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CT Clinical Innovation Center

Image Quality Assessment using Model Observers:

Clinical Implementation and Practical Considerations

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Acknowledgement

- Lifeng Yu, PhD
- Chris Favazza, PhD
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- Chi Ma, PhD
- Yi Zhang, PhD

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  - R01 EB071095
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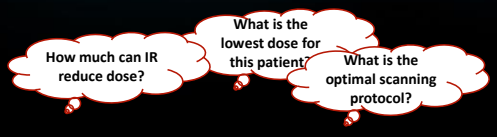
Common Clinical Questions



Presumption
Images are 'Good Enough' to accurately answer clinical questions

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Image Quality Assessment

- Standard Physical Metrics
  - Contrast
  - Noise
  - CNR
  - MTF
  - NPS …
- Limitations for assessing non-linear algorithms
  - IR or non-linear denoising algorithms
  - Contrast Dependent MTF

Fessler and Rogers, TMI, 1996
Li et al, Med. Phys. 2014
Chen et al, Med. Phys. 2014
Yu et al, Med. Phys. 2015

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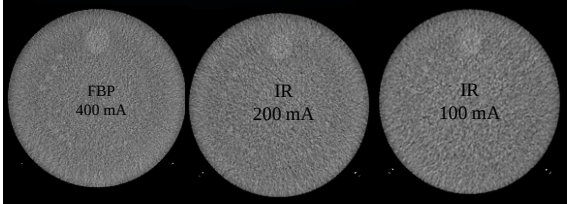
Limitation of CNR

All three have similar noise: 12-13 HU



McCollough et al. "Degradation of CT Low-Contrast Spatial Resolution Due to the Use of Iterative Reconstruction and Reduced Dose Levels" *Radiology* (2015)

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Task-based Image Quality Assessment

- Human observer
  - Labor intensive and costly
  - Intra- and Inter- observer variability
- Model observer
  - Composite image quality metric
  - Relevant to the clinical imaging task
  - Simulates human observer

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Clinical Implementation of Model Observer

- Diagnostic Task
- Image generation: signal and background
  - Phantom and ROI selections.
- Model observer type
- Test statistics and Figure of merit
- Compare to human observer performance

* Eckstein et al, *A practical Guide to Model observers for visual detection in synthetic and natural noise images*. Handbook of Medical Imaging (Ch 10), 2000
* Barrett and Myers, *Foundations of Image Science*, 2004
* Vaishnav et al, *Objective assessment of image quality and dose reduction in CT iterative reconstruction*, Med. Phys. 2014
* Verdun et al, *Image quality in CT: From physical measurements to model observers*, Phys. Med. 2015

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Diagnostic Task

- Detection
  - Low contrast detection
  - Low contrast Detection and Localization
- Classification
  - Shape,
  - Texture
- Estimation
  - Quantification, e.g. lung nodule volume

Yu et al. Med. Phys. 2013
Leng et al. Med. Phys. 2013
Richard et al, Med. Phys. 2008
Zhang et al,. PMB, 2014
Chen et al,. SPIE 2014

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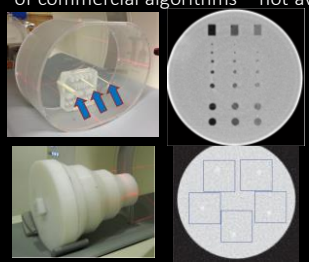
Image Generation: Phantoms

- Physical phantoms are used in most studies
- Needed to recon on scanners to assess the non-linearity of commercial algorithms – not available for simulations.



Ma et al, JMI, 2016
Yu et al, Med. Phys. 2013
Yu et al, RSNA 2014
Wilson et al. Med. Phys. 2013
Popescu et al, Med. Phys. 2013

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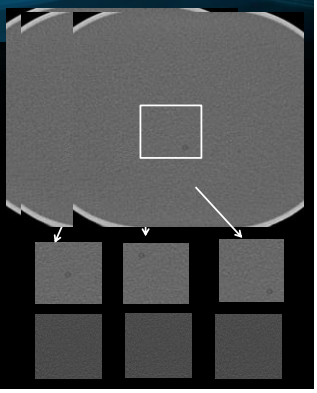
Image Generation



- Scan with relevant protocols and dose levels
- Reconstructed with algorithms to be investigated

