Photon Counting Detectors and
Their Applications in Medical Imaging

Principles, Pitfalls and Progress in Photon-Counting-Detector Technology

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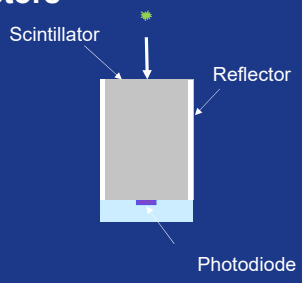
Current Technology: Energy Integrating Detectors

- Photon energy converted to light by scintillator
- Photodiodes convert light to electrical signal
- Detected photon energy integrated over a readout time
- Reflectors prevent cross-talk between pixels

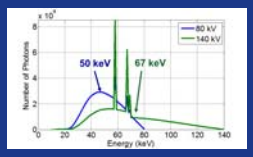


Disclosures

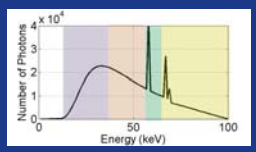
The speaker receives research funding from GE Healthcare

NIH R21 EB015094

Spectral Acquisition



Dual-kV



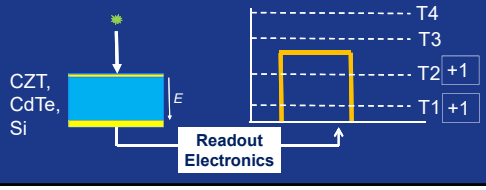
Energy Resolved

Overview

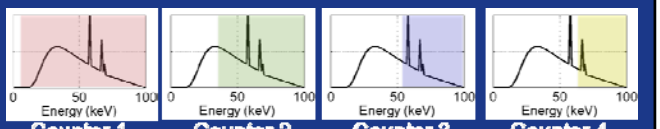
- Photon counting detection for spectral CT
- Potential impact of photon-counting detectors
  - CT images with improved contrast, spatial resolution, noise, performance
  - Material decomposition with less noise
  - K-edge material decomposition
- Current status, limitations, and potential solutions

Photon-Counting Spectral Detectors

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



Photon-Counting Spectral Detection



Current Clinical Prototypes

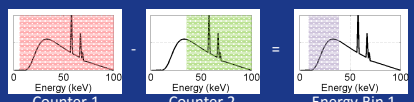
Mayo Clinic
http://advancingthescience.mayo.edu/2014/10/08/photon-counting-ct-scanner-makes-research-debut/

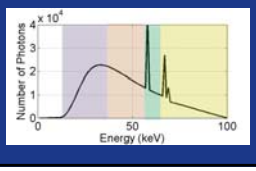
Université Claude Bernard Lyon 1

NIH
https://www.nih.gov/news-events/news-releases/nih-uses-photon-counting-ct-scanner-patients-first-time

https://www.francelifeimaging.fr/en/2016/04/01/spectral-photon-counting-ct-cermep-lyon/

Energy-Bin Processing



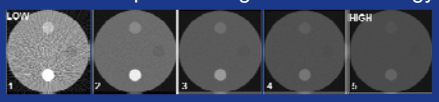


Advantages of Photon Counting

- Reduced electronic noise
- Improved spatial resolution
- Improved detected quantum efficiency
- Simultaneous acquisition of multi-spectral information
- Acquired as part of a conventional protocol
- 2+ spectral measurements
- Theoretically improved energy separation

Energy-Bin Processing

- Can reconstruct separate images for each energy bin



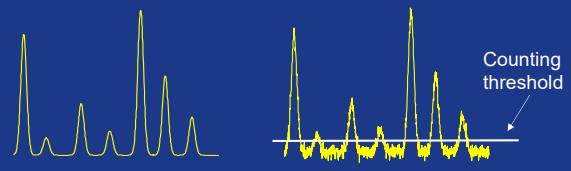
- Can combine energy-bin images to display 'conventional'
- Can process energy-bin projections or images to perform material decomposition

