Bringing Photon Counting Detectors to the Interventional Room

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- Dr. Meg Lubner (Body Radiology)

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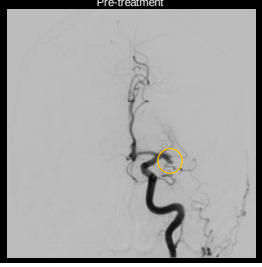
Dr. James Scheuermann

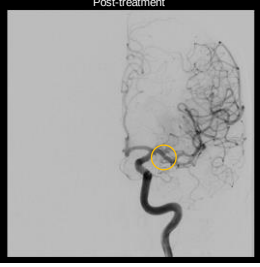
Introduction: Clinical Example of Image-Guided Intervention

62 y.o. diagnosed with acute ischemic stroke

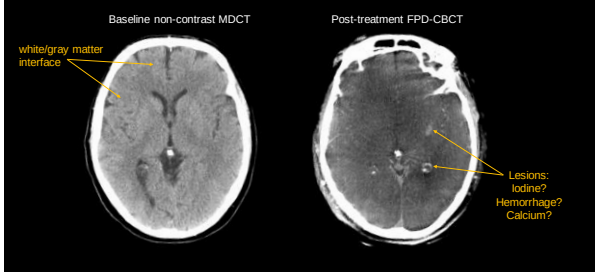
Pre-treatment



Post-treatment



Limitations of Current Flat Panel Detector CBCT



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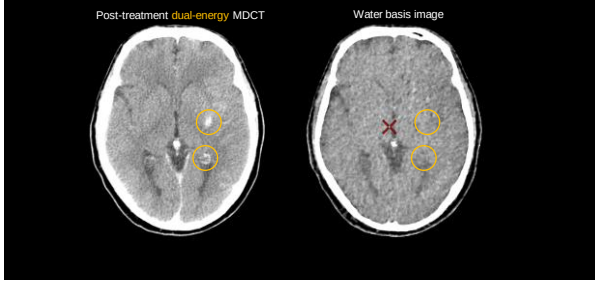
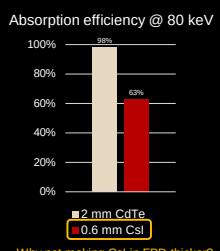


Existing Flat Panel Detectors (FPDs) in C-arm Systems

- Technical limitations of the existing scintillator-based energy-integrating FPDs:
  - Poor low-contrast detectability
  - Lack of material quantification capability

Poor Quantum Absorption Efficiency of Scintillator-Based Flat Panel Detectors



Why not making CsI in FPD thicker?

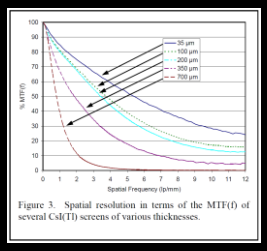


Figure 3. Spatial resolution in terms of the MTF(f) of several CsI(Tl) screens of various thicknesses.

Miller et al., Proc. SPIE, Vol. 5923, pp.59230F (2005)

Other Limitations of Scintillator-Based Flat Panel Detectors

- Swank noise[1]
- Lubberts noise[2]-[3]
- Long transmission distance of analog signals[4]
- Highly suboptimal photon weighting[5]

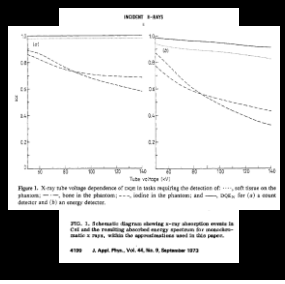


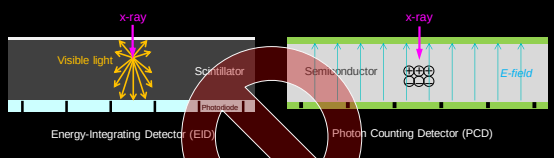
Figure 1. X-ray tube voltage dependence of snr in tasks requiring the detection of: ····, soft tissue on the phantom; — —, bone in the phantom; - - -, iodine in the phantom; and ——, DQE$_{ad}$ for (a) a smart detector and (b) an energy detector.