Leng et al. Med. Phys. 2013

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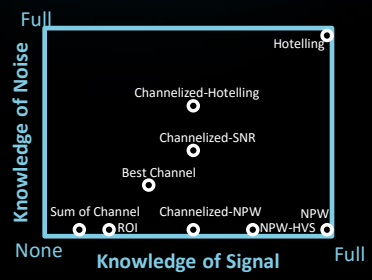
Observer Model– Types of Models



* Eckstein et al, *A practical Guide to Model observers for visual detection in synthetic and natural noise images*. Handbook of Medical Imaging (Ch 10), 2000

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NPWEi

- Non-prewhitening matched filter model observer with eye filter and internal noise (NPWEi)*

$$d'^{2}_{NPWEi} = \frac{\left[\int_0^{2\pi} d\theta \int_0^{Nyquist} |W(u)|^2 MTF^2(u) E^2(u) u du\right]^2}{\int_0^{2\pi} d\theta \int_0^{Nyquist} (|W(u)|^2 MTF^2(u) E^4(u) NPS(u) + N) u du}$$

*Burgess et al., JOSA A Opt Image Sci Vis **14**, 2420-2442 (1997).

- Multiple recent studies in CT

Boedeker and McNitt-Gray, PMB, 2007
Richard et al, Med. Phys. 2008
Gang et al, Med. Phys. 2011
Richard et al, Med. Phys. 2012
Chen et al, Med. Phys. 2014
Li et al, Med. Phys. 2015
.....

Image quality
NPS
MTF: contrast dependent in IR

Observer
- Internal noise (N_i)
- Eye filter (E)

Object
- Task function (W)

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Channelized Hotelling Observer (CHO)

- A linear model observer with a scalar response

$$\lambda = \omega_{CHO}^{t} g_c = \sum_{n=1}^{N} \omega_n g_{cn}$$

$$\omega_{CHO} = S_c^{-1}[\bar{g}_{sc} - \bar{g}_{bc}]$$

Barrett, HH, J Yao, JP Rolland and KJ Myers (1993). Proc Natl Acad Sci U S A 90(21): 9758-65.

- To mimic the existence of spatial frequency selective channels in human visual processing.
- Multiple recent studies in CT

Wunderlich and Noo, PMB, 2008
Yu et al, Med. Phys. 2013
Leng et al, Med. Phys. 2013
Popescu and Myers, Med. Phys. 2013
Zhang et al, PMB, 2014
Ma et al, JMI, 2016
.....

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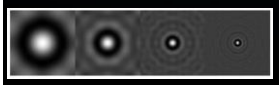
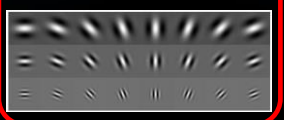
Model Development: Channel Type

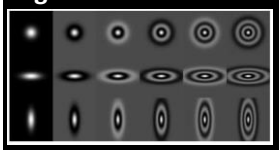
Band Pass:



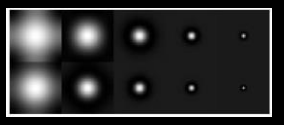
Gabor



Laguerre-Gauss:



Diff. of Gaussians



Abby and Barrett, 1995 Eckstein et al, 1998

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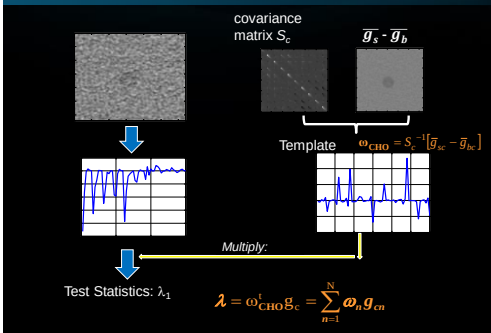
Test Statistics Calculation



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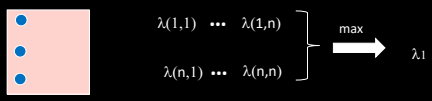
Localization Task

- Apply template at each possible location
- Final test statistics: highest value at all possible locations



Whitaker *et al*, Opt. Exp. 2008;
Gifford *et al*, TMI, 2005
Leng *et al*, Med. Phys. 2013
Popescu and Myers, Med. Phys. 2013

