Performance of Iterative Reconstruction Algorithms

AAPM Spring Clinical Meeting

March 17, 2012

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Toshiba Medical Research Institute

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HEALTH INDUSTRY | JUNE 15, 2010

Medical Radiation Is a Growing Concern

It's true that we get too much radiation, but not from the sources we fret about—airport scanners, power lines, cell phones, even microwaves. It's from too many medical tests.

View Full Image

Getty Images

Some researchers have suggested a 'radiation medical record' that would track patients' radiation exposure from tests such as CT scans.

Americans get the most medical radiation in the world—even more than folks in other rich countries—and the average American's dose has grown sixfold over the last couple of decades.

Too much radiation raises the risk of cancer. The risk is growing as people in everyday situations get imaging tests far too often. A New Hampshire teen was about to get a CT scan to check for kidney stones until a radiologist, Dr. Steven Birnbaum, discovered he'd already had 14 of these powerful X-rays for previous

Courtesy of Patrik Rogalla, UHN

CT overuse

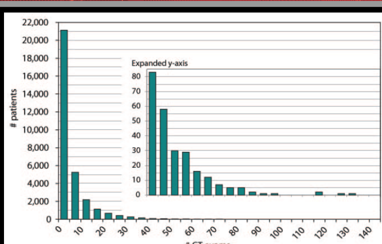


Figure 3: Histogram of total number of CT examinations per patient, over the 22-year study period in the cohort of 31 463 patients. The inset includes an expanded y-axis to display the right tail and contains the top percentile of per-patient examination counts; 33% of patients underwent more than five lifetime CT scans, 5% underwent more than 22 scans, and 1% underwent more than 38 scans.

Sodickson A, Radiology, 2009 251:175

Dose Reduction

- Conventional Approaches
  - mA Modulation, Gating
  - Post-processing algorithms
  - Bowtie
  - Active Collimation

Quantum Noise

- Noise
  - Random background variations
  - Competes with true signal
  - Static on radio, “snow” on television
- More photons
  - less noise
  - Signal to Noise ratio (SNR)

Quantum Noise

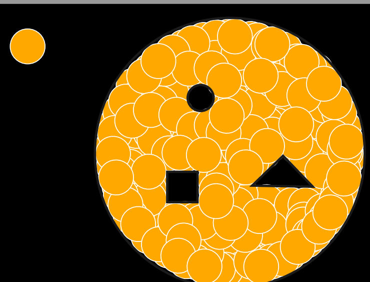
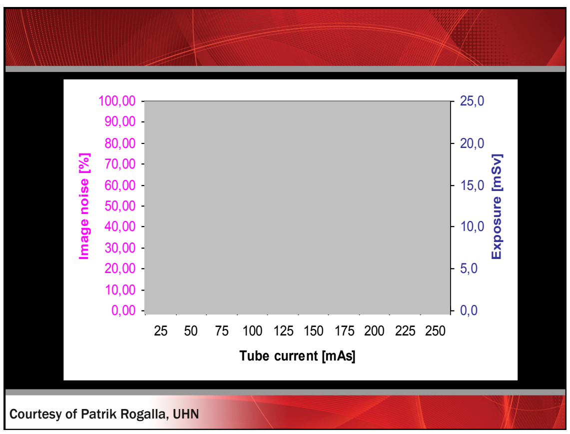


Image noise is heavily dependent on the number of photons (quanta) that define it!


100,00
90,00
80,00
70,00
60,00
50,00
40,00
30,00
20,00
10,00
0,00
Image noise [%]
25,0
20,0
15,0
10,0
5,0
0,0
Exposure [mSv]
25 50 75 100 125 150 175 200 225 250
Tube current [mAs]
Courtesy of Patrik Rogalla, UHN

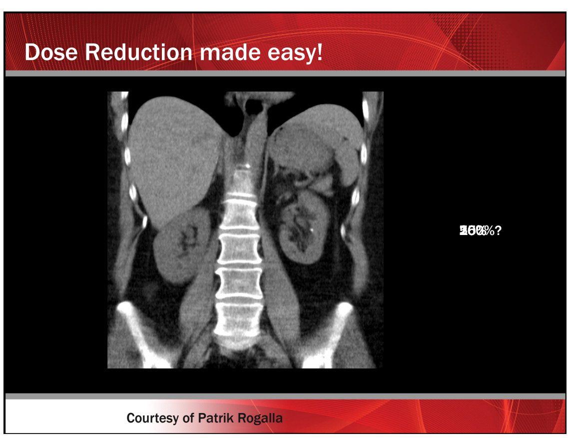
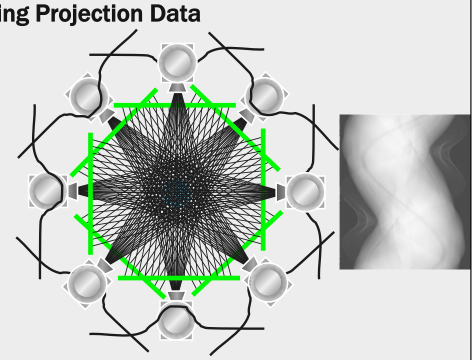

Dose Reduction made easy!
Courtesy of Patrik Rogalla

Image Reconstruction

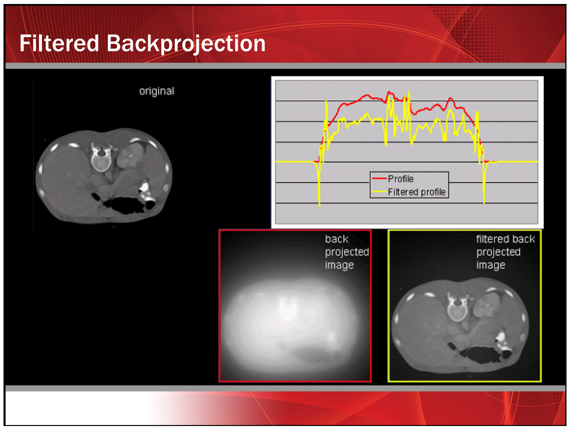
- Have raw data, need to make an image
- 2 major ways to do this
  - Fourier Backprojection
  - Iterative Reconstruction
- Both older than dirt
- Different strengths and tradeoffs for each

