Image Quality Assessment Methods for Photon Counting CT

Adam Wang

Stanford University

July 13, 2022

Stanford MEDICINE

Acknowledgements

Research support:

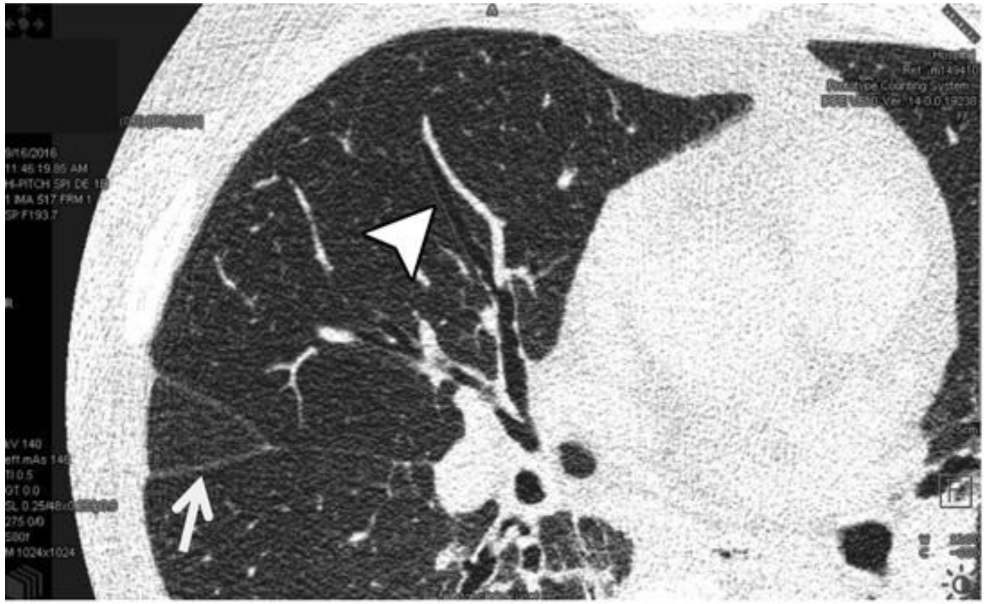
- GE Healthcare
- Siemens Healthineers
- Varex Imaging
- NIH R21EB030080

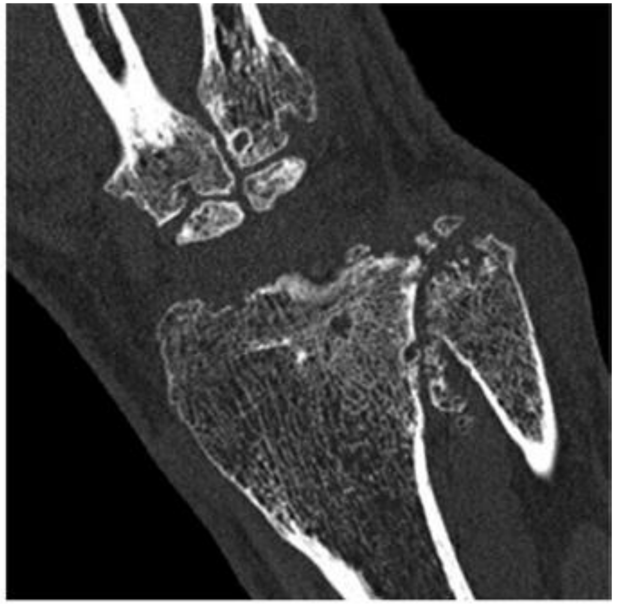
Outline

- Spatial resolution
- Artifact reduction
- Characterizing noise
- Detective quantum efficiency
- Detectability

Ultra high resolution

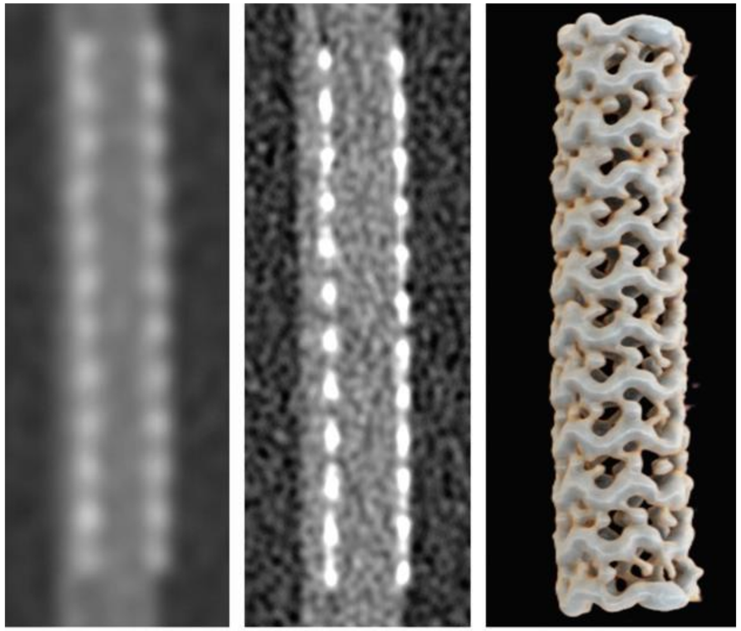
~2x higher spatial resolution than conventional CT





