Photon Counting Detector CT: An Emerging Technology for CT Imaging

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Disclosure

► None
Outline

► Introduction
  ■ PCD vs. EID
  ■ Whole body PCD-CT system
  ■ PCD Configuration

► Benefits
  ■ Reduced Electronic Noise
  ■ Increased CNR/Dose Efficiency
  ■ Increased Spatial Resolution
  ■ Simultaneous, single kV, multi-energy CT
  ■ Ability to differentiate multiple k-edge contrast agents

► Future development
Photon Counting Detector CT

**Energy integrating detector (EID)**
- X-ray to electrical signal: **Indirect** conversion (Accumulative Signal) -- **State of Art**

- TiO$_2$-based reflector
- Septa
- Photo-diodes
- GOS Scintillator
- Electrical Signal

**Photon Counting Detector (PCD)**
- X-ray to electrical signal: **Direct** conversion
- Pulse height proportional to x-ray energy

- CdTe Cathode
- Pixellated Anodes
- Electrical Signal
Whole-Body PCD-CT Systems

► Siemens: based on Flash platform
  - Siemens Healthcare (Erlangen, Germany); Mayo Clinic, NIH; German Cancer Research Center
  - First patient in 2015

► Philips: based on iCT system
  - Université Claude Bernard Lyon 1, France

<table>
<thead>
<tr>
<th></th>
<th>EID-CT</th>
<th>PCD-CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Size</td>
<td>0.6 mm</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>Collimation</td>
<td>128 x 0.6 mm</td>
<td>32 x 0.25 mm / 64 x 0.5 mm</td>
</tr>
<tr>
<td>FOV</td>
<td>500 mm</td>
<td>275 mm</td>
</tr>
<tr>
<td>Max Current</td>
<td>800 mA</td>
<td>550 mA</td>
</tr>
</tbody>
</table>
PCD-CT Detector Configuration

► Several clinical applications require high resolution (smaller acquisition pixel)

Yu et al., PMB 2016
PCD-CT Detector Configuration

- PCD Sub-pixel 0.225 mm
- PCD High Res
  Read-out 0.45 mm
- In-plane
- Macro Pixel 0.9 mm

PCD-CT ~ 0.25 mm @ iso-center
Clinical CT ~ 0.6 mm @ iso-center
PCD-CT Spectral Acquisition

- Counting individual photons
- Energy Discrimination with pre-defined threshold

Threshold L1: 25 – 140 keV
Threshold L2: 50 – 140 keV
Threshold H1: 75 – 140 keV
Threshold H2: 90 – 140 keV

Bin 1: 25 – 50 keV
Bin 2: 50 – 75 keV
Bin 3: 75 – 90 keV
Bin 4: 90 – 140 keV

Yu et al., PMB 2016
Willemink, et al., Radiology 2018
Benefits of PCD-CT

- Reduced Electronic Noise
- Increased CNR/Dose Efficiency
- Increased Spatial Resolution
- Simultaneous, single kV, multi-energy CT
- Ability to differentiate multiple k-edge contrast agents
Reduced Noise/Increased Contrast

<table>
<thead>
<tr>
<th></th>
<th>Clinical CT</th>
<th>PCD-CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iodine Contrast (HU)</td>
<td>603.76</td>
<td>721.79</td>
</tr>
<tr>
<td>Noise (HU)</td>
<td>11.36</td>
<td>10.82</td>
</tr>
<tr>
<td>CNR</td>
<td>53.15</td>
<td>66.68</td>
</tr>
</tbody>
</table>

Yu et al., PMB 2016
Gutjahr et al., Invest Radiol 2016
Reduced Noise/Increased Contrast

Clinical CT       PCD-CT

GM-WM Contrast
Noise

Table 3: Image-quality comparison between energy-integrating detector and photon-counting detector CT for gray matter, white matter, and CSF

