Multi-energy CT: Future Directions

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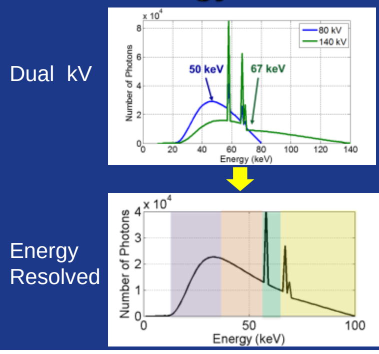
Overview

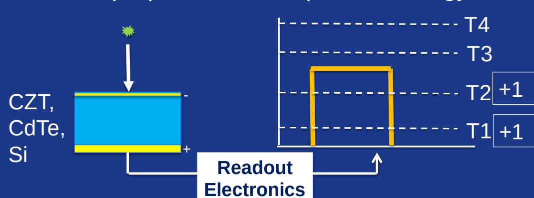
- How to acquire more energy information?
  - Photon-counting detectors
- What can we do with more energy information?
  - Material decomposition with less noise
  - K-edge material decomposition
  - Improved CNR using energy weighting
- Current limitations and potential solutions

More Energy Information

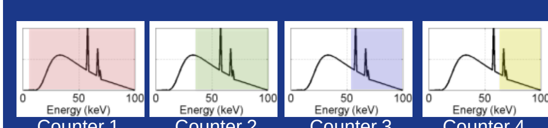


Photon-Counting Spectral Detection

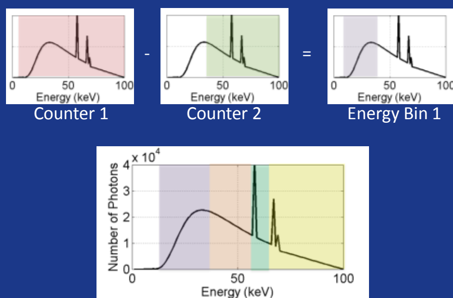
- Direct-conversion semiconductor detectors perform pulse-height analysis to acquire spectral information
- Pulse proportional to deposited energy



Photon-Counting Spectral Detection



Energy-Bin Processing



Advantages over Dual Kvp

- Simultaneous acquisition
- Can by acquired as part of a conventional CT protocol
- > 2 spectral measurements
- Improved energy separation

Also true for multi-layer detector

What can we do with more energy information?

- Material decomposition estimates with less noise (or at less dose)
- Quantification of K-edge contrast agents
- Improved CNR and reduced beam hardening through energy weighting

Decomposition with Less Noise

Example: Compare dual kV, 2 bins, 3 bins, at equal exposure

Water = PE + Compton

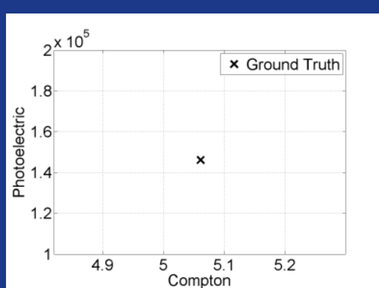
30 cm — A_1 cm — A_2 cm

$$\mu(r,E) = a_1(r)\cdot\frac{1}{E^3} + a_2(r)\cdot f_{KN}(E)$$

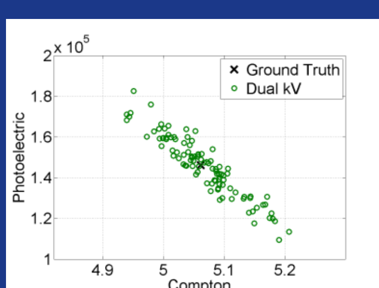
$$A_k(\alpha) = \int a_k(r)\,dl$$

$$I_j = \int dE\cdot\Omega_j(E)\cdot e^{-\sum_{k=1}^{K} A_k(\alpha) f_k(E)}$$

Decomposition With Less Noise

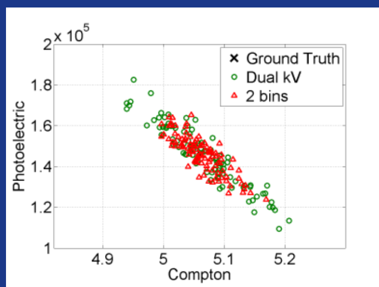


Decomposition With Less Noise



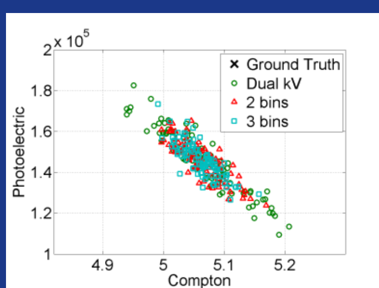
100 trials

Decomposition With Less Noise



100 trials

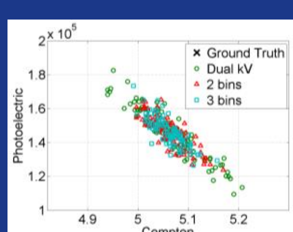
Decomposition With Less Noise



100 trials

Decomposition With Less Noise

- 40% reduction in noise standard deviation due to improved spectral separation
- 10%-15% noise reduction when going from 2 to 3 bins
- Same mean value

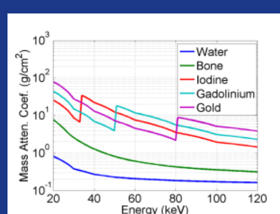


What can we do with more energy information?