Leng et al, Radiographics 2019

Coronary Stent



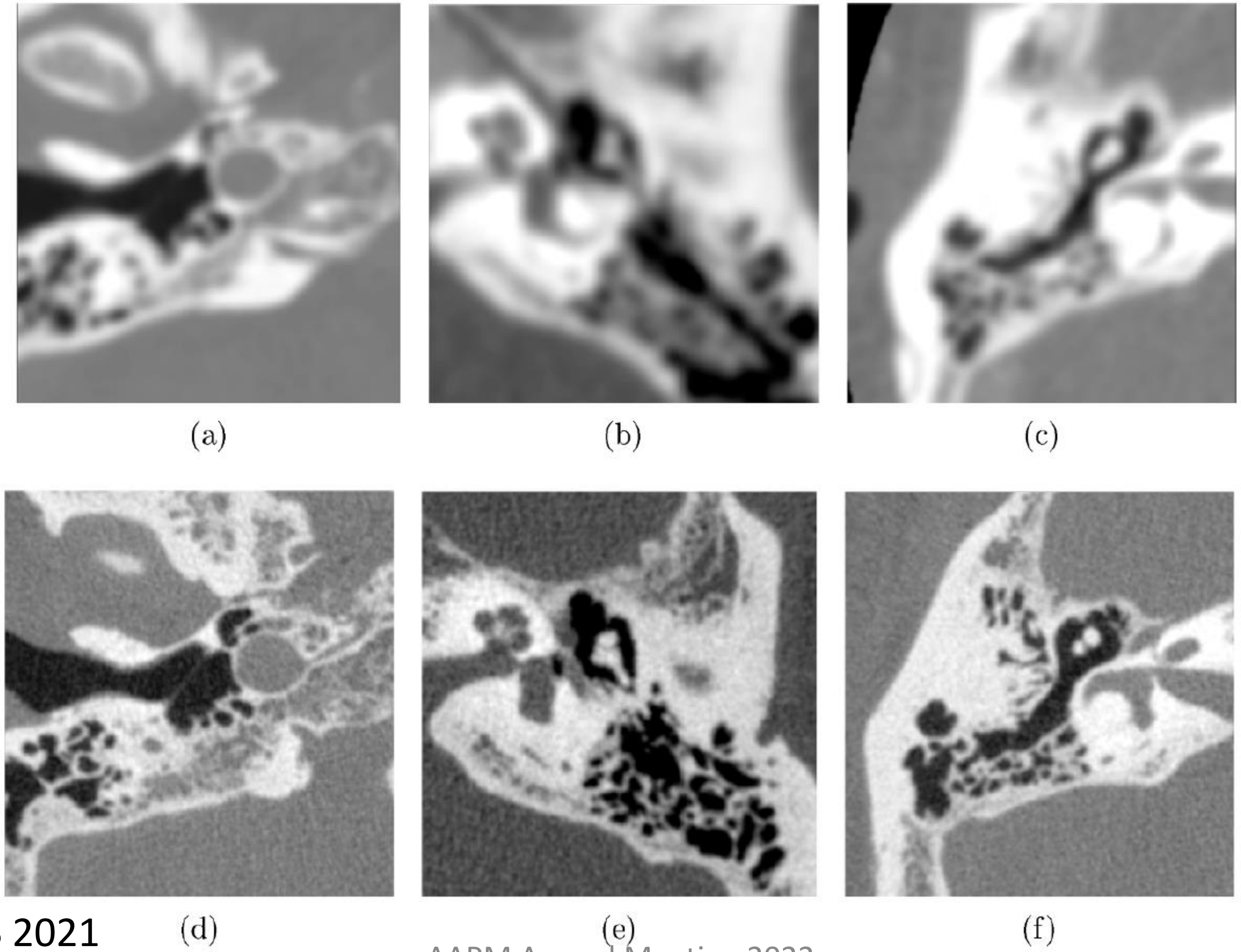
EID PCD

Stanford MEDICINE

Ultra high resolution

Conventional CT

PC CT



In vivo: Inner ear

Danielsson et al, PMB 2021

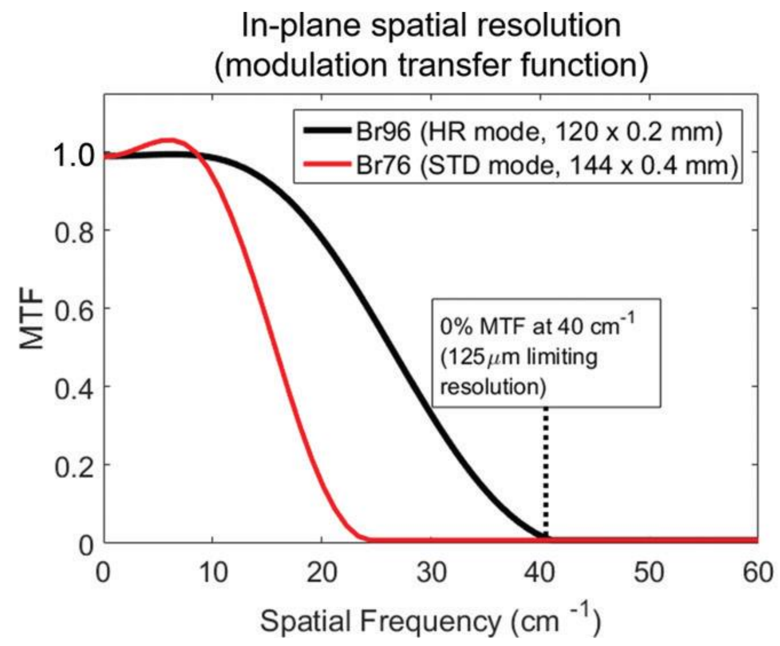
Spatial resolution: MTF, SSP

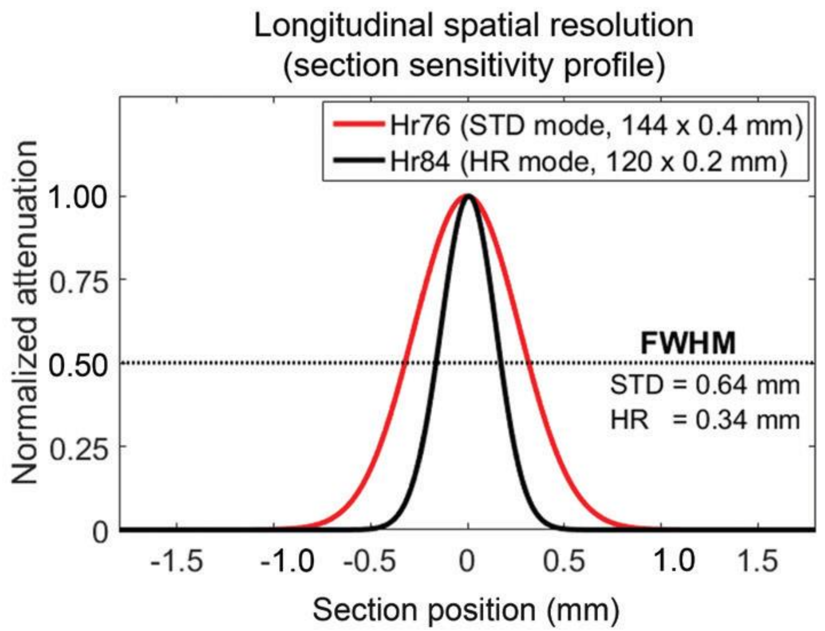
Direct conversion detectors have less charge spread than optical photons in scintillator

Modulation transfer function (MTF) characterizes CT spatial resolution (typically in-plane)

- High-resolution (HR) mode: Limiting spatial resolution of 0.125 mm (cutoff frequency 40 lp/cm)

Section sensitivity profile (SSP) quantifies longitudinal spatial resolution





Rajendran et al., Radiology 2022; 303:130–138

Stanford MEDICINE

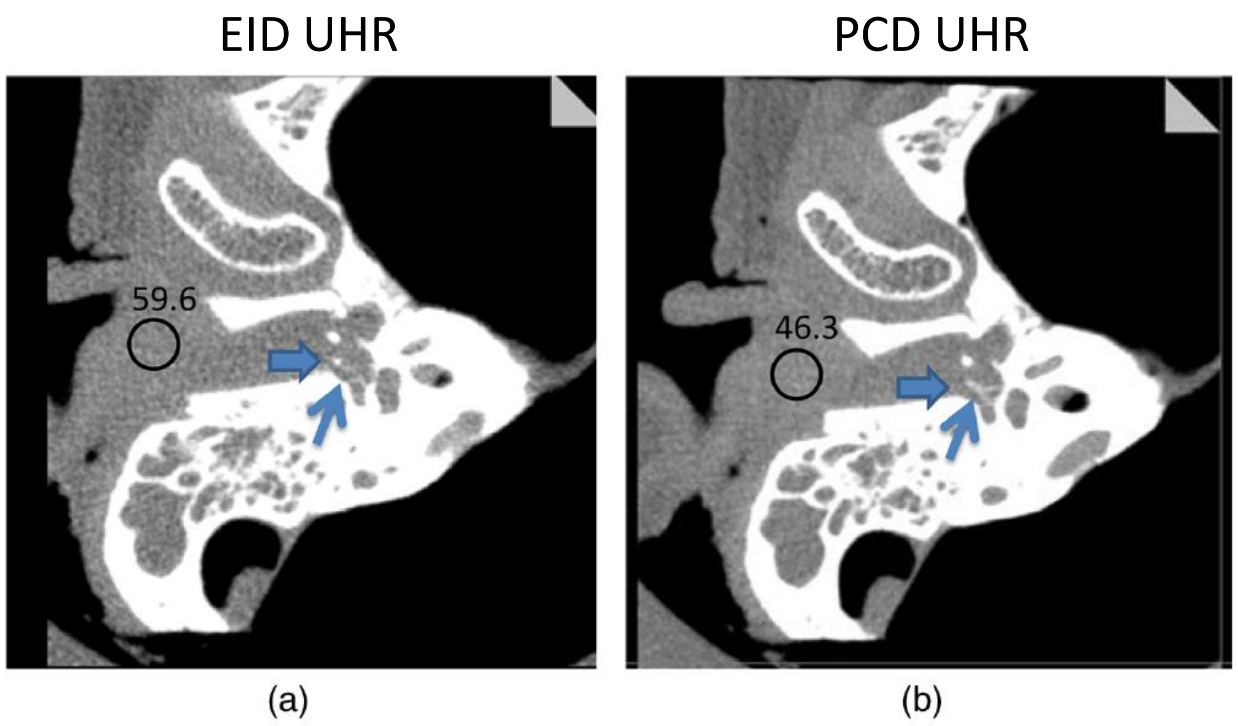
Other considerations for spatial resolution

EIDs can have smaller pixels but need septa in scintillator that reduce fill factor

Comb filter increases EID resolution but blocks x-rays at detector → increases noise

Need smaller focal spot (while ideally keeping mA) and higher angular sampling → lots more raw data!

MTF assumes linear, stationary system



Lower noise & higher resolution at **matched dose**

Leng et al., JMI 3(4), 043504 (2016)