Acquiring Projection Data



Backprojection

Filtered


Filtered Backprojection
original
Profile
Filtered profile
back projected image
filtered back projected image

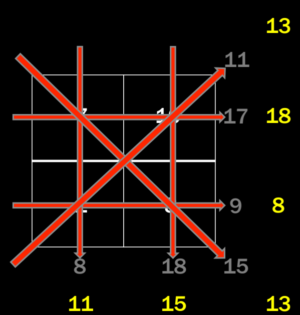
FBP Advantages

- Speed
  - 50-60+ images per second recon
- Well characterized
  - Primary recon since beginning of CT
  - Noise properties known; linear relationship between noise and resolution
  - Familiar look and feel
  - Artifacts known
- Linear
  - Predictable reconstruction behavior

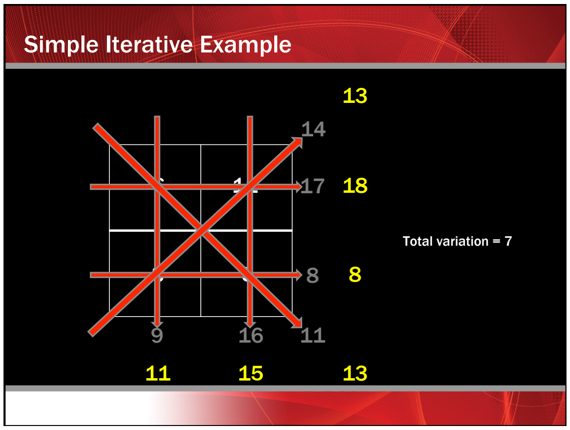
FBP Disadvantages

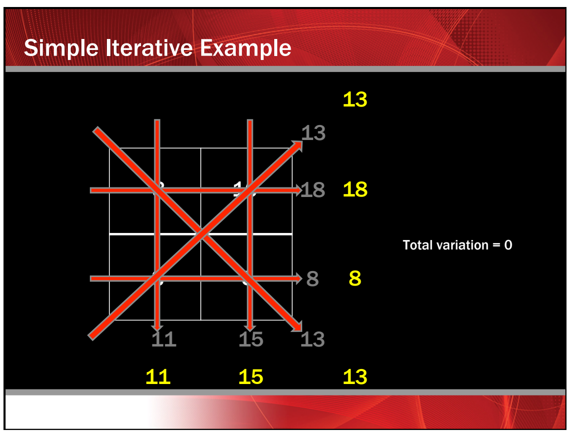
- Simplified assumptions
  - Point focal, point detector, pencil beam
  - Limits precision
- Trouble with truncated data
  - Needs to know all the projections
- Slight non-uniformities
  - Can be calibrated out
- Direct tradeoff between noise and resolution can be limiting

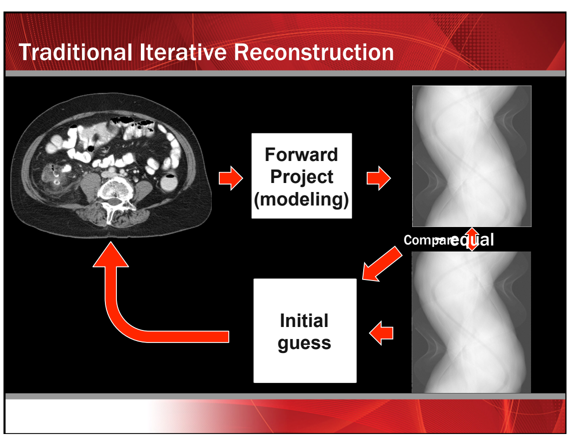
Simple Iterative Example



Total variation = 12


Simple Iterative Example
13
14
17
18
8
8
9
16
11
11
15
13
Total variation = 7


Simple Iterative Example
13
13
18
18
8
8
11
15
13
11
15
13
Total variation = 0


Traditional Iterative Reconstruction
Forward Project (modeling)
Compare
equal
Initial guess

Modeling for IR

- Statistical Modeling
  - Focused on controlling noise
  - Models only noise properties
  - Takes quantum noise into account
  - Does not improve resolution!
- Physics modeling
  - Models all aspects of the scanner
  - Focal spot size, system geometry, beam energy, cone angle
  - Extremely complex- better the model, the better the image quality
  - Can improve both noise and resolution

Possible Iterative Advantages

- Modeling
  - Allows more precise reconstructions
  - Can help with noise and resolution
  - Artifact reduction
- Good with truncated datasets
  - Short scans
  - Cone beam

Traditional Iterative Disadvantages

- Slow
  - Depending on model can be 400x slower
- Complex
  - Modeling noise is relatively fast
  - Modeling physics is slow!
- Non-linear
  - Can create plastic images
- Poorly characterized

Vendor-specific Iterative Reconstruction

GE	Philips	Siemens	Toshiba

Algorithm

• **Veo**	• **iDose[4]**	• **SAFIRE**	• **AIDR3D**
• Data domain	• Data and Image domain	• Data and Image domain	• Data and Image domain

GE's iterative reconstruction- Veo

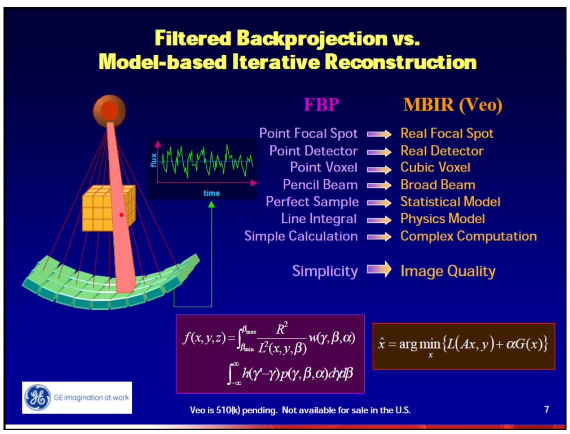
- Traditional IR- Model based IR
- Forward projection incorporates
  - Real focal spot
  - Real detector geometry
  - Cubic voxel
  - Broad beam
  - Statistical model of noise
  - Physics model
- "Lower noise and higher resolution can be achieved within a single image. " – GE website
- ~ 1 hour / case – Katsura et al, ECR March 2012