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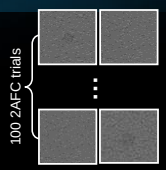
Figure of Merit

- Percent correct (Pc)
  - For MAFC tasks
- Area under ROC curve
- Detectability index



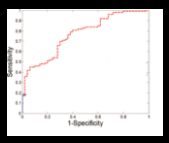


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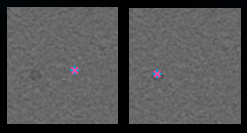
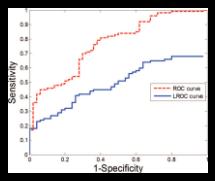
Figure of Merit

- Area under LROC curve
  - True positive:
    - ROC: Correct detection
    - LROC: Correct detection & Correct localization
- FROC, EFROC





Popescu, Med. Phys. 2007
Wunderlich et al, IEEE TMI, 2012

Leng et al, Med. Phys. 2013

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Validation with Human Observer

- Model observer usually outperforms human observer
- Internal noise added to final test variable.

$$\lambda_{final} = \lambda + \varepsilon$$

$$\varepsilon = a * \sigma(\lambda_{bg}) * rand(-1,1)$$

- Internal noise added to channel responses.

$$\lambda = \sum_{n=1}^{N} w_n (\boldsymbol{g}_{cn} + \varepsilon_n)$$

Zhang et al, Evaluation of internal noise methods for Hotelling observer models, Med. Phys. 2007

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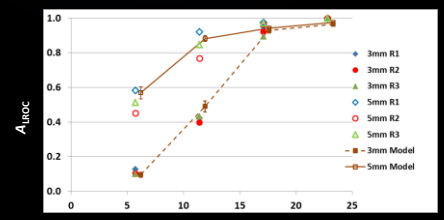
Validation with Human Observer

Human Observer vs Model Observer



Pearson Correlation Coefficients: 0.994 for 3mm and 5 mm lesions

Leng et al, RSNA. 2013

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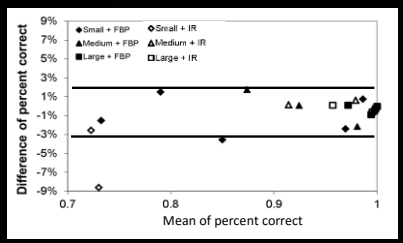
Validation with Human Observer

- Bland-Altman plot comparing human and model observer performance



* Yu *et al*, Med. Phys. 2013

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Practical Considerations

- Fourier domain vs spatial domain
- Number of images
- 2D/3D observers
- Homogeneous and heterogeneous background

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Fourier Domain vs Spatial Domain

- Fourier-domain implementations (e.g. NPWEi)
  - Fewer scans required
  - Assumption required: locally linear and shift-invariant
- Spatial-domain implementations (e.g. CHO)
  - No linear-shift-invariant assumption
  - Larger number of images required to get a good estimation of image statistics
- Studies comparing Fourier-domain and spatial domain implementations.

Solomon et al, SPIE 2015
Chen et al, SPIE 2016

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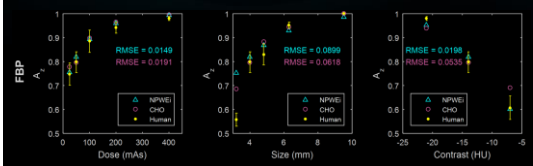
Fourier (NPWEi) vs spatial (CHO)



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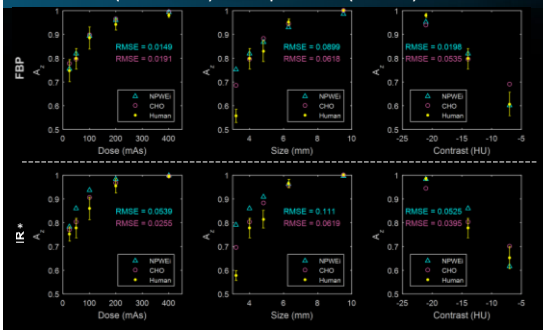
Fourier (NPWEi) vs spatial (CHO)



Chen et al, SPIE 2016

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Practical Considerations

- Fourier domain vs spatial domain
- Number of images/scans
- Single-slice vs Multi-slice observers
- Homogeneous and heterogeneous background

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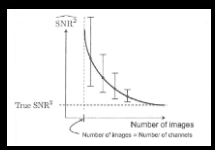
Number of Samples

- Theoretical work on the estimation of bias and variance.
  - The goodness of correlations depends on the number of repeated scans used in the training and testing.
- Clinical CT
  - Labor and machine usage limitations.