FIG. 1. Schematic diagram showing x-ray absorption events in CsI and the resulting absorbed energy spectrum for monochromatic x rays, within the approximations used in this paper.

4100 J. Appl. Phys., Vol. 44, No. 9, September 1973

[1] Swank, *JAP* 44, 4199 (1973)
[2] Lubberts, *JOSA* 58,1475 (1968)
[3] Howansky et al., Med. Phys. 45, 4927 (2018)
[4] Koniczek *et al., Med. Phys. 47, 3972* (2020)
[5] Tapiovaara and Wagner, *Phys. Med. Biol.* 30, 519 (1985)

What is photon counting detector?



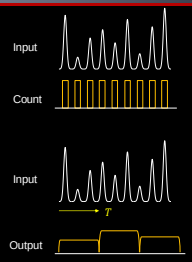
Energy-Integrating Detector (EID)

Photon Counting Detector (PCD)

- In EIDs, X-rays are first converted into visible lights in a scintillator and then to electrical signal; In PCDs, X-rays are directly converted to electric signal
- In PCDs, a bias voltage is applied to a photoconductor
- PCDs have better spatial resolution than EIDs
- PCDs resolve the energy of X-rays
- "PCD-CT is a radically new technology"

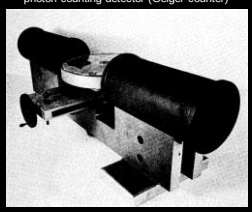
Fundamental Difference between PCDs and EIDs: The Detection Mode

- PCDs: pulse detection mode
  - Electric pulses induced by each input quanta are counted to
    - Estimate the number of input quanta
      - and the energy of each input quanta if multiple comparators are used
- EIDs: current/charge integration mode



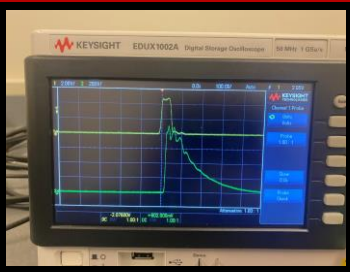
The First CT *IS* a Photon Counting Detector CT

The first experimental CT system developed by Allan Cormack in 1963 used a photon counting detector (Geiger counter)

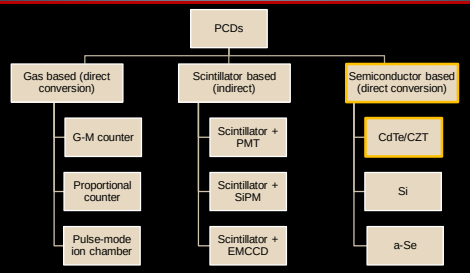


A. Cormack, Applied Physics 34, 2722 (1963)
A. Cormack, Nobel Lecture (1979)

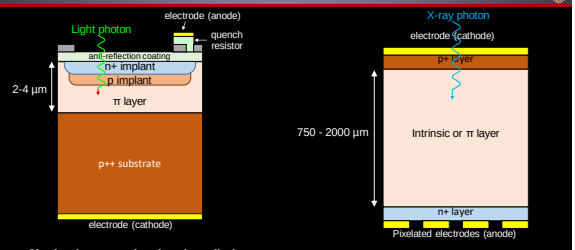
Detection of Individual X-Ray Pulses using a Silicon Photomultiplier (SiPM)



Photon Counting Detectors



Semiconductor-based Photon Counting Detectors



Single-photon avalanche photodiode (SPAD) in Si photomultiplier (SiPM)

Pulse-mode direct-conversion detector

Larger Number of Information Carriers/Input Energy

Glenn Knoll:*

- *" One of the major limitations of scintillation counters is … the energy required to product an information carrier (a photoelectron) is of the order of 100 eV or more…"*
- *"… the use of semiconductor materials as radiation detectors can result in a much larger number of carriers for a given incident radiation event than is possible with any other common detector type."*

Material	eV per secondary quanta generated	Average # of secondary quanta per 100 keV
Air	33.97	2,900
CsI(Tl)	17	5,900
Si	**3.6**	**28,000**
CdTe	**4.4**	**23,000**

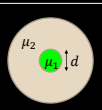
* Glenn Knoll, Radiation Detection and Measurement (4th edition), Wiley (2010)