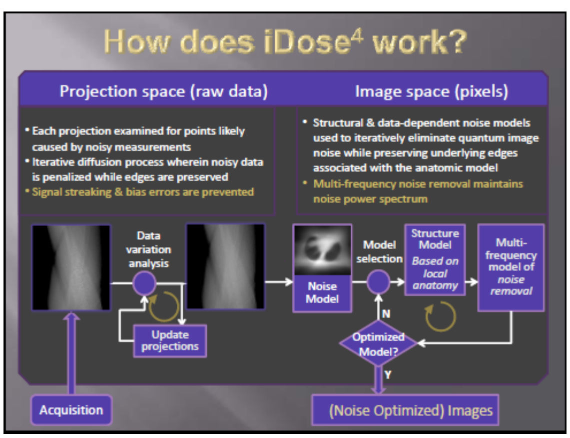
Philips' iterative reconstruction- iDose[4]

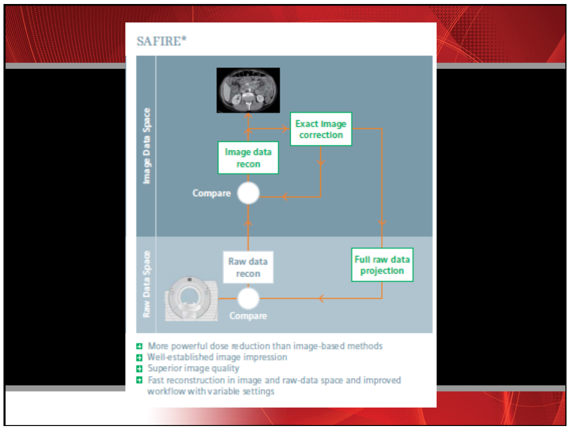
- Hybrid
  - Works in both raw data domain and image domain
- Raw data
  - Targets noisy projections
  - Noisy data penalized, edges preserved
- Image data
  - Noise model
  - Multi-frequency noise reduction
- "The majority of factory protocols are reconstructed in 60 seconds or less " – Philips website

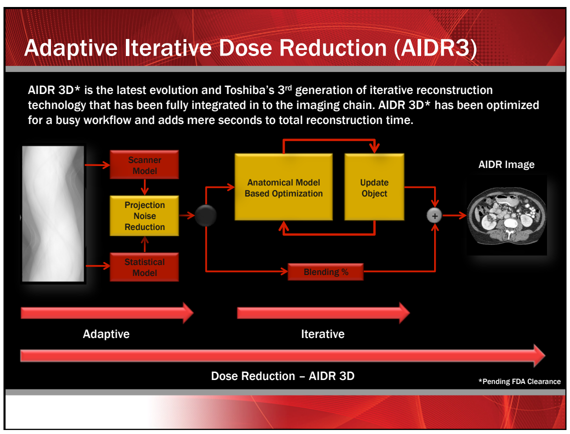
Siemens' iterative reconstruction- SAFIRE

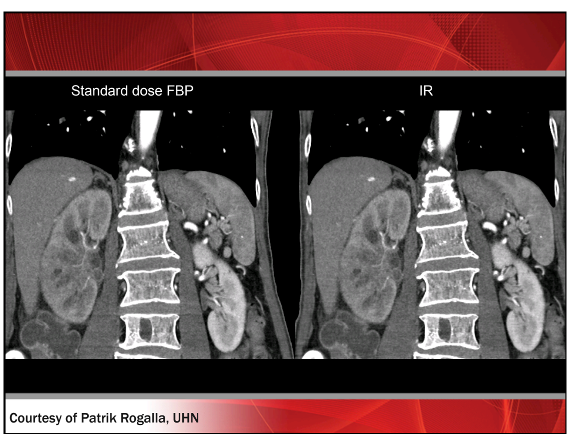
- Hybrid
  - Works in both raw data domain and image domain
- Primary work done in image space
  - "Iteratively 'cleaning up' and removing image noise without degrading image sharpness"
- Periodic comparison to sinogram
  - Forward project into raw data domain
  - Compare with original acquisition data
- "SAFIRE can achieve significant radiation dose reduction " – Siemens website

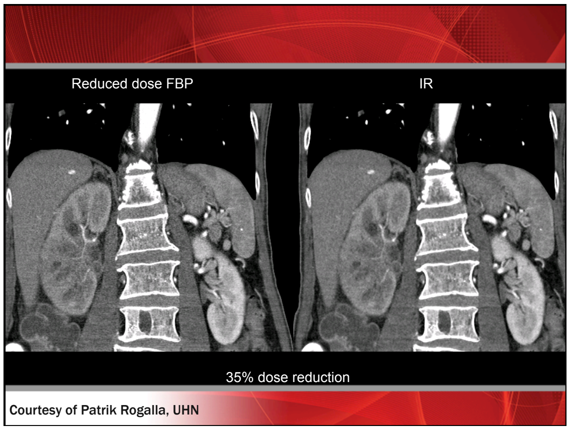


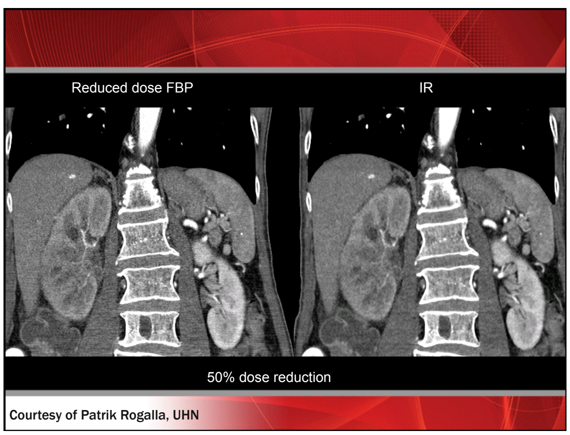


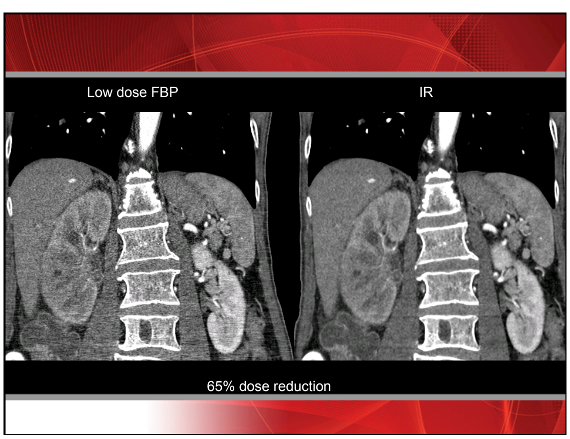

SAFIRE*
Image Data Space
Raw Data Space
Exact image correction
Image data recon
Compare
Raw data recon
Full raw data projection
Compare
More powerful dose reduction than image-based methods
Well-established image impression
Superior image quality
Fast reconstruction in image and raw-data space and improved workflow with variable settings