<table>
<thead>
<tr>
<th>Image-Quality Index</th>
<th>EIDᵃ</th>
<th>PCDᵇ</th>
<th>P</th>
<th>Improvement Ratioᵇ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM noise (HU)</td>
<td>3.9 ± 1.0</td>
<td>3.2 ± 0.5</td>
<td>&lt;.001</td>
<td>17.9</td>
</tr>
<tr>
<td>WM noise (HU)</td>
<td>3.4 ± 0.8</td>
<td>2.7 ± 0.7</td>
<td>.002</td>
<td>20.6</td>
</tr>
<tr>
<td>CSF noise (HU)</td>
<td>3.9 ± 0.8</td>
<td>3.4 ± 0.7</td>
<td>&lt;.001</td>
<td>12.8</td>
</tr>
<tr>
<td>GM SNR</td>
<td>10.5 ± 2.5</td>
<td>12.6 ± 2.2</td>
<td>&lt;.001</td>
<td>19.0</td>
</tr>
<tr>
<td>WM SNR</td>
<td>9.5 ± 2.3</td>
<td>11.4 ± 2.7</td>
<td>.01</td>
<td>20.0</td>
</tr>
<tr>
<td>GM–WM contrast (HU)</td>
<td>8.9 ± 1.8</td>
<td>10.3 ± 1.9</td>
<td>.02</td>
<td>15.7</td>
</tr>
<tr>
<td>GM–WM CNR</td>
<td>1.8 ± 0.5</td>
<td>2.4 ± 0.8</td>
<td>&lt;.001</td>
<td>33.3</td>
</tr>
</tbody>
</table>

Pourmorteza et al., AJNR 2018
Benefits of PCD-CT

- Reduced Electronic Noise
- Increased CNR/Dose Efficiency
- Increased Spatial Resolution
- Simultaneous, single kV, multi-energy CT
- Ability to differentiate multiple k-edge contrast agents
Increased Spatial Resolution - Phantom

► Improved assessment of nodule morphology using ultra-high-resolution (UHR) in PCD-CT system.

Photo of a 10-mm nodule

PCD UHR Mode

PCD Macro Mode (Similar to Clinical CT)

Zhou et al., JMI 2018
Increased Spatial Resolution – Patient

**Lung CT**
- Improved definition of fibrosis

**Shoulder CT**
- Sharper cortex and trabecular bone

Leng et al., Invest Radiol 2018
Bartlett et al., Invest Radiol 2019
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Simultaneous Multi-Energy - MAR

Use spectral shaping and high energy bin images (Bin2/TH) to reduce metal artifacts (MAR)

Zhou et al., Invest Radiol 2019
Simultaneous Multi-Energy – Universal Protocol

- kV needs to be manually selected or automatically determined in current workflow, based on patient size, clinical tasks, etc.
  - A substantially increased risk for unacceptable image quality

- Virtual mono-energetic images (VMIs) at low keV can be synthesized from dual energy (DE) CT or PCD-CT

Matsumoto et al., Radiology, 2010
Leng et al., Radiology, 2011
Shuman et al., AJR, 2014
McCollough, et al., Radiology 2015
Can we use a single-kV universal protocol (140 kV, 25/75 keV) to generate VMIs on PCD-CT for enhanced CT exams (abdominal iodine detection) across different adult patient sizes?

Zhou et al., Invest Radiol (In Press)

Lesion Absent

PCD-CT
VMI@50keV

EID DE
VMI@50keV

EID SE
100 kV

2.0 mgI/cc

4 mm
Simultaneous Multi-Energy – Universal Protocol

- VMI@50 keV generated from a universal PCD protocol provides comparable detectability relative to optimal EID-SE CT at size-specific kV settings.
- Streamline the clinical workflow for enhanced CT exams and reduce inadvertent selection of inferior settings.

Zhou et al., Invest Radiol (In Press)
Simultaneous Multi-Energy – SPR

- Stopping power ratio (SPR) calculation determines the accuracy of dose delivery in charged-particle therapy (e.g. proton).

- PCD-CT method produced similar or better SPR results than the SECT- and DECT-based methods.