Optimal Weighting of X-ray Photons

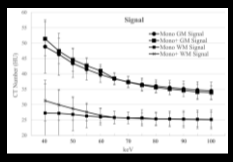
$$N_{out} = \sum_E w(E) N_{in}(E)$$

To maximize CNR, the optimal weighting scheme is*

$$w_{opt}(E) \approx [\mu_1(E) - \mu_2(E)]d$$



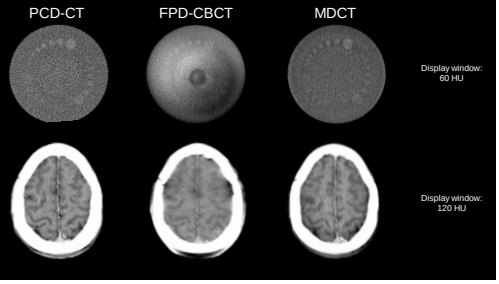
If $\mu_1(E) - \mu_2(E) =$ constant as in white and gray matters, then equal weighting is the optimal, and that is exactly what PCDs do!



* Tapiovaara and Wagner, Phys Med Biol, 30, 519 (1985)

Park et al., Pediatr Radiol, 47:1648 ((2017)

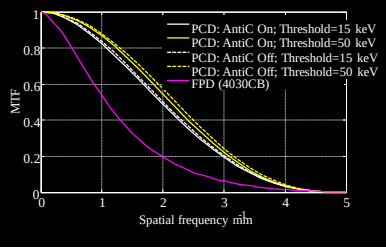
Low-Contrast Detectability Supremacy of PCDs



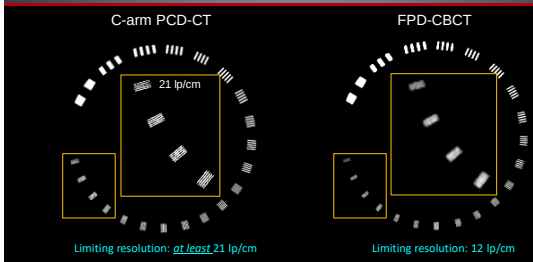
Better Spatial Resolution

Pre-sampling MTFs with Matched Detector Pixel Pitch

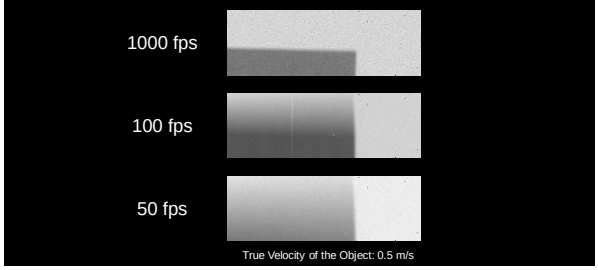
Detector	Pixel size (um)
Varex 4030CB	194
Xcounter PCD	200 (2x2 binned)



Better Spatial Resolution



Excellent Temporal Resolution (which also benefits LCD!)



Bringing PCD to Intervention Room: Prior Art

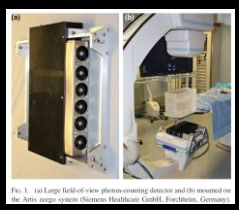
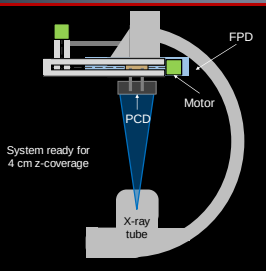


FIG. 1. (a) Large field-of-view photon-counting detector and (b) mounted on the Artis zeego system (Siemens Healthcare GmbH, Forchheim, Germany).

