Preconditioning of multi-material decomposition based imaging in photon-counting CT

Xiangyang Tang

PhD, DABR, FAAPM, FSPIE

Professor of Radiology and Imaging Sciences

Laboratory of Translational Research in CT (TriCT)

Department of Radiology and Imaging Sciences
Emory University School of Medicine

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Outlines

- CT's clinical relevance
- Spectral CT via energy-integration and photon-counting
  - Fundamentals
  - Questions have been and to be answered
  - Potential for advanced clinical applications
- Conditioning of multi-material decomposition based spectral imaging in photon-counting CT
  - Material space
  - Spectral channelization
- Prospects of photon-counting spectral CT

CT – A pivotal imaging modality in clinics

US Mortality, 2019 (Total: 2,854,838)

Rank	Cause of Death	No. of deaths	% of all deaths
1.	Heart Diseases	659,041	23.1
2.	Cancer	599,601	21.0
3.	Accidents (unintentional injuries)	173,040	6.1
4.	Chronic lower respiratory diseases	156,979	5.5
5.	Cerebrovascular diseases	150,005	5.3
6.	Alzheimer disease	121,499	4.3
7.	Diabetes mellitus	87,674	3.1
8.	Nephropathy*	51,565	1.8
9.	Influenza & pneumonia	49,783	1.7
10.	Intentional self-harm	47,511	1.7

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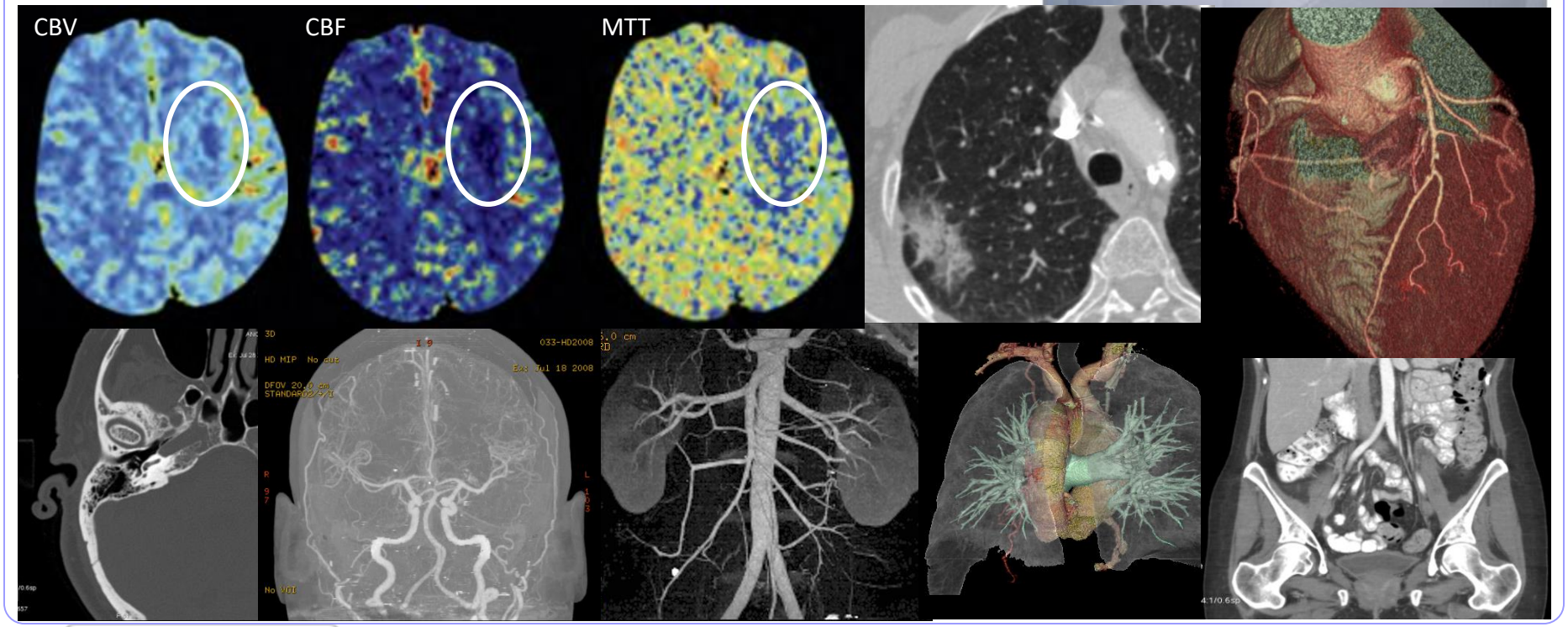
*: Includes nephrotic syndrome and nephrosis.
Source: Death: Final Data for 2019 (Table B), National Vital Statistics Reports, Centers for Disease Control and Prevention, 2019.

X. Tang, PhD, Dept. of Radiology

CT – A popular imaging modality in clinics

- Cardiovascular: stenosis, plaque, stenting
- Neurovascular: perfusion, traumatic, …
- Oncological diagnosis and interventions: thoracic, abdominal, pelvic, head/neck



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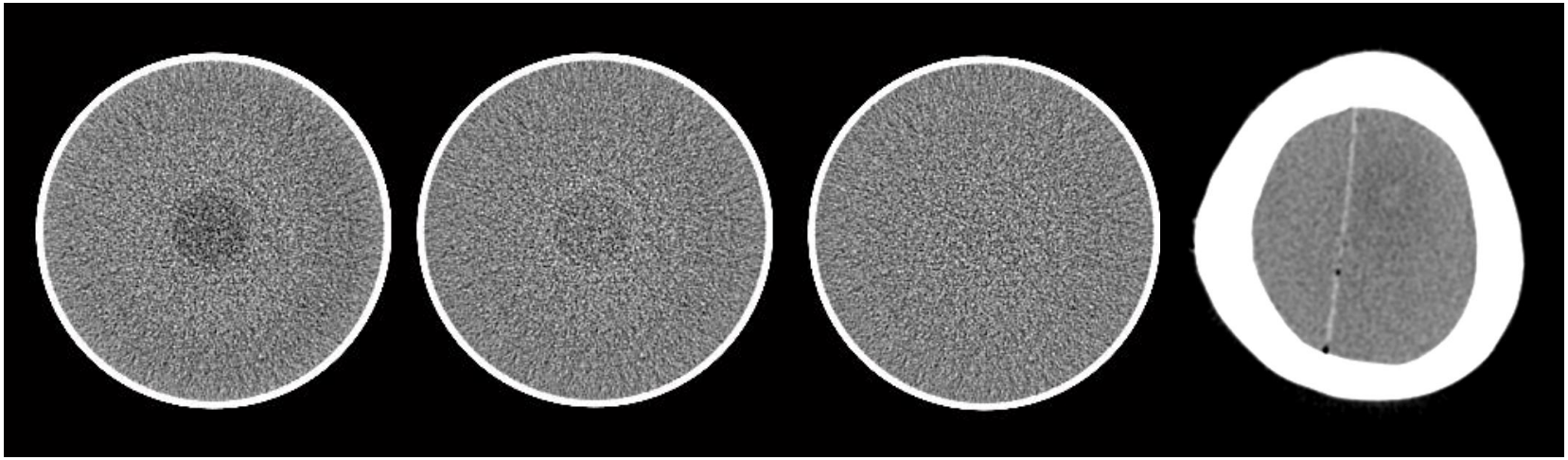
Daily tasks of diagnostic MP: Image quality

Head is the #1 challenge in clinical CT for diagnostic imaging

- Skull attenuates x-ray substantially and complicated bony structure induces artifacts;
- Low contrast between white/gray matters, as well as infarction/ ischemic and normal tissues.