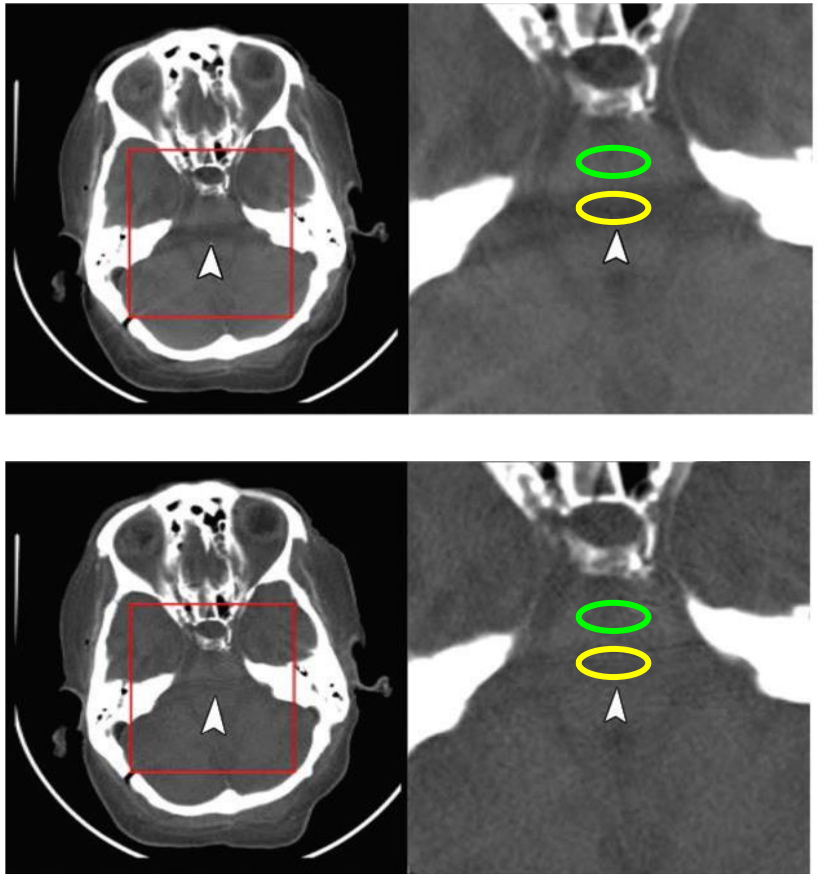
Artifact reduction

PCCT robust against beam hardening and metal artifact

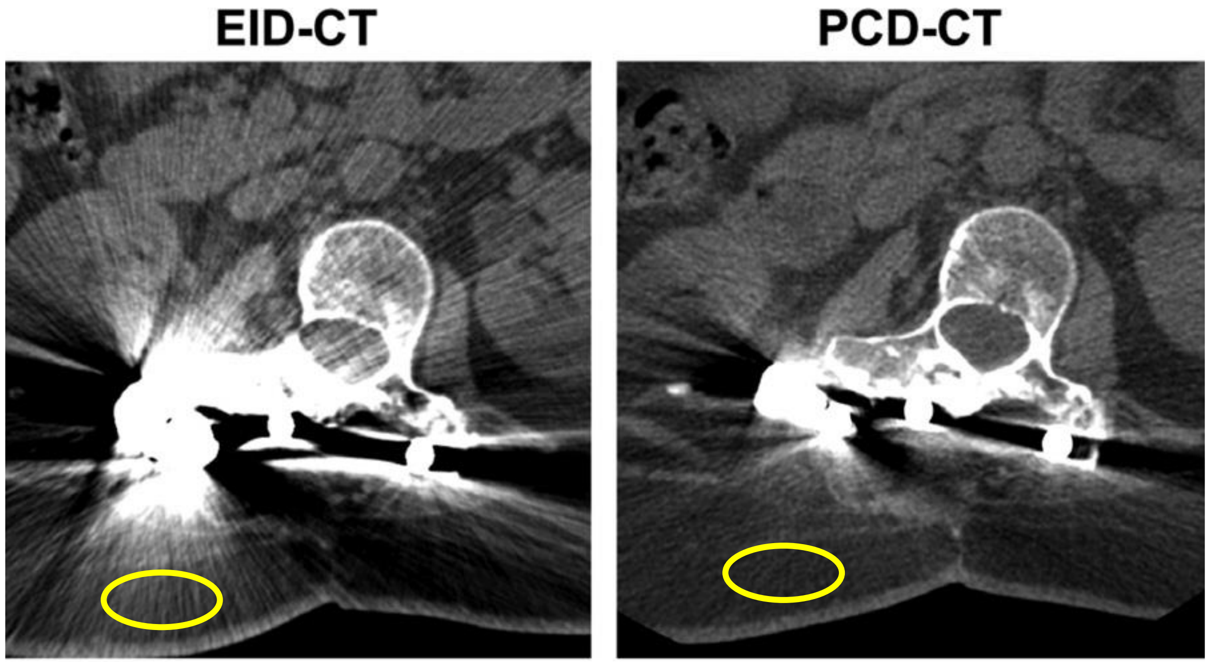
Can quantify shading/streak artifact – object specific

EID

PCD



Leng et al, Radiographics 2019



Stanford MEDICINE

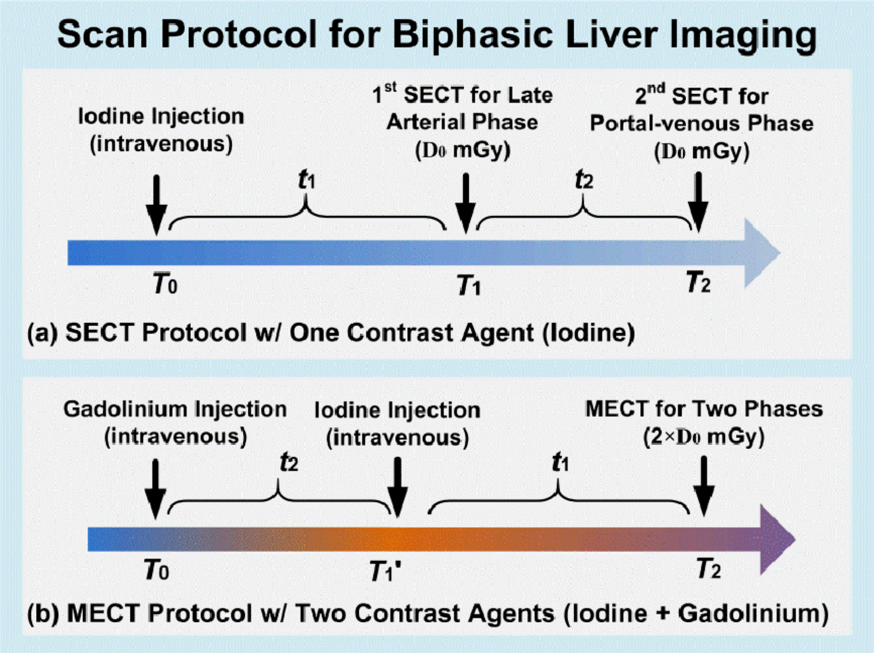
Dose efficiency

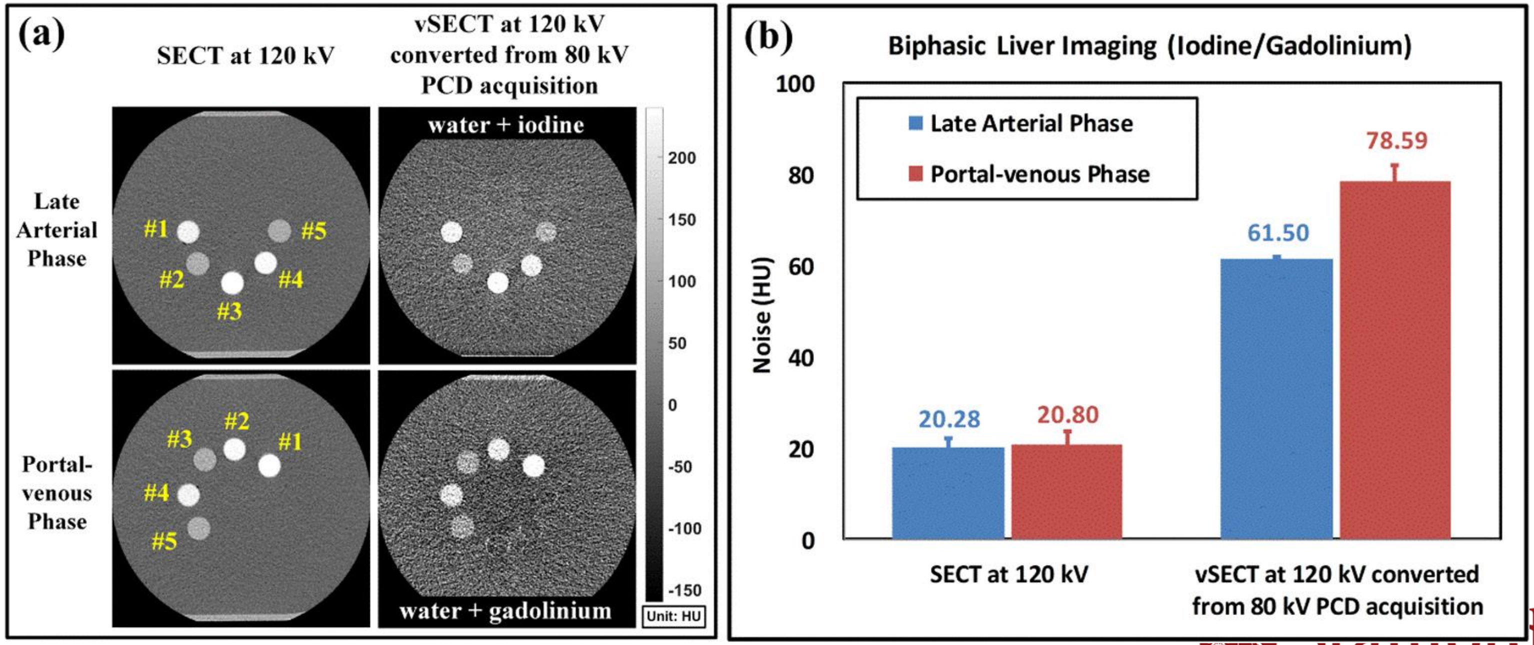
Dose efficiency important part of grayscale and spectral imaging performance

For fixed dose, how does noise compare? Or vice versa

Example: Traditional single contrast / two-phase scan or two contrast / single scan?

Latter has no motion issues, but increases noise by >200%





Additional basis materials increase noise

Estimation theory tells us that increasing the dimensionality increases the variance not only of the parameter added but also of all the lower dimension parameters

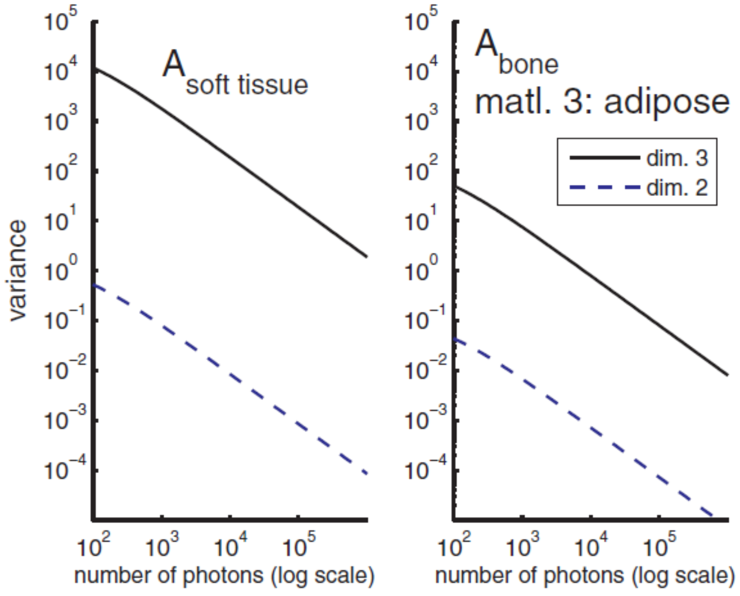


FIG. 2. The variance for the soft tissue and bone A-vector components as a function of photon number with two and three dimension processing. The third basis function was the attenuation coefficient of adipose tissue. The left panel shows the variance of $A_{\text{soft tissue}}$ and the right panel is the variance of A_{bone}.

