CT imaging using energy-sensitive photon-counting detectors

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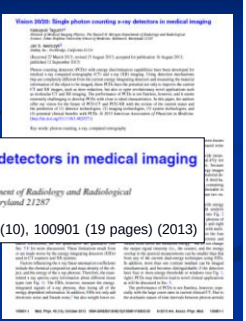
Disclosure

- No financial interest
- Research grants
  - Siemens Healthcare
- Past relationships/grants
  - Former employee of Toshiba Medical Systems
  - Former Co-I of a project funded by Philips Healthcare
  - AHA, NIH R01 and SBIRs (DxRay)
- Consultant
  - Life Saving Imaging Technology (LISIT) (Tokyo, Japan)

Vision 20/20 paper

- Detector technology
- Imaging technology
- System technology
- Potential clinical benefits



Vision 20/20: Single photon counting x-ray detectors in medical imaging

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DxRay, Inc., Northridge, California 91324

Med Phys **40**(10), 100901 (19 pages) (2013)

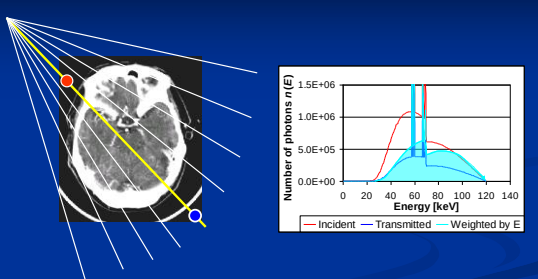
Outline

- Current CT detectors to higher dose exams
- Low-dose CT by integrating 3 technologies
  - Photon counting detectors (PCDs)
  - Iterative reconstruction for PCDs (PIECE)
  - Joint estimation with tissue types (JE-MAP)
- Whole-body prototype PCD-CT system
- Other clinical merits of PCD-CT

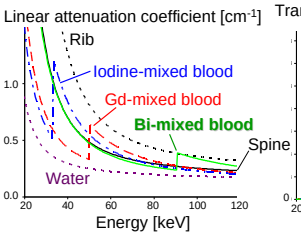
Major problems of current CT

- Relatively high-dose procedure
- Insufficient contrast between tissues
- CT images are not tissue-type specific
- Pixel values, Hounsfield units or linear atten. coeff., are not quantitative but qualitative

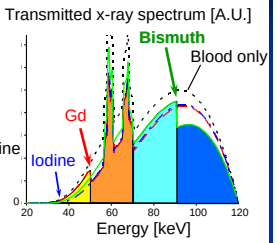
Energy weighted integration



Energy binning for spectral CT



Four materials would provide an identical pixel value if scanned with current CT



Transmitted spectra with 25 cm water and 5 cm blood w/ or w/o contrast agents

Strategy for low-dose CT

Combine the following 3 technologies:

Technologies	Relative amount of dose reduction	Liver CT (mSv)
Current CT system with FBP*1	N/A	10
Photon counting detectors (PCDs)	30–40 %	6–7
Iterative reconstruction for PCDs (PIECE)	>35 %	3.9–4.6
Joint estimation with tissue types (JE-MAP)	>35 %	2.6–3.0

Note 1. Dose for current CT with iterative reconstruction may be 6–8 mSv

Note 2. Annual background radiation: 3.1 mSv

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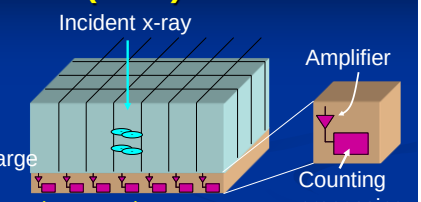
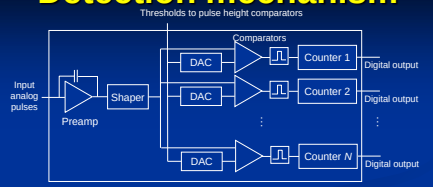
Photon counting detector (PCD)