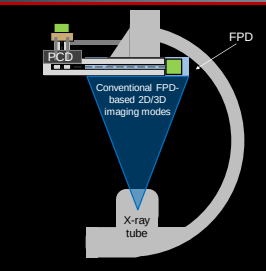
[1] K. Muller et al., Proceedings of The Fourth CT Meeting, pp. 479-482, 2016
[2] M. Ahmed et al., Proceedings of The Fourth CT Meeting, pp. 105-108, 2016
[3] M. Ahmed et al., Med. Phys., vol. 44, no. 11, 2017

C-arm Photon Counting CT Prototype at UW-Madison



[1] Ji *et al.*, *IEEE TMI*, 2021 [2] Treb *et al.*, *SPIE Medical Imaging*, 2021

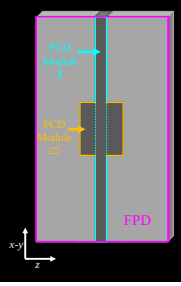
C-arm Photon Counting CT Prototype at UW-Madison



[1] Ji *et al.*, *IEEE TMI*, 2021 [2] Treb *et al.*, *SPIE Medical Imaging*, 2021

Dagger (†)-shaped Hybrid Detector Design

- **I** module
  - Full axial FOV **low-contrast / spectral** PCD-CT
- ▭ module
  - 3D VOI and 2D ROI **high-res / spectral** imaging
- PCD can be surrounded by EID modules to form single piece for full-FOV imaging
  - PCD output can be combined with output from the rest of the flat-panel EID to form a single projection image



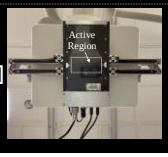
Treb *et al.*, *SPIE Medical Imaging*, 2022
US patent pending

Dagger (†) Hybrid Detector: Proof-of-Concept

	I Module	▭ Module
Manufacturer	Direct Conversion AB (Now with Varex Imaging)	
Model	XC-Hydra FX50	Thor FX10
Dimensions	51 x 0.6 cm	10 x 5 cm
Sensor material	CdTe	
Sensor thickness	0.75 mm	2 mm
Maximal frame rate	150 fps	1000 fps
# energy thresholds	2	
Pixel fill factor	100%	
Pixel size	100 µm	

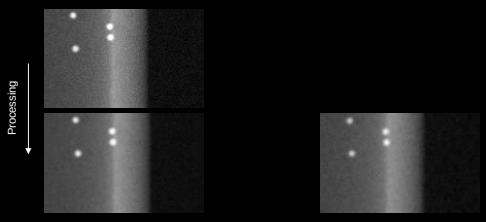
I

▭



Treb *et al., SPIE Medical Imaging, 2022*

Dagger (†) Hybrid Detector: Proof-of-Concept



PCD
2D image

FPD
2D image

Treb *et al., SPIE Medical Imaging, 2022*

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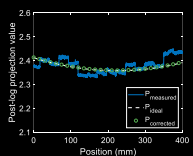
PCD Nonuniformity Correction

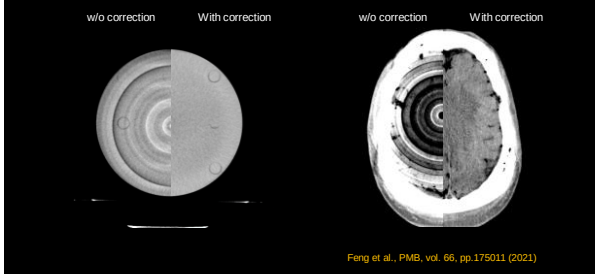


Uncorrected projection image

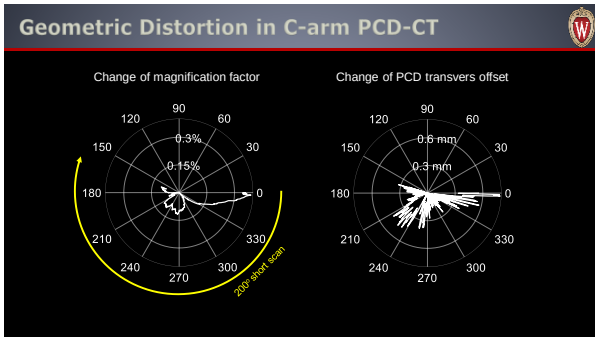
Corrected projection image

Feng et al., PMB, vol. 66, pp.175011 (2021)