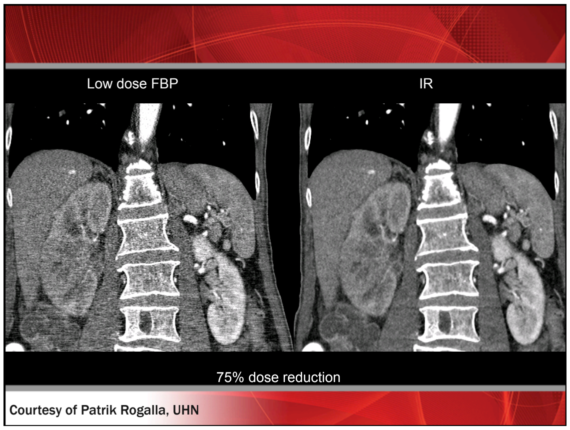

Adaptive Iterative Dose Reduction (AIDR3)
AIDR 3D* is the latest evolution and Toshiba's 3rd generation of iterative reconstruction technology that has been fully integrated in to the imaging chain. AIDR 3D* has been optimized for a busy workflow and adds mere seconds to total reconstruction time.
Scanner Model
Projection Noise Reduction
Statistical Model
Anatomical Model Based Optimization
Update Object
Blending %
AIDR Image
Adaptive
Iterative
Dose Reduction – AIDR 3D
*Pending FDA Clearance


Standard dose FBP
IR
Courtesy of Patrik Rogalla, UHN


Reduced dose FBP
IR
35% dose reduction
Courtesy of Patrik Rogalla, UHN


Reduced dose FBP
IR
50% dose reduction
Courtesy of Patrik Rogalla, UHN


Low dose FBP
IR
65% dose reduction



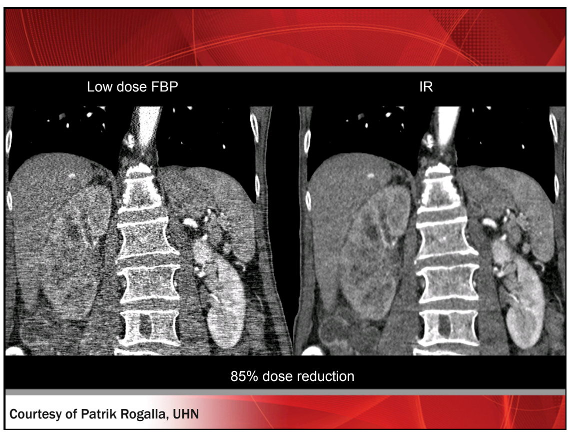


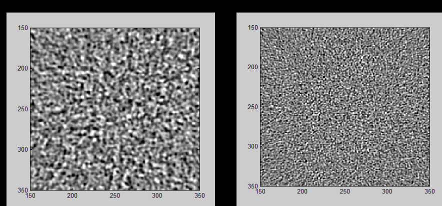
Image Quality

Medical:		Technical:
• we can see very small structures	→	high contrast resolution
• we can see subtle density differences	→	low contrast resolution
• no motion artefacts	→	temporal resolution
• low image pixel noise	→	pixel SD, noise power spectrum
• sharp contours, crisp image	→	kernel, edge preservation
• tissue contrast	→	tube settings, CM
Mental:		
• “nice images”	→	psychology

Courtesy of Patrik Rogalla, UHN

Evaluating Image Quality

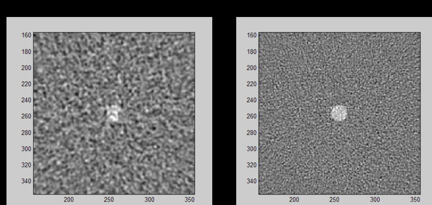
- Noise
- Spatial Resolution
- Detectability

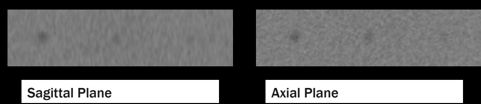


SD=21.5HU SD=21.5HU

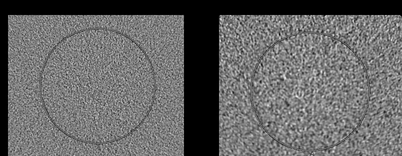
Both images have the same standard deviation

Impacts Detectability

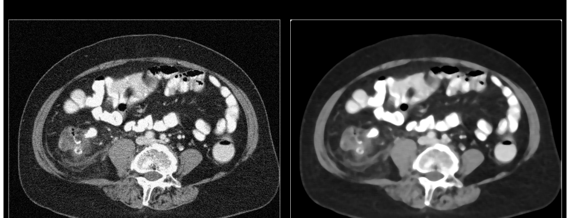




Iterative Reconstruction



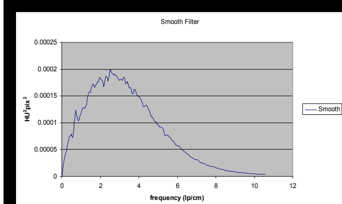
Texture Changes

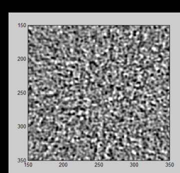


Noise Power Spectrum

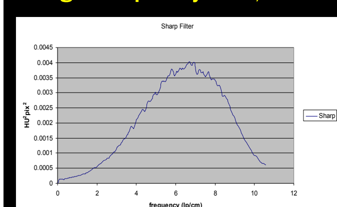
- Based on Fourier technique, images of uniform, noise-only material are converted into frequency space to yield a power spectrum.
- Shows in which spatial frequencies the noise power is concentrated.
- Area under NPS curve is equal to the variance.