Potential Impact of Photon Counting

- Conventional CT images with improved:
  - Spatial resolution
  - Noise/dose performance
  - Contrast
- Material decomposition estimates with less noise and/or dose than existing dual-energy approaches
- Quantification of K-edge contrast agents

Reduction of Electronic Noise

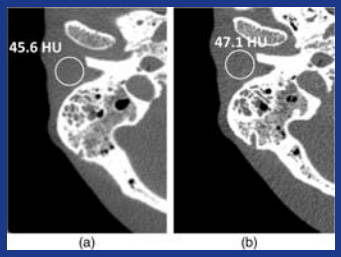
- Electronic noise: Gaussian noise added to analog signals by electronic components
- At low dose, electronic noise significant factor



Analog Detected Signal

Analog Detected Signal + Electronic Noise

Improved Spatial Resolution



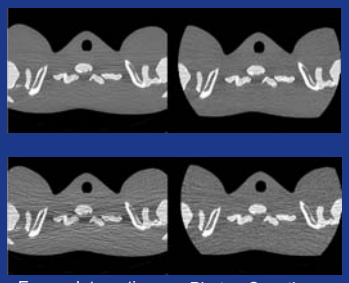
Energy Integrating Photon Counting

Leng, et. al, J. Med. Imag. 2016;3(4):043504

Reduction of Electronic Noise

120 mAs

20 mAs

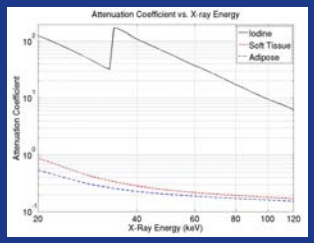


Energy Integrating Photon Counting

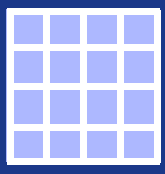
Yu, et. al, J. Med. Imag. 2016;3(4):043503.

Optimal Energy Weighting

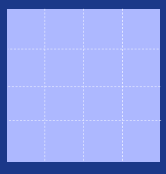
Low-energy photons provide the most contrast information



Improved Spatial Resolution



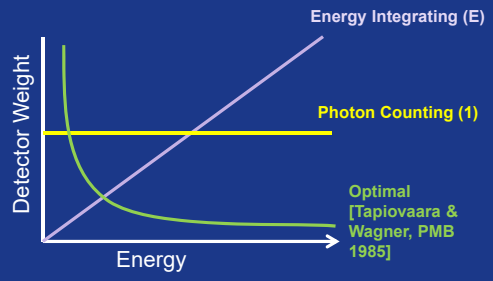
Energy Integrating



Photon Counting

Absence of reflectors facilitates smaller pixel sizes, improves DQE

Optimal Energy Weighting

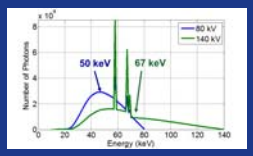


Optimal Energy Weighting

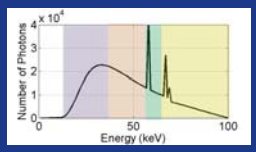
- Optimal linear combination of energy-bin data
- Weighting can be performed on
  - Raw photon counts (projection based)
  - Energy-bin images (image based)
- Optimal weights proportional to contrast-to-noise-variance ratio in each bin

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

Spectral Acquisition

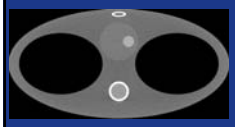


Dual kV

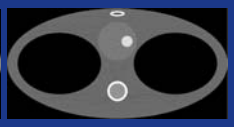


Energy Resolved

Optimal Energy Weighting



Energy Integrating



Optimal spectral weighting

~ 30% CNR improvement demonstrated experimentally

reduced beam hardening

Schmidt , Med. Phys. 2009

Le, et. al, Med Phys, 2010
Shikhaliev, et. al, PMB, 2011.

