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CT Clinical Innovation Center

Multi-energy CT using Energy integrating detectors

Lifeng Yu, PhD
Professor of Medical Physics

Department of Radiology, Mayo Clinic, Rochester, MN

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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

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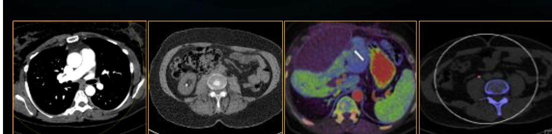
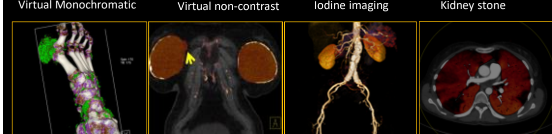
DECT Clinical Applications



Virtual Monochromatic | Virtual non-contrast | Iodine imaging | Kidney stone



Gout | Breast implant | Auto bone removal | Lung PBV

McCollough CH et al, Radiology 2015

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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)

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Why MECT beyond DECT?

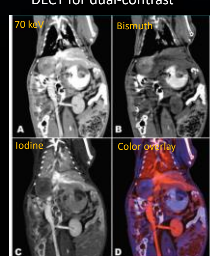
- DECT can actually solve 3-material problem with an additional prior (e.g., volume conservation).

$$\begin{cases} \mu(E_1) = \left(\frac{\mu}{\rho}\right)_1 (E_1)\cdot\rho_1 + \left(\frac{\mu}{\rho}\right)_2 (E_1)\cdot\rho_2 + \left(\frac{\mu}{\rho}\right)_3 (E_1)\cdot\rho_3 \\ \mu(E_2) = \left(\frac{\mu}{\rho}\right)_1 (E_2)\cdot\rho_1 + \left(\frac{\mu}{\rho}\right)_2 (E_2)\cdot\rho_2 + \left(\frac{\mu}{\rho}\right)_3 (E_2)\cdot\rho_3 \\ 1 = \frac{\rho_1}{\rho_{10}} + \frac{\rho_2}{\rho_{20}} + \frac{\rho_3}{\rho_{30}} \end{cases}$$

DECT for 3-material quantification

Kelcz et al, Med Phys, 1979

DECT for dual-contrast



Iodine(intravenous)/Bismuth(oral)

Mongan et al, Radiology, 2012

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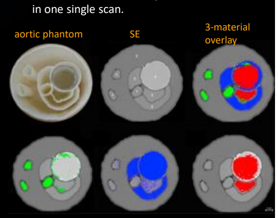
Why MECT beyond DECT?

- MECT (N>2) benefits
  - Better noise properties to solve 3-material problem
  - DECT cannot solve 4 or more material problem

$$\begin{cases} \mu(E_1) = \sum_{m=1}^{M} \left(\frac{\mu}{\rho}\right)_m (E_1)\cdot\rho_m \\ \mu(E_2) = \sum_{m=1}^{M} \left(\frac{\mu}{\rho}\right)_m (E_2)\cdot\rho_m \\ \vdots \\ \mu(E_N) = \sum_{m=1}^{M} \left(\frac{\mu}{\rho}\right)_m (E_N)\cdot\rho_m \\ 1 = \sum_{m=1}^{M} \frac{\rho_m}{\rho_{m0}} \end{cases}$$

MECT for M-material quantification (N≥M-1)

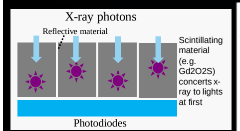
- MECT (N=5) for 4-material problem (Iodine, Gadolinium, Calcium, blood)
- Task: capture endoleak dynamics and discriminate intra-aneurysmatic calcifications in one single scan.