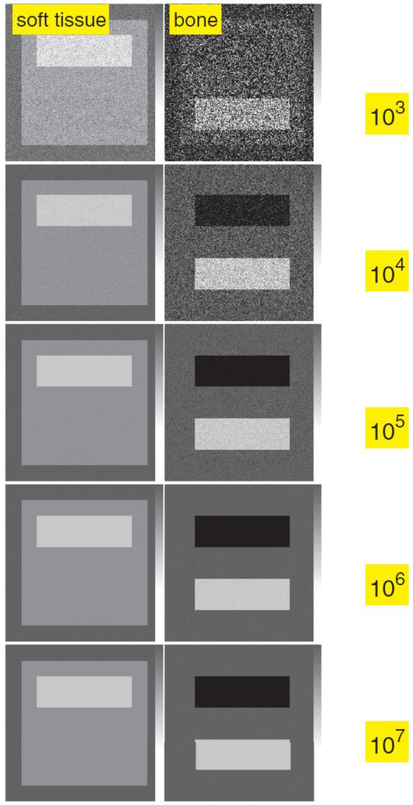


FIG. 7. The noisy data in Fig. 6 are processed using a two dimension basis set. The noise is much less but the adipose tissue is not imaged separately and it appears as a positive amount of soft tissue and a negative amount of bone.

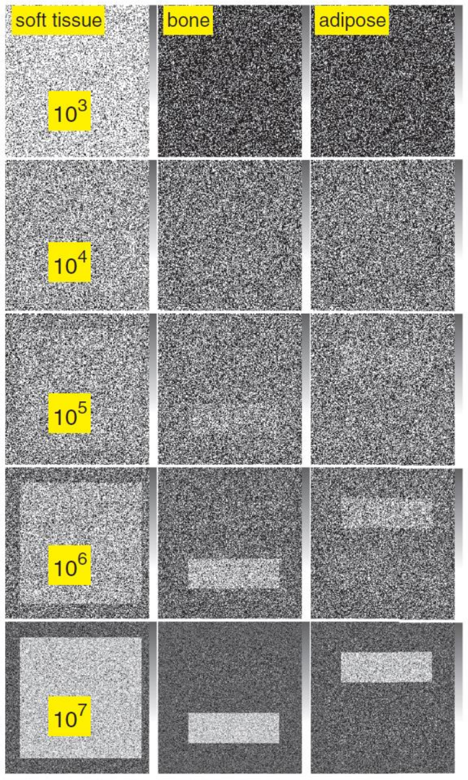


FIG. 6. Simulated images with three dimension processing when the third basis function is the attenuation coefficient of adipose tissue. A-space processing is used with 100 energy bin PHA data to compute the effective line integrals with a basis set consisting of the attenuation coefficients of soft tissue, adipose tissue, and cortical bone. The A-vector components are shown in the three columns. For each row, the spectra are multiplied by a constant so the expected number of photons per pixel increases from 10^{3} in the top row to 10^{7} in the bottom row. Note the gray bar at the right of each image with a range from 0 to 2.5 cm.

3 MD correctly separates adipose but much higher noise

Alvarez, Med Phys 40 (11) 2013

Characterizing noise

Noise power spectrum (NPS) captures noise magnitude & texture

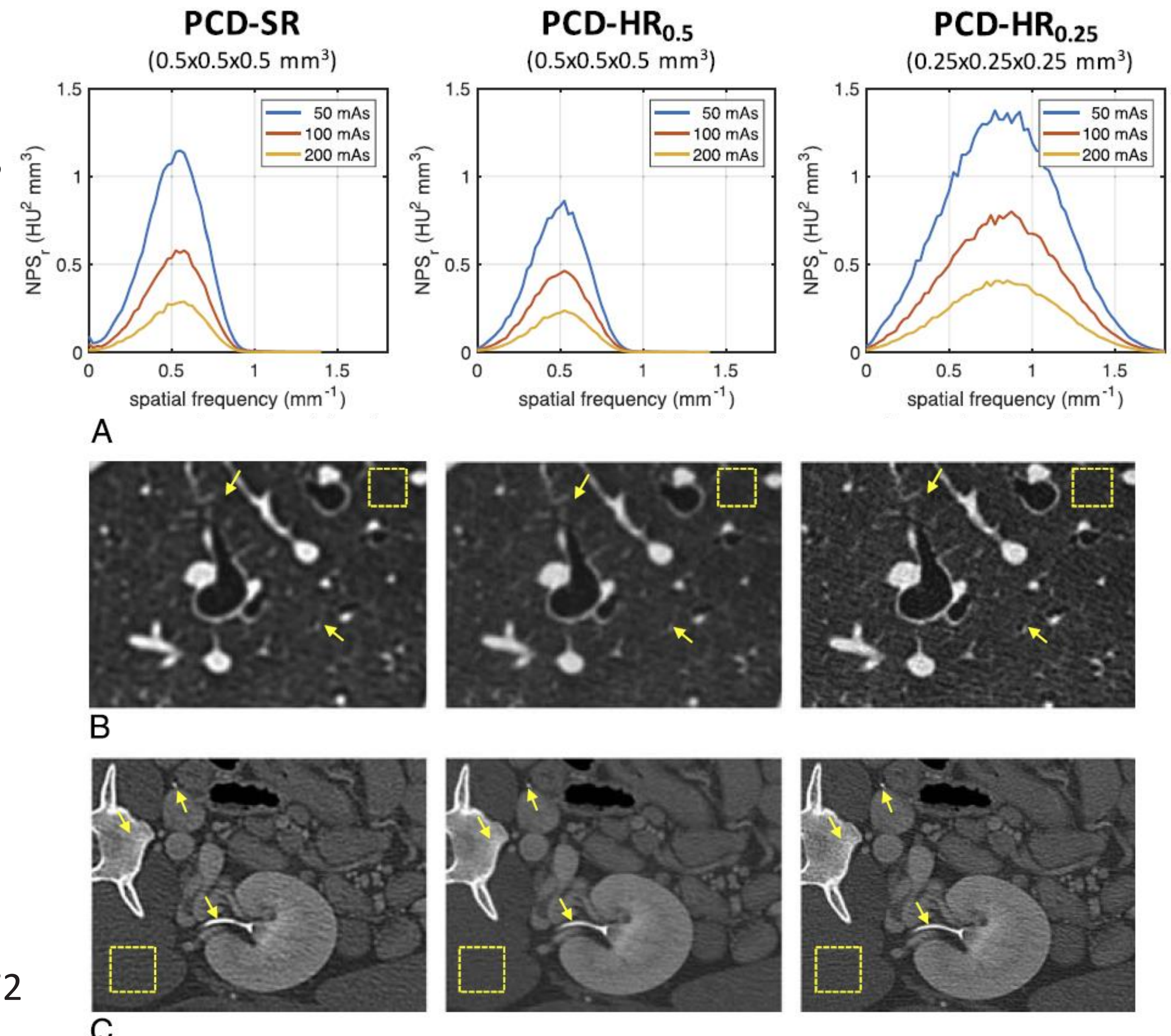
Average or peak NPS frequency often used to compare NPS shape

Assumes noise is stationary – not necessarily true for iterative / deep learning reconstruction

Dose savings of 19% at matched image resolution when acquired with higher resolution pixels (2nd vs 1st col)

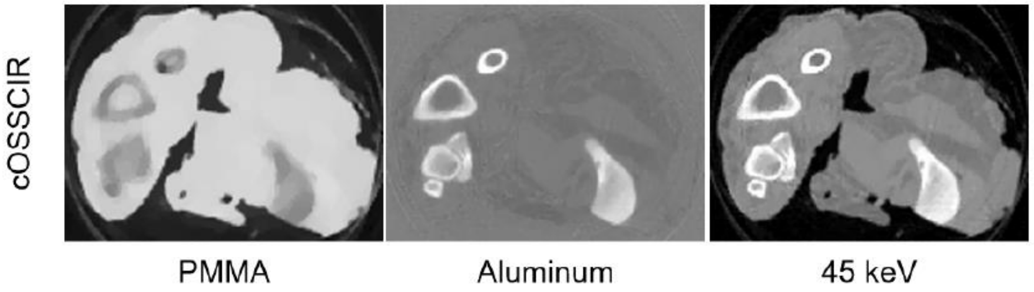
Higher resolution noisier, as expected (3rd vs 2nd col)

Pourmorteza et al., Invest Radiol 2018;53: 365–372

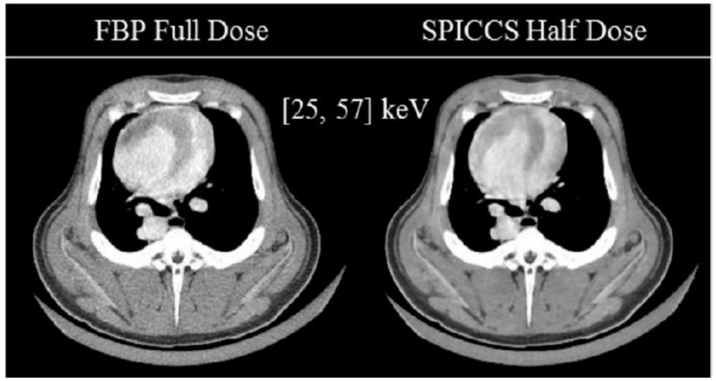


Noise reduction

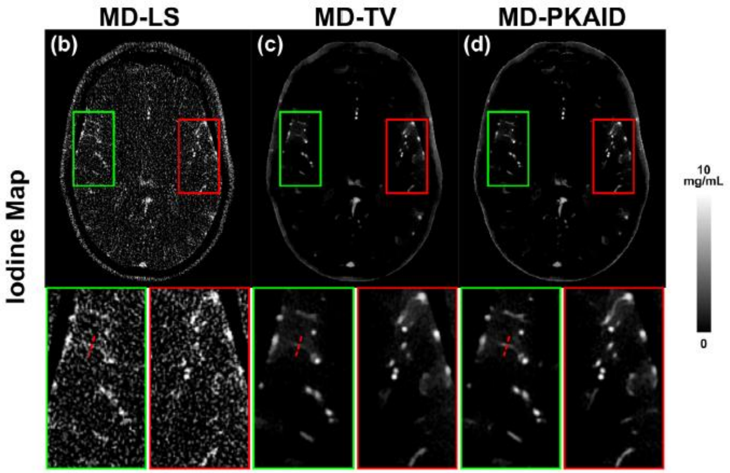
- **Noise reduction introduces non-linear behavior**
- Noise in MD is highly correlated – more of one material is compensated by less of other material(s), and vice versa
- Suppress anti-correlated noise in basis images
- Additional regularization in projection domain or image domain
- Summed image as prior
- Structural similarities between basis material and energy bin images
- Volume conservation
- Joint MD and reconstruction
- Deep learning image reconstruction