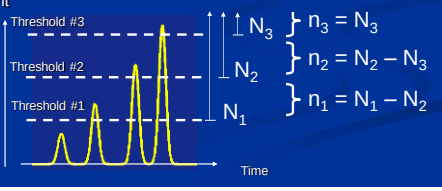
Charge measured, counted, and stored digitally

Courtesy of W. Barber, Ph.D. and J. Iwanczyk, Ph.D. (DxRay, Inc)

Detection mechanism



Pulse height = photon energy

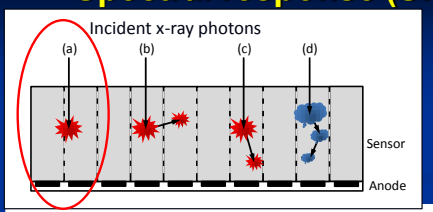


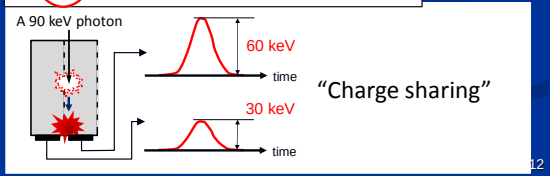
$n_3 = N_3$

$n_2 = N_2 - N_3$

$n_1 = N_1 - N_2$

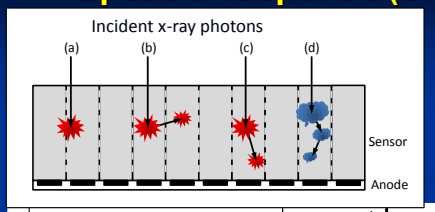
"Spectral response (SR)"

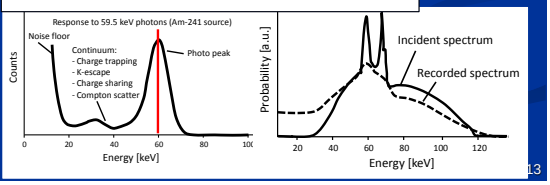




"Charge sharing"

"Spectral response (SR)"





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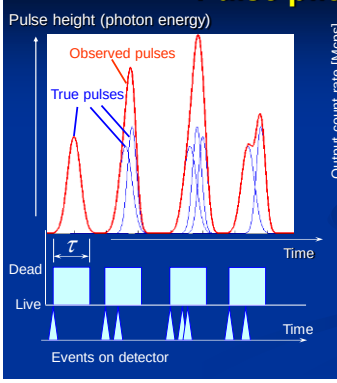
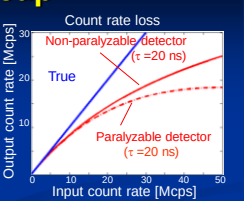
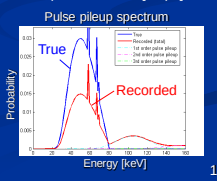
Pulse pileup







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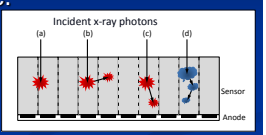
Spectral distortion

- Spectral response (SR): Charge sharing, K-escape, Compton, etc.

  → Larger, slower PCD



- Pulse pileups

  → Smaller, faster PCD

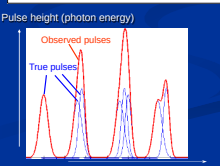


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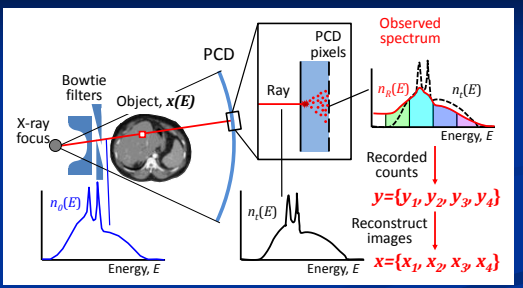
Image artifacts due to SR and PP



