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
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Clinical applications

“What is the killer application?”

There is no “killer application”

New generation CT has been developed for

- improving everything CT does (whole body)
- adding new dimension to everything CT does
- enabling new applications
New generation CT has been developed for

**AAPM 2018. K Taguchi (JHU)**

- 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)

In 1998, MDCT with 4 detector rows

- Shorter scan duration, larger coverage, better resolution

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

![Binned system vs High reso system](image)

- J. Baek, PMB 2013
Spatial resolution

Molecular CT

Simultaneous multi-agent imaging

Gd → (10 min) → Iodine → PCD-CT scan
Simultaneous multi-agent imaging

Gd → (10 min) → Iodine → PCD-CT scan

Material-specific imaging for better diagnosis

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

New generation CT has been developed for

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

<table>
<thead>
<tr>
<th>Index</th>
<th>Name (Ref.)*</th>
<th>Operating mode</th>
<th>Maximum count rates (Mpc-rates)</th>
<th>Photon type</th>
<th>Maximum count rates (Mpc-rates)</th>
<th>No. of charge thresholds</th>
<th>Taping capability</th>
<th>Anti-charge sharing</th>
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<tbody>
<tr>
<td>1</td>
<td>Siemens (2014)</td>
<td>H 900 × 1000</td>
<td>3.5</td>
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<td>5</td>
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<td>5</td>
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<tr>
<td>4</td>
<td>Siemens (2014)</td>
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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

- Input analog pulses
- Preamp
- Comparator
- Comparator
- Comparator

Thresholds:

- \( n_1 \)
- \( n_2 \)
- \( n_3 \)

Weights:

- \( W_Y = n_1 - n_2 \)
- \( W_Z = n_3 - n_2 \)
- \( W_X = n_3 - n_1 \)

Charge sharing

- Incident x-ray photons
- A 90 keV photon
- 60 keV
- 30 keV

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
Fluorescence x-ray emission (K-escape)

“K-escape”

Re-absorption of fluorescence x-rays

Compton scattering
Spectral distortion

- Charge sharing, K-escape, etc.
  - 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

\[
x(E) = \sum \frac{W_m \Psi_m(E)}{\mu \text{cm}^{-1}}
\]

\[
\mu = \frac{\text{Pho} \text{toelectric} + \text{Compton} \text{Scattering} + \text{X-edge(Iodine)}}{\text{Photon energy} [\text{keV}]}
\]

Estimate object \( W \) by maximizing the likelihood.
Spectral distortion: How to mitigate it?

- Balanced design + PCD model + compensation algorithm

(a) Truth  (b) Without pulse pileup model  (c) With pulse pileup model

WW 400 HU, WS 50 HU

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Spectral distortion: How to mitigate it?

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

Spectrum

Non CSM  CSM


The winner takes all

CSM

Non CSM

Spectrum

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Prototype PCD-CT systems

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- Siemens (Mayo Clinic and NIH)
  - Dual-source CT, PCD for \(\varnothing7.5\) cm x 8–24 mm, EID for \(\varnothing950\) cm
  - (225 µm\(^2\)) 2 thresholds (staggered 4 thresholds), (450–900 µm\(^2\)) output
  - 128x10\(^6\) counts/s/mm\(^2\) with 13.5% loss, 256x10\(^6\) with 25.2% loss

- Philips (Louis Pradel University Hospital, Bron, France)
  - Brilliance 64 CT, \(\varnothing16.8\) cm x 2.5 mm
  - (500 µm\(^2\)), 5 thresholds\(^{1,1}\)
  - \(>150\times10^6\) counts/s/mm\(^2\)\(^{1,1}\)

- University of Canterbury, Christchurch, NZ (on site)
  - Their own open gantry CT, PCD for \(\varnothing?\) cm x ? mm
  - (110 µm\(^2\)), 8 thresholds, anti-charge sharing
  - 10–20x10\(^6\) counts/s/mm\(^2\) with 7% loss

- KTH Royal Inst of Tech, Stockholm, Sweden (on site)
  - Philips CT(T), \(\varnothing7\) cm x 7 mm
  - (400 µm\(^2\))(500 µm\(^2\)), 8 thresholds (Medipix3RX by CERN)
  - 10–20x10\(^6\) counts/s/mm\(^2\) with 2% loss

Prototype PCD-CT systems

Phonon Counting Toolkit (PcTK, ptk.jhu.edu)

- "Spectral response" model of photon counting detectors
- 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
Acknowledgement

JHU (my group)
- Cibyreon Lee, Ph.D.
- Somesh Srinivasa, Ph.D.
- Joshua Cammen, Ph.D.
- Qixin Tong, Ph.D.
- Zhishu Sun, M.Sc.

JHU
- Eric C. Frey, Ph.D.
- Benjamin W. Tsui, Ph.D.

Siemens Healthineers
- Steffen Eppinger, Ph.D.
- Karl Stienstra, Ph.D.
- Christoph Holzer, Ph.D.
- Thomas G. Rohe, Ph.D.
- Matthew K. Fuld, Ph.D.
- George S. K. Fung, Ph.D.

TTech
- Kenji Amaya, Ph.D.
- Kento Nakada, M.Sc.

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