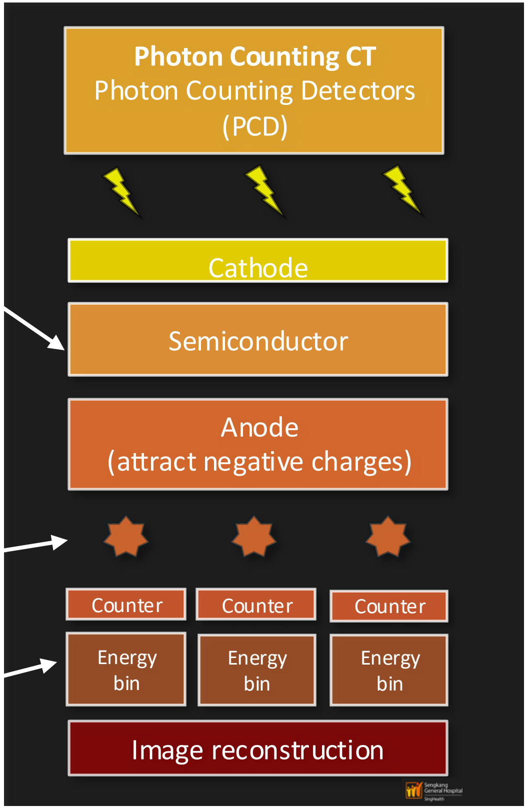
How do Photon Counting CT (PCT) scanners work?

1. PCT have **photon counting detectors** instead of EIDs.
2. The X-ray photons first encounter a **single thick semiconductor layer**, which has electricity running across it.
3. The electrical voltage causes the X-ray photon to **generate positive and negative charges** which are forced to separate rapidly.
4. The **cathode** and **anode** attract the positive and negative charges respectively.
5. This produces an **electrical pulse** with a **height proportional to the energy deposited** by the photon.
6. Photon counting detectors record and sort each pulse into respective **energy bins** based on their energy level.

One step process



Learning Objectives

1. Overview of Photon Counting CT technology
2. Differences compared to current CT technology
3. **Advantages and Clinical applications**
4. Potential Challenges of a Photon Counting CT scanner

Learning Objectives

1. Overview of Photon Counting CT technology
2. Differences compared to current CT technology

3. Advantages and Clinical applications

4. Potential Challenges of a Photon Counting CT

a. Higher Spatial Resolution
b. Reduced Electronic Noise
c. Artefact Reduction
d. Higher Dose Efficiency
e. Enhanced Material Differentiation
f. Reduced Contrast Requirements

Higher Spatial Resolution

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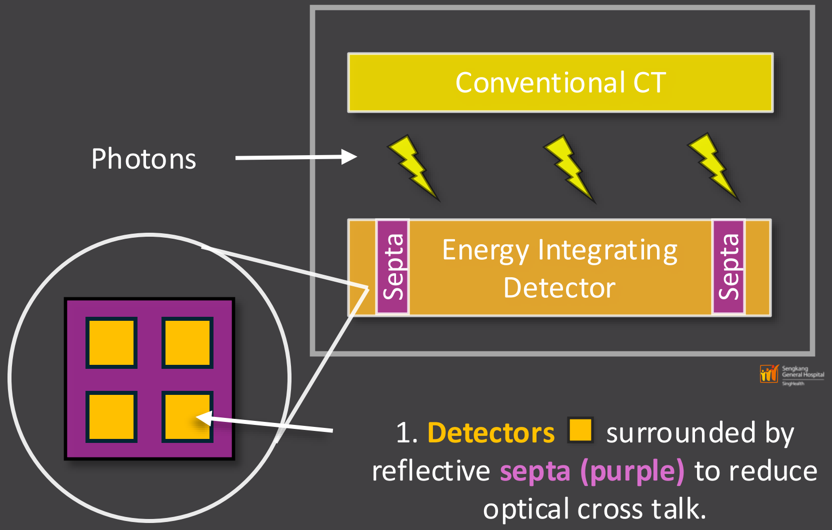
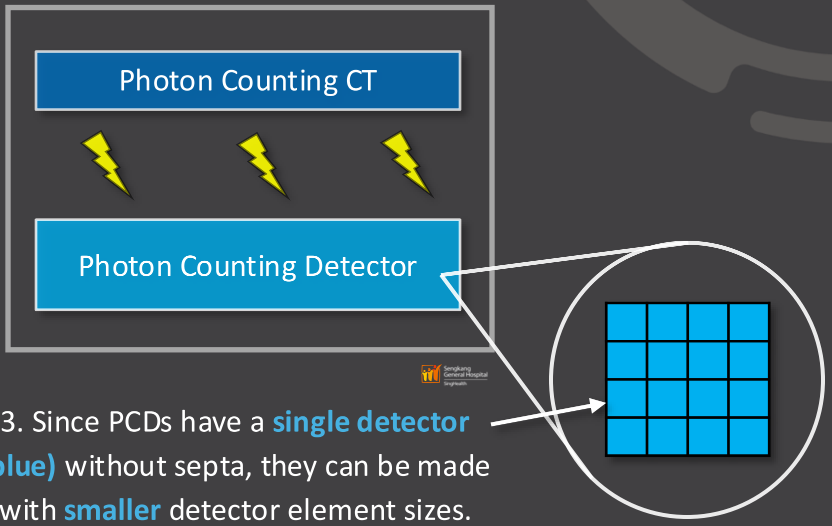


1. **Detectors** surrounded by reflective **septa (purple)** to reduce optical cross talk.