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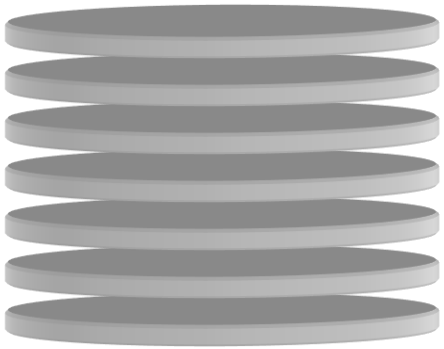
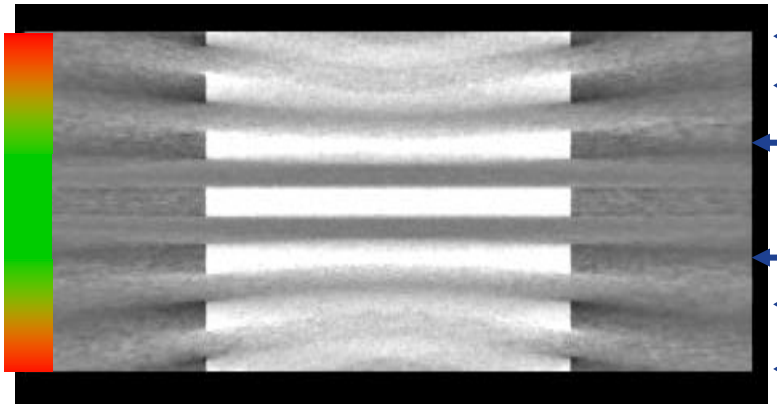
Daily tasks of diagnostic MP: Research (I)

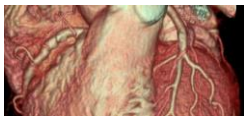


Phantom

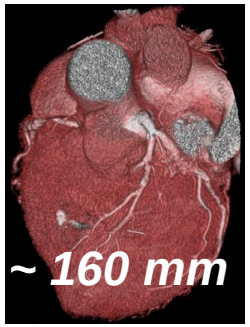
Reconstruction



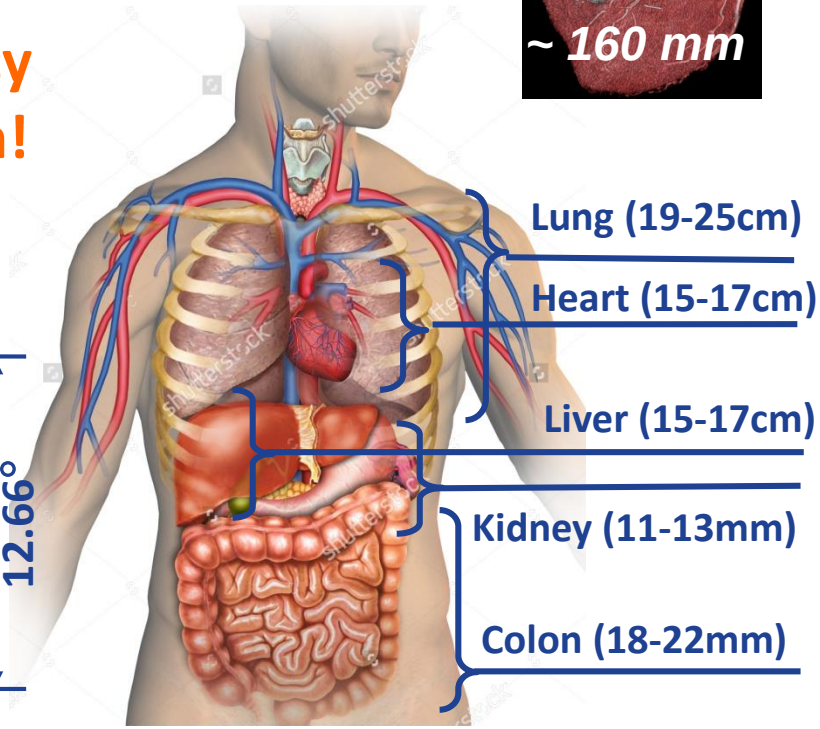
10 mm



40 mm



Data Sufficiency Condition!



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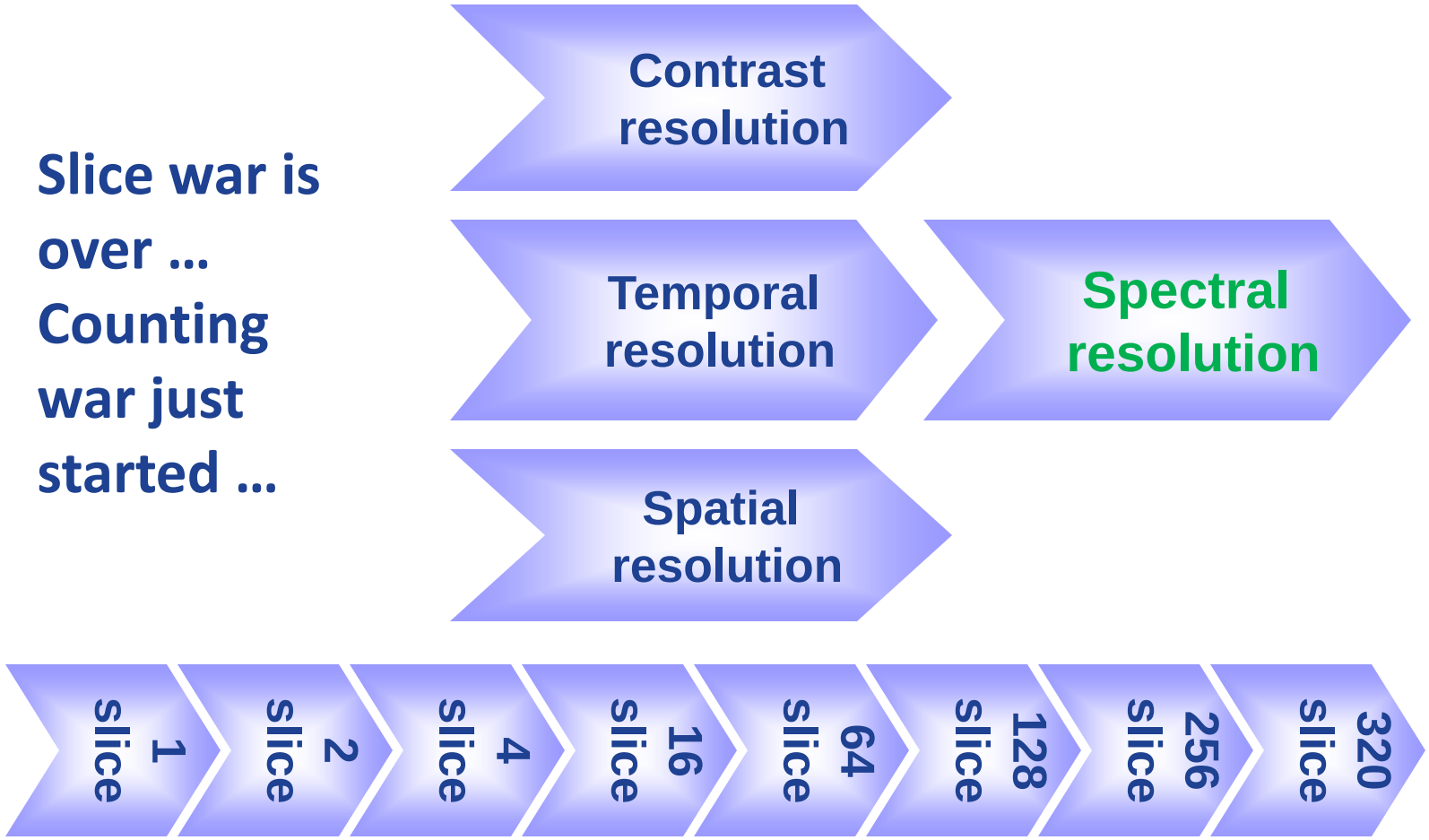
Daily tasks of diagnostic MP: Research (II)