Important to quantify the statistics associated with limited but reasonable number of repeated scans.



Conceptual plot from Barrett and Myers, P 972; Resubstitution method

Gallas et al. SPIE 2003.
Barrett and Myers 2004,
Wunderlich et al. TMI 2009,

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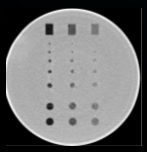
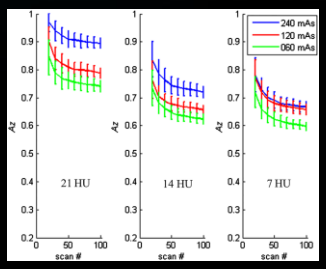
Area under ROC curve (Az) vs Scan

- Az calculated using subsets of 10 to 100 scans.





Ma et al,. J Med Imaging . 2016

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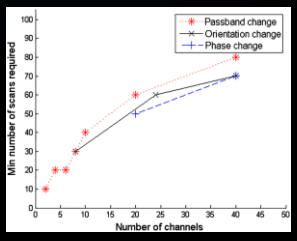
Dependence on Number of Channels



Ma et al,. J Med Imaging . 2016

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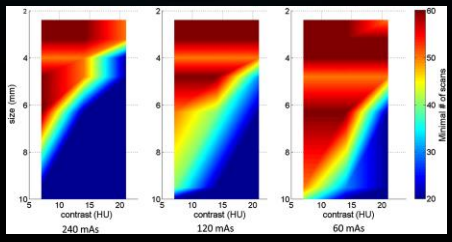
Dependence on Object Size and Contrast



- Minimum number of repeated scans increased when the radiation dose level decreased, object size and contrast level decreased (more challenging tasks)

Ma et al,. J Med Imaging . 2016

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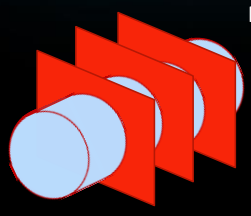
Repeat scan reduction: Increase images/scan



N = number of scans

1 Slice: N = 100

2 Slices: N = 50

3 Slices: N = 33

:

:

n Slices: N = 100/n

Favazza et al, AAPM, 2015

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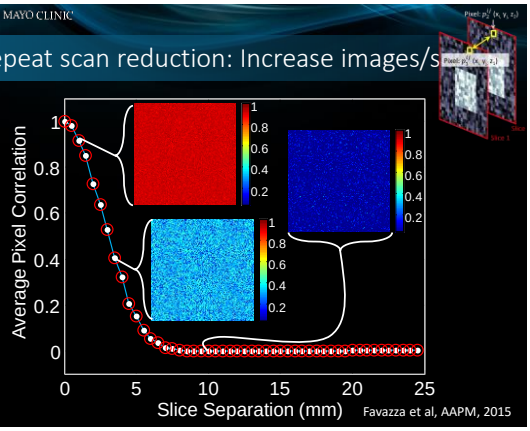
Repeat scan reduction: Increase images/s



Favazza et al, AAPM, 2015

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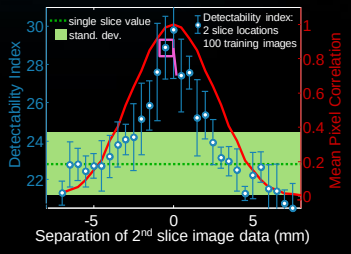
Repeat scan reduction: Increase images/scan



Favazza et al, AAPM, 2015

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Number of Scans Needed

- Example
  - 6 mm cylindrical object (small)
  - 10 HU contrast (low contrast)
  - 60 mAs (low dose)
  - 20 channels

→ 60 images

- Each Scan
  - 6 Image @ Every 1cm (6 cm)

→ 10 scans

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Practical Considerations

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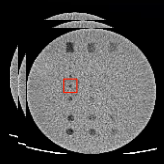
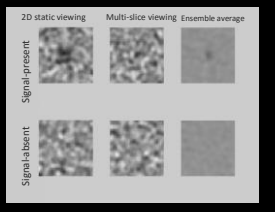
Multi-slice CHO