- Material decomposition estimates with less noise (or at less dose)
- Quantification of K-edge contrast agents
- Improved CNR and reduced beam hardening through energy weighting

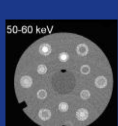
K-edge Contrast Agent Imaging

If we have > 2 measurements, we can decompose into > 2 basis materials if K-edge is detectable in each additional material

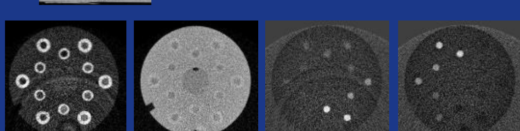


Iodine (Z = 53, 33 keV) → Bismuth (Z=83, 90 keV)

K-edge Contrast Agent Imaging



$$\mu(r,E) = a_1(r)\cdot\frac{1}{E^3} + a_2(r)\cdot f_{KN}(E) + a_3(r)\cdot\mu_I(E) + a_4(r)\cdot\mu_{Gd}(E) + \ldots$$

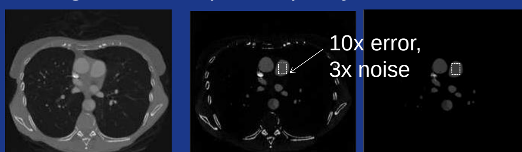


Photoelectric Compton Iodine Gadolinium

Schlomka, et. al., PMB 2009

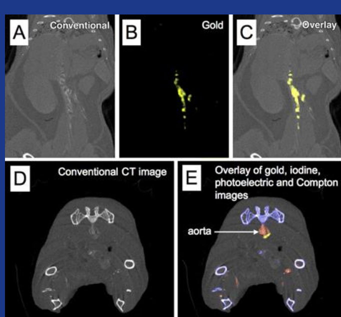
K-edge Contrast Agent Imaging

- *Detect* contrast agent, even if CT number is indistinguishable from soft tissue
- Direct quantification of concentration
- K-edge of iodine (33 keV) may be too low



Conventional CT | Dual kVp | Spectral CT

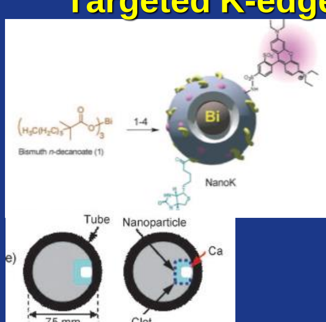
Targeted K-edge Agents

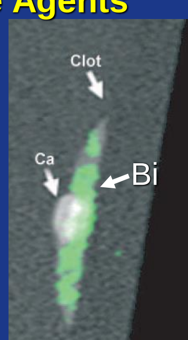


Gold nanoparticles targeted to atherosclerosis (Au-HDL)

Cormode, Radiology 2010

Targeted K-edge Agents





D. Pan, Angew Chem Int Ed (2010)

Comparison to Other Modalities

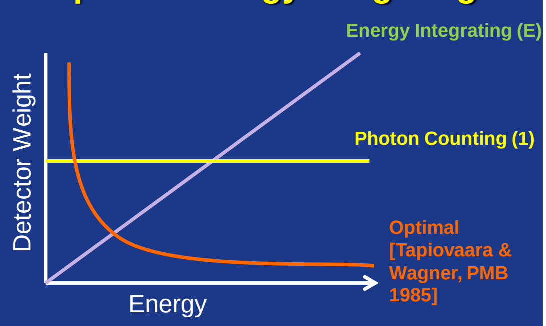
- Higher spatial resolution
- Higher temporal resolution
- Direct quantitative information
- Lower contrast agent sensitivity:
  - PET: $<10^{-10}$ mol/L
  - MRI: 10^{-3} – 10^{-5} mol/L
  - CT: 10^{-1} – 10^{-3} mol/L

Roessl, IEEE TMI, 2011

What can we do with more energy information?