- Slice war is over …
- Counting war just started …



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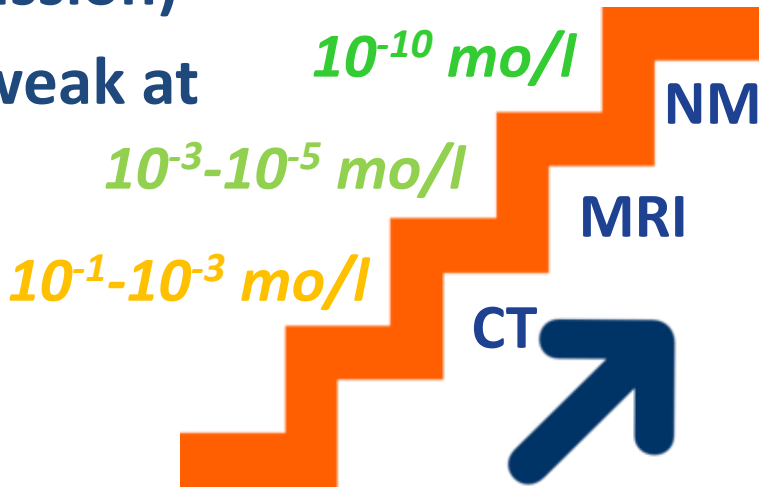
Physics: why need spectral CT for clinical imaging?

- Conventional x-ray and CT work at atomic level at which pathology induces little variation (transmission)
- Pathology induces variation at molecular level and can be detected by MRI (transmission)
- Biomarker targeted radio-pharmaceuticals empower PET/SPECT with high sensitivity (emission)
- CT is most popular in clinics but weak at sensitivity, due to limitations in
  - radiation (compared to MRI)
  - short scan time for data acquisition (compared to NM)



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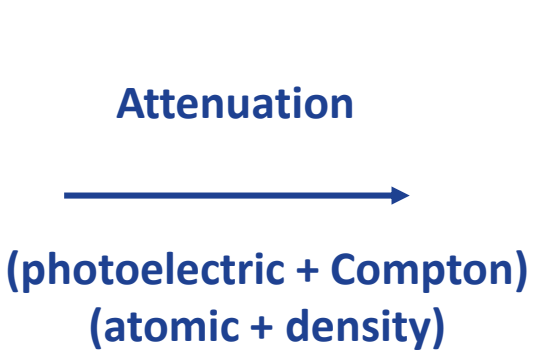
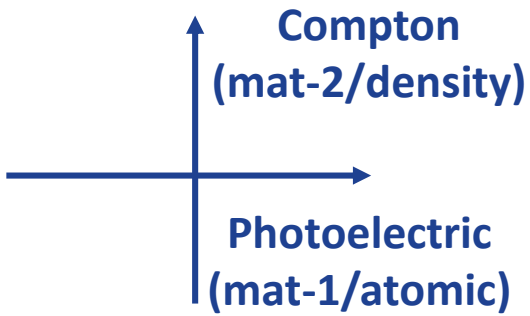
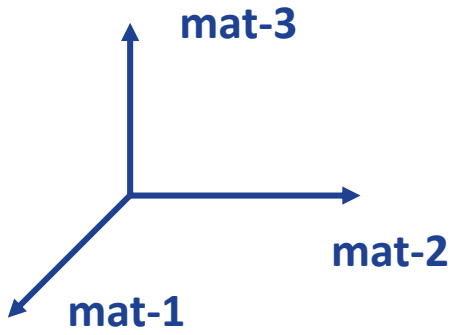
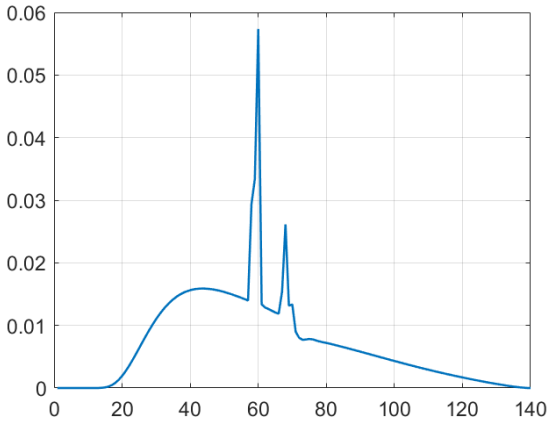
Physics: Spectral CT vs. conventional CT

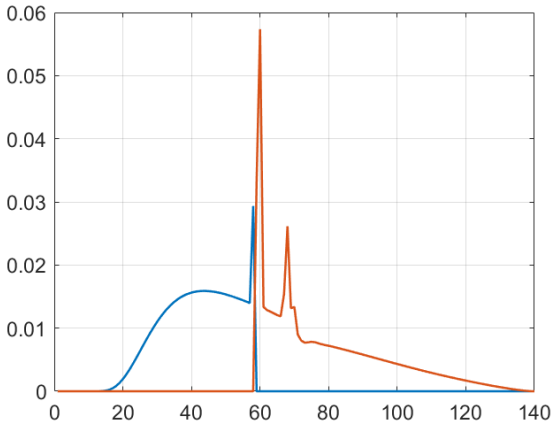
Mapping: projection → A-space (observation → presentation)

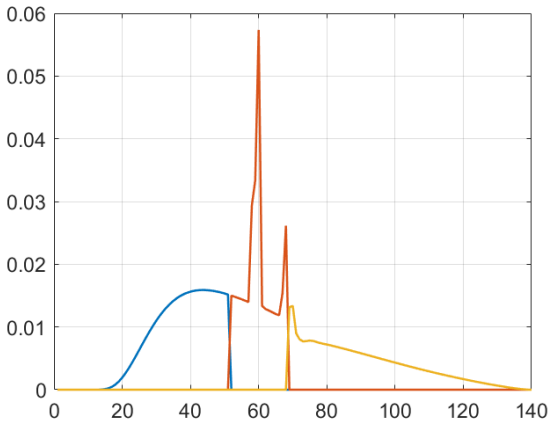












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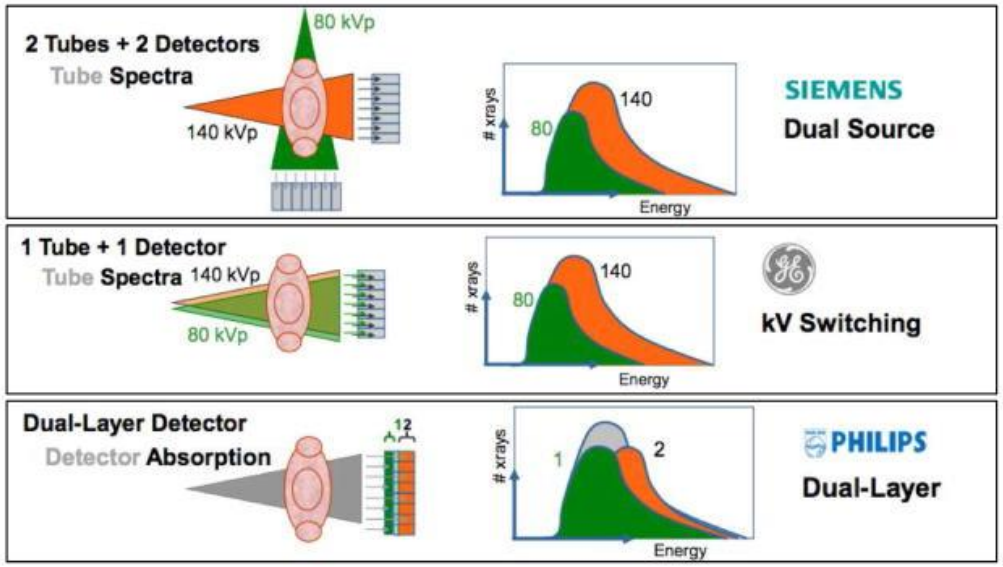
(EID) Spectral CT for diagnostic imaging in clinics

