Multi-energy CT using photon counting detectors

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Disclosure

- No financial interest
- Research grants and relationships
  - Siemens Healthineers JHU-2016-CT-1-01-Taguchi_C0022
  - NIH R56 HL125680
  - Previous: DxRay (NIH SBIRs), Philips (C-arm), Toshiba/Cannon (employee)
- Former consultantship
  - Suzhou Bowing Medical Technologies, Life Saving Imaging Technology (LISIT), JOB Corporation

Outline

- Photon counting detectors (PCDs) and properties
- Algorithms (data correction and image reconstruction)
- System designs
- Clinical applications

Design types	Groups	Prototype CT (beta site installation)
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Clinical applications

“What is the killer application?”

There is no “killer application”

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New generation CT has been developed for

- improving everything CT does (whole body)
- adding new dimension to everything CT does
- enabling new applications

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New generation CT has been developed for

In 1998, MDCT with 4 detector rows

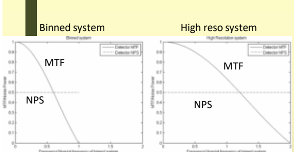
- Improving everything CT does (whole body)
  - 10 mm slice → 2–3 mm slice (→ 0.5 mm)
  - Shorter scan duration, larger coverage, better resolution
- Adding new dimension to everything CT does
  - 2D slice-by-slice view → 3D view (coronal, sagittal, MIP, 3D)
- Enabling new applications
  - Cardiac CT (coronary artery)

New generation CT has been developed for

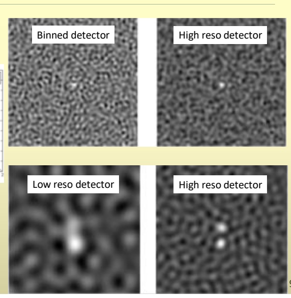
In 202x, PCD-CT with 3–6 energy windows

- Improving everything CT does (whole body)
  - Contrast, contrast-to-noise, radiation dose, contrast dose, spatial reso, accuracy, quantitative values, CT radiomics
- Adding new dimension (**material info**) to everything CT does
  - Simultaneous image-and-measure (IAM-XX), CT tissue biomarkers
- Enabling new applications
  - Simultaneous multi-agent, molecular CT, personalized CT

Spatial resolution



J. Baek, PMB 2013



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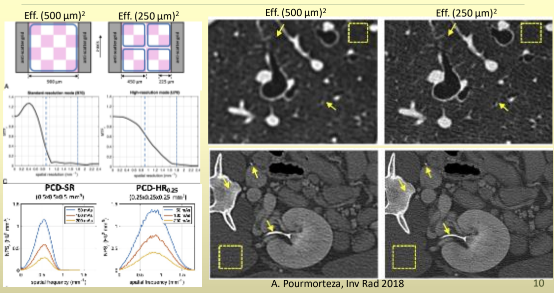

A. Pourmorteza, Inv Rad 2018

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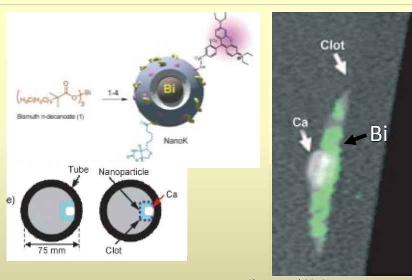
Molecular CT



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D. Pan, Angew Chem Int Ed 2010

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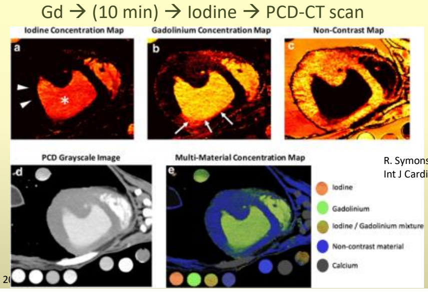
Simultaneous multi-agent imaging

Gd → (10 min) → Iodine → PCD-CT scan



R. Symons,
Int J Cardiovasc Imag 2017

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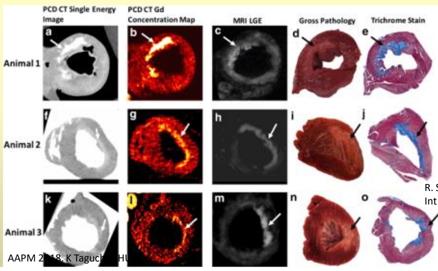
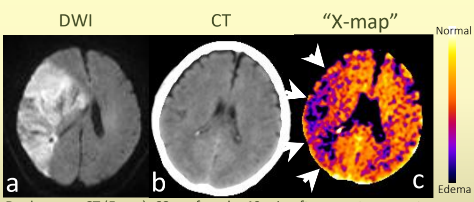


R. Symons,
Int J Cardiovasc Imag 2017

Material-specific imaging for better diagnosis

Acute ischemic stroke delineated clearly by water density images (for edema)



Dual-energy CT (Force). 68 yo, female, 40 min after symptom onset.