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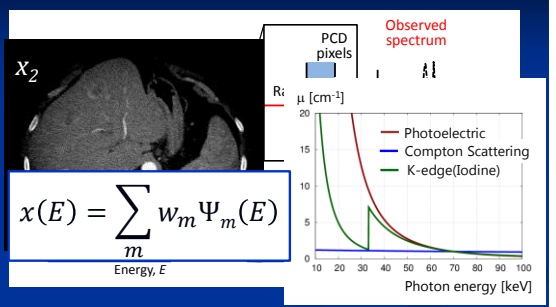
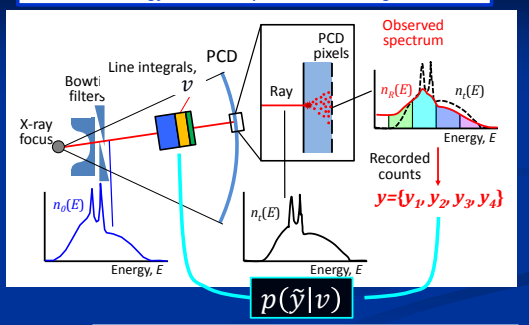


PIECE = **P**hysics-modeled **I**terative reconstruction for **E**nergy-sensitive photon **C**ounting d**E**tector



Estimate object v by maximizing the likelihood

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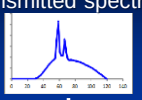
PCD model

Transmitted spectrum



Energy

Spectral response

Pulse pileups

Recorded spectrum

Energy

Spectral response[1]

$$n_{SRE}(E) = \sum_k a_{SRE}(E, E_k) n_t(E_k)$$

or

$$\boldsymbol{n_{SRE}} = A_{SRE}\boldsymbol{n_t}$$

Pulse pileups[2,3]

$$n_R(E) = n_{SRE}(E) Pr("rec" = 1) \times \sum_l Pr(l|"rec" = 1) Pr(E|l)$$

l = # of photons piled up for one recorded count

1: J. Cammin, *Med. Phys.* **41**: 041905 (2014)
2: K. Taguchi, *Med. Phys.*, **37**: 3957 (2010)
3: K. Taguchi, *Med. Phys.*, **38**: 1089 (2011)

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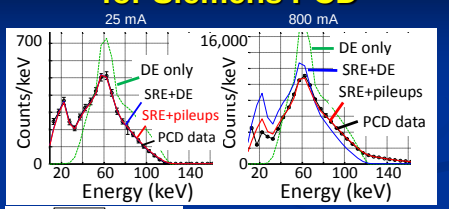
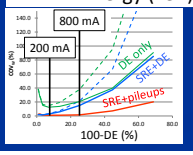
Monte Carlo simulation study for Siemens PCD





100 mm water, 3.5 mm Al, 0.9 mm Ti; 120 kVp; pulse height analyzer; unipolar pulse

DE = Detection efficiency (%)
COVw = Weighted coefficient of variation (%)

J. Cammin, *presented at IEEE NSS/MIC 2014*

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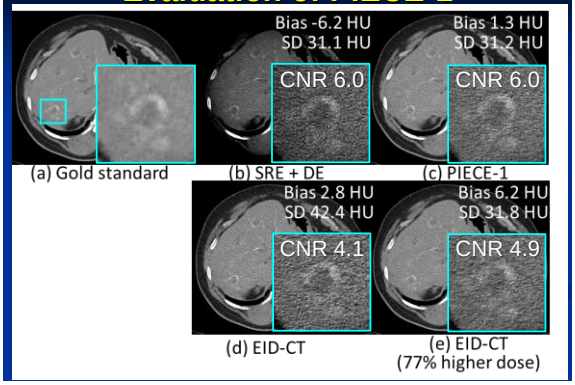
Evaluation of PIECE-1