2. Presence of septa increases pixel size, causing **poorer resolution**.

Only able to achieve resolution of **0.3 - 0.6 mm**[iv].



3. Since PCDs have a **single detector (blue)** without septa, they can be made with **smaller** detector element sizes.

4. This decreases pixel size and **improves spatial resolution**.

Maximum spatial resolution of **0.11 – 0.16 mm.**

Application in CT temporal bone

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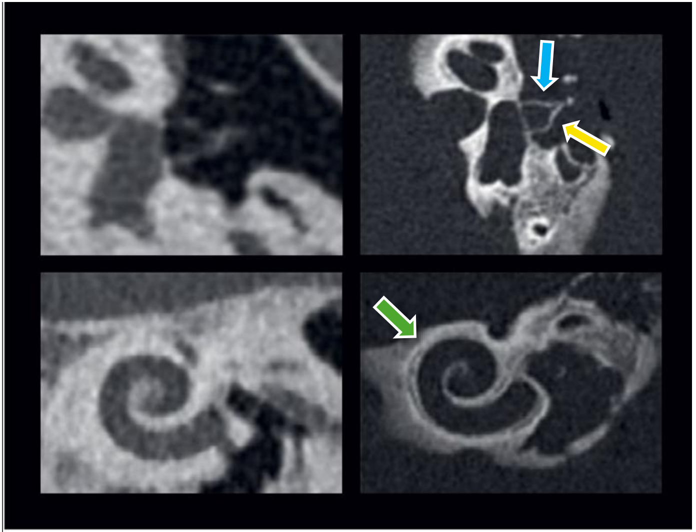

Figure 7: Ultra-high resolution image of inner ear specimen displaying stapes bone (top row) and cochlea (bottom row) acquired with EID-CT using 0.4 mm collimation (left column) and PCD-CT using 0.2 mm collimation (right column)
Image Courtesy of A. Persson, University Linkoeping, Linkoeping, Sweden

1. The inner ear has typically been a **challenging region for imaging** due to the tiny and delicate anatomical structures, such as the **auditory ossicles and joints** [v,vi].

2. The figure on the left demonstrates the superior resolution of PCT for the **cochlea (green),** the **anterior crus of the stapes (blue)** and the **posterior crus of the stapes (yellow)**.

3. With PCT, better visualization is even possible with **lower radiation doses up to 31%**[vii].

4. In conclusion, PCT can obtain thinner slices with higher spatial resolution and lower radiation doses, proving useful for difficult anatomical regions.

Images from the White Paper for NAEOTOM Alpha for Cardiac CT by Siemens Healthineers.

Application in CTCA

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1. CT Coronary Angiography (CTCA) is also **challenging to perform** due to heart motion and high spatial resolution requirements[viii].

2. The figure below demonstrates **high resolution** and **reduced blooming artifacts (orange arrows)** on CTCA.

3. This is essential in accurately evaluating coronary artery stenosis **without overestimation.**

4. PCT is also superior in detecting **non-calcified** and **lipid-rich** plaques[ix], which can better risk stratify patients with **unstable atherosclerosis.**

5. Lastly, there is potential to eliminate the need for **betablockers** or **mitigate motion artifacts** from breathing or high heart rates.

Figure 6: In the image reconstructed with standard resolution (Bv40, 0.6 mm) (Fig. 6a), only calcified plaques are visible in the distal segment 3 of the RCA. In the UHR image (Bv64, 0.2 mm) (Fig. 6b), a fibrous cap beneath the calcified plaque is visualized, due to reduced calcium blooming. OCT correlation (Fig. 6c) of the same plaque confirms the plaque composition. *Courtesy of Johannes Gutenberg University Medical Center, Mainz, Germany.*

Images from the White Paper for NAEOTOM Alpha for Cardiac CT by Siemens Healthineers.