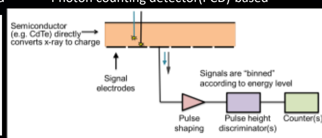
Dangelmaier et al, Eur Rad, 2018

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)

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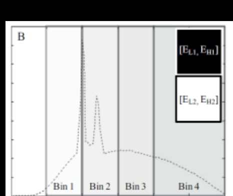
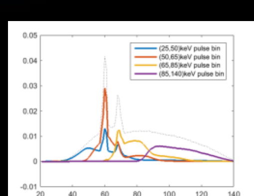
Limitations of Current PCD-CT Technology

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





Ideal spectrum separation

True spectrum distortion

Yu Z et al, PMB, 2016

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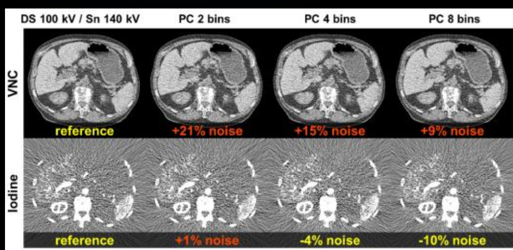
Limitations of Current PCD-CT Technology

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



Faby et al, Med Phys 2015

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EID-based MECT

- Multi-source MECT[1]
- Single-source MECT with spatial-spectral filters[2]
- Dual-source MECT with split filter[3]

[1]E. Dafni and D. Ruimi, "Multiple source CT scanner," U.S. Patent 5966422, 1999.
[2]J. W. Stayman and S. Tilley II, "Model-based Multi-material Decomposition using Spatial-Spectral CT Filters," 5th CT meeting, 2018.
[3]L Yu. et al, "Dual-Source Multi-Energy CT with Triple or Quadruple X-ray Beams",, SPIE Medical Imaging Conference, 2016
[4]L Yu. et al, "Dual-Source Multi-Energy CT with Triple or Quadruple X-ray Beams", J Med Imaging, 2018 (In press).
[5]Chen BX et al, Image reconstruction and scan configurations enabled by optimization-based algorithms in multispectral CT, PMB, 2017

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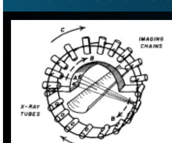
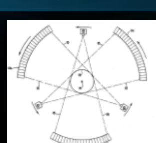
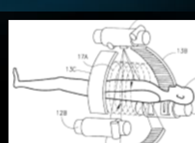
Multi-source MECT







Sinak LJ et al, The Dynamic Spatial Reconstructor: Investigating Congenital Heart Disease in Four Dimensions, Cardiovascular and Interventional Radiology, 1984

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

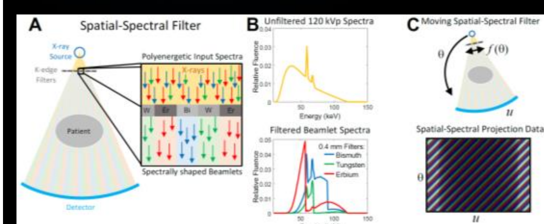
E. Dafni and D. Ruimi, "Multiple source CT scanner," U.S. Patent 5966422, 1999 (Picker)
V. B. Neculaes, et al, "Multisource X-ray and CT: lessons learned and future outlook," IEEE Access, Jan. 13, 2015.

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

Single-source MECT with spatial-spectral filters

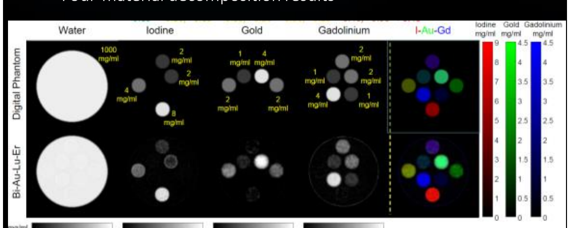
- X-ray beam is modulated using a repeating pattern of filter materials, allowing for collection of many different spectral channels within one scan
- Model based material decomposition



J. W. Stayman and S. Tilley II, "Model-based Multi-material Decomposition using Spatial-Spectral CT Filters ," 5th CT meeting, 2018.

Single-source MECT with spatial-spectral filters

- Four-material decomposition results



J. W. Stayman and S. Tilley II, "Model-based Multi-material Decomposition using Spatial-Spectral CT Filters ," 5th CT meeting, 2018.