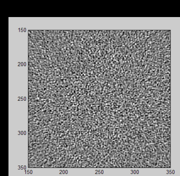
Low Frequency NPS, Large Grain Noise





High Frequency NPS, Fine Grain Noise





Iterative Reconstruction and NPS

- IR can shift the NPS to lower frequencies
- Amount of the shift can depend on:
  - 1. Dose level
  - 2. Algorithm Strength

Figure 5

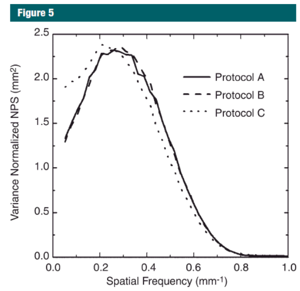
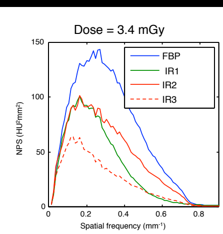
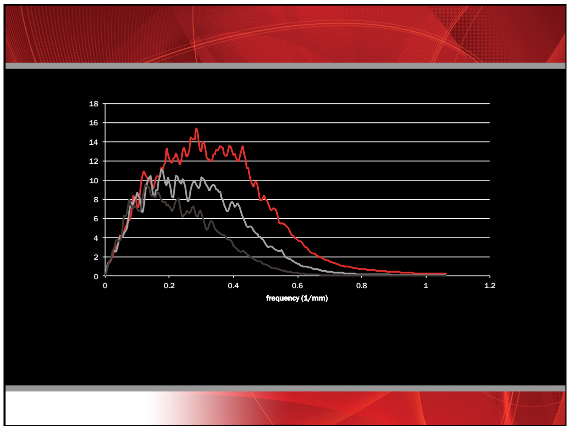


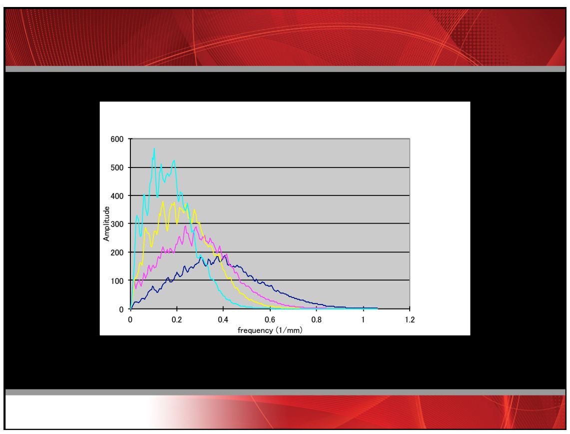
Figure 5: Graph shows NPS curves for the three CT protocols. Compared with the two standard FBP algorithms (protocols A and B), the ASIR algorithm (protocol C) yielded relatively more pronounced noise reduction at higher spatial frequencies (ie, fine detailed texture features) than at lower spatial frequencies (ie, broad texture features).

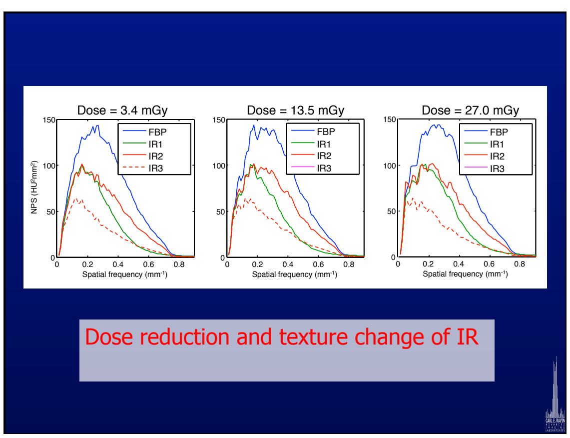
Marin D et al Radiology 2010



Courtesy of Ehsan Samei


frequency (1/mm)

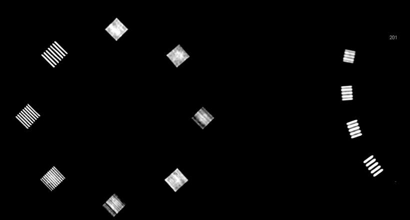

Amplitude
frequency (1/mm)


Dose = 3.4 mGy
Dose = 13.5 mGy
Dose = 27.0 mGy
FBP
IR1
IR2
IR3
NPS (HU²mm²)
Spatial frequency (mm⁻¹)
Dose reduction and texture change of IR

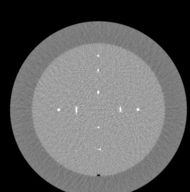
Noise and Iterative Reconstruction

- Like with FBP, standard deviation does not tell the whole story
- NPS can vary with IR algorithm and strength
- NPS can vary with dose level
- SD and NPS should be quantified for range of typical use.

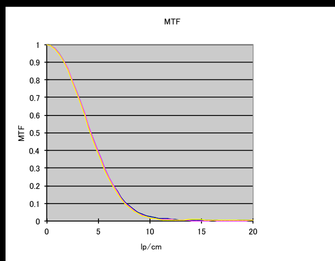
Resolution



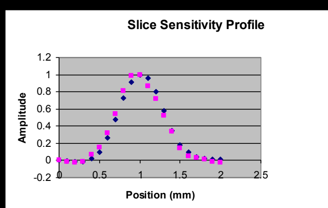
MTF Bead or Wire



MTF



Slice Sensitivity Profile



Modulation Transfer Function

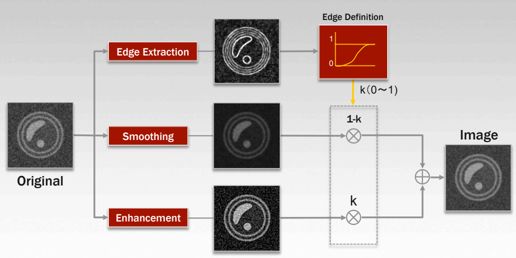
- Highly attenuating wire or bead for test object
- Presumes linear behavior of algorithm
  - Linear algorithm =>Performance at high contrast reflects spatial resolution properties at low contrasts

60

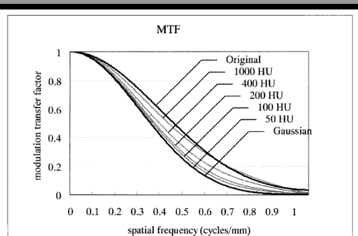
Iterative Reconstruction

- Non Linear Algorithms spatial resolution preservation depends on contrast level and noise level
  - Traditional test objects not robust
  - Traditional test condition (very small FOV or pre-sampled) do not reflect clinical scanning/display conditions