Less Electronic Noise

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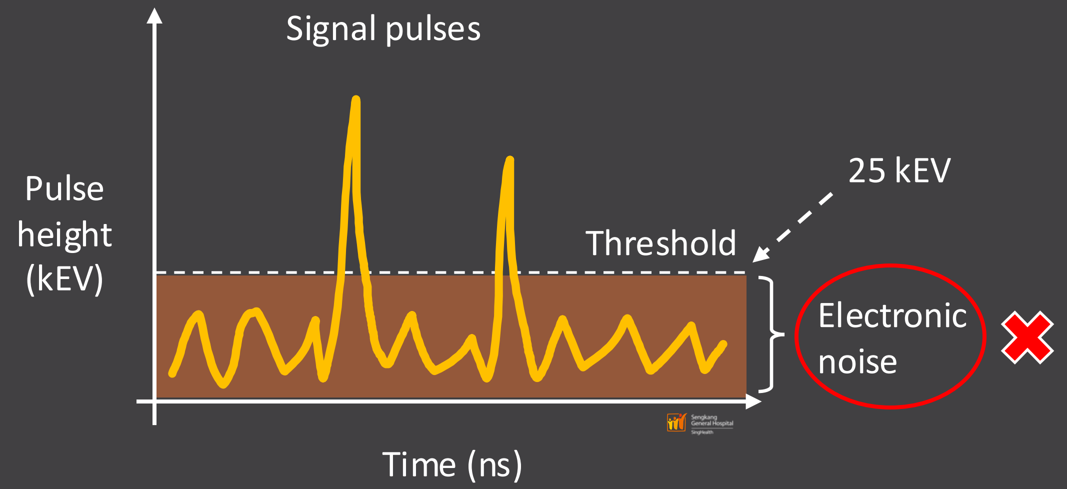

1. X-ray photons with energy levels **less than 25 keV** will fall below the threshold and be **treated as noise.**

2. Images have less noise and improved **contrast to noise ratio** (CNR)[x].

3. Potential to **reduce the radiation dose** while preserving image quality.

Artefact Reduction

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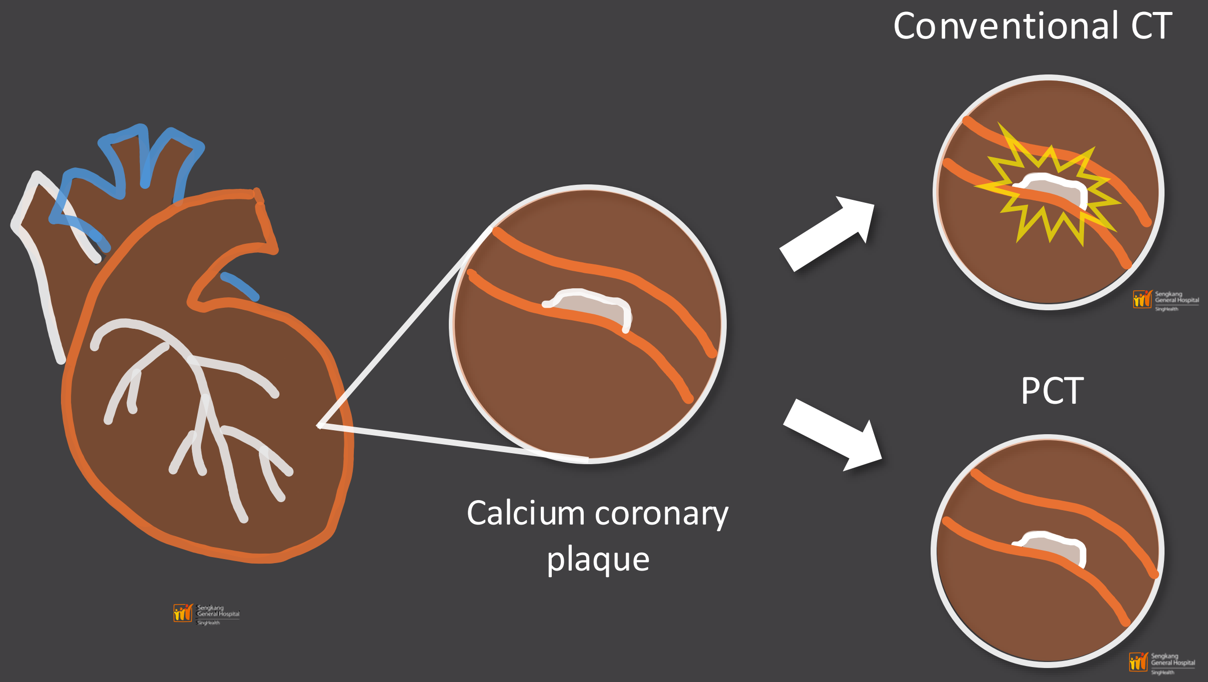


1. The **high density** of calcium and metal stents distort reconstructed images and appear as **blooming artifacts**[xi].