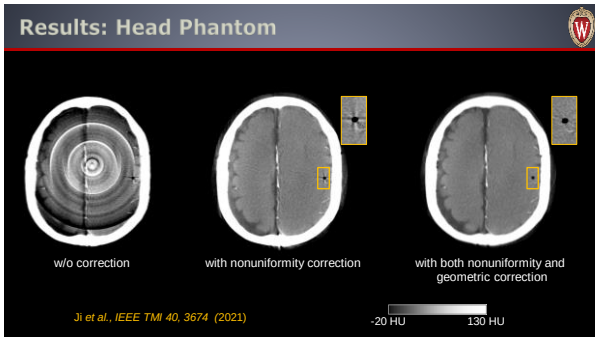
PCD Nonuniformity Correction



Geometric Distortion in C-arm PCD-CT

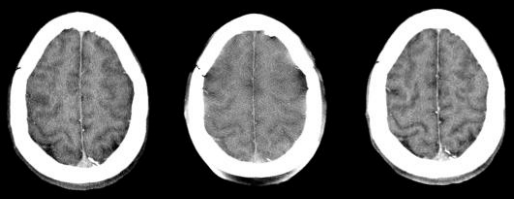


Results: Head Phantom



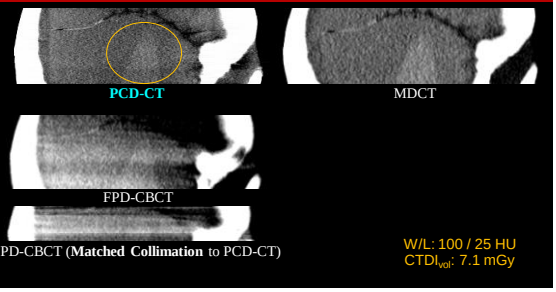
Potential Applications of C-arm PCD-CT in Image-guided Interventions

Grey-White Matter Differentiation



PCD-CT FPD-CBCT MDCT

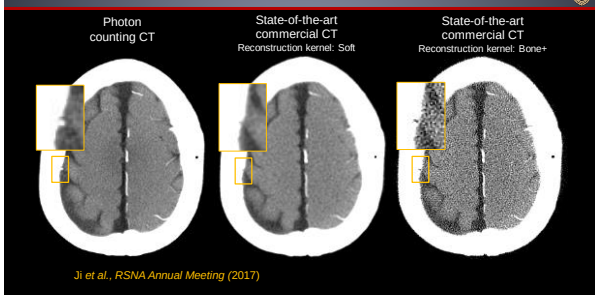
Detection of Intraparenchymal Hemorrhage



FPD-CBCT (**Matched Collimation** to PCD-CT)

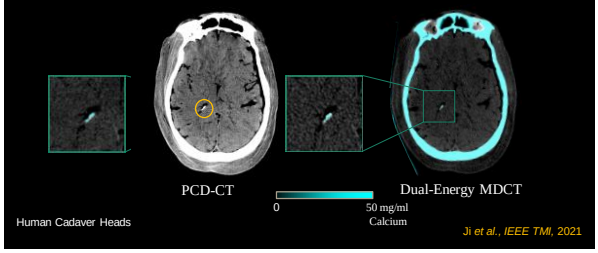
W/L: 100 / 25 HU
$CTDI_{vol}$: 7.1 mGy

Detection of Subarachnoid Hemorrhage



Ji *et al., RSNA Annual Meeting* (2017)

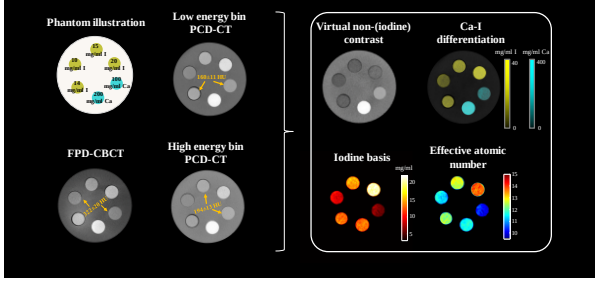
Intracranial Calcification/Iodine Discrimination



