ICTP 2019

Role of image quality in dose management via/through DRL

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Duke
Clinical Imaging Physics Group

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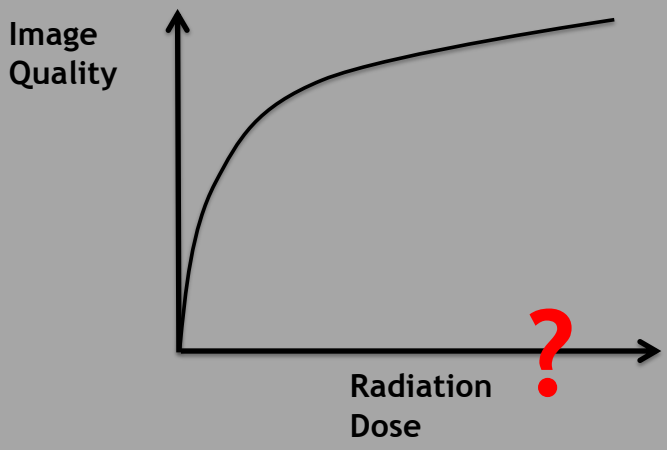
The challenge of dose optimization: the monotonic relationship between quality and dose!



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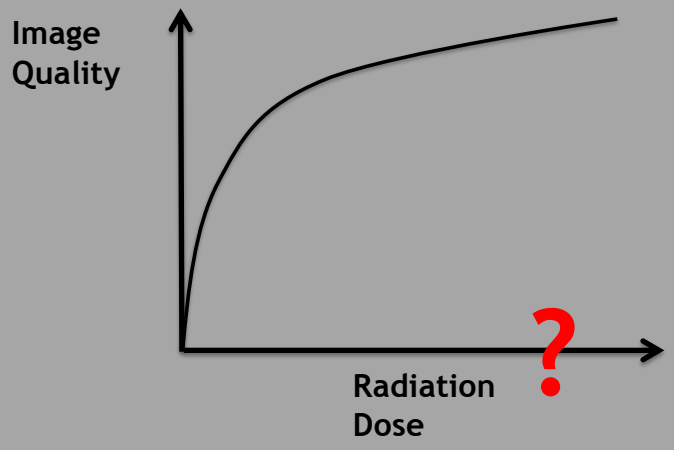

relevance
robust
smart
relatable
practical

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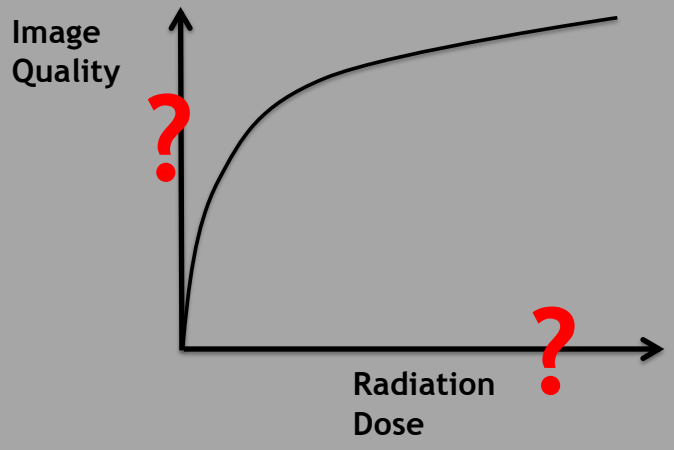
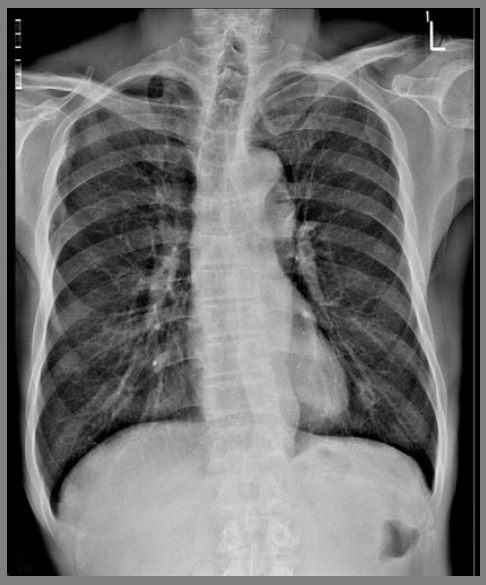