- Multi-slice CHO to incorporate multi-slice viewing model during clinical reading





Yu et al, RSNA 2015

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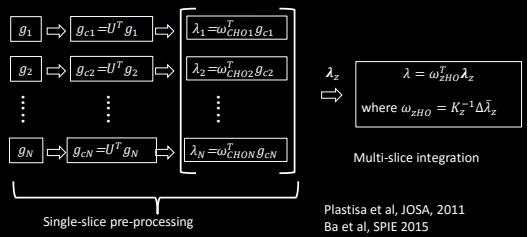
Model Observers: MS_CHO

- Single-slice preprocessing
- Integrate decision variables from multiple slices



$\boldsymbol{\lambda}_z$

$\lambda = \omega_{zHO}^T \boldsymbol{\lambda}_z$

where $\omega_{zHO} = K_z^{-1}\Delta\bar{\lambda}_z$

Multi-slice integration

Plastisa et al, JOSA, 2011
Ba et al, SPIE 2015
Yu et al, RSNA 2015
Ba et al, JMI 2016

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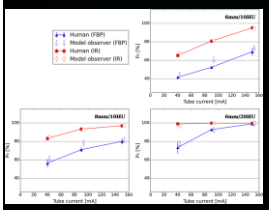
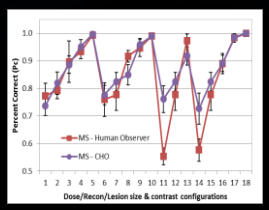
Correlation between Human and MS_CHO



Ba et al, SPIE 2015
Ba et al, JMI 2016



Yu et al, RSNA 2015

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3D Printing Phantoms

Solomon et al, SPIE, 2014

Leng et al, JMI, 2016

Michael. A. Miller and G. Hutchins, IEEE NSSC 2007, M26-28
Yoo, T., Hamilton, T. et al, IEEE ISBMI, 2011, 1770-1773

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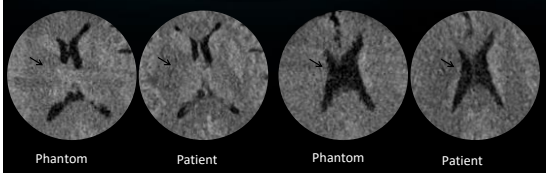
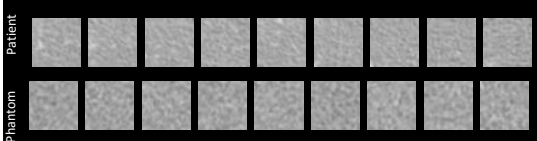
3D Printing Phantoms





Leng et al, Construction of realistic phantoms from patient images and a commercial three-dimensional printer. Journal of Medical Imaging 3(3), 033501 (2016)

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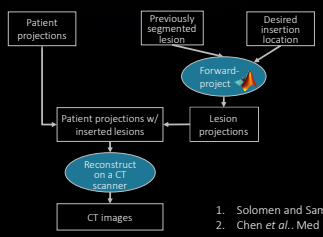
Lesion Insertion

- Image based method[1]
- Projection based method[2]



1. Solomen and Samei. PMB. 2014 7;59(21):6637-57
2. Chen *et al*.. Med Phys. **42**, 7034 (2015).

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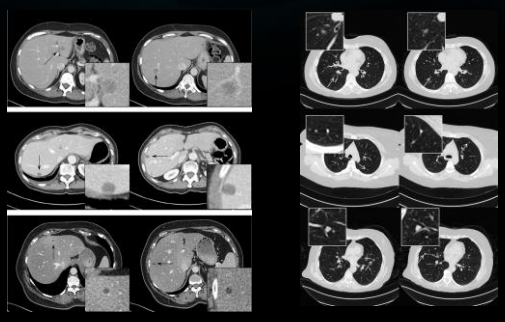
Projection-domain lesion insertion



Chen *et al.*, Acad. Radiol. 2016

Ma *et al.*, SPIE. 2016

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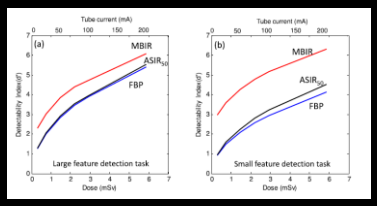
Sample Applications