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

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

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

Potential Impact of Photon Counting

- Conventional CT images with improved:
  - Spatial resolution
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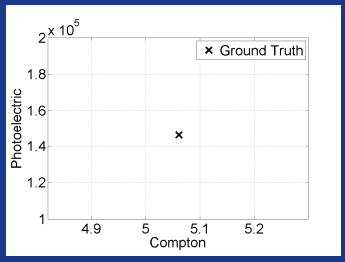
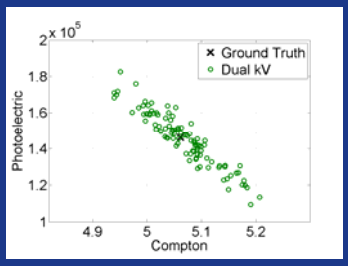
  - Contrast
- Material decomposition estimates with less noise and/or dose
- Quantification of K-edge contrast agents

Decomposition With Less Noise



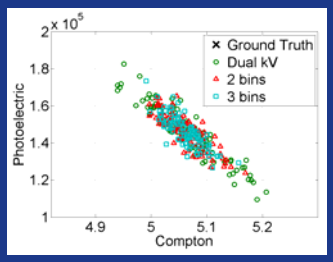
Decomposition With Less Noise



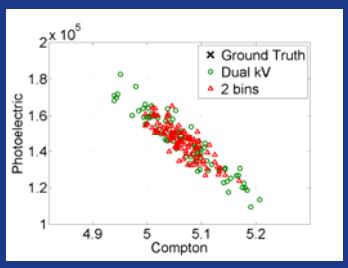
100 trials

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



Decomposition With Less Noise



100 trials

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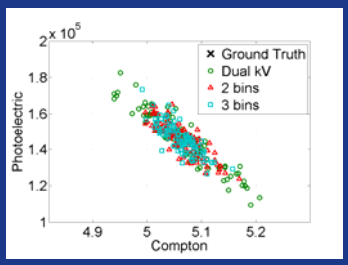
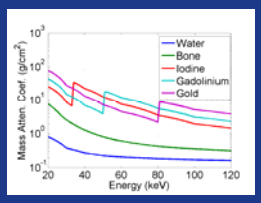
Decomposition With Less Noise



100 trials

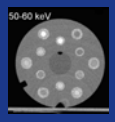
K-edge Contrast Agent Imaging

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

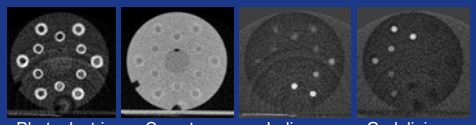


Iodine (Z = 53, 33 keV) → Bismuth (Z=83, 90 keV)

K-edge Contrast Agent Imaging

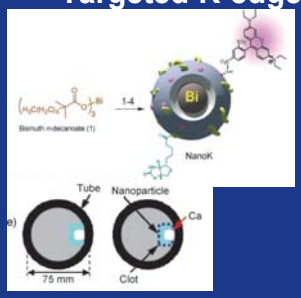


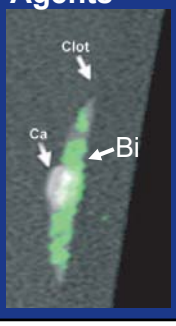
$$\mu(r,E) = a_1(r)\cdot\frac{1}{E^3} + a_2(r)\cdot f_{KN}(E) + a_3(r)\cdot\mu_I(E) + a_4(r)\cdot\mu_{Gd}(E) + \ldots$$



Schlomka, et. al., PMB 2008 53 4031

Targeted K-edge Agents





D. Pan, et. al., Angew Chem Int Ed, 2010

K-edge Contrast Agent Imaging

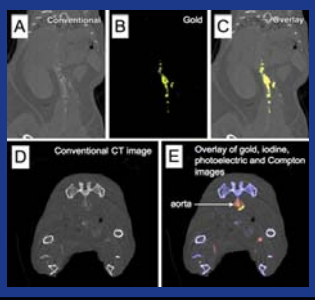
- K-edge contrast agent images
- Direct quantification of concentration
- Can detect contrast agent even if CT number is indistinguishable from other materials
- Enables multi-contrast agent imaging
- K-edge of iodine (33 keV) may be too low