relevant
robust
smart
relatable
practical

Image quality



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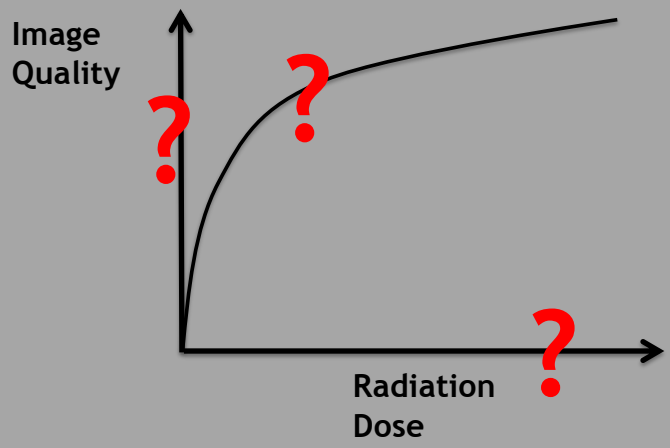
The challenge of dose optimization: the monotonic relationship between quality and dose!



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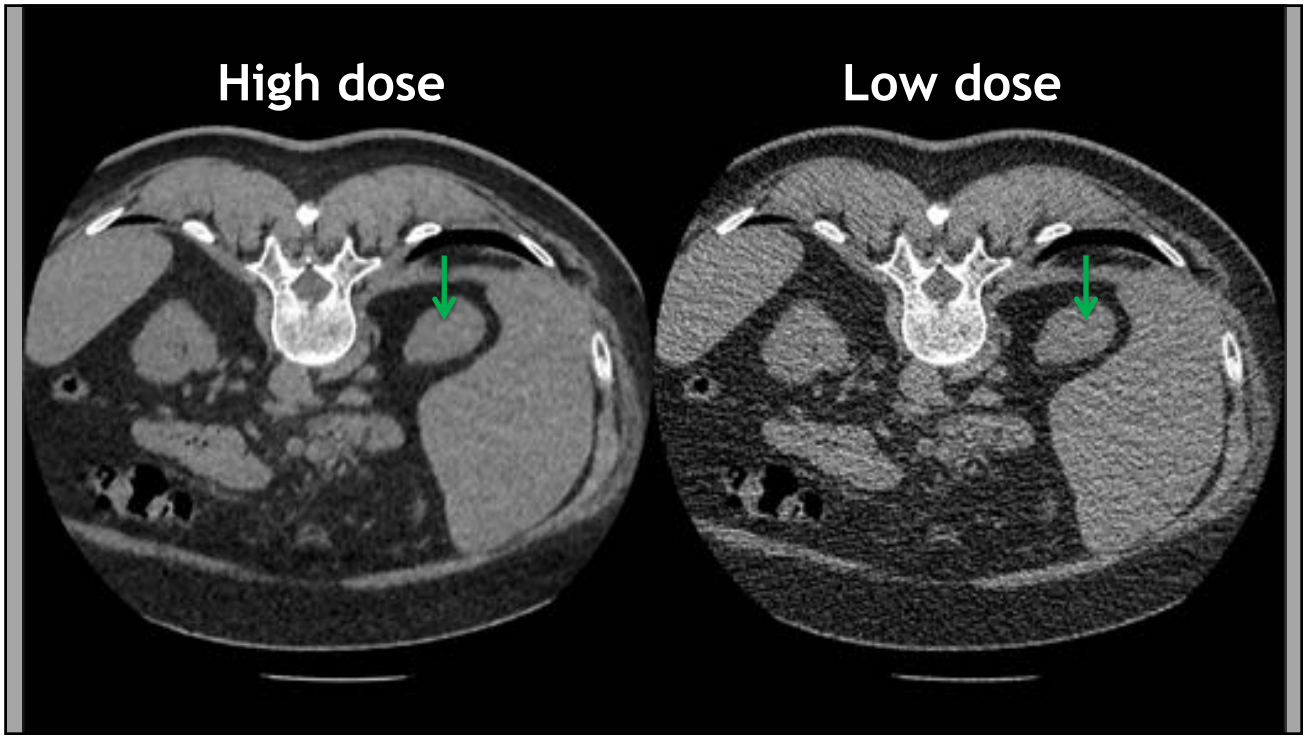
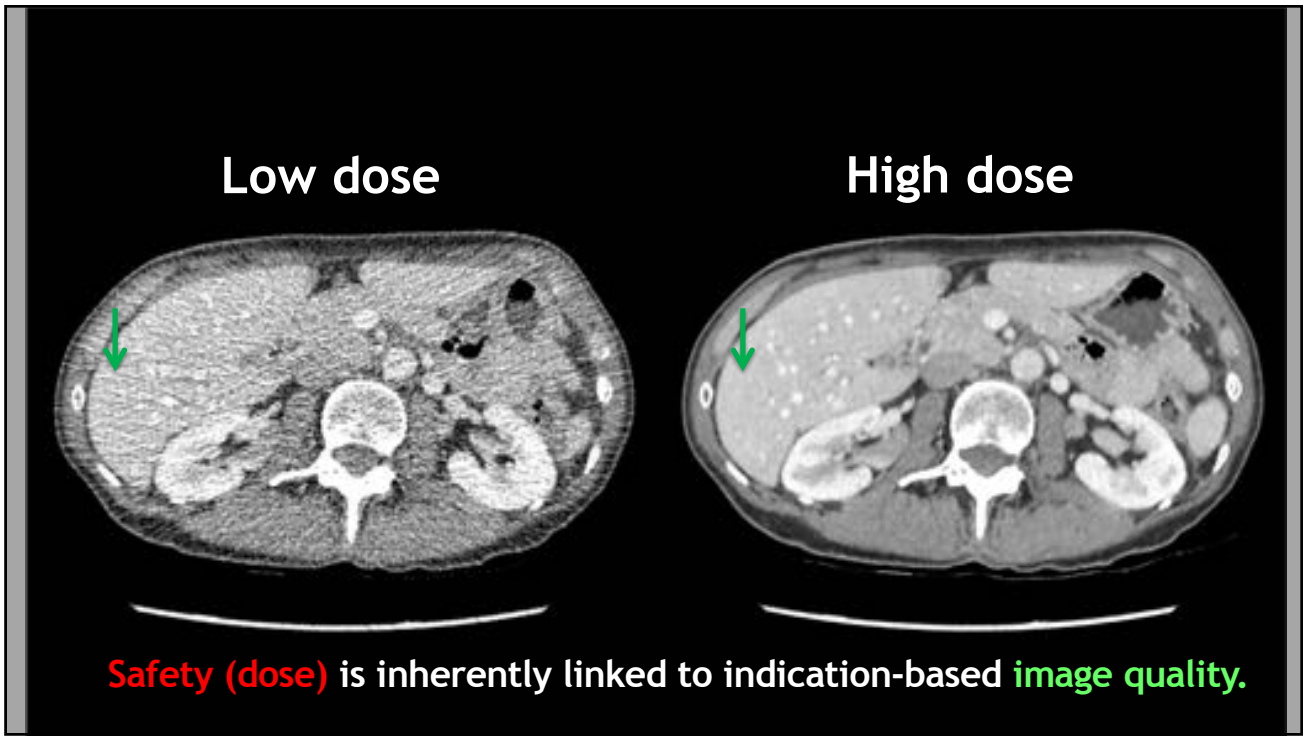
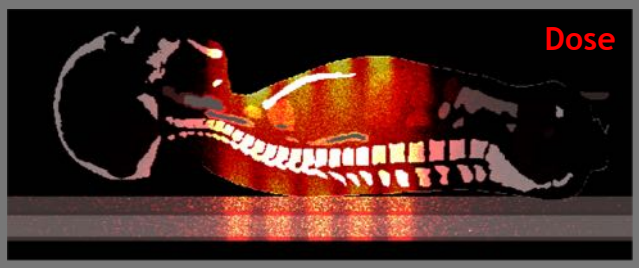
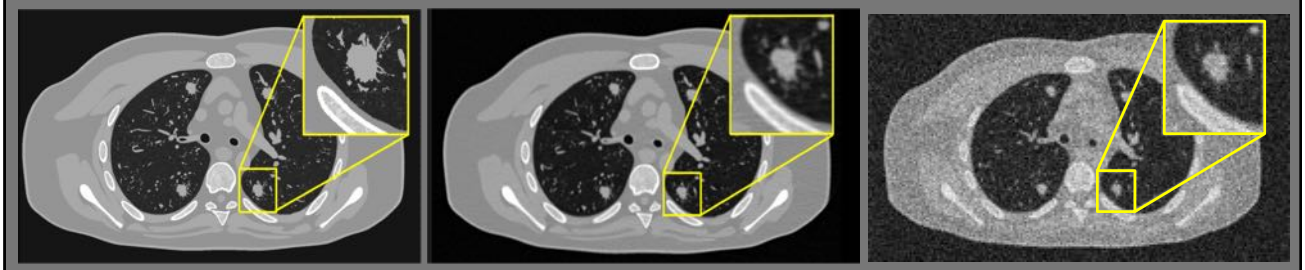