Schmidt et al, IEEE TMI 36 (9) 2017



Tao *et al* 2018 *Phys. Med. Biol.* **63** 195003



Yu *et al* 2016 *Phys. Med. Biol.* **61** 6707

Cramér-Rao Lower Bound (CRLB)

CRLB propagates uncertainty from one domain (binned counts) to another (material decomposition)

Minimum covariance matrix (best performance) for unbiased estimator

Useful for comparing detector or system design

Requires probability distribution of counts, often approximated as Gaussian with mean m, covariance Σ for object t

Fisher information: $F_{ij}(t) = \left(\frac{\partial m}{\partial t_i}\right)^T \Sigma^{-1} \left(\frac{\partial m}{\partial t_j}\right) + \frac{1}{2}\mathrm{tr}\left(\Sigma^{-1}\left(\frac{\partial \Sigma}{\partial t_i}\right)\Sigma^{-1}\left(\frac{\partial \Sigma}{\partial t_j}\right)\right)$

CRLB: $C(t) = F^{-1}(t)$

Diagonal elements are minimum variance of each material, off-diagonal are correlations

Used in original dual energy paper by Alvarez & Macovski (PMB 1976)

Example CRLB analysis

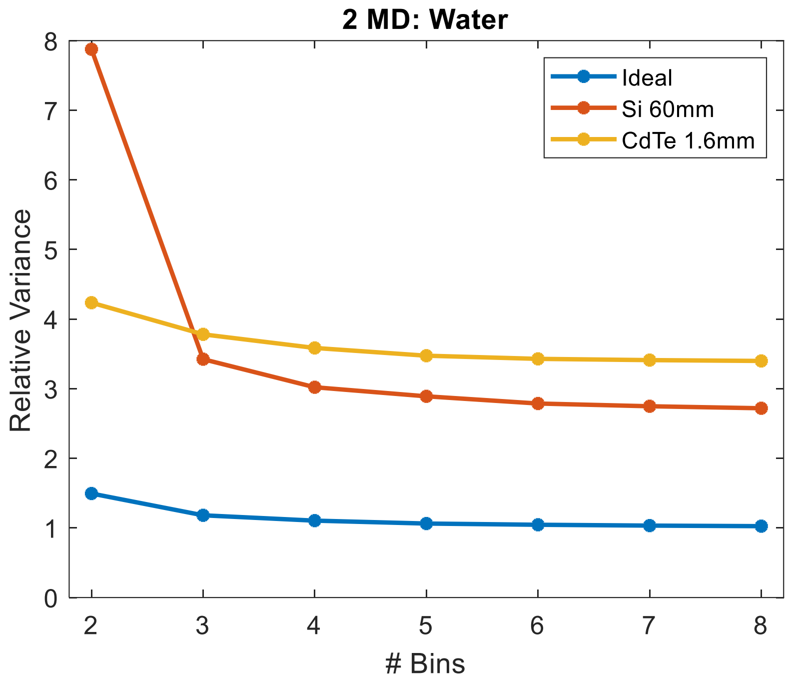
Predict noise variance of water MD & VM (60 keV) tasks

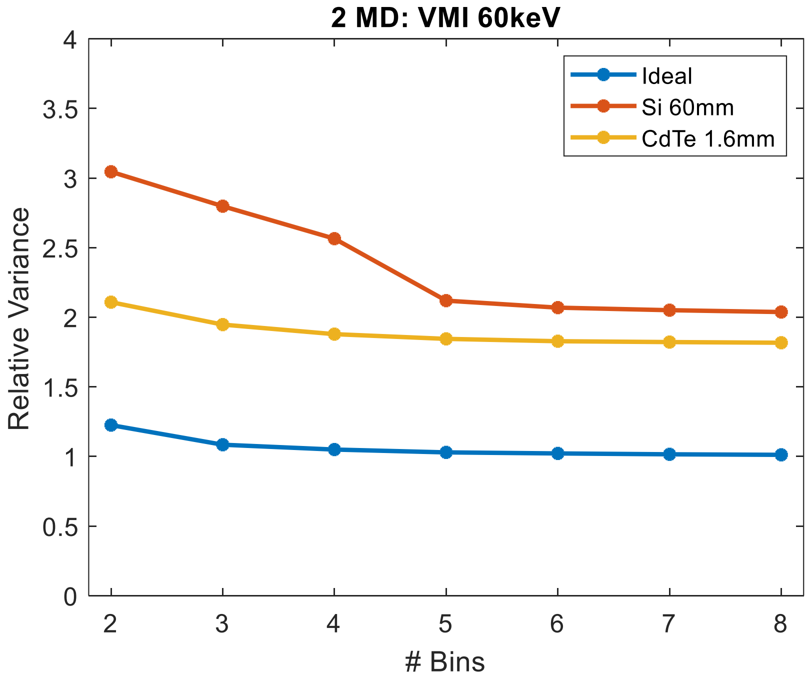
Ideal detector vs realistic energy response (Si 60 mm, CdTe 1.6 mm)

How do the number of energy bins affect noise?

Noise higher for realistic PCDs relative to ideal PCD, especially for spectral task

More bins reduces noise, especially for Si PCD





Wang et al., WE-G-201-4, AAPM 2022

Detective Quantum Efficiency (DQE)

DQE is comprehensive metric of detector/system performance over all frequencies f

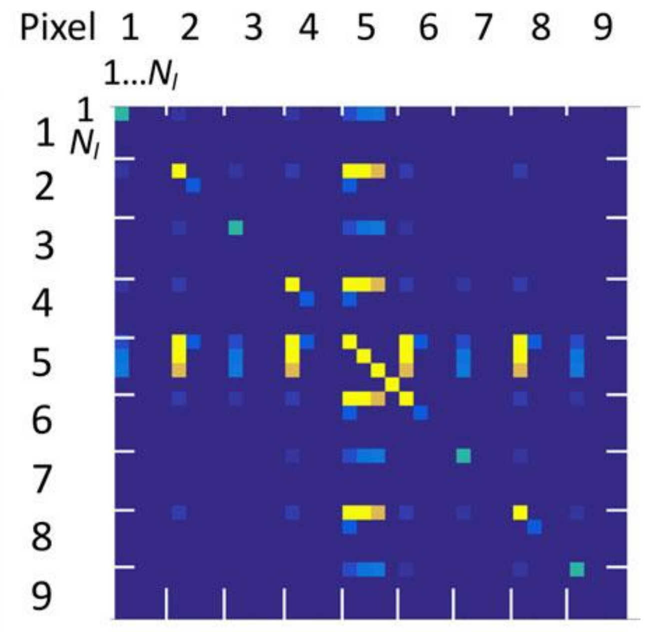
$$\mathrm{DQE}(f) = \frac{\mathrm{SNR}_{\mathrm{out}}^2(f)}{\mathrm{SNR}_{\mathrm{in}}^2(f)} \propto \frac{\mathrm{MTF}^2(f)}{\mathrm{NPS}(f)}$$

DQE(0) often easier to evaluate – reflects large-area tasks (“large” compared to spatial correlations caused by cross talk)

Cascaded systems analysis helps create DQE models by analyzing individual physical processes that lead to signal creation:

- Stochastic conversion of x-ray photons to secondary quanta
- Cross talk from characteristic/scatter photons
- Depth-dependent charge collection
- Aperture, sampling, additive noise, thresholding

Spatial-Spectral Correlations



(b) *nCov3x3w*

Taguchi et al., Med. Phys. 45 (5) 2018

NPS (and DQE) complicated by spatial-spectral correlations from:

- Charge sharing – charge clouds collected by 2 or more pixels
- Cross talk from secondary photons (K fluorescence in CdTe, Compton scattering in Si)

Effects include:

- Incorrect energy assignment
- Incorrect counts, including undercount (signal is no longer above the trigger threshold)
- Overcount (multiple pixels have signal above the trigger threshold)
- Reduced spatial resolution (counts in neighboring pixels)
- Spatial-spectral correlations between energy bins in different pixels

Reduces DQE, especially for spectral tasks

DQE for comparing CdTe & silicon (simulation study)