K. Taguchi, Inv Rad 2018

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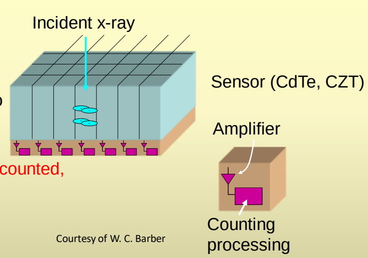
PCDs ("Standard," "ACS," and "Edge-on Si")

Index	Name/ASIC	Operation mode	Maximum count rates (Mcps/pixel)	Pixel size ($\mu m \times \mu m$)	Maximum count rates [Mcps/mm^2]	No. of energy thresholds per pixel	Tileup capability	Anti-charg sharing
1	DXMCT-1 (Refs. 5 and 8)		5.5	1000 × 1000	5.5	2	2D	No
2	DXMCT-2 (Ref. 20)		5.5[a]	500 × 500	22[a]	4	2D	No
3	Siemens 2010 (Refs. 17 and 28)		NA	225 × 225	NA	2 or 4[b]	NA[c]	No
4	ChromAIX (Ref. 16)		13.5[d]	300 × 300	150[d]	4	1D	No
5	Hamamatsu (Refs. 10 and 11)		1-2	1000 × 1000	1-2	5	1D	No
6	GMI CA3 (Refs. 6 and 9)		1-2	400 × 1000	2-5	6	1D	No
7	Medipix3RX (Refs. 13, 29, and 52)	FM[e]-SPM[f]	0.21[g]	55 × 55	69.4[g]	2	1D with 2 × N (3-side buttable)	No
		FM[e]-CSM[f]	0.036[g]	55 × 55	11.9[g]	1		Yes
		SM[e]-SPM[f]	0.145[h]	110 × 110	12[h]	8		No
		SM[e]-CSM[f]	0.034[h]	110 × 110	2.8[h]	4+4[i]		Yes
8	CIX (Ref. 15)		3.3	250 × 500	26	1	NA	No
9	Nexis Detector (Refs. 21 and 22)		2.0	1000 × 1000	2.0	5	1D	No
10	MicroDose SI (Silicon strip) (Refs. 24–26)		0.056[j]	50 × 50	NA	2	1D	Yes[k]
11	KTH Silicon strip (Refs. 23, 27, and 30–32)		2.5 or 7.5[l]	400 × 500	200 or 600[m]	8[n]	2D[o]	No

Table I of K Taguchi and J Iwanczyk, Med Phys, Vision 20/20 (2013)

PCD ("Standard" type)



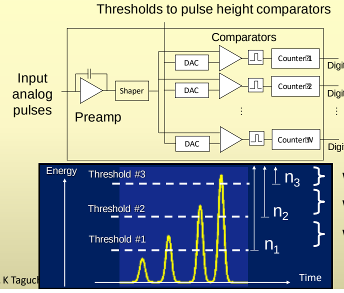
Convert a photon to a charge cloud

Charge measured, counted, and stored digitally

Courtesy of W. C. Barber

PCD ("Standard" type)

Thresholds to pulse height comparators



$w_3 = n_3$

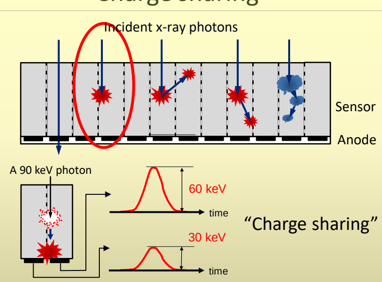
$w_2 = n_2 - n_3$

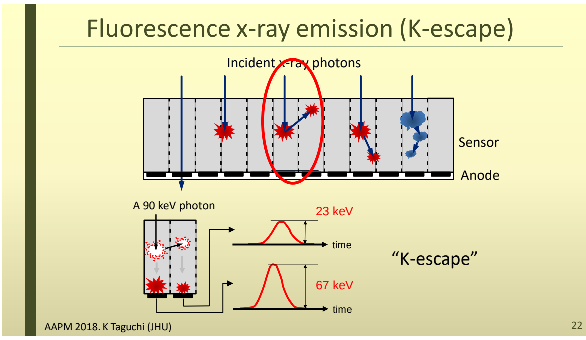
$w_1 = n_1 - n_2$

PCD not flawless: Spectral distortion

- Independent of x-ray intensities: Charge sharing, K-escape, Re-absorption, Compton scattering
- Dependent on x-ray intensities: Pulse pileups