Factors that govern quality and safety of medical imaging





An Ideal Image | (low) Resolution | (high) Noise

What is image quality?

- Aesthetic: Subjective perception of quality
- Task-generic: The realism of the image to represent the reality of the object being imaged
- Task-specific: The ability of the image to render the information pertinent to the task at hand

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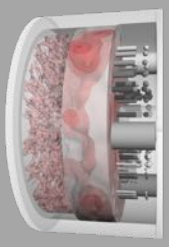
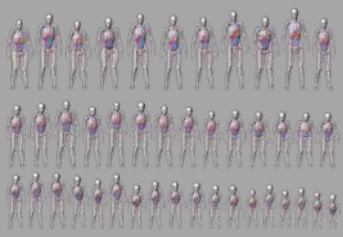
What is the right quality metric?

Goal

Intrinsic Specs | Phantom Measures | Anthro. Models | Animal Models | Virtual Clinical Trials | Case studies | Clinical Trials | Clinical Quality



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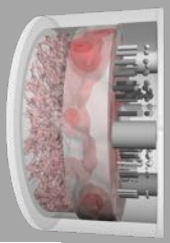

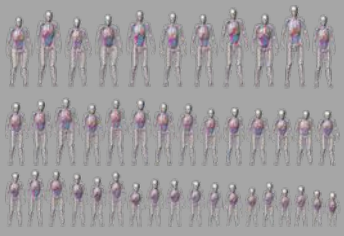

Simple
Relevance inferred

Complex
Relevant

What are the right metrics?

1. Relevant: As much as possible, patient-/indication-centric (not modality or machine)
2. Robust: To ensure reliability and applicability (quantitative not subjective)
3. Smart: Maintained balance between robustness and relevance
4. Relatability: Surrogates relatable to clinical task
5. Practical: Economic to measure

Balance robustness and relevance

ARARA!