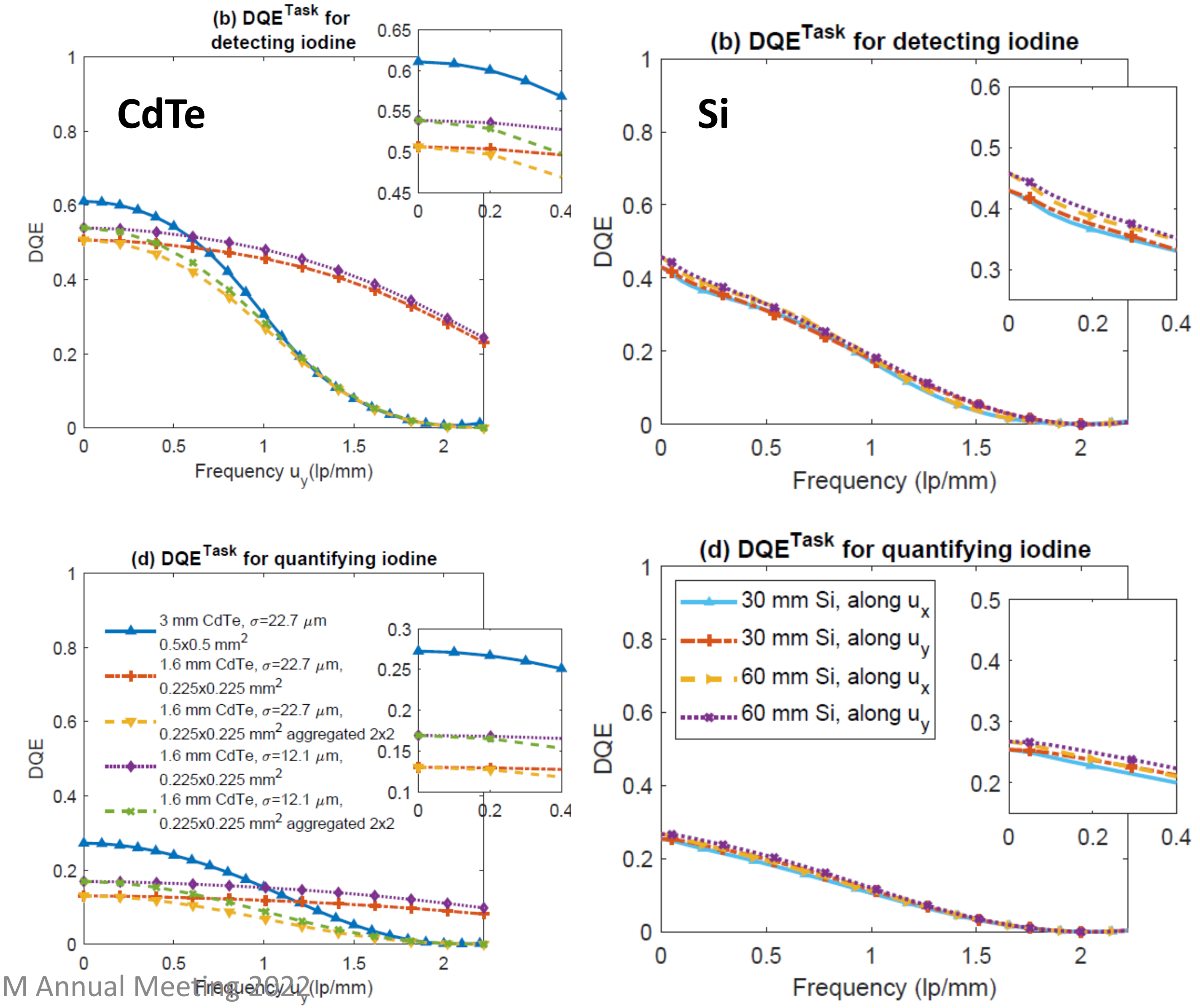
Detection task: determine whether a feature of specified frequency content and material composition is present or absent in an image

- CdTe > Si for iodine detection

Quantification task: measure the amount of a given basis material

- Si generally > CdTe for iodine quantification
- CdTe impacted by increased charge sharing & fewer bins

All results ignore pileup



Persson et al., J. of Medical Imaging, 7(4) (2020)

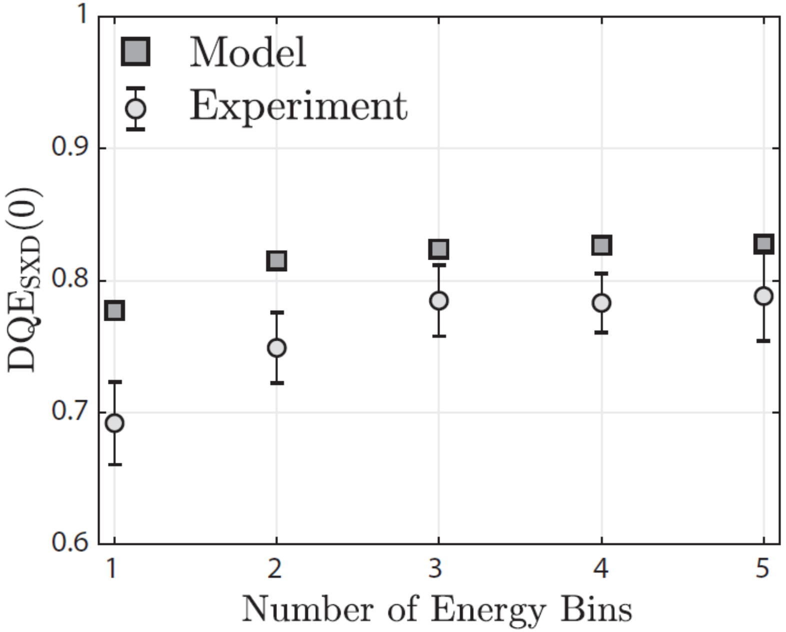
Measuring detector DQE

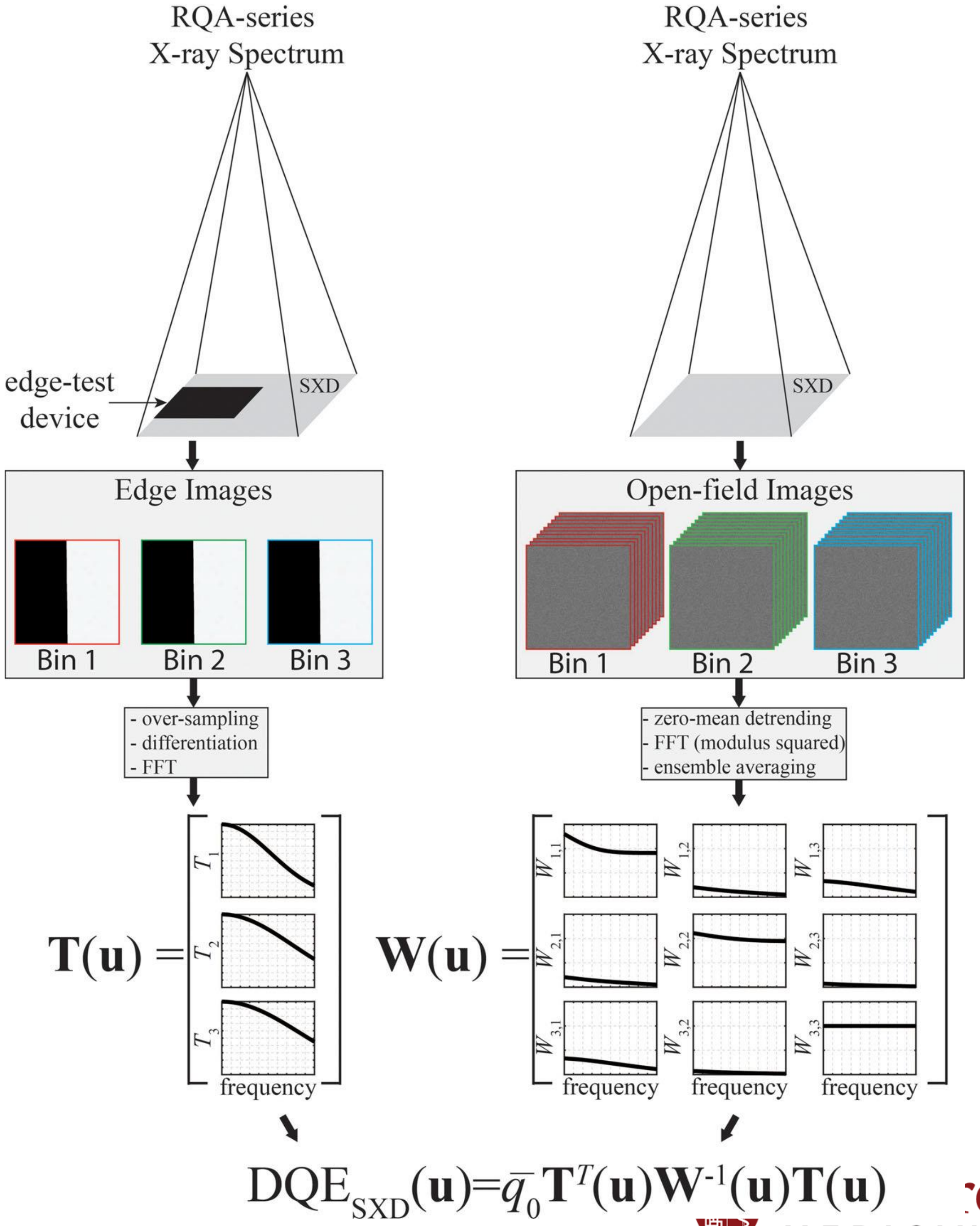
Task-independent DQE

Extension of established DQE methods:

- Measure MTF of each energy bin

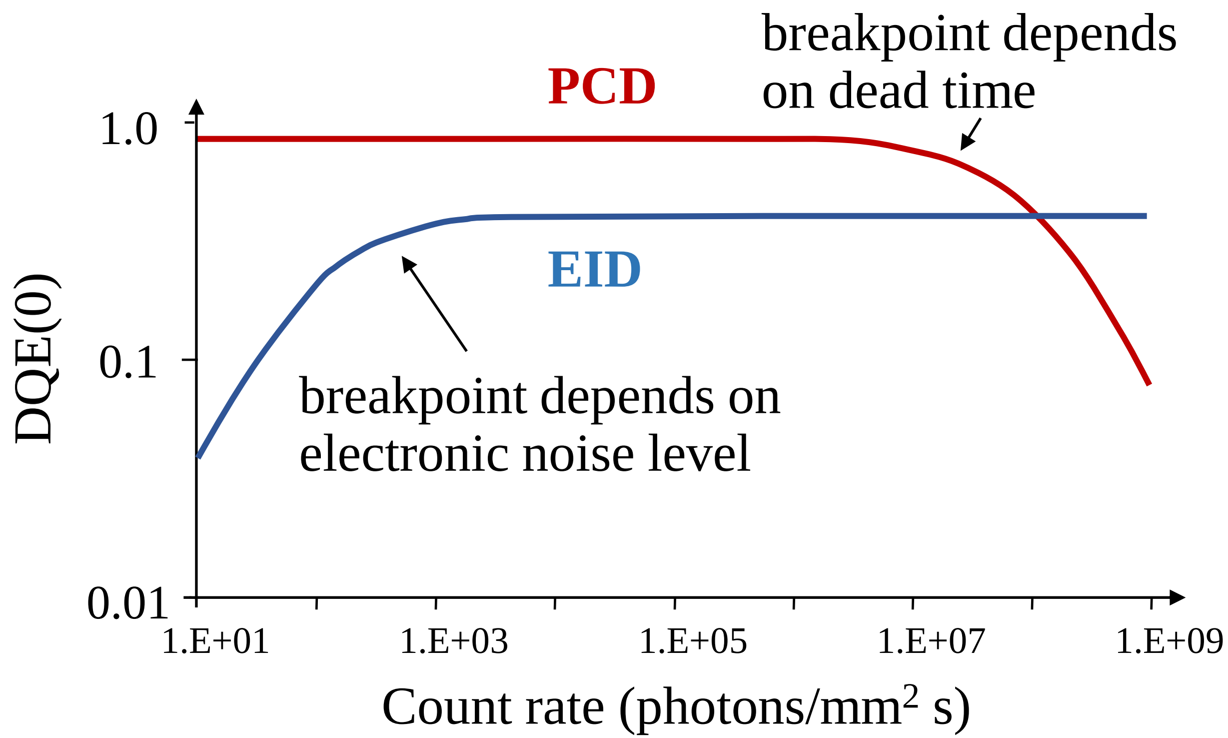
- Measure NPS of each energy bin, as well as cross-bin NPS





Tanguay et al., Med. Phys. 48:6781 (2021)

DQE depends on count rate



Courtesy of Norbert Pelc

Relative performance of PCD > EID at low count rates due to lack of electronic noise

Worse at high count rates due to pileup

Comprehensive DQE model is still needed to combine spatial–spectral effects with pileup

Stanford MEDICINE

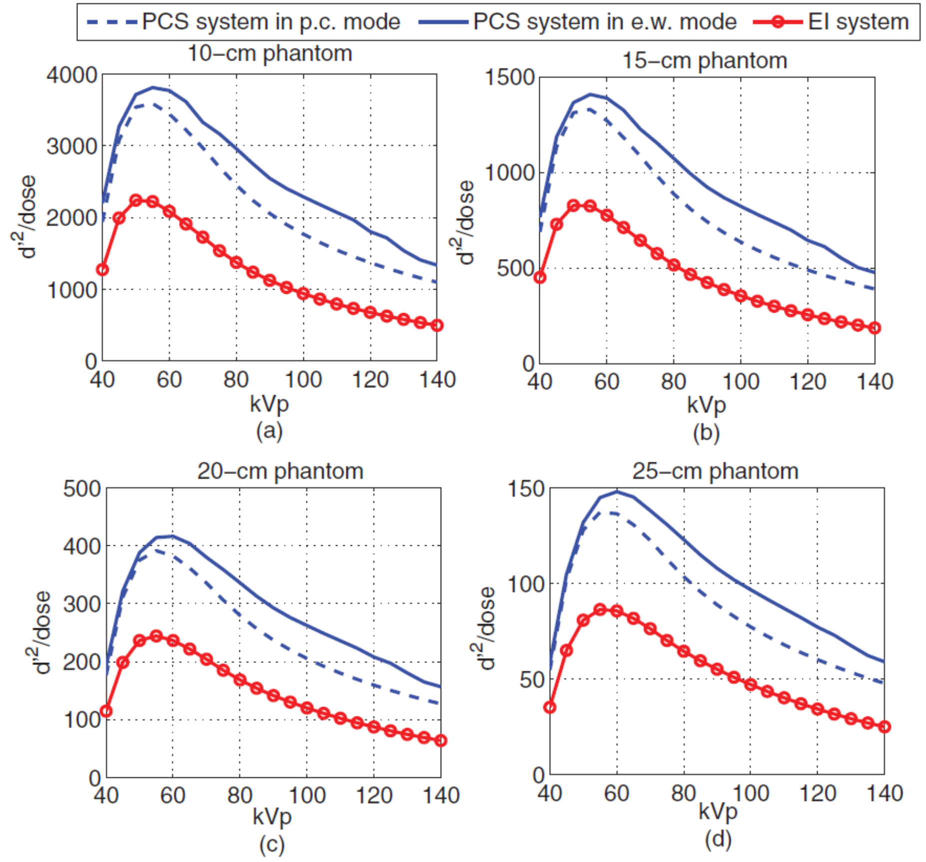
Detectability in CT images

Detectability metric incorporates system's spatial resolution (MTF), noise power (NPS), and imaging task (W) across all frequencies f

Example task: Iodinated blood sphere with 1 mm diameter and 5 mg/ml iodine

Can normalize by dose to compare different spectra

$$d'^2 = (\Delta\mu)^2 V^2 \iint \frac{\left| \int \mathrm{MTF}_{3\mathrm{D}}(f_x, f_y, f_z) W(f_x, f_y, f_z) \mathrm{d}f_z \right|^2}{\int \mathrm{NPS}_{3\mathrm{D}}(f_x, f_y, f_z) \mathrm{d}f_z} \mathrm{d}f_x \mathrm{d}f_y$$



→ 60 kVp optimal for iodine task for pediatric size

→ Increases detectability by up to 70% over EID

Chen *et al* 2016 *Phys. Med. Biol.* **61** 4105

Detectability depends on observer

Ideal observer: uses all available information at all frequencies

Hotelling observer: optimum linear discriminant

- Ideal when signal known exactly / background known exactly
- Can also be used when signal known statistically

Channelized Hotelling observer: Includes spatial-frequency-selective channels

- Gabor filters can be used to represent the human visual system
- Helps determine lowest detectability of any signal (e.g., iodine concentration)

Human observer: Ultimate test, but time consuming

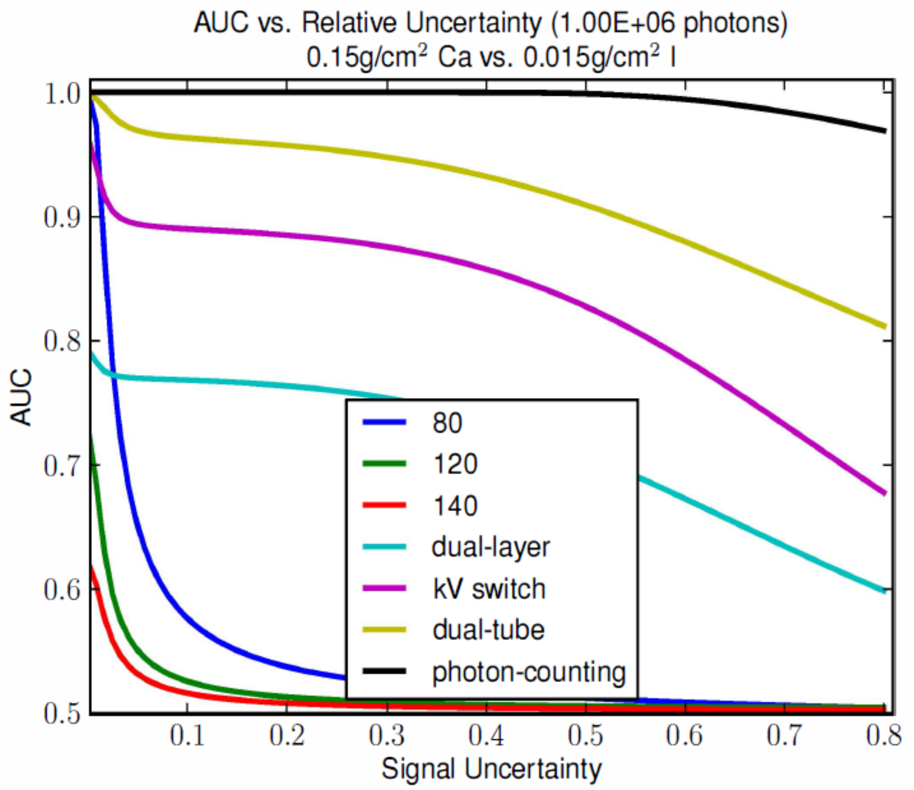


Fig. 4. Plot of Hotelling Observer AUC for Calcium/Iodine task as a function of signal uncertainty.