⬇

Calcifications and stents appear bigger, resulting in coronary lumens **falsely appearing smaller.**

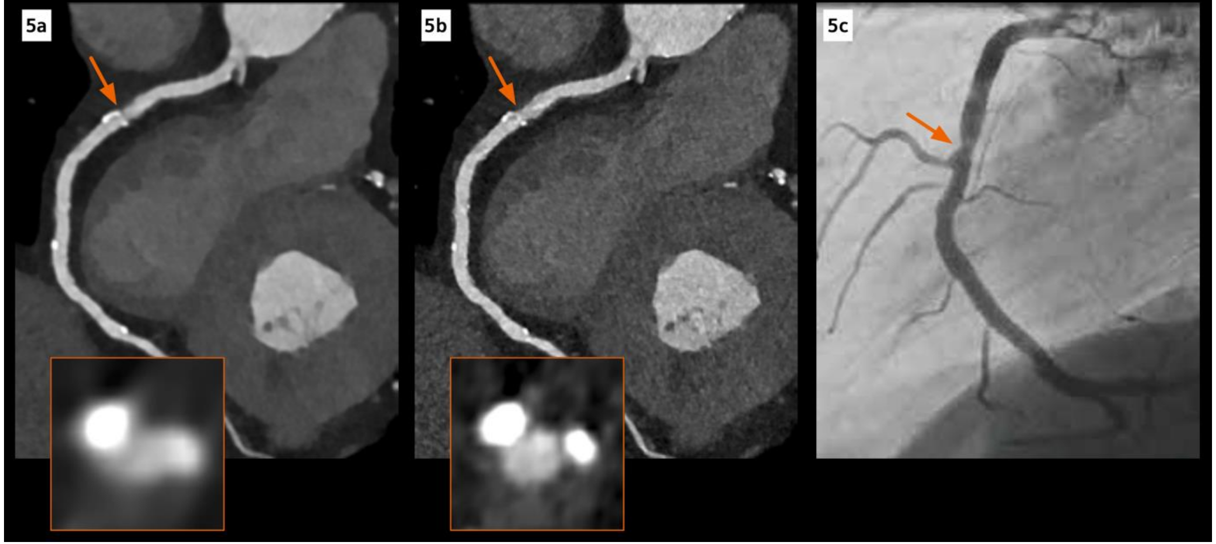
2. **Tin filters** shape incoming X-ray beams, reducing blooming artifacts.

⬇

More **accurate grading** of stenosis[xi].

Application in CTCA

Figure 5: Curved MPR images (Figs. 5a & 5b) show a proximal RCA stenosis caused by calcified plaques (arrows). Images are reconstructed at 0.6 mm with kernel Bv40 (Fig. 5a) and at 0.2 mm with kernel Bv60 (Fig. 5b). The corresponding axial slices, perpendicular to the vessel centerlines at the stenosis, are shown in the left lower corners. The blooming effect of the calcified plaques affecting the visualization of the vessel lumen and the stenosis grading is clearly reduced in the UHR images. An invasive catheter coronary angiography (Fig. 5c) confirmed a mild stenosis in the proximal RCA (arrow) consistent with the result from the UHR image evaluation.
Courtesy of University Hospital Zurich, Switzerland.



PCT has **reduced blooming effect** and **thinner slices** (0.2mm)

⬇

More accurate assessment of **intraluminal stenosis (orange arrows)** and graft assessment in **post-CABG patients**

⬇

Reduces the need for invasive coronary angiography.

Images from the White Paper for NAEOTOM Alpha for Cardiac CT by Siemens Healthineers.

Application in stent evaluation

1. Overview of PCT
2. Comparison with current CT
3. **Advantages & applications**
4. Potential Challenges

a) Higher Spatial Resolution
b) Reduced Electronic Noise
c) **Artefact Reduction**
d) Higher Dose Efficiency
e) Enhanced Material Differentiation
f) Reduced Contrast Requirements

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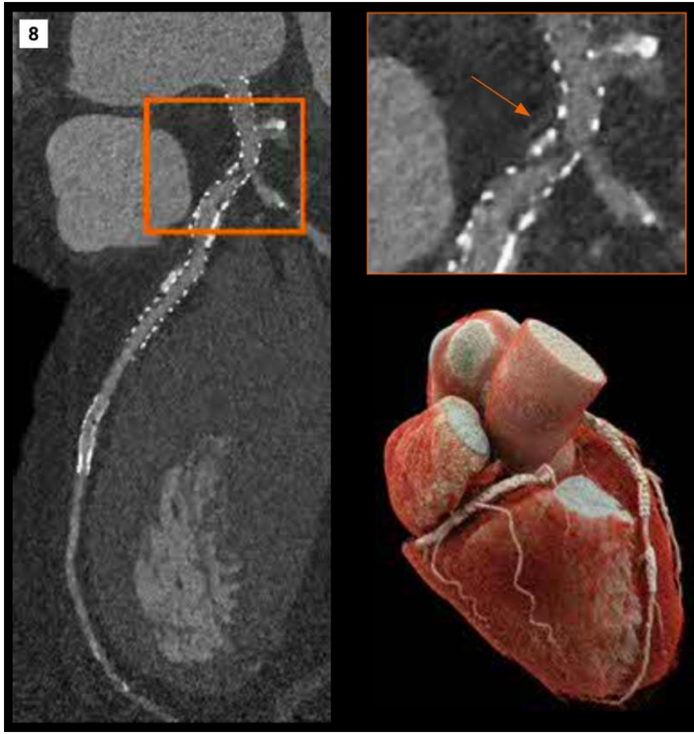


Severe in-stent restenosis at the ostium of the LAD

Figure 8: Stent imaged in Quantum HD Cardiac mode (Bv72, 1024 × 1024, QIR 4, 0.2 mm slice thickness) on NAEOTOM Alpha, demonstrating in-stent restenosis. The patient underwent coronary stent implantation multiple times and had 8 stents implanted in total in the left and right coronary arteries. The orange arrow shows a focal, severe in-stent restenosis at the ostium of the LAD. *Courtesy of Semmelweis University Hospital, Budapest, Hungary.*

This figure demonstrates how PCT produces **fewer metal artifacts** and beam hardening from stents.