- To extent possible, we need to move toward relevance while keeping robustness in check
- As Relevant as Reasonably Achievable

Image quality metrics

Task Generic	Task Specific
1. Contrast	1. Threshold Contrast
2. Resolution	2. Detectability, d’
3. Noise	3. Estimability, e’
4. SNR, CNR, SdNR	4. d’ *in vivo*
5. DQE, eDQE, eDE	
6. TG IQ *in vivo*	

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1. Contrast

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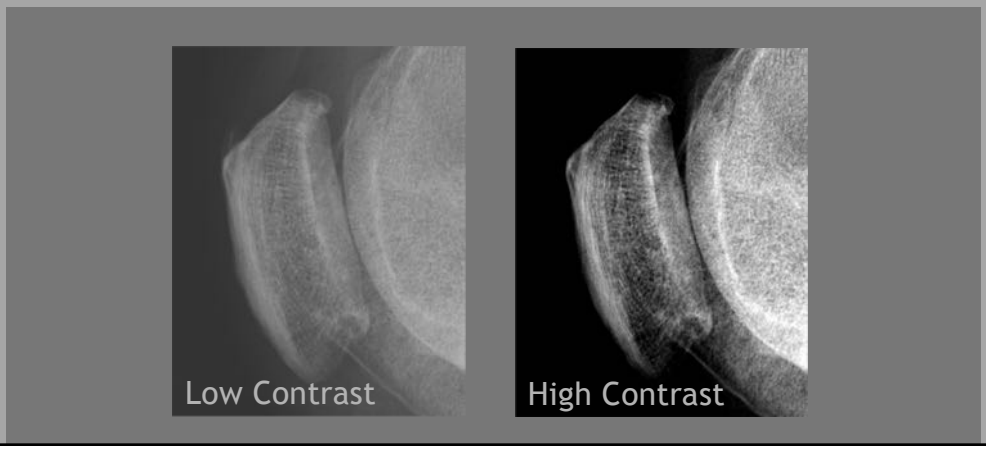
Contrast

- Fractional difference in the signal or brightness between two regions of an image



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Contrast

- Best characterized by fractional signal difference (ie, subject contrast) or fractional brightness difference (ie, display contrast) of a target in comparison to background:

$$C = \frac{I_{target} - I_{Background}}{I_{Background}} = \log\left(\frac{I_{target}}{I_{Background}}\right)$$

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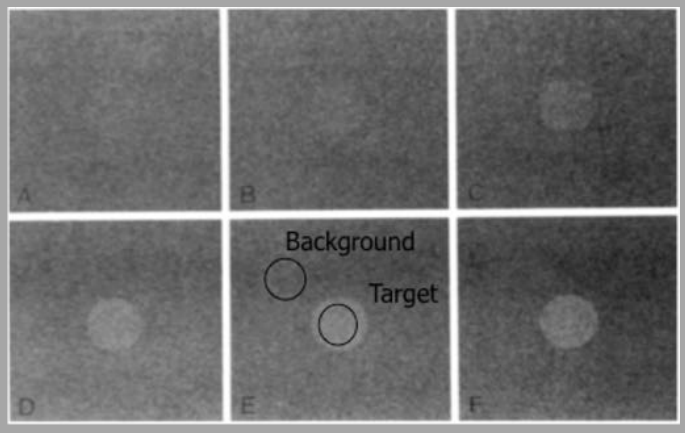
Contrast

$$C = \frac{I_{target} - I_{Background}}{I_{Background}} = \log\left(\frac{I_{target}}{I_{Background}}\right)$$



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2. Resolution

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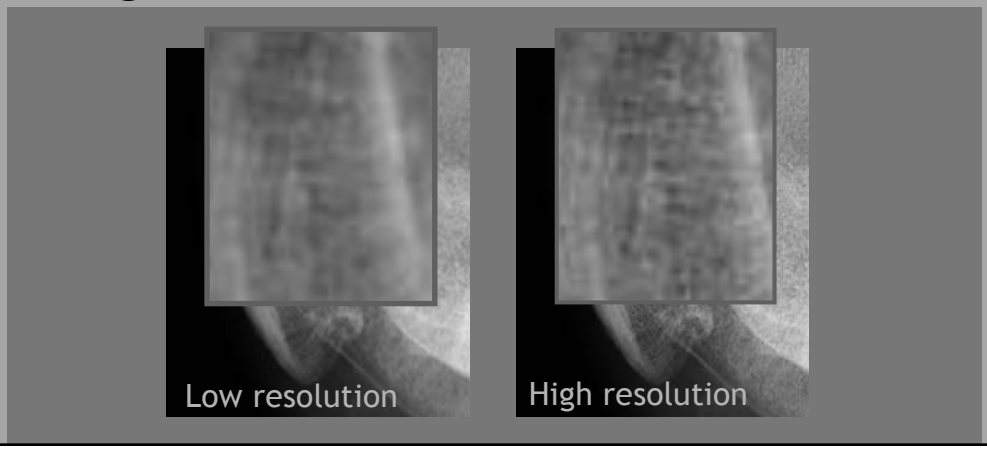
Resolution