Rigie & La Riviere, IEEE NSS MIC 2012

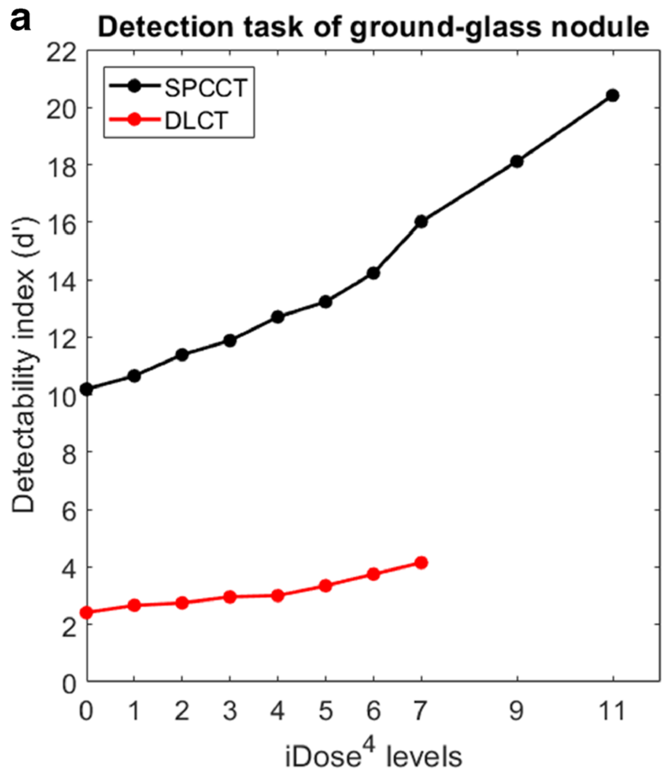
Stanford MEDICINE

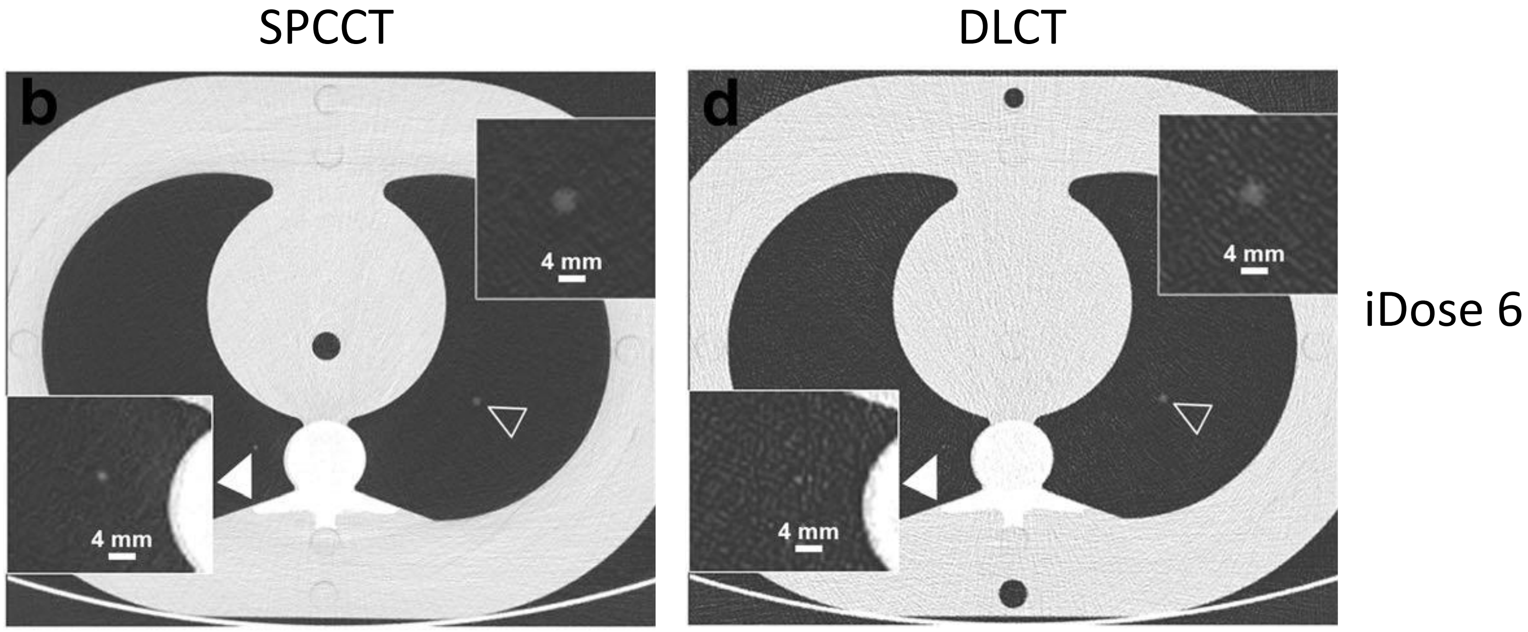
Reader study: phantom

Compared spectral PCCT vs dual-layer CT with iterative recon levels (Philips iDose^4)

Nonprewhitening observer model with eye filter (NPWE) detectability for ground-glass nodule and solid nodule tasks

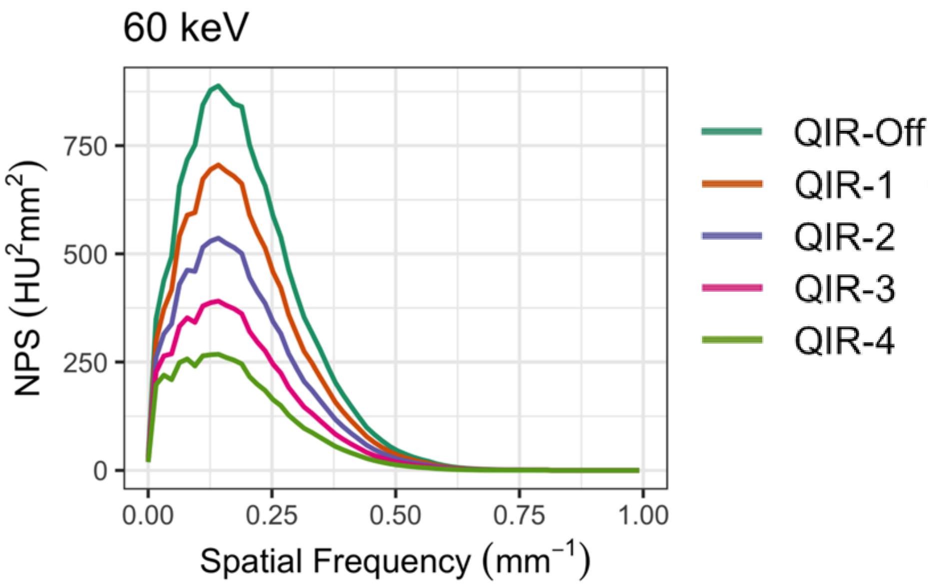
Correlates with human observer image quality preferences





Si-Mohamed et al., Eur Rad (2022) 32:524–532

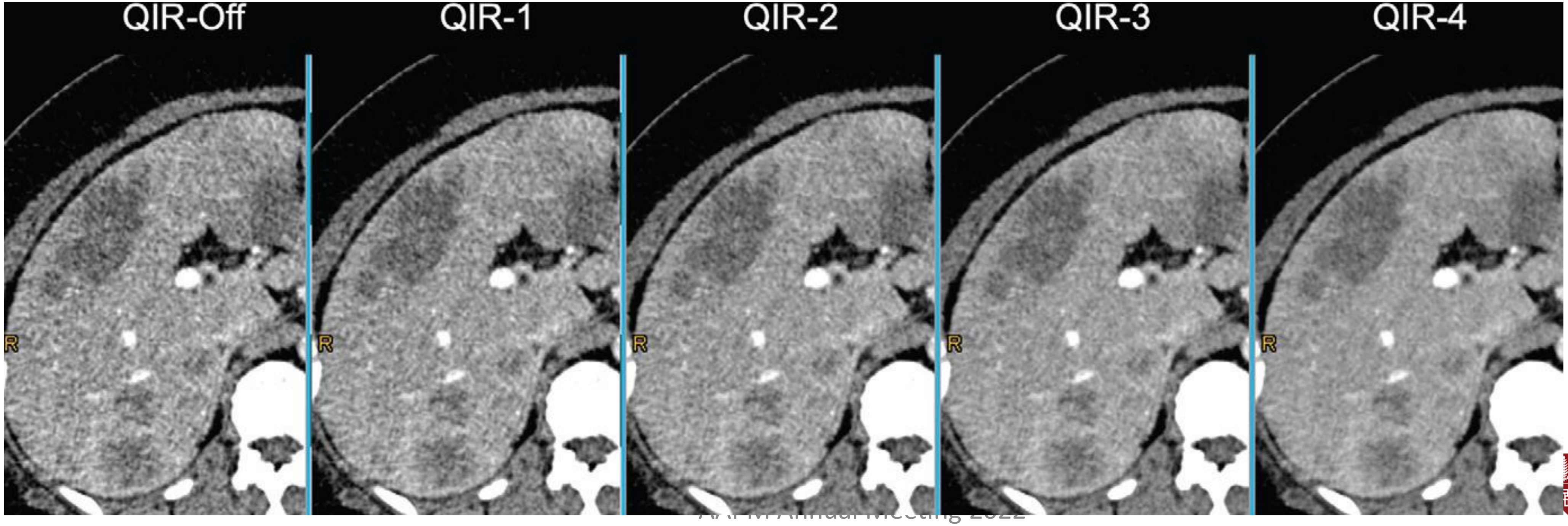
Reader study: clinical



PCCT + iterative reconstruction (Siemens QIR) reduces noise

Reader study showed improved image quality and liver lesion conspicuity

Clinical image, clinical task



Sartoretti et al., Radiology 2022; 303:339–348

Summary

- PCCT offer vast potential, including higher spatial resolution, unique spectral information, and higher dose efficiency
- Potential for spectral tasks is greater than grayscale tasks, but spectral tasks tend to be more sensitive to nonidealities than grayscale tasks
- Performance analysis tools help quantify image quality and the impact of nonidealities
- Metrics needed for range of tasks & reconstruction methods

- Questions?

Contact: adamwang@stanford.edu