- Material decomposition estimates with less noise (or at less dose)
- Quantification of K-edge contrast agents
- Improved CNR and reduced beam hardening through energy weighting
  - Non-material specific imaging

Optimal Energy Weighting



Optimal Energy Weighting

- Optimal linear combination of energy-bin data
- Weighting can be performed in
  - Projection domain (projection based)
  - Image domain (image based)
- Optimal weights proportional to contrast-to-noise-variance ratio in each bin

Shikhaliev , PMB. 2005
Schmidt , Med. Phys. 2009

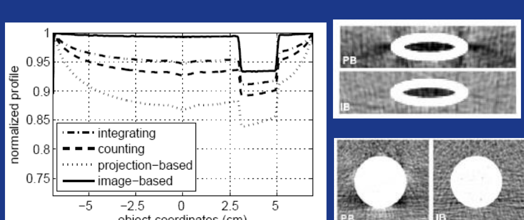
Background: CT Energy-weighting

Le, et. al, Med Phys, 2010	Improvement in CNR (relative to Energy Integrating)		
	PC	PB	IB
Iodine/PMMA	1.04	1.28	1.25
Hydroxylapatite/PMMA	1.02	1.30	1.35

Shikhaliev, et. al, PMB, 2011.	Improvement in CNR (relative to Energy Integrating)
	PB
Iodine/acrylic	1.03 - 1.29
Calcium/acrylic	1.11

PB = optimal projection-based
PC = photon-counting   IB = optimal image-based

Beam Hardening Reduction



Schmidt , Med. Phys. 2009

Photon-counting has several *potential* benefits, but…

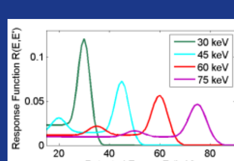
Non-ideal effects

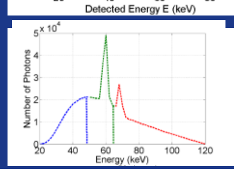
- Stochastic generation of electron/hole pairs
- Incomplete charge collection
- Charge sharing between neighboring pixels
- K-fluorescence escape
- Charge trapping
- Pulse pileup
- Temperature Drift
- Energy-bin threshold variability across pixels
- And more...

Photons detected in wrong energy bins

Flux-Independent Spectral Degradations

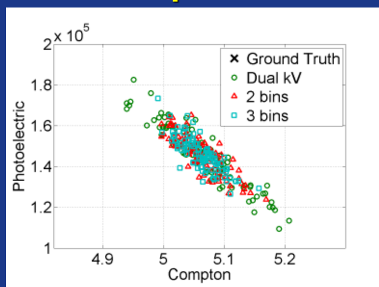
- R(E,E'): The probability of a photon with energy E' detected at energy E
- Determined by monoenergetic measurements



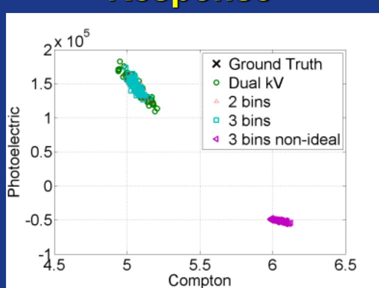


Schlomka et. al, PMB 2009

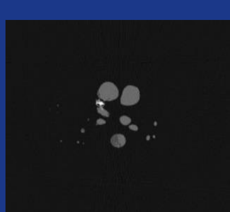
Example: Ideal Spectral Response



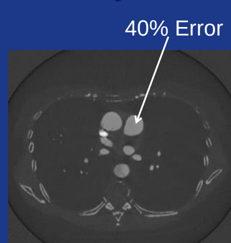
Example: Non-ideal Spectral Response



Nonideal Spectral Response

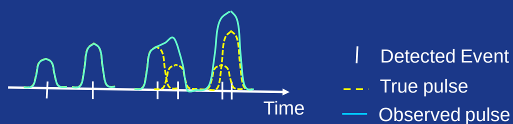


Gd Image: Ideal Spectral Response



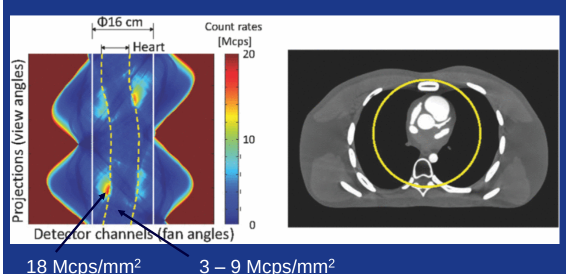
Gd Image: Nonideal Spectral Response

Flux-dependent Spectral Degradations (Pulse Pileup)



- Loss of counts
- Photons counted in incorrect energy bins
- Distortion depends on detector properties and incident flux

Required count rate?