Comparison to Other Molecular Imaging 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

Targeted K-edge Agents

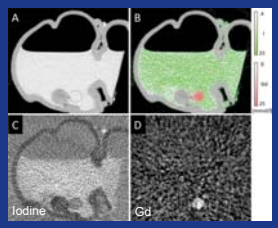


Gold nanoparticles targeted to atherosclerosis (Au-HDL)

Cormode, et., al, *Radiology* **2010,** 256, 774-782.
© RSNA, 2010

Towards In-vivo Dual-Contrast Imaging

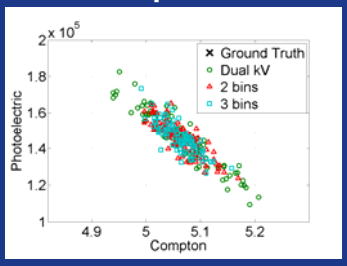
- Colon phantom
- Iodine for fecal tagging
- Gadolinium blood pool agent to enhance polyps
- Spectral CT to create iodine / gadolinium maps



D. Muenzel,et. al,. *Radiology* **2017,** 283, 723-728.

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

Example: Ideal Spectral Response

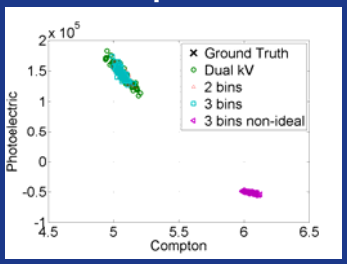


Non-ideal effects

- 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...

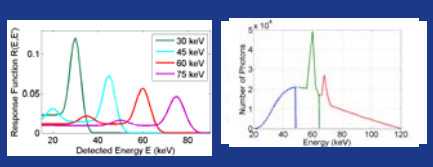
Photons detected in wrong energy bins

Example: Non-ideal Spectral Response



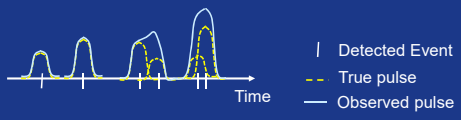
Flux-Independent Spectral Degradations

Detector Response Functions: The probability of a photon with energy E' detected at energy E



Schlomka et. al, PMB 2009

Flux-dependent Spectral Degradations (Pulse Pileup)



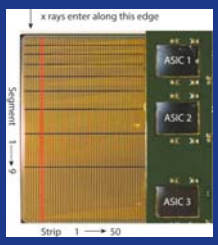
- Loss of counts
- Photons counted in incorrect energy bins
- Distortion depends on detector properties and incident flux

Potential Solutions

- Hardware
  - Larger pixels to reduce flux-independent degradations
  - Smaller pixels to reduce pileup
  - 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 to reduce charge sharing effects
    Ballabriga, et. al., IEEE NSS, 2006, Koenig, IEEE TNS, 2013

Depth segmented pixels

- Divide pixels in depth direction
- Comparator channel for each depth segment
- Reduces pulse pileup and increases count rate



Xu, et. al., Nucl. Instr. Meth. Phys. Res., 2013
Xu, et. al., Nucl. Instr. Meth. Phys. Res., 2016

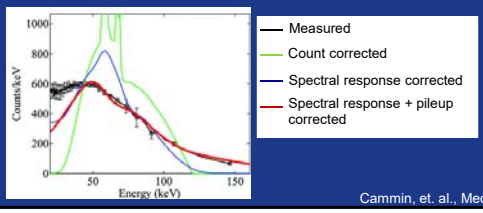
Potential Solutions

- System
  - Improved bowtie filters to control flux
    Szczykutowicz & Mistretta, Med Phys 2013
    Hsieh & Pelc, Med Phys 2013, PMB 2014, PMB 2016
  - 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
    Zimmerman & Schmidt, PMB 2015
  - Iterative reconstruction