Energy-integration spectral CT is adding clinical value

- **Physics: Interaction decomposition, material decom., virtual monochromatic, (effective) atomic number map…**
- **Clinical: Virtual no contrast (VNC), iodine map, renal stone, gout, plaque component analysis, oncologic, neurovascular…**



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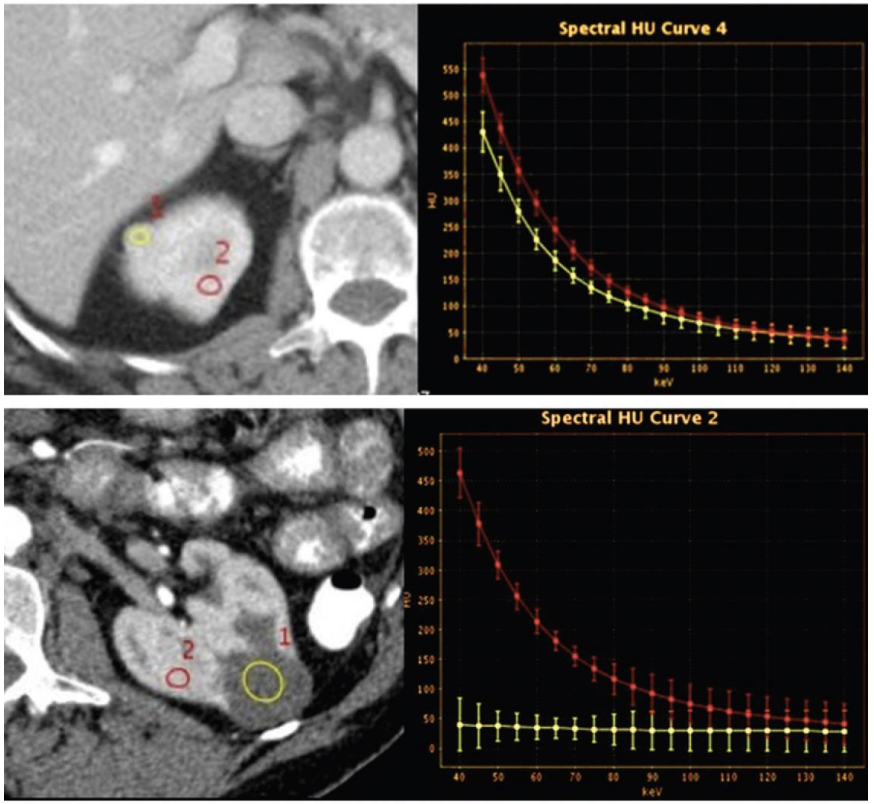
An example of added value by spectral CT in Oncology

Clinical case: Characterization of renal tumor/cyst

Energy-integration based spectral CT is being successfully used in advanced clinical applications, such as differentiation and characterization of malignant neoplasms and metastasis against benign lesions aided by iodinated contrast agents.



Agrawal MD, RadioGraphics 2014

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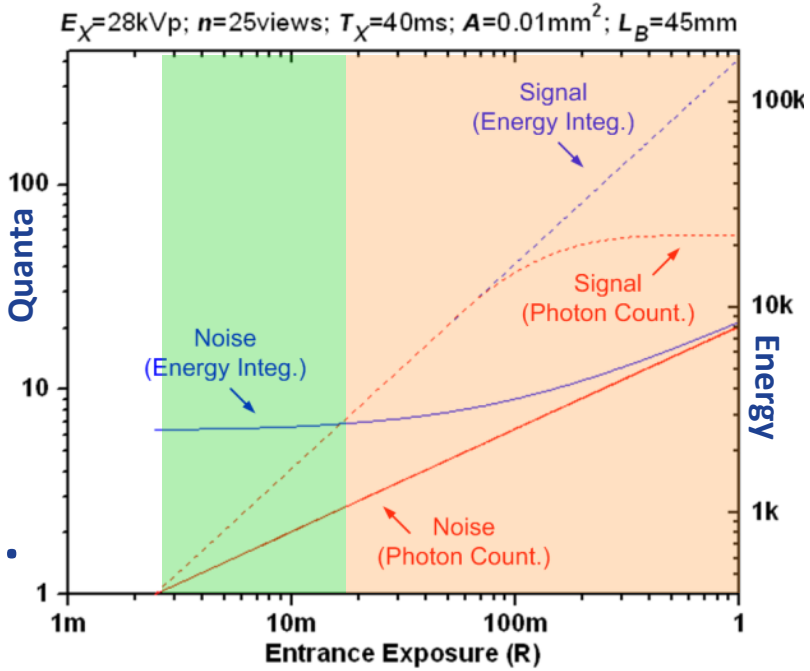
Spectral CT: Photon-counting vs. energy-integration

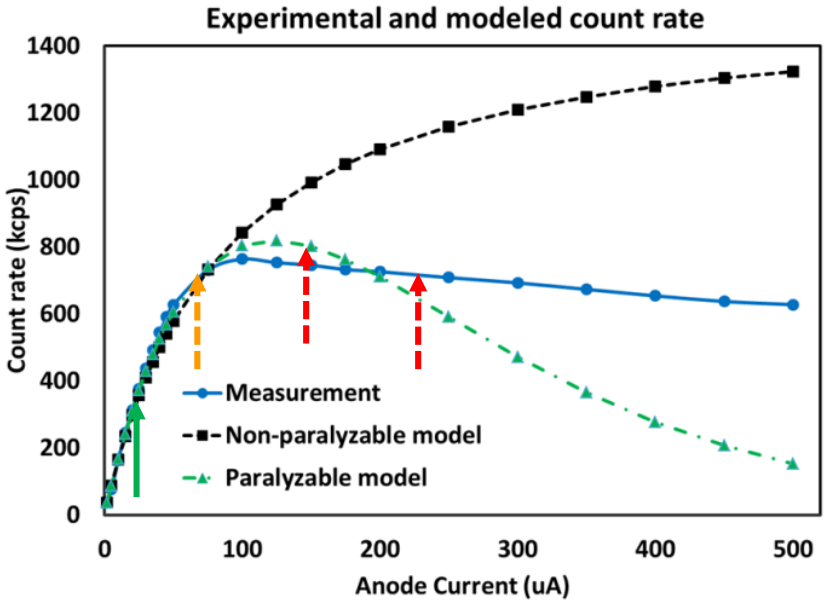
Major benefits in photon counting spectral CT

- Recover the subject contrast embedded in energy domain
- Immune of electronic noise
- Energy thresholding
- Spectral channelization
- Spectral weighting
- Facilitating K-edge imaging
- Enabling multiple material decom.
- Supporting Principal Component Analysis (PCA)



Photon-counting CT: Addressing of photon piling-up

- Pulse piling-up used to be the biggest challenge in photon-counting ($5\times 10^5 : 10^7$), but is being successfully addressed via finer detector cell ($1.0\times1.0\ mm^2 \rightarrow 0.1\times0.1 mm^2$) …
- Detector cell refinement lines up with advanced applications that demand high spatial resolution



Photon-counting CT: A few fundamental topics (I)

Metrics under the framework of signal detection/estimation (Fisher Matrix) have been used to answer the questions in 2-MD:

Q1: What is the correct (general) physical modeling of spectral CT?

Q2: What is the dimensionality of material space?

Q3: What is the conditioning of basis materials?

Q4: What is the optimal binning (especially in *K*-edge) in energy?

Q5: What is the optimal weighting scheme in energy?

- **Detective quantum efficiency (Tapiovaara-Wagner)**
- **Cramér-Rao Lower Bound (Alvarez, Roessl, …)**
- **Sufficient statistic (Wang-Pelc)**
- **Ideal observer index d^2 (Alvarez)**
- **Confidence interval (Nik)**

Photon-counting CT: A few fundamental topics (II)

Singular value decomposition (SVD) based analysis can answer or re-answer the questions related to *m*-MD based spectral imaging:

Q0: Can the added value by photon-counting spectral CT be bigger than incremental in clinical applications?