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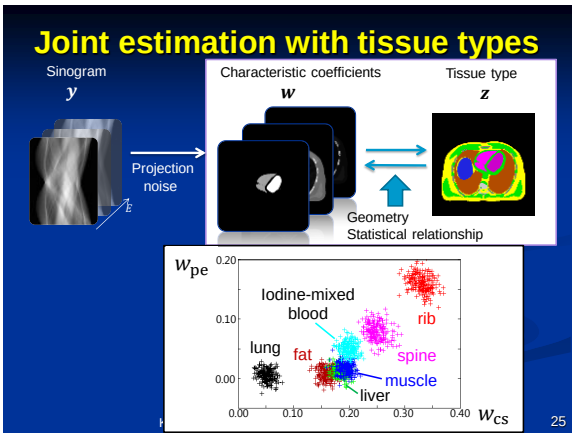
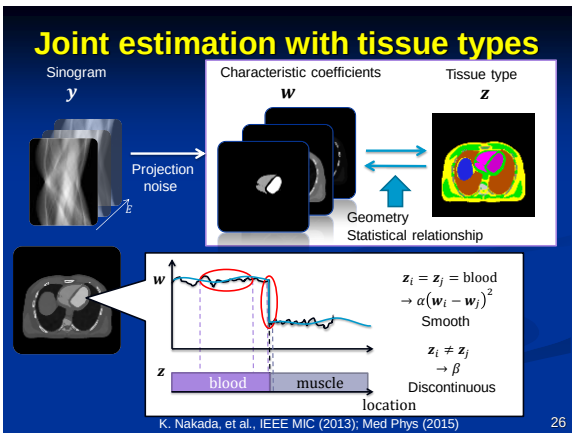
Note 2. Annual background radiation: 3.1 mSv

Joint estimation with tissue types

K. Nakada, et al., IEEE MIC (2013); Med Phys (2015) 24


Joint estimation with tissue types
Sinogram
y
Projection noise
Characteristic coefficients
w
Tissue type
z
Geometry
Statistical relationship
w_{pe}
Iodine-mixed blood
rib
lung
fat
spine
muscle
liver
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
w_{cs}
25


Joint estimation with tissue types
Sinogram
y
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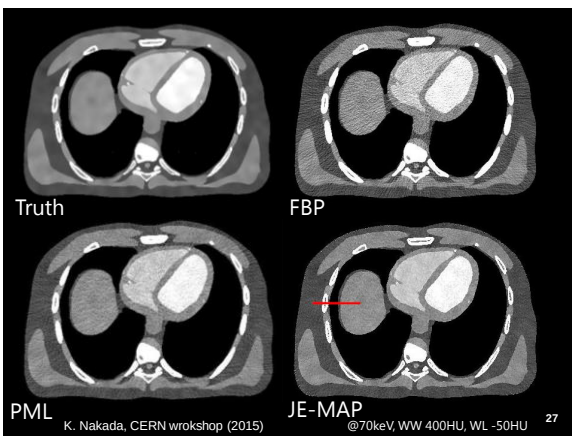
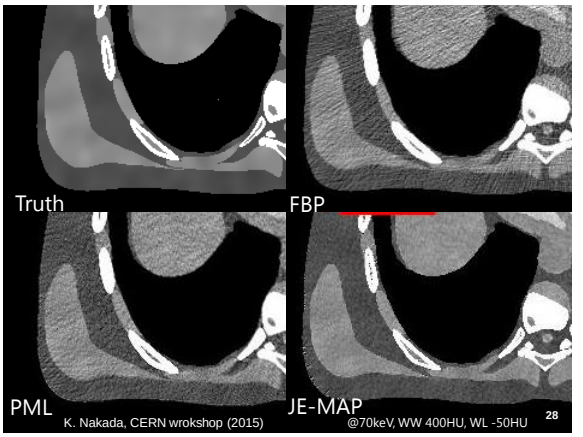
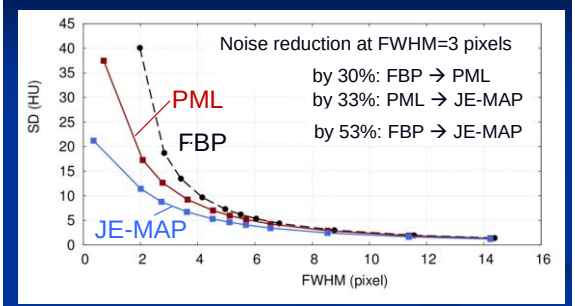
Characteristic coefficients
w
Tissue type
z
Geometry
Statistical relationship
w
z
blood
muscle
location
$z_i = z_j = \text{blood}$
$\rightarrow \alpha(w_i - w_j)^2$
Smooth
$z_i \neq z_j$
$\rightarrow \beta$
Discontinuous
K. Nakada, et al., IEEE MIC (2013); Med Phys (2015)
26