⬇

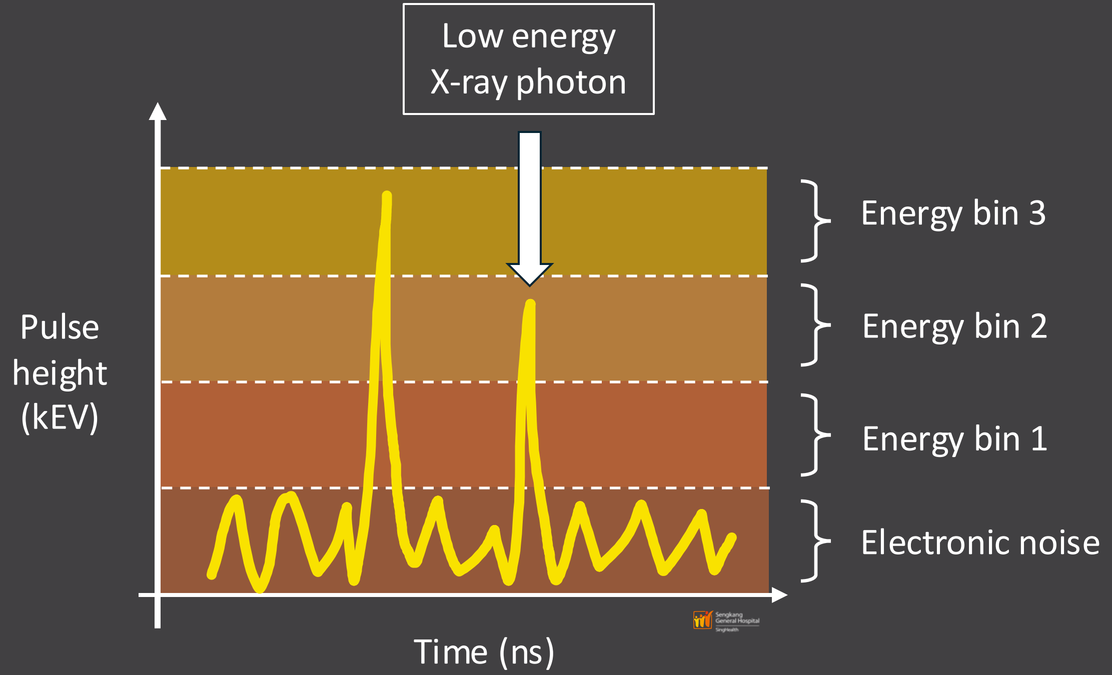
More accurate assessment of in-stent stenosis **(orange arrow).**

⬇

Reduces the need for invasive coronary angiography.

Images from the White Paper for NAEOTOM Alpha for Cardiac CT by Siemens Healthineers.