Q1: What is the dimensionality of material space?

Q2: How detector's spectral response impact imaging performance?

Q3: How to optimize the setting of basis materials?

Q4: Any other forms of spectral imaging?

Q5: What is the optimal binning in energy?

Q6: What is the optimal weighting scheme in energy?

Q7: Noise correlation: from data space to A-space and image space.

Revisiting the fundamentals: Material space

What is the dimension of material space for material decomposition based spectral imaging?

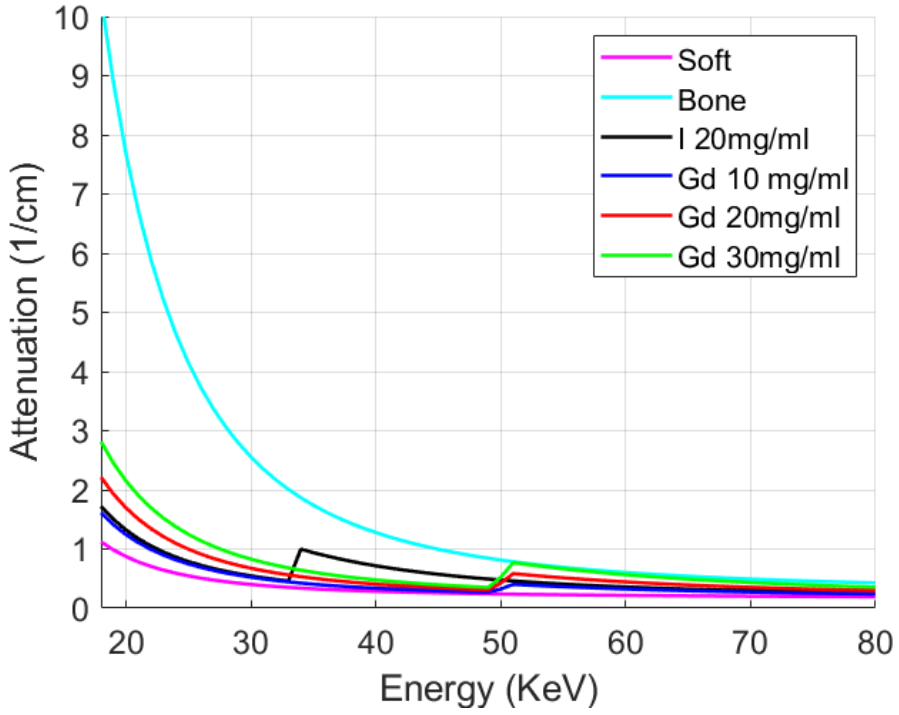
- **Up to 12 interactions, not the 3 only, between x-ray photons and medium while x-ray photons propagate (Lehmann 1981)**
- **The hypothesis that the dimension of the material space enclosing all biological tissues is equal to 4 cannot be rejected (Bornefalk,2012)**
- **Our SVD based investigation confirms that the dimension of the material space enclosing all biological tissue is effectively equal to 2 at sufficient accuracy in practice**
- **The basis materials should match the materials to be decomposed while K-edge material(s) is (are) is one (or more) of the materials.**

Fundamentals: Conditioning of basis materials

The selection of basis materials in 2-MD does not matter too much, but becomes extremely tricky in 3-MD …

$$\boldsymbol{Condition\ number}$$

$$CN = \frac{Eigen\ value_{max}}{Eigen\ value_{min}}$$



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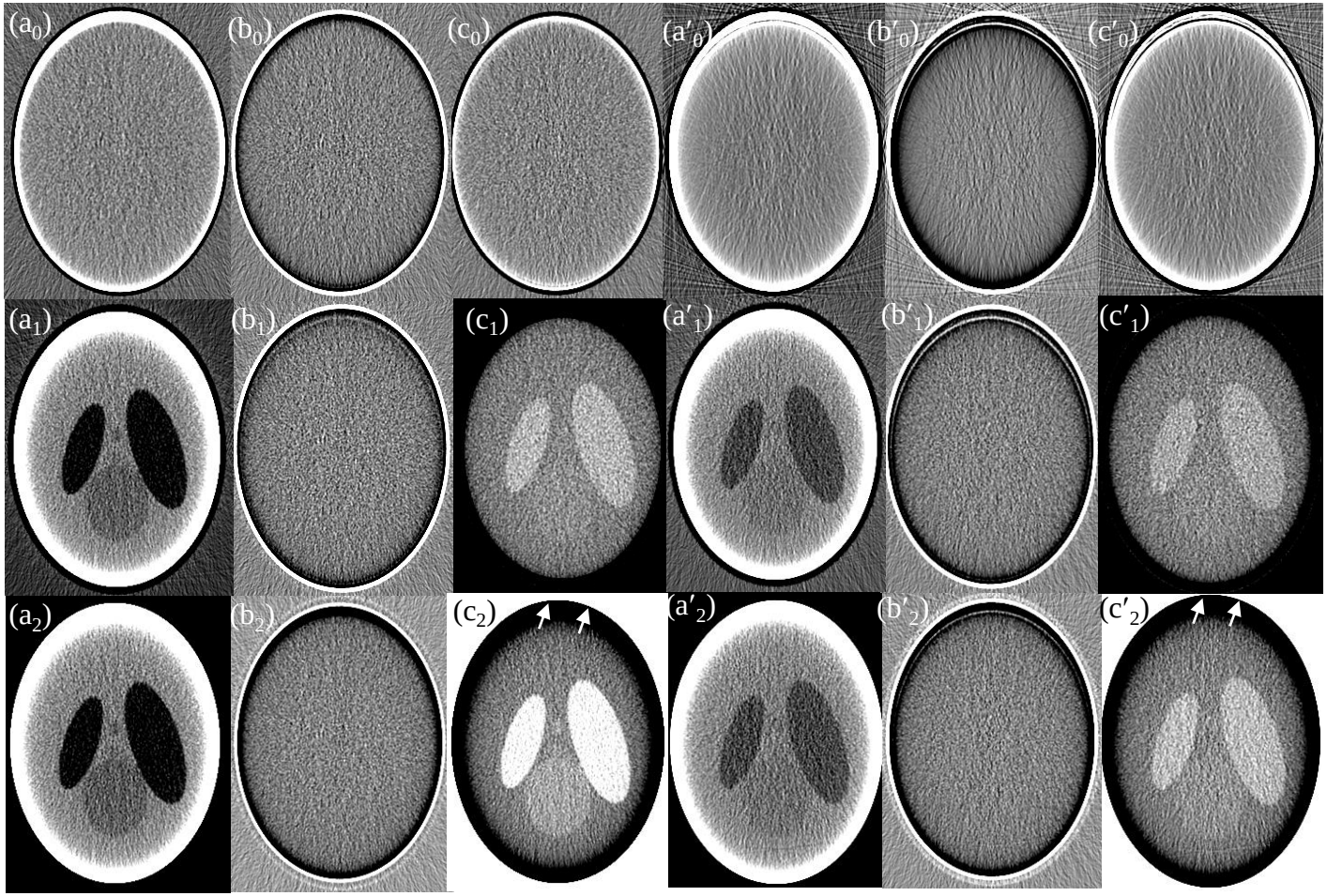
Fundamentals: Conditioning of basis materials