Charge sharing




Fluorescence x-ray emission (K-escape)
Incident x-ray photons
Sensor
Anode
A 90 keV photon
23 keV
time
67 keV
time
“K-escape”
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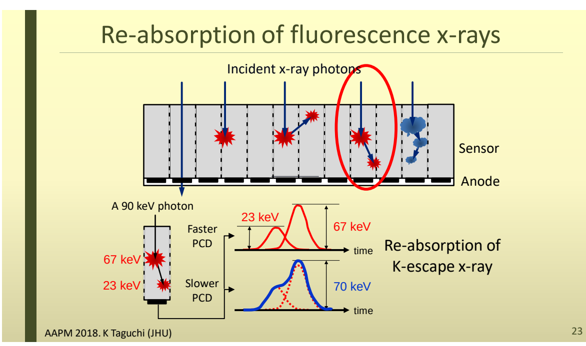
Re-absorption of fluorescence x-rays
Incident x-ray photons
Sensor
Anode
A 90 keV photon
Faster PCD
23 keV
67 keV
time
67 keV
23 keV
Slower PCD
70 keV
time
Re-absorption of K-escape x-ray
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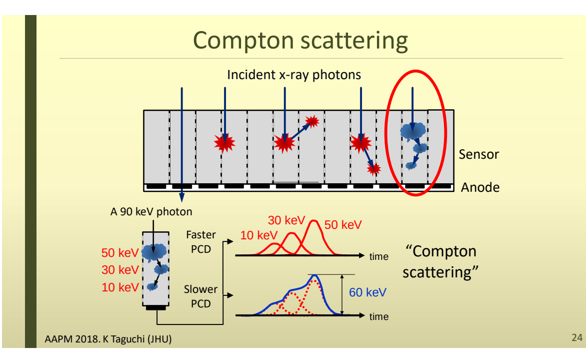
Compton scattering
Incident x-ray photons
Sensor
Anode
A 90 keV photon
Faster PCD
30 keV
10 keV
50 keV
time
50 keV
30 keV
10 keV
Slower PCD
60 keV
time
“Compton scattering”
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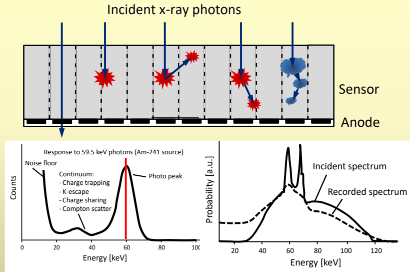
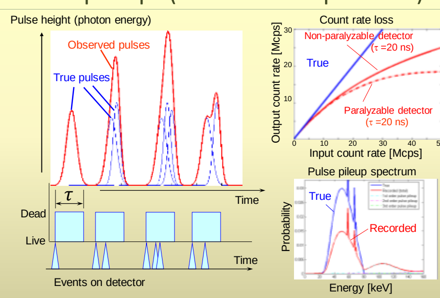
Spectral distortion

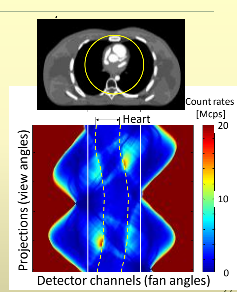


Pulse pileups (count rate dependent)



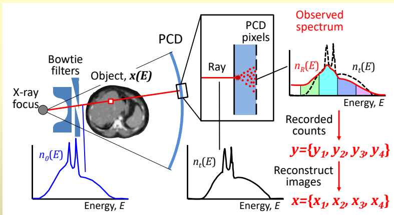
PCD not flawless: Spectral distortion

- Charge sharing, K-escape, etc.
  - Always
  - Lower energy, more counts
  - Solution: Larger, slower PCD
- Pulse pileups
  - Only near skins
  - Higher energy, fewer counts
  - Solution: Smaller, faster PCD



Spectral distortion: How to mitigate it?