Adaptive image filters



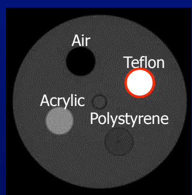
Non-linear Algorithms



10% MTF	Original	1000 HU	400 HU	200 HU	100 HU	50 HU	Gaussian
cycles/mm	0.83	0.86	0.78	0.7	0.68	0.64	0.64

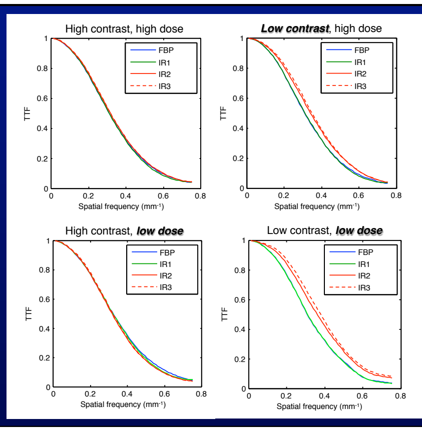
Taken from : Okurura, et al,. New Method of Evaluating Edge-preserving Adaptive Filters for Computed Tomography (CT): Digitial Phantom Method. Japanese Society of Radiological Technology. 2006

TTF measurements: Task-specific, edge technique



- Edge of rods. Similar to MTF measurements, but
- Task-specific: object contrast, dose, and recon

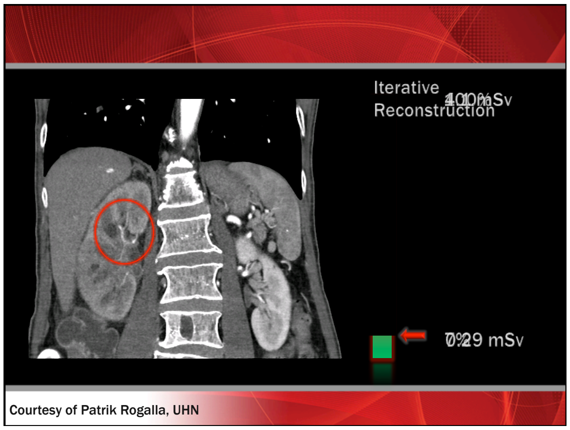
Courtesy Ehsan Samei

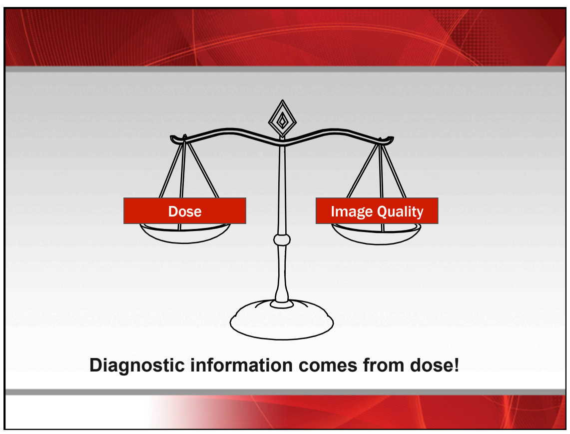


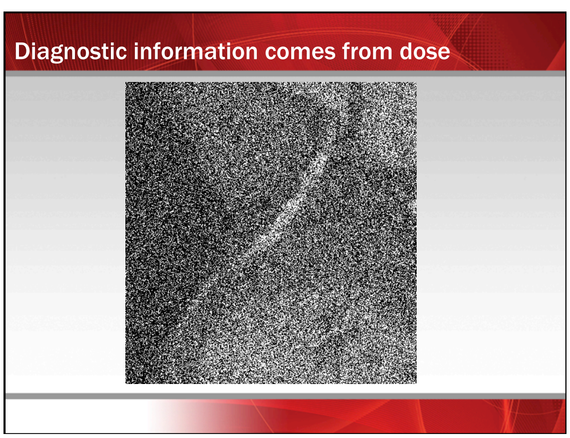
Courtesy Ehsan Samei

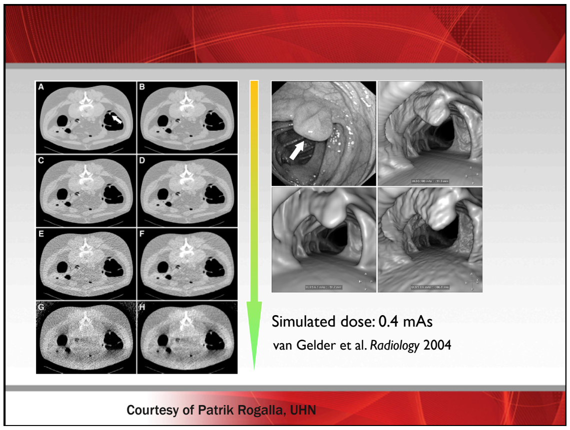
Detectability and Image Quality

- What is low dose?
- Full Dose w FBP vs Reduced Dose w IR


Iterative
Reconstruction
Courtesy of Patrik Rogalla, UHN


Dose
Image Quality
Diagnostic information comes from dose!


Diagnostic information comes from dose



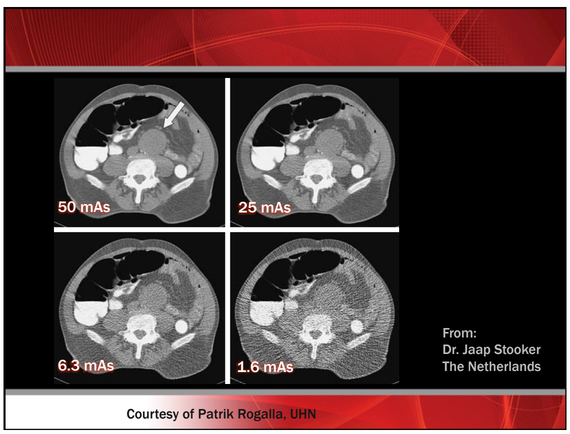
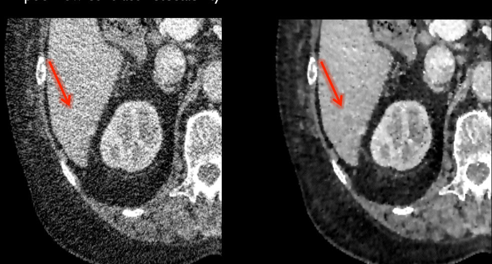


