Overview

- Why MECT beyond DECT
- Techniques for EID-based MECT
  - Multi-source MECT
  - Single-source MECT with spatial-spectral filters
  - Dual-source MECT with split filter
- Summary and discussions

DECT Clinical Applications

- Virtual Monochromatic
- Virtual non-contrast
- Iodine imaging
- Kidney stone
- Gout
- Breast implant
- Auto bone removal
- Lung PIV

McCollough CE et al, Radiology 2015
Why MECT beyond DECT – Multi-contrast Imaging

- Iodine and gadolinium
  - Single scan for multi-phase liver and kidney imaging – potential to reduce radiation dose (Muenzel et al, 2016; Rolf et al, 2017)
- Iodine and bismuth
  - Small bowel imaging – separate lumen and bowel wall (Qu et al, 2010, Morgan et al, 2012)
- Iodine and tungsten
  - Multi-phase in one single scan – potential to reduce radiation dose (Mongan et al, 2012)
- Iodine and gold + calcification
  - Cardiovascular – characterize macrophage burden, calcification, and stenosis of atherosclerotic plaques (Cormode et al, 2010; Baturin et al, 2012)
- Iodine and gadolinium + calcification
  - CTA – detect endoleaks at arterial phase (I) and at venous/delayed phase (Gd) following endovascular aortic repair (Dangelmaier et al, 2018)

Why MECT beyond DECT?

- DECT can actually solve 3-material problem with an additional prior (e.g., volume conservation).
  \[
  \begin{align*}
  \mu(E_1) &= \sum_{m=1}^{N} \left( \mu_{E_1} \rho_{m} \right) \\
  \mu(E_2) &= \sum_{m=1}^{N} \left( \mu_{E_2} \rho_{m} \right) \\
  \mu(E_N) &= \sum_{m=1}^{N} \left( \mu_{E_N} \rho_{m} \right)
  \end{align*}
  \]
  DECT for 3-material quantification
  Kelcz et al, Med Phys, 1979

Why MECT beyond DECT?

- MECT (N=2) benefits
  - Better noise properties to solve 3-material problem
  - DECT cannot solve 4 or more material problem
  \[
  \begin{align*}
  \mu(E_1) &= \sum_{m=1}^{N} \left( \mu_{E_1} \rho_{m} \right) \\
  \mu(E_2) &= \sum_{m=1}^{N} \left( \mu_{E_2} \rho_{m} \right) \\
  \mu(E_N) &= \sum_{m=1}^{N} \left( \mu_{E_N} \rho_{m} \right)
  \end{align*}
  \]
  MECT for M-material quantification (NoM+1)
  Dangelmaier et al, Eur Radiol, 2018
MECT platforms

Energy integrating detector (EID)-based

Photon counting detector (PCD)-based

McCollough CH et al, Radiology 2015

Benefits of PCD-CT Platform

• Improve SNR (optimal energy weighting)
• Improve low-dose performance (reduced electronic noise)
• Improve spatial resolution (direct conversion)
• Enable MECT (energy resolving and multiple energy thresholds)

Limitations of Current PCD-CT Technology

• High cost due to lack of mass production
• Spectrum distortion due to non-ideal detectors (charge sharing, K-escape, pulse pileup, etc.)

Yu Z et al, PMB, 2016
Limitations of Current PCD-CT Technology

- As a result of spectra distortion, no advantage has been shown compared to EID-based DECT for dual-energy tasks.

<table>
<thead>
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<th>DS 100 kV / Sn 140 kV</th>
<th>PC 2 bins</th>
<th>PC 4 bins</th>
<th>PC 8 bins</th>
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<td>-7% noise</td>
<td>+9% noise</td>
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</table>

Faby et al, Med Phys 2015

EID-based MECT

- Multi-source MECT
- Single-source MECT with spatial-spectral filters
- Dual-source MECT with split filter


Multi-source MECT

- Each X-ray source is operated at a different tube voltage, providing multi-energy imaging capability

Multi-source MECT

- Advantages
  - Flexible to adjust tube voltage and spectrum
  - Flexible to adjust dose distribution
- Challenges
  - Cost
  - Limited space in a CT gantry
  - Limited field of view (FOV)
  - Cross scatter

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Single-source MECT with spatial-spectral filters

- X-ray beam is modulated using a repeating pattern of filter materials, allowing for collection of many different spectral channels within one scan
- Model-based material decomposition

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Four-material decomposition results

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Single-source MECT with spatial-spectral filters

- Advantages:
  - Cost effective
  - One single acquisition, no need to switch filters
  - Spectra separation appears to be reasonable

- Challenges:
  - Alignment of each beamlet (after each filter) with corresponding detector pixels
  - Penumbra region between adjacent filters
  - Sampling pattern of filters