Higher dose efficiency



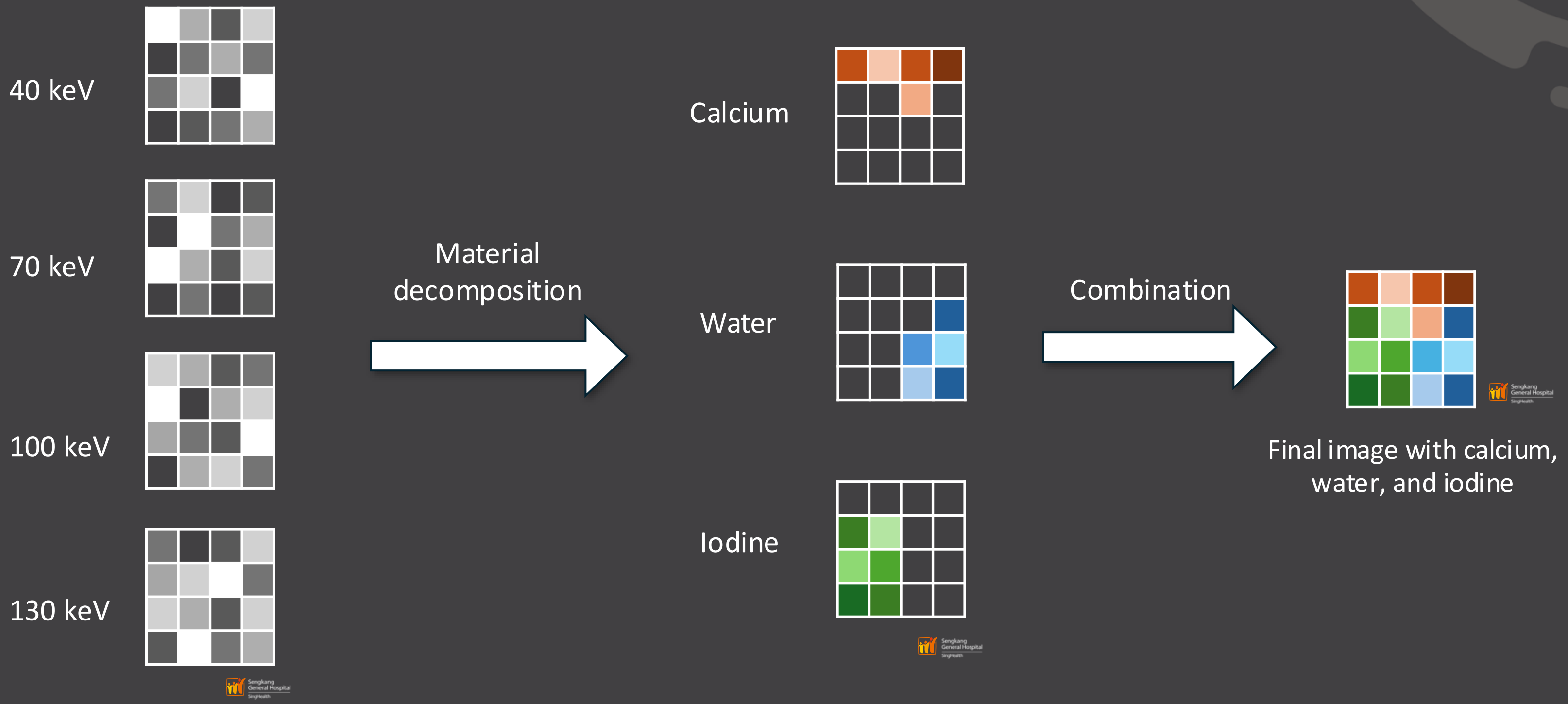
1. Low energy X-ray photons are not down-weighted **(no "energy-weighting " effect)**[xii].

2. Hence there is increased iodine signal and **higher sensitivity** at **low X-ray energy levels.**

3. Improved soft tissue contrast and dose efficiency means **lower radiation doses** required.

4. Low-dose thoracic and abdominal scans possible with better image quality and **35.7 - 44% dose reduction** compared to dual energy CT [xiii-xv].

Overview of Material Differentiation



How Material Differentiation works (Part 1)

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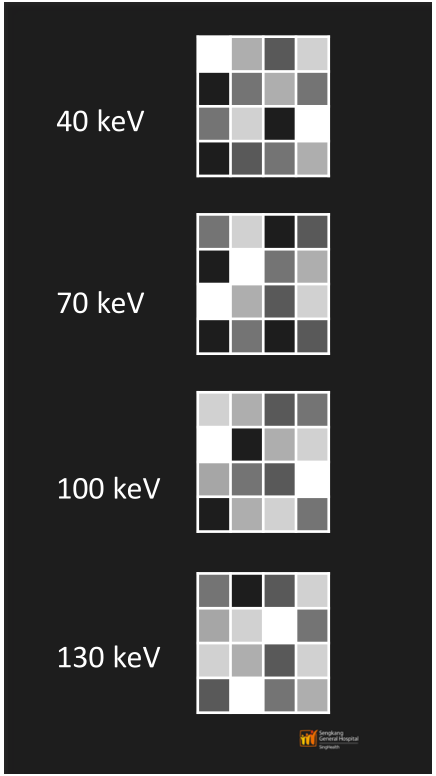


1. Conventional CT **estimates the density** of basic materials by scanning them at **two different X-ray energy levels** (high and low) and producing two equations[xvi].