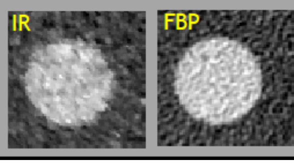
Image Quality

poor low contrast detectability



CNR qualifications

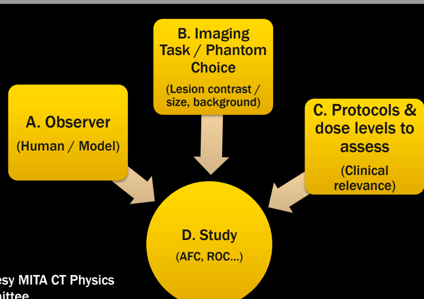
- Only 1st order approximation of image quality
- Task-generic
- Not reflective of resolution and noise texture attributes of images



Courtesy of Ehsan Samei

- How do we quantify dose reduction associated with IR?
- Objective phantom data
- Reproducible
- The focus is on the detection tasks -> most challenging in low dose imaging conditions is Low Contrast Detectability.

Observer study



Courtesy MITA CT Physics Committee

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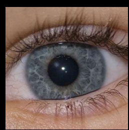
Choose an observer

Human observer



Model observer

	Human Observers	Model Observers
Positives	• Straightforward implementation. • Directly incorporates human perception	• Objective and consistent • Demonstrated correlation with human performance for certain tasks
Challenges	• Time consuming – observer fatigue – statistical power • Controlled study needed • Inter- and Intra-Observer variability	• How choose from the wide variety of published observers? • Need validation with human observers for CT non-linear algos • No single model observers can do all the tasks (detection, estimation, etc)

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Model Observers

Choice of model observer

- Many observers to choose from
  - Ideal Observer
  - Hotelling
  - Non-prewhitening (NPW)
  - Channelized models
  - Eye and Internal Noise filters

$$NPW = \frac{\left|\int O(f)^2 MTF(f)^2 df\right|^2}{\int O(f)^2 MTF(f)^2 NPS(f)\, df}$$

Each observer represents a different set of starting assumptions. The ideal observer, for example, assumes the correlations in the noise can be undone. The non-prewhitening model assumes they cannot (bc the human eye cannot undo them). The NPWE (with Eye filter) incorporates the frequency response of the human eye.

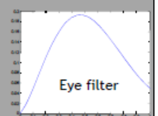
Model observers

Fisher-Hotelling observer (FH)

$$\left(d'_{FH}\right)^2 = \iint \frac{MTF^2(u,v)W^2_{Task}(u,v)}{NPS(u,v)}dudv$$

Non-prewhitening observer (NPW)

$$\left(d'_{NPW}\right)^2 = \frac{\left[\iint MTF^2(u,v)W^2_{Task}(u,v)dudv\right]^2}{\iint MTF^2(u,v)W^2_{Task}(u,v)NPS(u,v)dudv}$$

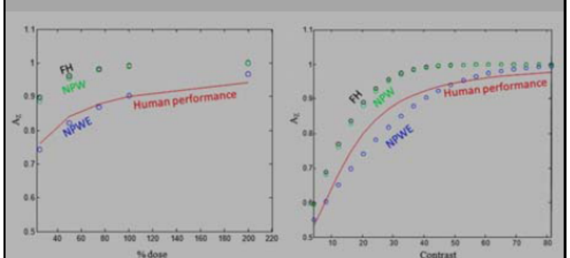


NPW observer with eye filter (NPWE)

$$\left(d'_{NPWE}\right)^2 = \frac{\left[\iint MTF^2(u,v)W^2_{Task}(u,v)E^2(u,v)dudv\right]^2}{\iint MTF^2(u,v)W^2_{Task}(u,v)NPS(u,v)E^4(u,v)+MTF^2(u,v)W^2_{Task}(u,v)N_i dudv}$$

Courtesy of Ehsan Samei

Validation of model observers



Richard, Li, Samei, SPIE 2011

Observer Study Design: Imaging Task

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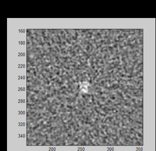
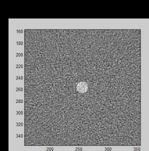
- Type of Task
  - Classification task?
  - Estimation task?





Observer Study Design: Imaging Task

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1. Defining the test object (i.e. signal)
   - What is the object of interest?
     - Sphere? Simulated anatomy?
     - Contrast level
     - Size
     - Position in field
   - What is background of interest?
     - Correlated electronic and quantum noise (water phantom)
     - Anatomical noise
- SKE/BKE? Search?

> Known Object (SKE) & Location, BKE

> Known Object (SKE), Unknown Location, BKE

> Shape discrimination and size estimation

Courtesy of MITA CT Physics Group

	Industry Standard Phantoms (Catphan, ACR phantom, etc.)	Custom Phantoms
Positives	• Standardized • Reproducible	• Can be tailored to task
Challenges	• Fixed object sizes and contrasts • Limited ability to isolate and analyze individual objects	• Non-standard • Not readily available to the field • Need to be defined

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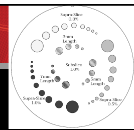
Courtesy of MITA CT Physics Group

Imaging Task



- Phantom/Task
  - Low contrast detection task for different contrast levels: 0.3%, 0.5%, 1.0%
  - Selectable disk sizes (9 cylinders of diameters): 2, 3, 4, 5, 6, 7, 8, 9, 15 mm
- Positives
  - Industry standard phantom
  - Radial symmetry in object locations
  - Background closer to soft tissue
  - Relatively higher flexibility in reference dose selection due to availability of multiple contrast and disk sizes
- Challenges
  - Limited ability to ioslate and analyze individual test objects
  - Single realization for each object (contrast & size)
  - Available disk sizes and contrast may not be enough to cover range of all dose levels/protocols
  - Known pattern may reduce imaging task to "Signal Known Exactly"
  - Inter-phantom variability due to tolerance (some Catphans better than others)