BM: adipose, PMMA, Teflon
CN = 3,1668

BM: tissue, Gd, bone
CN = 50.8

BM: adipose, PMMA, Gd
CN = 569.3



Ideal **Realistic**

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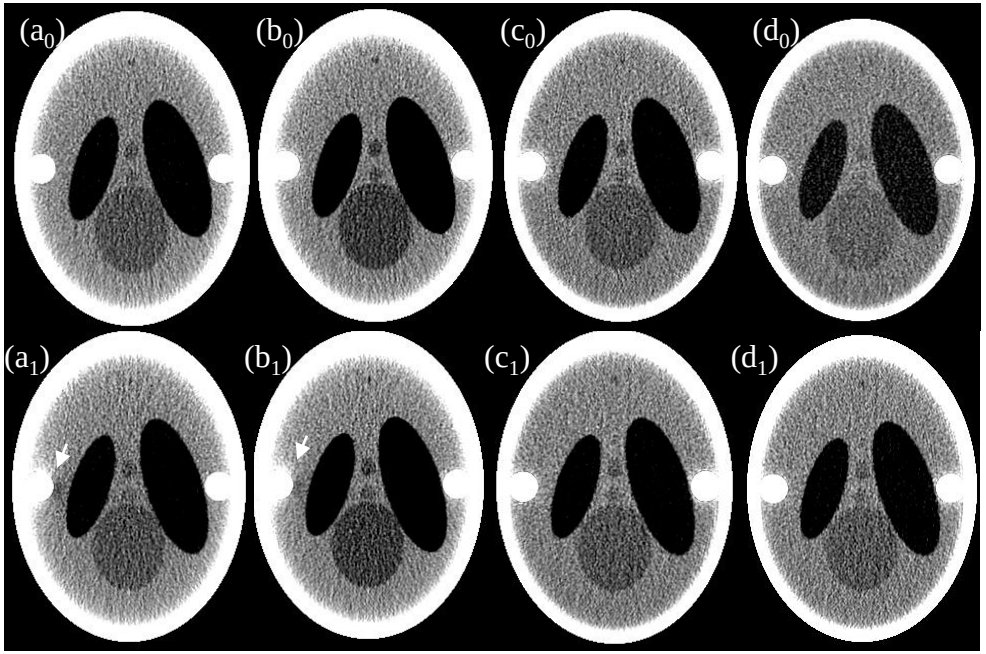
Fundamentals: Matching of basis materials in *m*-MD

If a *K*-edge material is in the materials to be decomposed, the *K*-edge material must be in the basis materials, though its concentration does not matter too much …

Phantom with Gd rods

BM: tissue, 20 mg/ml Gd & bone

Phantom with both I & Gd rods



Virtual monochromatic images **@35keV** **@50keV** **@65keV** **@85keV**

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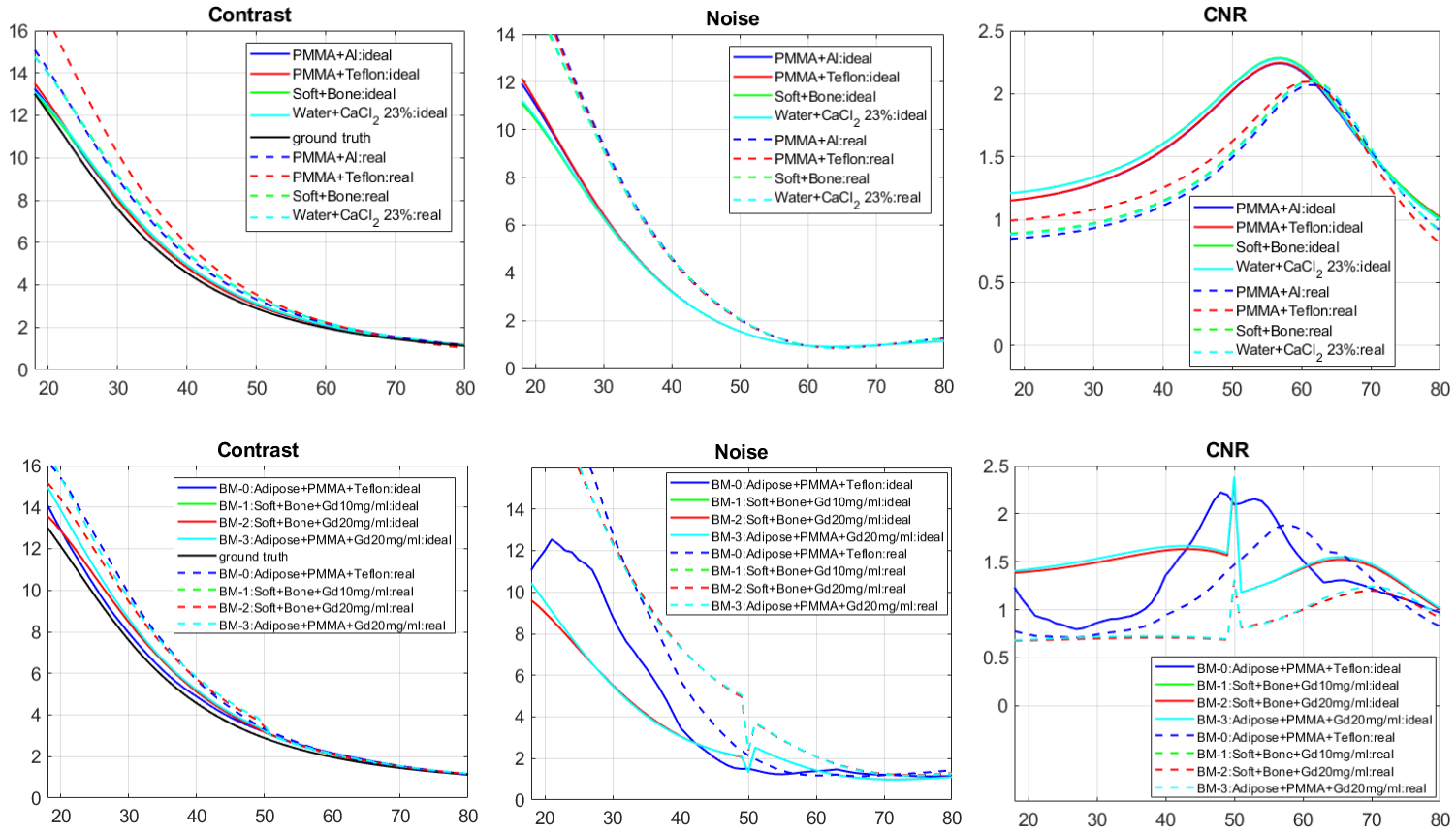
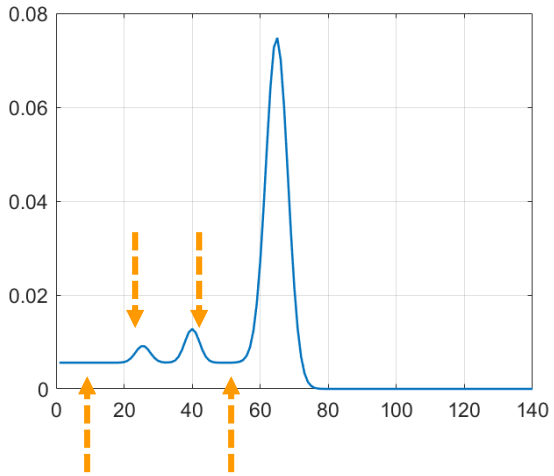
Noise and CNR in 3-MD & 4-MD based virtual mono.

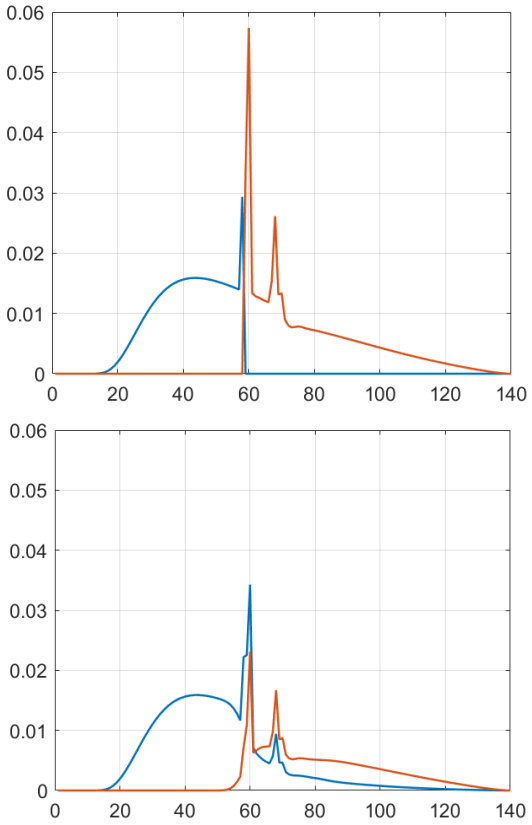
Contrast in 3-MD behaves the same as in 2-MD, but noise and CNR becomes much more complicated, and so do in 4-MD ...