Model-based Corrections

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

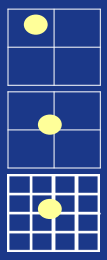
Model pileup and spectral response during decomposition



Cammin, et. al., Med Phys 2014

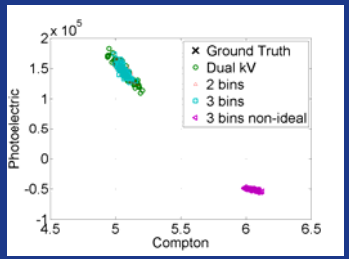
Charge Summing

- Divide pixels into sub pixels
- Sum charge across 2 x 2 subpixels
- Assign charge to pixel with highest local deposited charge
- Reduces degradations due to charge sharing
- Reduces count rate

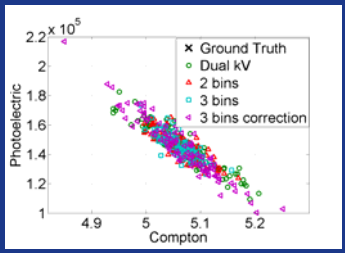


Koenig, et. al., IEEE TNS, 2013

Example: Non-ideal Spectral Response



Example: Non-ideal Spectral Response, Corrected

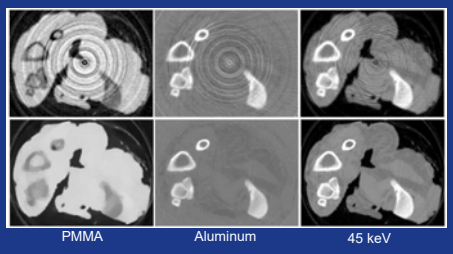


Bias removed, but noise increased due to spectral overlap

Iterative Reconstruction

FBP after material decomposition

Iterative reconstruction that also optimizes detector response model

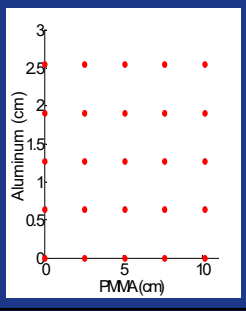


PMMA Aluminum 45 keV

Schmidt et. al., IEEE TMI 2017

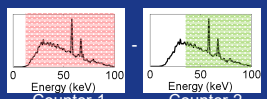
Empirical Material Decomposition

- Measure energy-bins counts for known combinations of basis material thicknesses
- Algorithm estimates basis material thicknesses for energy-bin measurements of unknown material



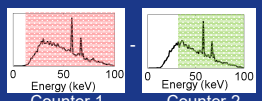
Photon-Counting Detector Design

Threshold measurements acquired at same pixel location at same time



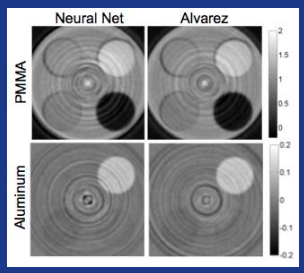
Noise from photons with energy above threshold 2 removed

Threshold measurements acquired at different pixel location and/or time



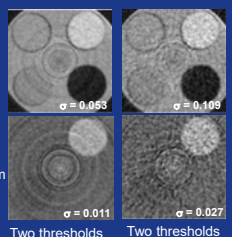
Noise penalty + Additional dose penalty

Empirical Decomposition



Alvarez, Med Phys 2011 Zimmerman et al., PMB 2015

Photon-Counting Detector Design



200-260% noise increase

Two thresholds acquired at same pixel / time

Two thresholds acquired at different pixel / time

To avoid noise penalty, all threshold measurements should be performed at same pixel location at the same time

Schmidt et., al., 2015 Phys. Med. Biol. 60 1583

Conclusions

- Photon-counting CT has potential benefits
  - CT images with increased contrast, improved spatial resolution, reduced noise / dose
  - Material decomposition with less noise / dose
  - Imaging K-edge contrast agents
- Photon-counting CT currently limited by nonideal effects
- Potential hardware, system, and algorithmic solutions under investigation
- Clinical studies underway