2. However, PCT scans can **obtain data from 2–8 energy levels** due to multiple energy bins.

3. This generates different maps over a range of energy levels.

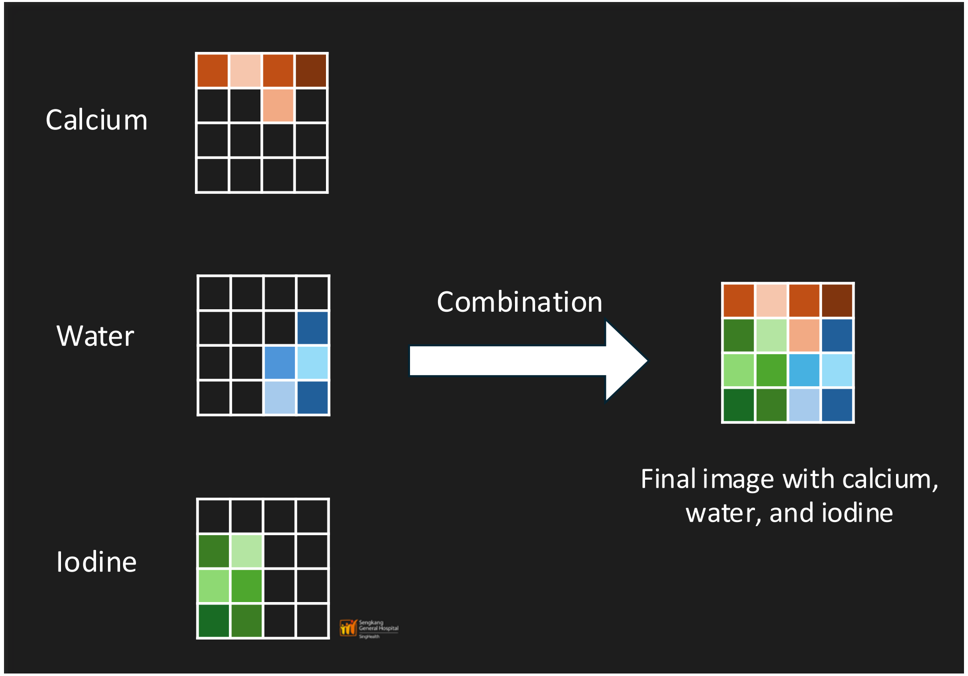
4. More equations can be generated, achieving a **more robust and accurate** estimation.

How Material Differentiation works (Part 2)

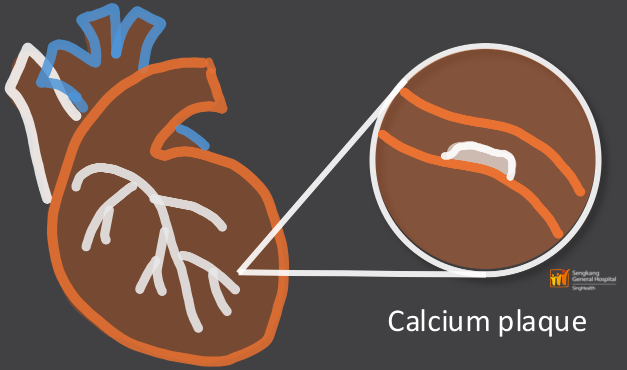
5. The PCT scanner has been calibrated to **recognize different materials** based on the **K-edge**, or the abrupt and distinct increase in the absorption of x-rays by one material at a specific energy level[xvii].

6. Basic materials like iodine, water, and calcium can be detected and quantified at **their specific K-edge energy level**.

7. These help with constructing the final image after processing.



How is Material Decomposition useful?



Calcium plaque

Virtual non-calcium image:
Iodine and water

Virtual non-iodine image:
Calcium and water

1. With material decomposition, iodine and calcium can be **selectively differentiated** and isolated.

2. Calcifications can be subtracted with a specific algorithm to produce a **virtual non-calcium image** to assess the vessel lumen.

3. Iodine can be subtracted from contrasted scans to produce a **virtual non-iodine image** visualizing calcifications alone.

This is useful for **quantitative calcium scoring** and eliminates the need for extra plain scans.

Explanation from the White Paper for NAEOTOM Alpha for Cardiac CT by Siemens Healthineers.

Application in CTCA

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a) Higher Spatial Resolution
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1. Virtual non-iodine image