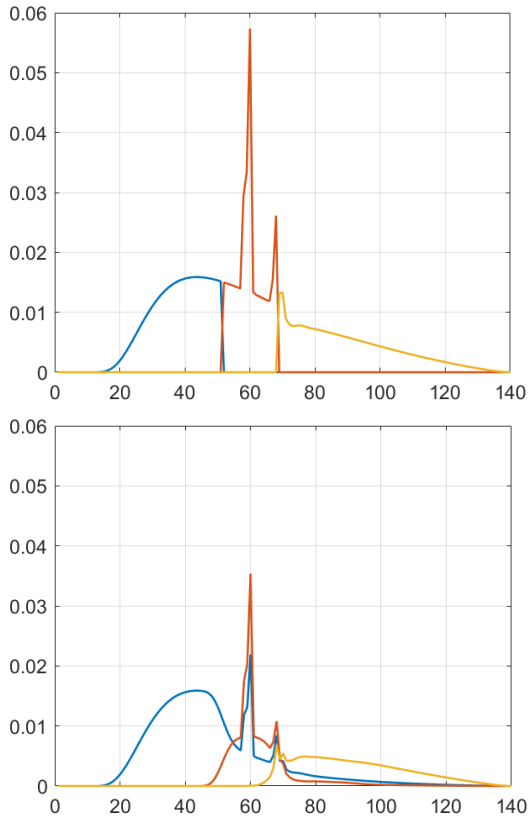


Conditioning of spectral channelization in *m*-MD

It should be noted that photon-counting detection facilitates spectral channelization substantially, but not perfectly …

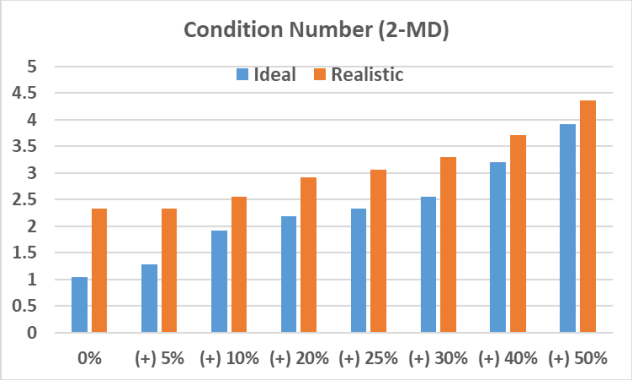


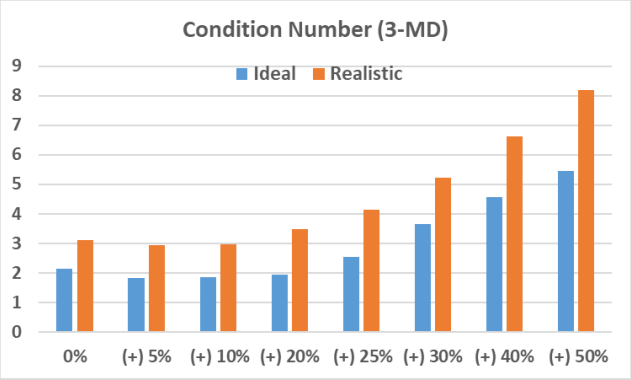


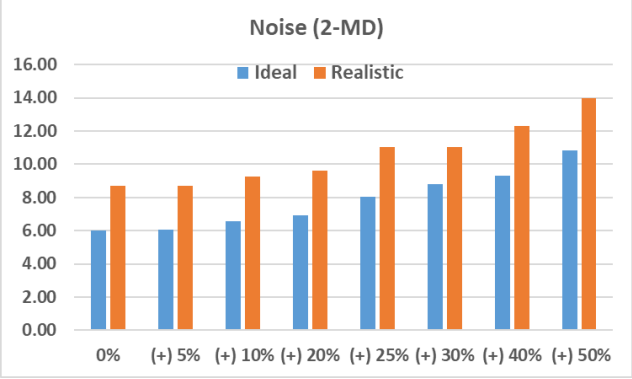


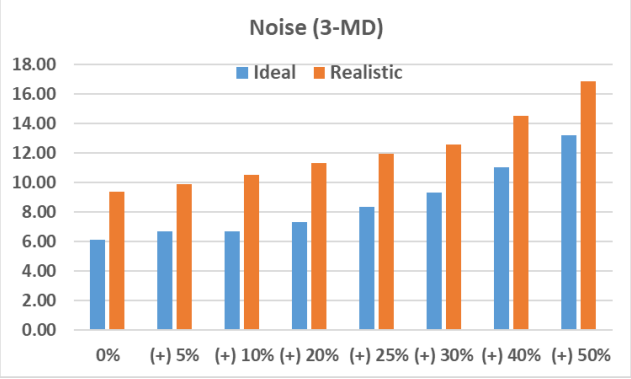
Conditioning of spectral channelization in *m*-MD

Inevitable inter-channel spectral overlap degrade noise and CNR in spectral imaging significantly, and sometimes radically …









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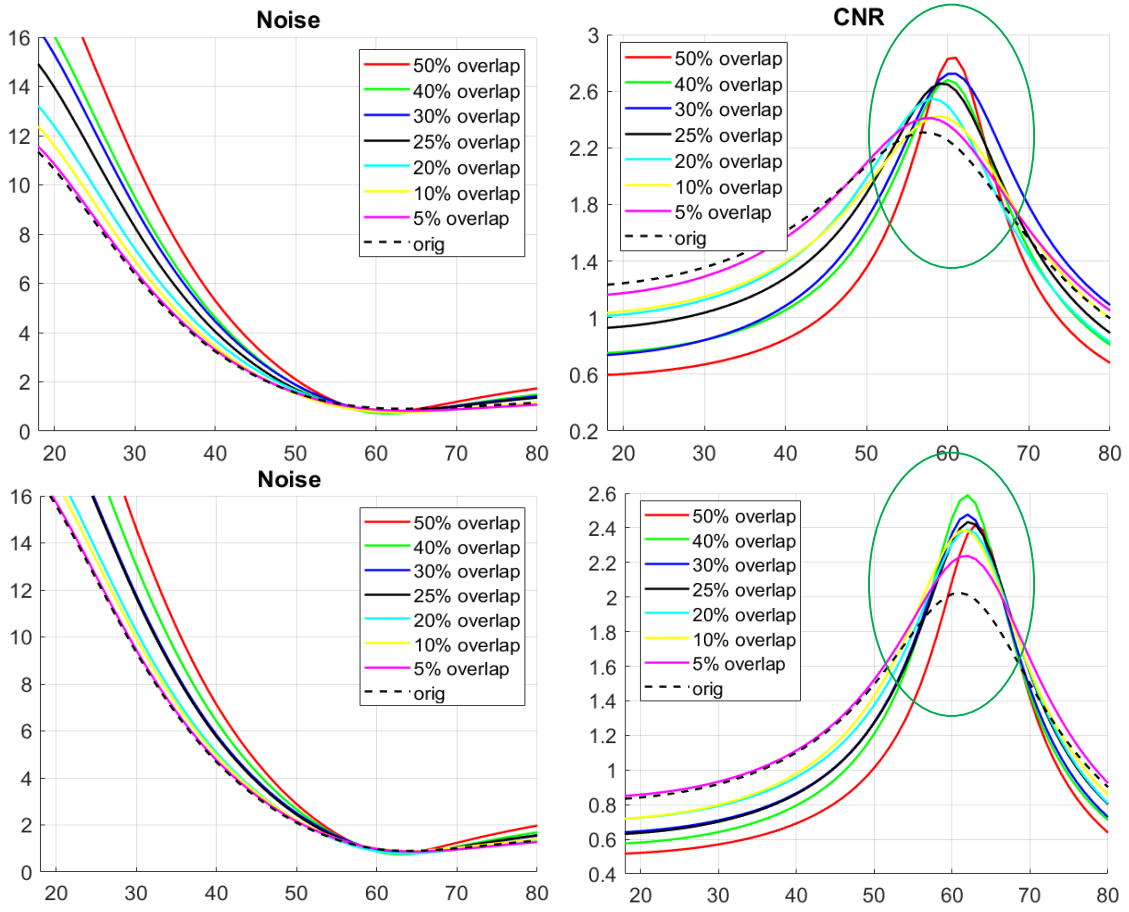
Conditioning of spectral channelization on CNR (2-MD)