Taguchi and Iwanczyk, et. al., Med Phys 2013

Status of Current Detectors

Name	Pixel Size (μm x μm)	Count rate (Mcps/mm^2)	Number of energy bins
DXMCT-1	1000 x 1000	5.5	2
DXMCT-2	500 x 500	22	4
ChromAIX	300 x 300	150	4
Hamamatsu	1000 x 1000	1-2	5
GMI CA3	400 x 1000	2 - 5	6
Medipix3RX	55 x 55	69.4	2
Medipix3RX	110 x 110	12	8
Nexis	1000 x 1000	2	5
KTH	400 x 500	200 or 600	8

Taguchi and Iwanczyk, et. al., Med Phys 2013

Potential Solutions

- Hardware
  - Smaller pixels to reduce pileup
  - Larger pixels to reduce flux-independent degradations
  - Layered detector / depth-dependent readout
    Xu et al, Nuc. Inst. Methods. Phys Res. A 2012
  - Parallel-drift structures
    Iwanczyk et. al., IEEE TNS, 2009
  - Charge summing
    Ballabriga, et. al., IEEE NSS, 2006

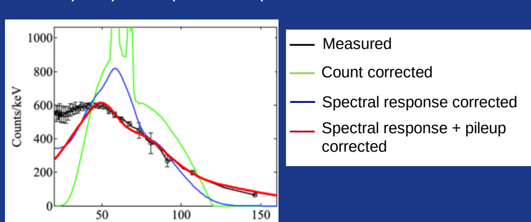
Potential Solutions

- System
  - Improved bowtie filters to control flux
    Szczykutowicz & Mistretta, Med Phys 2013
    Hsieh & Pelc, Med Phys 2013
  - Interior reconstruction or ROI imaging
    Taguchi et. al., Med Phys 2011
    Schmidt & Pektas, Med Phys 2011
- Decomposition algorithms
  - Model non-ideal effects
    Cammin, et. al., Med Phys 2014
  - Empirical methods
    Alvarez, Med Phys 2011

Model-based Corrections

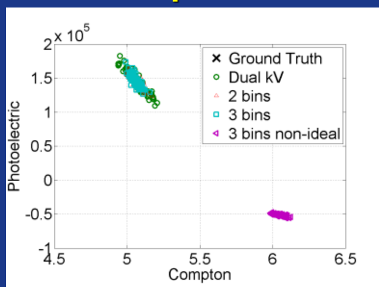
$$I_j = \int dE \cdot \Omega_j(E) \cdot e^{-\sum_{k=1}^{K} A_k(\alpha) f_k(E)}$$

Add pileup and spectral response models

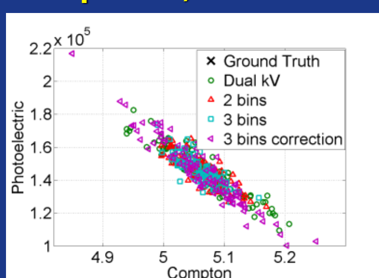


Cammin, et. al., Med Phys

Example: Non-ideal Spectral Response



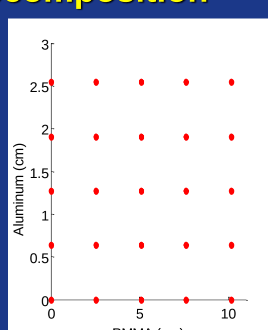
Example: Non-ideal Spectral Response, Corrected



Bias removed, but noise increased due to spectral degradations

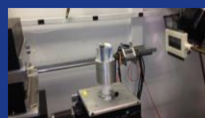
Empirical Decomposition

- Measure transmission for known combinations of basis material thicknesses
- Algorithm estimates basis material thicknesses for transmission measurement of unknown material

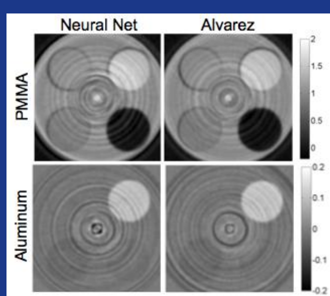


Empirical Decomposition

- NEXIS detector (Kromek)
- [25-40], [40-50], [50-60], [60-100] keV
- Linearized MLE method
  Alvarez, Med Phys 2011
- Neural network empirical decomposition
  Zimmerman et al., CT Meeting, 2014



Empirical Decomposition



Alvarez, Med Phys 2011 Zimmerman et al., CT Meeting, 2014

Conclusions

- Photon-counting CT has potential benefits over dual-kV
  - Material decomposition with less noise / dose
  - Imaging K-edge contrast agents
  - Improved CNR through optimal weighting
- Photon-counting CT currently limited by nonideal effects
- Potential hardware, system, and algorithmic solutions under investigation

Recommended Review Paper:

K. Taguchi, and J. S. Iwanczyk. "Vision 20/20: Single photon counting x-ray detectors in medical imaging." *Medical physics* 40.10 (2013): 100901.