2. Virtual non-calcium image

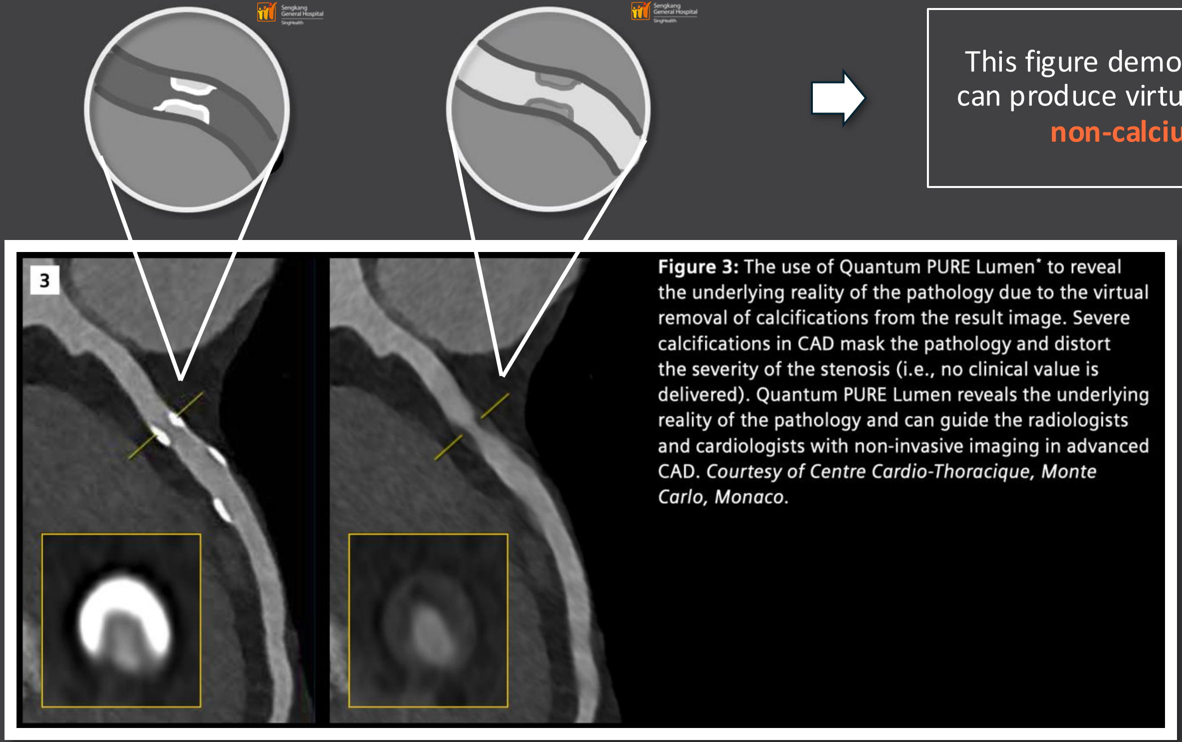

Figure 3: The use of Quantum PURE Lumen* to reveal the underlying reality of the pathology due to the virtual removal of calcifications from the result image. Severe calcifications in CAD mask the pathology and distort the severity of the stenosis (i.e., no clinical value is delivered). Quantum PURE Lumen reveals the underlying reality of the pathology and can guide the radiologists and cardiologists with non-invasive imaging in advanced CAD. *Courtesy of Centre Cardio-Thoracique, Monte Carlo, Monaco.*

This figure demonstrates how PCT can produce virtual **non-iodine** and **non-calcium images.**

Images from the White Paper for NAEOTOM Alpha for Cardiac CT by Siemens Healthineers.

Reduced Contrast Requirements

- Contrast volume greater than 100ml is a **risk factor** for **contrast-induced nephropathy (CIN)**[xviii].

- PCT has potential to reduce contrast requirements.
  - Studies have achieved **40-50% reduction** in contrast media volume for **CTCA** with the aid of virtual monoenergetic image reconstruction, without compromising image quality[xix,xx].
  - Studies have reported **27% reduction** in contrast media volume for **abdominal CT**, with comparable SNR and CNR[xxi].

- This would benefit patients who have **additional risk factors**[xviii] for CIN, such as:
  - Diabetes
  - Pre-existing renal impairment
  - Elderly patients > 75 years old
  - Congestive heart failure (CHF)
  - Hypotension
  - Anaemia

Learning Objectives

1. Overview of Photon Counting CT technology
2. Differences compared to current CT technology
3. Advantages and Clinical applications
4. **Potential Challenges of a Photon Counting CT scanner**

Potential Challenges

1. Overview of PCT
2. Comparison with current CT
3. Advantages & applications
4. **Potential Challenges**

a) **Cost**
b) **System Integration**
c) PCT Phenomenon
d) Learning Curve
e) Research Opportunities
f) Infrastructure Requirements

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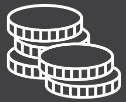

Cost

- PCT are significantly **more expensive** than conventional CT.
- It remains to be seen if the potential of the new technology **justify the immense cost** to departments and healthcare systems.

System Integration

- **Vast data storage requirements** for high resolution images and advanced post-processing.
- Need to ensure **compatibility** with existing Radiology Information System (RIS) software.

Potential Challenges

Charge sharing

- A phenomenon that occurs when incoming X-ray photons **hit the boundary between pixels** and are spread amongst them.
- The pulse generated is **detected in multiple pixels** instead of one, which may cause image artifacts[xxii].

Pulse pile-up

- Millions of photons hit the detector every second.
- If the detector cannot **count the photons fast enough,** some of the electric pulses **overlap** and are registered as a single pulse.
- This can cause "count loss", or the photon count to be **underestimated,** leading to resolution degradation[xxiii].

Learning Curve

- **Steep learning curve** for both radiographers and radiologists.
- Provisions need to be put in place, i.e. support from vendors & experts – this is essential for **smooth implementation.**
- Training of **dedicated personnel** may incur further costs.

Research Potential

- **New contrast agents** can be utilised due to **K-edge imaging,** by tuning the detector to the K-edge energy of certain contrast agents (eg: Gadolinium)[xxiv].

Infrastructure requirements

- Installation of PCT may require **shielding and reinforcement** of floors and walls and would require **robust radiation dose testing.**
- Strict temperature regulation to **prevent condensation and damage** leading to artifacts.
- PCT may also use **significantly more electricity** than conventional scanners

Delivery of PCT machine to Sengkang General Hospital, Singapore

Waterproofing and lead-lining works of the walls and floor

Temperature regulation at 22 degrees Celsius

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