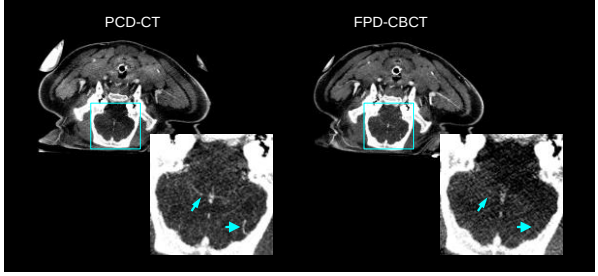
Human Cadaver Heads

Ji *et al., IEEE TMI*, 2021

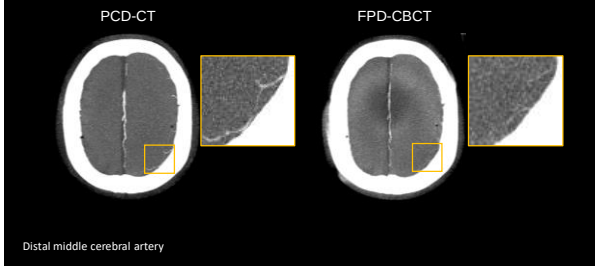
Material Quantification



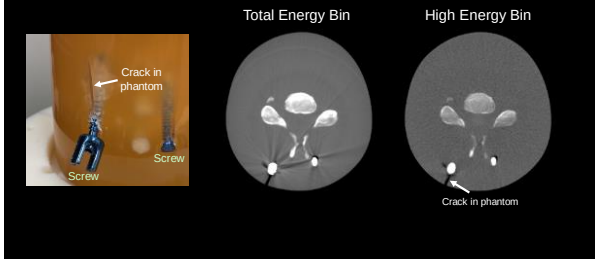
Small Vessel Imaging with IV Contrast Injection



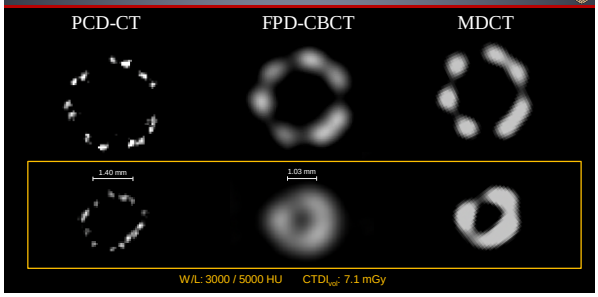
High-Quality Small Vessel Imaging



Metal Artifacts Reduction



Ultra-High Resolution Stent Imaging



High-Speed Angiography and Flow Imaging

- Presentations from the University at Buffalo:
  - TH-C-201-4: Vanderbilt *et al*., **"**BEST IN PHYSICS (IMAGING): Implementation of 1000 Fps CdTe Photon-Counting Detectors (PCD's) for Simultaneous Biplane High-Speed Angiography (HSA)."
  - TH-C-201-1: Wu *et al*., **"**1000 Fps High Speed Angiography (HSA) of Contrast Injections in An In-Vitro Model with Pulsatile Flow Using Simulated Cardiac Gating Techniques"
  - TH-B-207-1: Shields *et al*., "Evaluation of Shear Forces Within Stenotic Vessel Models Using 1000 Fps X-Ray Particle Image Velocimetry (X-PIV)."
  - TH-A-207-3: "Effect of Realistic Pulsatile Flow Versus Constant Flow On Contrast Visualization for 1000 Fps High-Speed Angiography (HSA) in Patient-Specific 3D-Printed Models."

Summary

- The fundamental difference between PCDs and energy-integrating FPDs in existing C-system systems:
  - Pulse mode vs. current integration mode
- Semiconductor-based direct-conversion PCD is a sub-type of the PCD family
- Advantages of semiconductor-based direct-conversion PCD
  - Low-contrast detectability supremacy
  - Single-shot dual-energy imaging
  - Superior spatial and temporal resolution

Summary

- *With proper calibration and correction*, high-quality C-arm PCD-CBCT images can be generated
- Potential applications of PCD-CBCT in interventional imaging
  - Spectral imaging for material quantitation and differentiation *without compromising dose efficiency and speed of non-spectral imaging*
  - Non-spectral imaging applications should not be overlooked:
    - Improved gray/white matter delineation (for ASPECTS and hemorrhagic transform risk evaluation)
    - Improved detection of intraoperative hemorrhage
    - Improved detection of small blood vessels and devices
    - High frame rate angiography and flow imaging

Thank You!

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