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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

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Dual-source MECT with split filter

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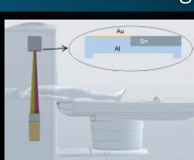
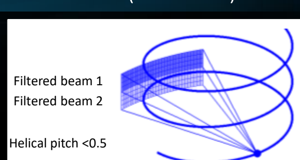
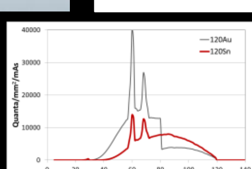
Twin-beam on Single Source CT (Siemens)





Saba et al, 2015



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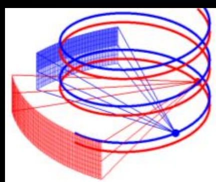
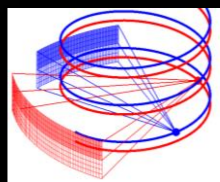
Triple- and Quadruple-beams on Dual-source CT

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



Triple-beam geometry



Quadruple-beam geometry

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

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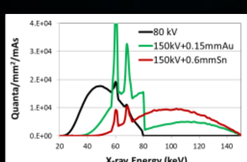
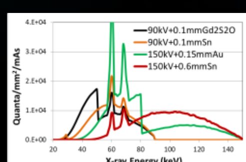
Spectra in triple-beam and quadruple beams





Mean energy:

80 kV:	52.2 keV
150 kV + Au:	79.7 keV
150 kV + Sn:	98.6 keV

Mean energy:

90 kV + Gd_2S_2O:	56.1 keV
90 kV + Sn:	60.8 keV
150 kV + Au:	79.7 keV
150 kV + Sn:	98.6 keV

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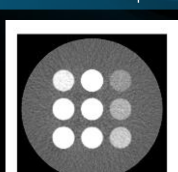
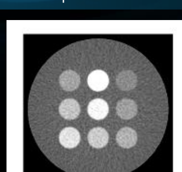
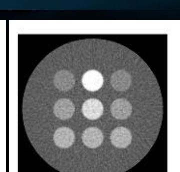
Material decomposition: Triple-beam



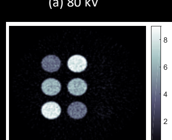
(a) 80 kV



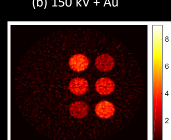
(b) 150 kV + Au



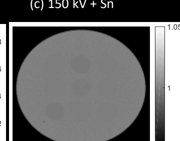
(c) 150 kV + Sn



(d) Iodine



(e) Bismuth



(f) Water

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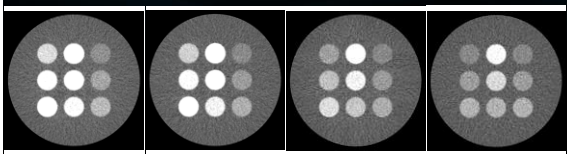
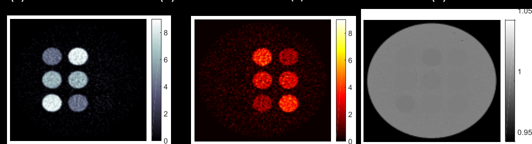
Material decomposition: Quadruple-beam



(a) 90 kV + Gd (b) 90 kV + Sn (c) 150 kV + Au (d) 150 kV + Sn



(e) Iodine (f) Bismuth (g) Water

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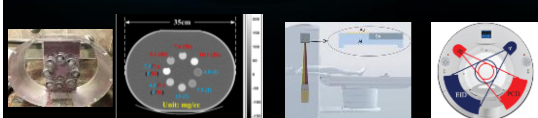
Preliminary Experiment before Implementation



	EID-based MECT (N=3)	PCD-CT (N=4)
CT Scanner Platform	Definition Edge	PCCT
kV	80 + AuSn120	140: [25 50 75 90 keV]
Mean Energies (keV)	[52.2 67.5 85.3]	[64.6 69.5 88.7 108.7]
Pitch	0.35	0.6
Rotation time (s)	0.5	0.5
Collimation (mm)	64 × 0.6	32 × 0.5
Slice thickness/increment/kernel	3.0/2.8 mm, D30	3.0/2.8 mm, D30
CTDIvol (mGy)	35cm: 7.6+15.1=22.7	35cm: 46.0*