- Samei and Richard, *Assessment of the dose reduction potential of a model-based iterative reconstruction algorithm using a task-based performance metrology,* Med. Phys. 2015



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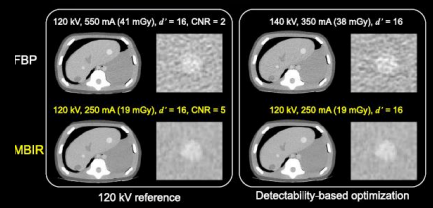
Sample Applications

- Li et al, *Statistical model based iterative reconstruction in clinical CT systems. Part III. Task-based kV/mAs optimization for radiation dose reduction*. Med. Phys. 2015



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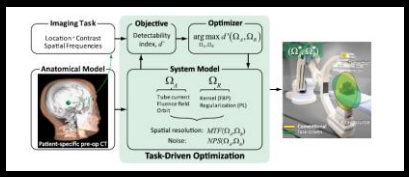
Sample Applications

- Gang et al, *Task-driven image acquisition and reconstruction in cone-beam CT*. PMB, 2015



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Standardize Protocols in Large Practice

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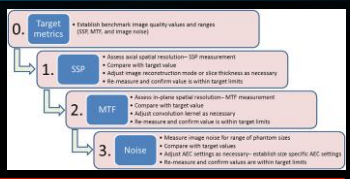
Standardize Protocols in Large Practice

Stage 1: FBP
Standardize Protocols with physical IQ metrics



Stage 2: IR
Standardize Protocols with task-based image quality metrics
- Default setting resulted in 60-75% dose reduction
- How does IR perform? What is the appropriate amount of dose reduction?

Favazza et al, A cross-platform survey of CT image quality and dose from routine abdomen protocols and a method to systematically standardize image quality, PMB, 2015

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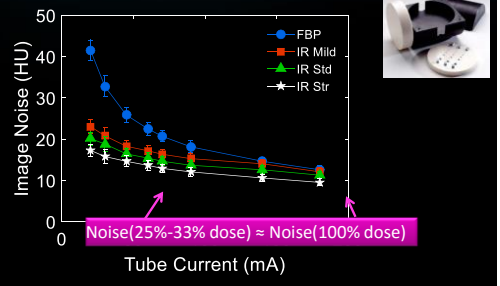
Image noise vs Tube Current



C Favazza et al, Low-Contrast Detectability Vs. Dose for CT Images Reconstructed Using FBP and IR: Assessment with a Model Observer. SU-G-206-10 (Sunday, July 31, 2016)

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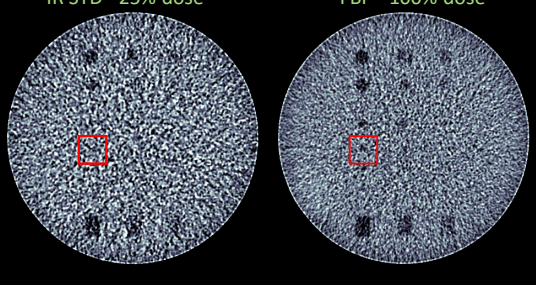
AUC vs Tube Current

Object 4: 25 HU Contrast– 4.8 mm diameter

IR STD– 25% dose FBP– 100% dose



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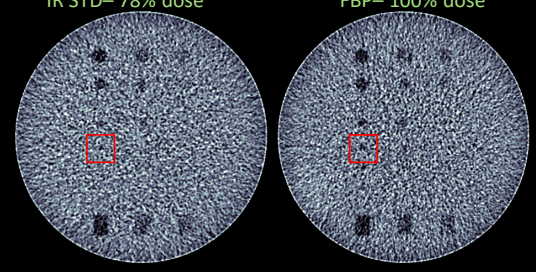
AUC vs Tube Current

Object 4: 25 HU Contrast– 4.8 mm diameter

IR STD– 78% dose FBP– 100% dose



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Summary

- Multiple studies showed correlation and validation with human observers
- Methods have been investigated to make model observer studies more practical
- Various applications have used model observers for task-based image quality assessment, especially in iterative reconstruction
- Studies with textured background, 3D (peudo-3D) observers are actively investigated

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http://mayoresearch.mayo.edu/ctcic