- Balanced design + PCD model + compensation algorithm



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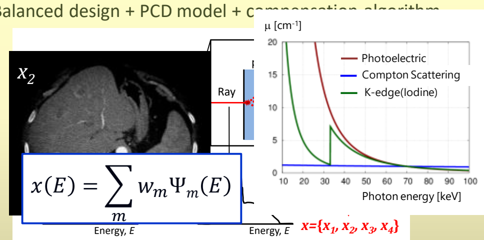

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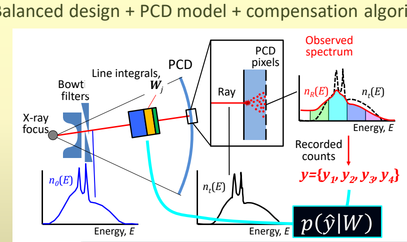

Estimate object *W* by maximizing the likelihood

Spectral distortion: How to mitigate it?

- Balanced design + PCD model + compensation algorithm

WW 400 HU, WL 50 HU

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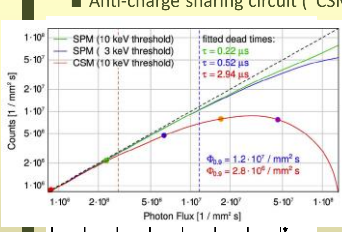
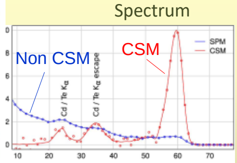
Spectral distortion: How to mitigate it?

- Anti-charge sharing circuit ("CSM" in Medipix 3RX)



Spectrum



Th. Koenig, *et al.*, IEEE TNS (2013).

AAPM 2018. K Taguchi (JHU) Courtesy of M. Campbell 33

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Prototype PCD-CT systems

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- **Siemens (Mayo Clinic and NIH)**
  - *Dual-source CT, PCD for $\varnothing$27.5 cm x 8–24 mm, EID for $\varnothing$50 cm*
  - *$(225\ \mu m)^2$, 2 thresholds (staggered 4 thresholds), $(450–900\ \mu m)^2$ output*
  - *128×10^6 counts/s/mm^2 with 13.5% loss, 256×10^6 with 25.2% loss*
- **Philips (Louis Pradel University Hospital, Bron, France)**
  - *Brilliance 64 CT, $\varnothing$16.8 cm x 2.5 mm*
  - *$(500\ \mu m)^2$, 5 thresholds [*1]*
  - *>150×10^6 counts/s/mm^2 [*1]*

1. R. Steadman, et al., Nucl Inst Meth Phys Res A (2017)

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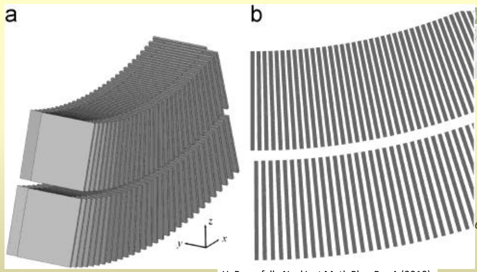
"Edge-on silicon"	KTH Royal Institute of T	

- **University of Canterbury, Christch**
  - *Their own open gantry CT, PCD fo*
  - *$(110\ \mu m)^2$, 8 thresholds, anti-char*
  - *10–20×10^6 counts/s/mm^2 with ?%*
- **KTH Royal Inst of Tech, Stockholm**
  - *Philips CT(?), $\varnothing$? cm x ? mm*
  - *$(400\ \mu m)$x$(500\ \mu m)$, 8 thresholds/*
  - *200×10^6 counts/s/mm^2 with 2% lo*


New York Times, July 17, 2018.
https://www.nytimes.com/2018/07/17/health/3d-color-xrays-cern.html

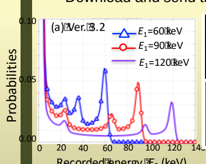
Prototype PCD-CT systems

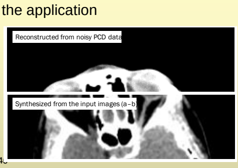


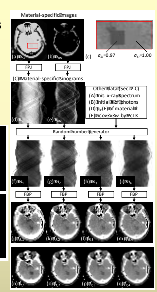
H. Bornefalk, Nucl Inst Meth Phys Res A (2010)

Photon Counting Toolkit (PcTK, pctk.jhu.edu)

- "Spectral response" model of photon counting detectors
- Medical Physics 2018;45(5):1985–1998
- Matlab programs
- Available for academic research, free of charge
- Download and send the application







Summary

- PCD-CT with 3–6 energy windows in Year 202x that
  - *Improves contrast, noise, spatial reso, quant. accuracy, etc.*
  - *Add material-axis to 3-D images* → ***How to use it effectively?***
  - *Enables multi-agent CT, molecular CT, personalized CT*
  - ***No killer application!***
- Algorithms needed for data correction and image recon

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- Kishore Rajendran, Ph.D.

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- Kento Nakada, M.Sc.

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