Dual-source MECT with split filter

Twin-beam on Single Source CT (Siemens)

Saba et al, 2015
Triple- and Quadruple-beams on Dual-source CT

- One tube for low-energy; the other tube uses a split filter to generate 2 high-energy beams
- Both tubes use split filter

Yu et al SPIE 2016; Yu et al J Med Imaging, 2018 (in press)

Spectra in triple-beam and quadruple beams

Mean energy:
- 80 kV: 52.2 keV
- 150 kV + Au: 79.7 keV
- 150 kV + Sn: 58.6 keV

Mean energy:
- 90 kV + Gd$_2$S$_2$O: 56.1 keV
- 90 kV + Sn: 60.8 keV
- 150 kV + Au: 79.7 keV
- 150 kV + Sn: 98.6 keV

Material decomposition: Triple-beam

(d) Iodine
(e) Bismuth
(f) Water
Material decomposition: Quadruple-beam

(a) 90 kV + Gd
(b) 90 kV + Sn
(c) 150 kV + Au
(d) 150 kV + Sn
(e) Iodine
(f) Bismuth
(g) Water

Preliminary Experiment before Implementation

<table>
<thead>
<tr>
<th>CT Scanner Platform</th>
<th>ED-based MECT [0-3]</th>
<th>PCD-CT [kV]</th>
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<tr>
<td></td>
<td>Definition Edge</td>
<td></td>
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<tr>
<td>Mean Energies (keV)</td>
<td>[52.2 67.5 85.3]</td>
<td>[52.2 67.5 85.3]</td>
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<tr>
<td>Pitch</td>
<td>0.15</td>
<td>0.6</td>
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<tr>
<td>Rotation (m s⁻¹)</td>
<td>64 ± 0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Slice thickness/increment/kernel</td>
<td>3.0/2.8 mm, D30</td>
<td>3.0/2.8 mm, D30</td>
</tr>
<tr>
<td>CTDIvol (mGy)</td>
<td>35 cm: 7.6 + 15.1 = 22.7</td>
<td></td>
</tr>
</tbody>
</table>

*Note: CTDIvol for PCD-CT was doubled to compensate 50% detector dose efficiency in the "chess" mode.

Spectra comparison with PCD-CT

Mean energy:
80 kV: 52.2 keV
120 kV + Au: 67.5 keV
120 kV + Sn: 67.5 keV
Mean energy:
80 kV: 64.6 keV
120 kV + Au: 69.5 keV
120 kV + Sn: 88.7 keV
120 kV + Sn: 108.7 keV
Comparison with PCD-CT

EID-MECT (80kV + AuSn120kV)

Iodine  Bismuth

PCD-MECT (140kV [25 50 75 90keV])

Iodine  Bismuth

Comparison with PCD-CT

Noise Summary (I/Bi, 35 cm, CTDvol: 23.0mGy)

<table>
<thead>
<tr>
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<th>Noise: I</th>
<th>Noise: Bi</th>
<th>Noise: Water</th>
<th>Condition Number</th>
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<td>1.4</td>
<td>0.1</td>
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<tr>
<td>EID-based</td>
<td>1.2</td>
<td>1.4</td>
<td>0.1</td>
<td>5.1</td>
</tr>
<tr>
<td>PCD-CT</td>
<td>1.2</td>
<td>1.9</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Implementations (Still ongoing)

Filter thickness optimization

Split filter installation

Ren L et al, The CT meeting at Utah, 2018
• **Advantages**
  - Cost effective to implement based on dual-source scanners
  - Reasonable spectra separation
  - Dose efficiency comparable to or better than current PCD-CT to perform multi-contrast agent imaging
  - More flexible dose allocation among beams

• **Challenges**
  - Half-rotation (~125 ms) temporal difference between the split beams
  - Transition area of split beams may slightly degrade the dose efficiency in multi-energy mode
  - Cross scatter between sources and between split filters

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**Summary and Discussions**

- Multiple techniques have been proposed or under development to perform MECT (n>2) on EID-based scanner platform.
  - Multi-source MECT
  - Single-source MECT with spatial-spectral filters
  - Dual-source MECT with split filter
- EID-based MECT may have similar dose efficiency compared to current PCD-based scanners in multi-energy multi-contrast tasks.
- Due to spectral distortion, potential benefit of PCD-CT in multi-contrast imaging remains to be shown.
  - May improve with better correction algorithms or PCD technology
- Clinical benefit of multi-contrast imaging itself remains to be demonstrated
  - For example, dose efficiency may not be good compared to multi-phase single-energy scans
  - *(Ren L et al, AAPM, Thursday morning CT session)*

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