Truth
FBP
PML
JE-MAP
K. Nakada, CERN wrokshop (2015)
@70keV, WW 400HU, WL -50HU
27



Joint estimation with tissue types



K. Taguchi (JHU) – AAPM, July 12-16, 2015 K. Nakada, et al., IEEE MIC (2013) 29

Photon counting low-dose CT

- Current CT detectors lead to higher dose exams
- Low-dose CT by integrating 3 technologies
  - Photon counting detectors (PCDs)
  - Iterative reconstruction for PCDs (PIECE)
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K. Taguchi (JHU) – AAPM, July 12-16, 2015 30

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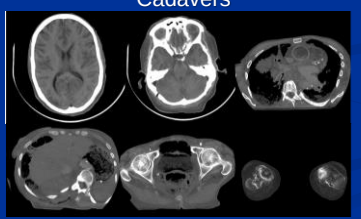
- Other clinical merits of PCD-CT

Whole-body prototype PCD-CT system

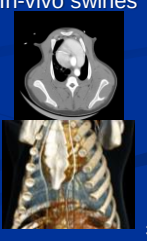
Developed by Siemens, installed at Mayo Clinic

- Dual-source CT, EID for ∅50 cm, PCD for ∅27.5 cm
- (225 μm)^2 pixel, 2 thresholds (staggered 4 thresholds)
- 128x10^6 counts/s/mm^2 with 13.5% loss, 256x10^6 with 25.2% loss
- Shading artifacts due to energetic cross-talks (not shown)

Cadavers



In-vivo swines



Courtesy of Cynthia H. McCollough, Ph.D. (Mayo Clinic)

Clinical benefits of spectral CT

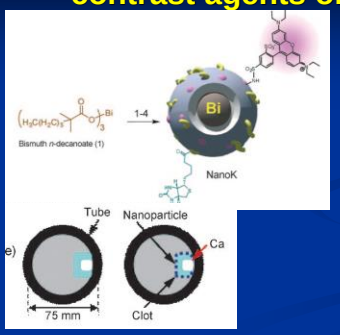
Improvement of current CT images

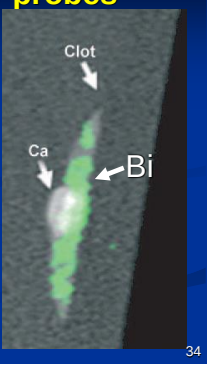
1) Contrast-to-noise ratio (CNR) and contrast of CT images, or doses of radiation & contrast agents
2) Quantitative CT imaging
3) Material- or tissue type-specific imaging
4) Accurate K-edge CT imaging
5) Simultaneous multi-agent imaging
6) Molecular CT with nanoparticles
7) Personalized medicine

New class of CT imaging

K Taguchi, Med Phys **40**(10), 100901 (19 pages) (2013)

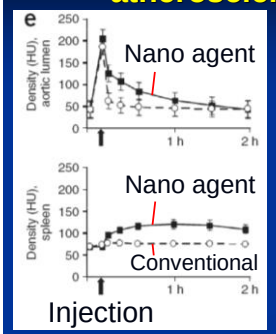
Molecular CT with nanoparticle contrast agents or probes

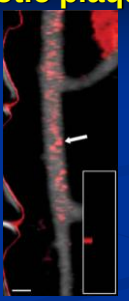




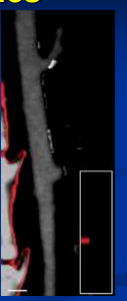
D. Pan, Angew Chem Int Ed **49**: 9635-9639 (2010)