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

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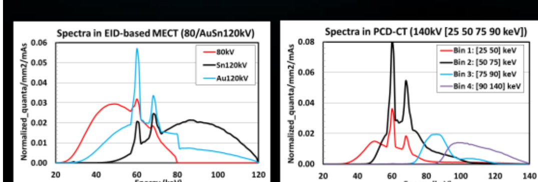
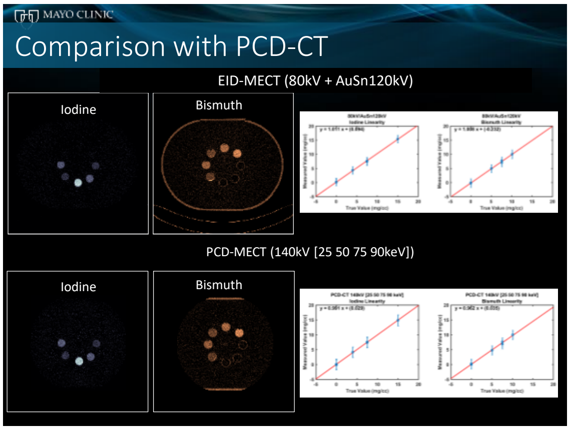
Spectra comparison with PCD-CT



Mean energy:
80 kV: 52.2 keV
120 kV + Au: 67.5 keV
120 kV + Sn: 85.3 keV

Mean energy:
[25 50] keV: 64.6 keV
[50 75] keV: 69.5 keV
[75 90] keV: 88.7 keV
[90 140] keV: 108.7 keV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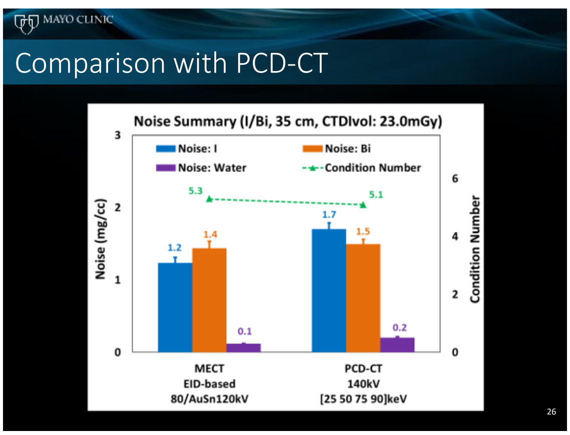
Comparison with PCD-CT
EID-MECT (80kV + AuSn120kV)
Iodine
Bismuth
PCD-MECT (140kV [25 50 75 90keV])
Iodine
Bismuth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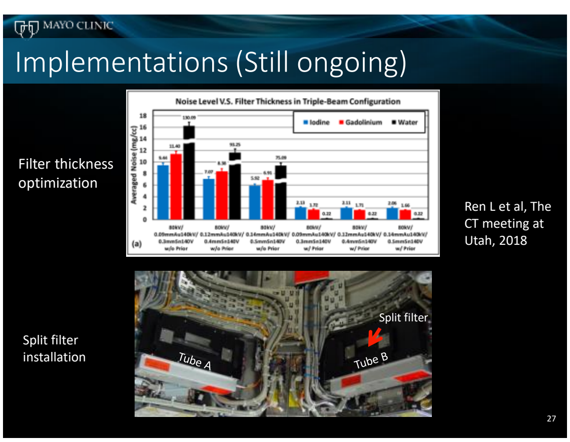
Comparison with PCD-CT
Noise Summary (I/Bi, 35 cm, CTDIvol: 23.0mGy)
Noise: I
Noise: Bi
Noise: Water
Condition Number
Noise (mg/cc)
Condition Number
5.3
5.1
1.2
1.4
0.1
1.7
1.5
0.2
MECT
EID-based
80/AuSn120kV
PCD-CT
140kV
[25 50 75 90]keV
26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Implementations (Still ongoing)
Filter thickness optimization
Noise Level V.S. Filter Thickness in Triple-Beam Configuration
Iodine
Gadolinium
Water
Averaged Noise (mg/cc)
Ren L et al, The CT meeting at Utah, 2018
Split filter installation
Split filter
Tube A
Tube B
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MECT with Dual-source + split filter

- 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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