<table>
<thead>
<tr>
<th>Noise level</th>
<th>RMSE (%)</th>
<th>Mean error (%)</th>
<th>[5%,95%] (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PCD-CT 4 Bins</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No noise</td>
<td>0.5</td>
<td>0.0</td>
<td>[−0.9,0.9]</td>
</tr>
<tr>
<td>Low</td>
<td>1.6</td>
<td>0.1</td>
<td>[−2.4,2.7]</td>
</tr>
<tr>
<td>Medium</td>
<td>2.1</td>
<td>0.1</td>
<td>[−3.0,3.4]</td>
</tr>
<tr>
<td>High</td>
<td>3.1</td>
<td>−0.1</td>
<td>[−4.3,4.2]</td>
</tr>
<tr>
<td><strong>PCD-CT 2 Bins</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No noise</td>
<td>0.5</td>
<td>−0.0</td>
<td>[−0.9,0.9]</td>
</tr>
<tr>
<td>Low</td>
<td>1.6</td>
<td>0.1</td>
<td>[−2.4,2.7]</td>
</tr>
<tr>
<td>Medium</td>
<td>2.1</td>
<td>0.1</td>
<td>[−3.0,3.3]</td>
</tr>
<tr>
<td>High</td>
<td>3.0</td>
<td>−0.0</td>
<td>[−4.2,4.2]</td>
</tr>
<tr>
<td><strong>DECT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No noise</td>
<td>0.4</td>
<td>−0.1</td>
<td>[−0.8,0.6]</td>
</tr>
<tr>
<td>Low</td>
<td>3.0</td>
<td>0.0</td>
<td>[−4.5,5.0]</td>
</tr>
<tr>
<td>Medium</td>
<td>5.8</td>
<td>0.2</td>
<td>[−8.3,9.9]</td>
</tr>
<tr>
<td>High</td>
<td>10.6</td>
<td>0.2</td>
<td>[−15.9,16.4]</td>
</tr>
<tr>
<td><strong>SECT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No noise</td>
<td>1.5</td>
<td>0.0</td>
<td>[−2.4,2.6]</td>
</tr>
<tr>
<td>Low</td>
<td>1.6</td>
<td>0.0</td>
<td>[−2.6,2.8]</td>
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<tr>
<td>Medium</td>
<td>2.0</td>
<td>0.1</td>
<td>[−3.0,3.2]</td>
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<tr>
<td>High</td>
<td>3.2</td>
<td>0.1</td>
<td>[−4.3,4.7]</td>
</tr>
</tbody>
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Taasti et al., Med Phys 2018
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Multi K-edge Contrasts Imaging

► Differentiate multiple contrast agents simultaneously in a single acquisition

<table>
<thead>
<tr>
<th>PCD CT Single Energy Image</th>
<th>PCD CT Gd Concentration Map</th>
<th>MRI LGE</th>
<th>Gross Pathology</th>
<th>Trichrome Stain</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
<td>e</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rabbits N = 4</th>
<th>Attenuation (HU)</th>
<th>Concentration of Gadolinium (mg/mL)</th>
<th>Concentration of Iodine (mg/mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aorta</td>
<td>1103.1 ± 108.0</td>
<td>20.5 ± 2.07</td>
<td>6.9 ± 0.5</td>
</tr>
<tr>
<td>Hepatic Artery</td>
<td>605.6 ± 171.9</td>
<td>8.5 ± 3.9</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>Portal Vein</td>
<td>253.5 ± 49.0</td>
<td>0 ± 1.3</td>
<td>4.2 ± 0.3</td>
</tr>
<tr>
<td>Liver</td>
<td>149.2 ± 18.25</td>
<td>0.5 ± 0.3</td>
<td>2.1 ± 0.1</td>
</tr>
</tbody>
</table>

Symons et al., Int J Cardiovasc Imaging 2017
Si-Mohamed et al., Scientific Reports 2019
Challenges/Opportunities

Techniques
► Pulse pile-up
► Charge sharing
► Elevated noise in narrow bin/ultra high resolution images
► Spectral image post-processing

Clinical Applications
► Chest
► Breast (Experimental PCD breast CT systems)
► Cardiovascular
Q & A