Imaging macrophages in atherosclerotic plaques





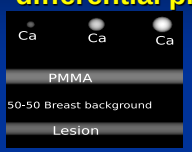
Nano agent



Conventional agent

F. Hyafil, Nat Med **13**(5): 636-641 (2007)

The use of PCDs and coded-aperture for simultaneous absorption, phase, and differential phase contrast imaging

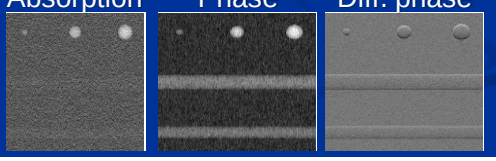


Low-dose single scan followed by a novel retrieval algorithm

- 5cm average breast tissue
- 1.5 mGy dose
- 6 energy bins, CdTe detector

M. Das, AAPM 2015, TH-AB-204-07 (8:30 am)

Absorption Phase Diff. phase



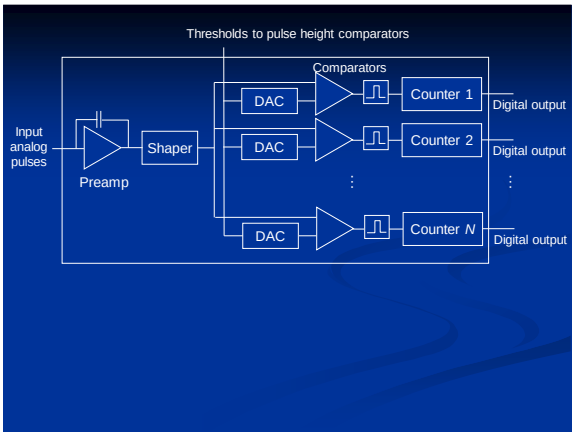
Summary

- Current CT detectors cause the major limitations of CT images
- PCDs address them and enable new applications
- Low-dose CT by integrating 3 technologies
  - Photon counting detectors (PCDs)
  - Iterative reconstruction for PCDs (PIECE)
  - Joint estimation with tissue types (JE-MAP)
- A few whole-body prototype PCD-CT systems being evaluated at hospitals

Acknowledgment

- Kenji Amaya, Ph.D. (TITech)
- Kento Nakada, B.Sc. (TITech)
- Cynthia H. McCollough, Ph.D. (Mayo Clinic)
- Jan S. Iwanczyk, Ph.D. (DxRay, Inc)
- William Barber, Ph.D. (DxRay, Inc)
- Neal E. Harsough, Ph.D. (DxRay, Inc)
- Steffen Kappler, Ph.D. (Siemens Healthcare)
- Thomas G. Flohr, Ph.D. (Siemens Healthcare)
- Karl Stierstorfer, Ph.D. (Siemens Healthcare)

- Eric C. Frey, Ph.D. (JHU)
- Jochen Cammin, Ph.D. (JHU)
- Somesh Srivastava, Ph.D. (JHU)
- Benjamin M.W. Tsui, Ph.D. (JHU)
- Current and former students and colleagues in DMIP and JHU



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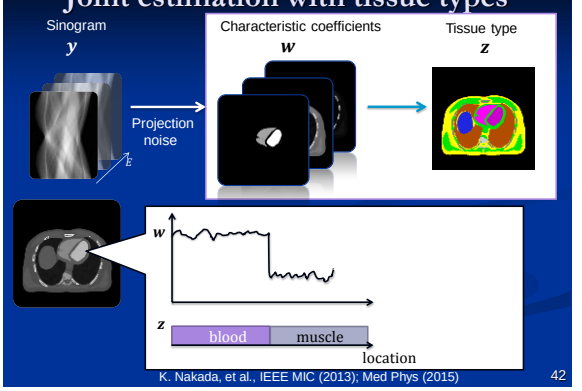
1) Contrast-to-noise ratio (CNR) and contrast of CT images, or doses of radiation & contrast agents

Joint estimation with tissue types



K. Nakada, et al., IEEE MIC (2013); Med Phys (2015)