The inter-channel spectral overlap degrades the noise and CNR in virtual monochromatic imaging and analysis, but, surprisingly, may increase the CNR at the sweet spot …



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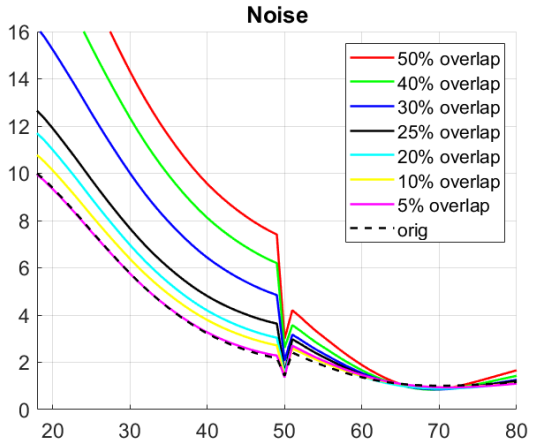

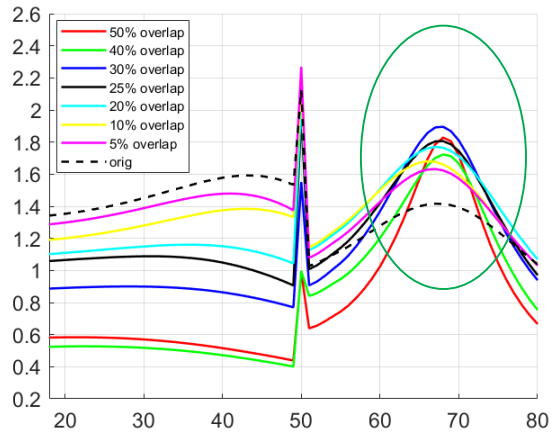

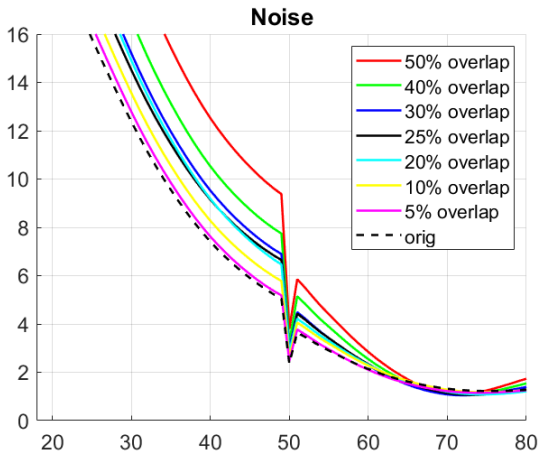

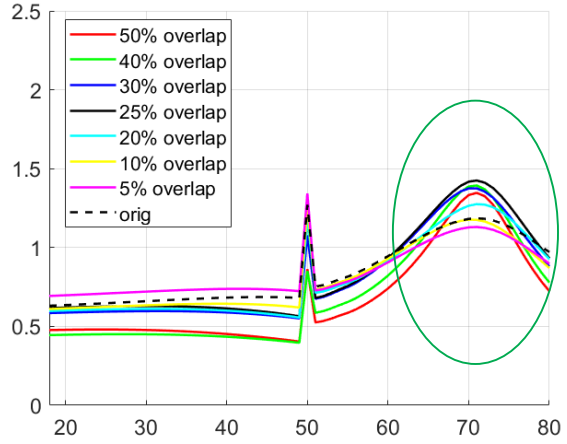

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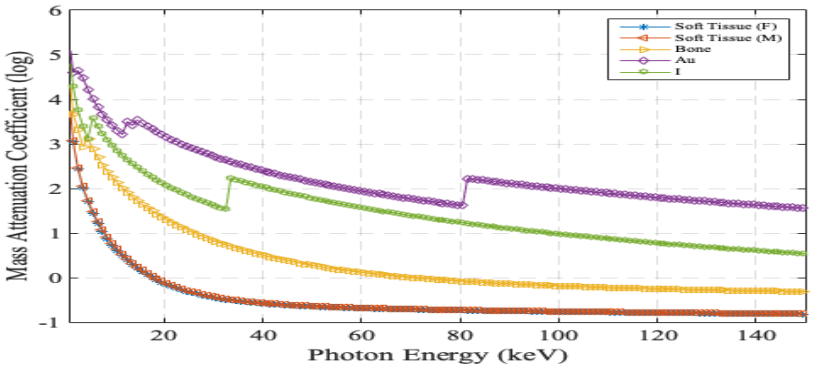
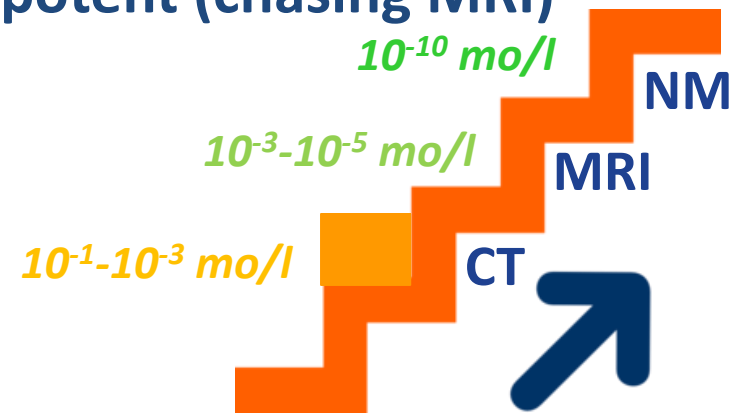
Photon-counting spectral CT: Potentials

- X-ray photon is at 10^4–10^5eV, but electrons at outer shell are only 1–2eV. So the chemical state (molecular state) of material does not generate contrast in x-ray imaging
- Compartment based iodinated contrast agent is efficient in vascular imaging, but inefficient in cancer imaging
- Photon-counting CT & Biodegradable biomarker targeted nanoparticle contrast agent (Ta, Au, Bi) may bear the hope to make photon-counting CT more potent (chasing MRI)





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Thank you!

xiangyang.tang@emory.edu

On the conditioning of basis materials and its impact on multimaterial decomposition-based spectral imaging in photon-counting CT

Xiangyang Tang[a)] and Yan Ren
Imaging and Medical Physics, Department of Radiology and Imaging Sciences, Emory University School of Medicine, 1701 Uppergate Dr., C-5018, Atlanta, GA 30322, USA

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On the Conditioning of Spectral Channelization (Energy Binning) and Its Impact on Multi-Material Decomposition Based Spectral Imaging in Photon-Counting CT

Yan Ren, Huiqiao Xie, Wenting Long, Xiaofeng Yang, and Xiangyang Tang