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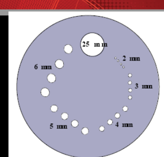
Courtesy of MITA CT Physics Group

Imaging Task



- Phantom/Task
  - Low contrast detection task for 0.6% contrast (fixed)
  - Selectable disk sizes out of five cylindrical objects (discrete)
- Positives
  - Industry standard phantom
  - Better spacing processing
  - Multiple realizations of the same object (4)
- Challenges
  - Requires flexibility in reference dose selection/protocol due to fixed contrast and discrete diameters.
  - Compromise from radial symmetry in object locations.
  - Background denser than soft tissue -- clinical relevance ?
  - Not commonly used outside the US.
  - Known pattern may reduce imaging task to "Signal Known Exactly"

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Courtesy of MITA CT Physics Group

Imaging Task

- For non-linear processes (where performance varies non-linearly with contrast, position, dose, etc) what protocols of interest capture a good representation of performance?
  - Typical Performance (i.e. Clinical protocols)
  - Max Performance
- Produce non-trivial comparisons in a dose range typical for the organ (e.g. a non-trivial ROC curve)
  - The choice of imaging task should result in clinically relevant dose levels.
- Reproducible with commercially available phantoms in the field?

Study Design

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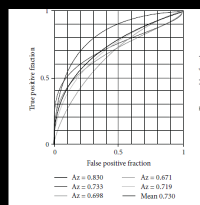
- ROC Study
  - Traditional method with a “confidence” rating scale.
  - More time consuming to run, requires greater observer expertise.
  - Many options: LROC, FROC, etc



Study Design

- Alternative Forced Choice (AFC)
  - 2-AFC experiments are the easiest / fastest to run.
  - 4-AFC experiments are not much more difficult, and provide better statistics for reasonable sample sizes (~100 images).

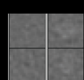


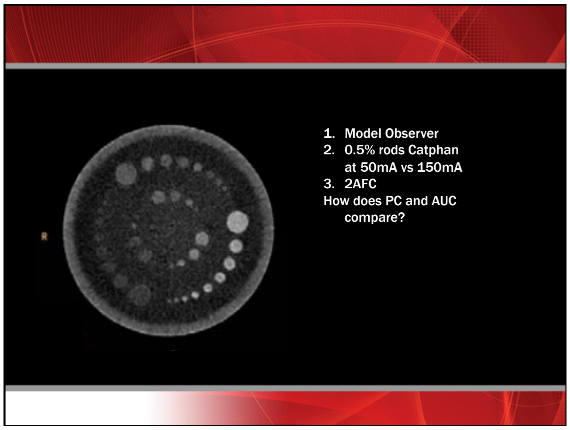
Figure of Merit

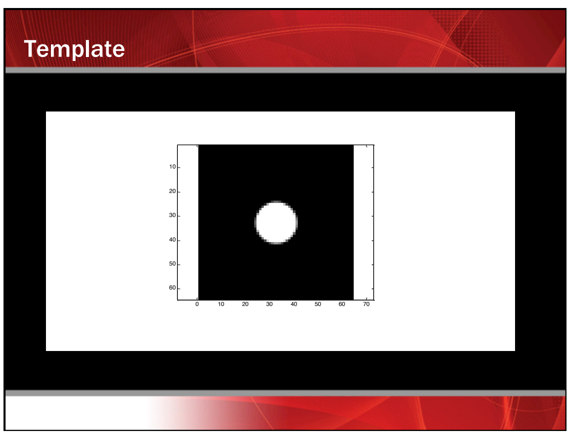
-AUC

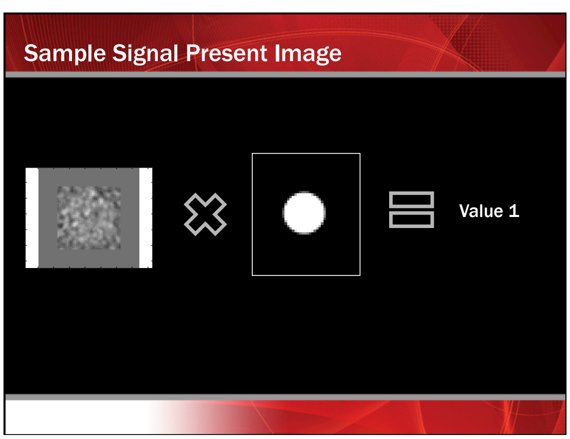
-d’

-SNR

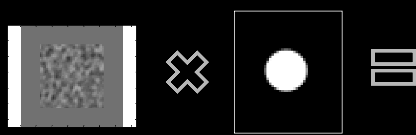
-Percent Correct


1. Model Observer
2. 0.5% rods Catphan at 50mA vs 150mA
3. 2AFC
How does PC and AUC compare?


Template

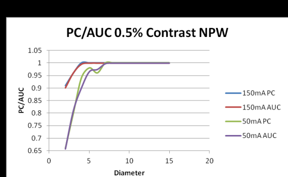

Sample Signal Present Image
Value 1

Sample Absent Present Image

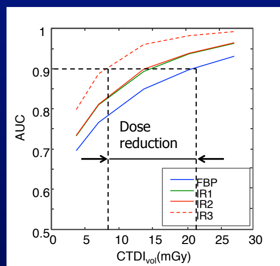


Who won?

- If Value1 (signal present) exceeds Value2 (signal absent), then a correct "hit" is recorded.
- If Value2 exceeds Value1 a "miss" is recorded.
- Process is repeated for a large number of signal present and signal absent images



AUC vs. dose



Courtesy of Ehsan Samei

- Medium patient
- 10 mm lesion diameter, 250HU lesion enhancement

Model observer qualifications

- Limited to specific tasks
- Requires generalization for optimizing application-generic systems
  - eg, CT, radiography
- Non-linear systems require prescribed evaluation conditions
  - eg, using contrast/noise relevant to the targeted task

Courtesy of Ehsan Samei

Conclusions

- Goal = Dose Reduction
- Iterative Reconstruction offers excellent potential dose reduction and good noise/resolution properties
  - Slow
  - "Unnatural" look and feel
  - Some loss of edge/detail
  - NON-LINEAR
- IQ Characterization
  - Traditional Metrics come up short
    - NPS at variety of dose levels and IR strengths
    - Contrast-dependent MTF
  - Detectability Studies