- Ability to resolve distinct features of an image from each other



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Resolution

- Best characterized by the modulation transfer function (MTF):
  - **The efficiency of an imaging system in reproducing subject contrast at various spatial frequencies**

$$MTF(f) = F\{LSF(x)\}$$

LSF = response of a system to a perfect line

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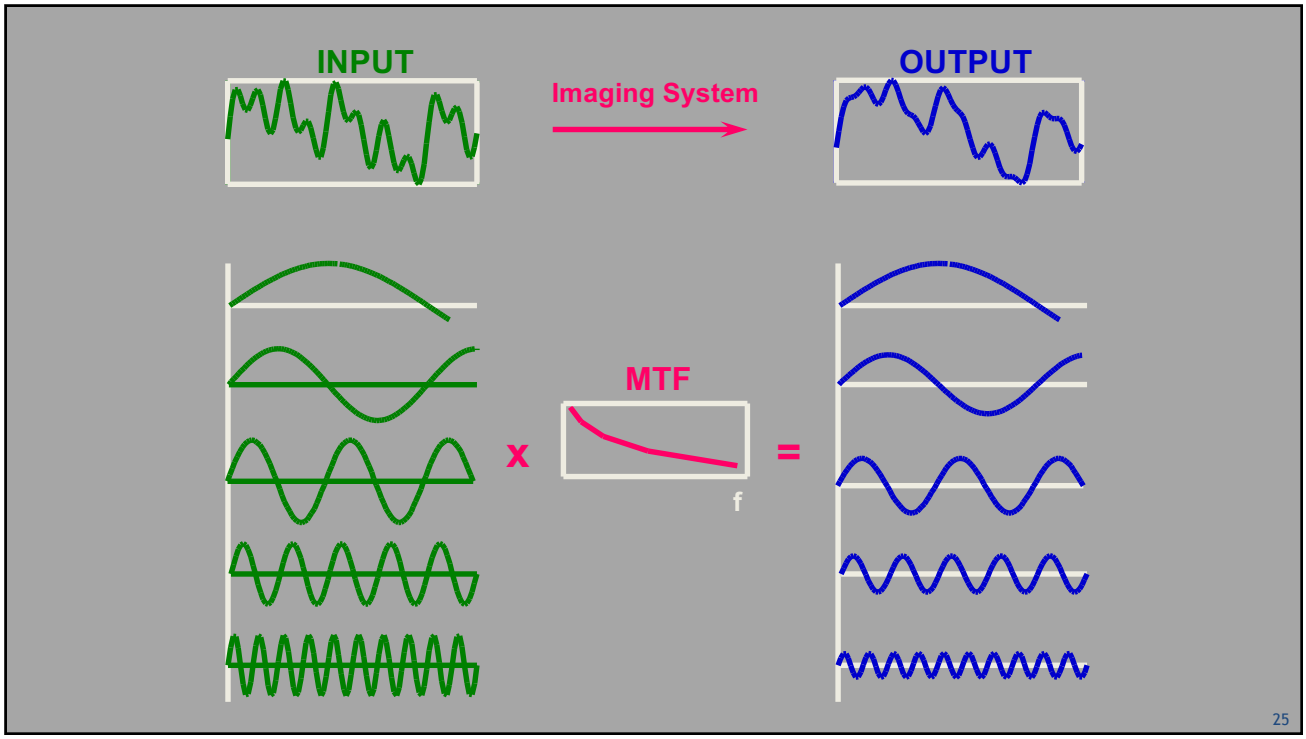
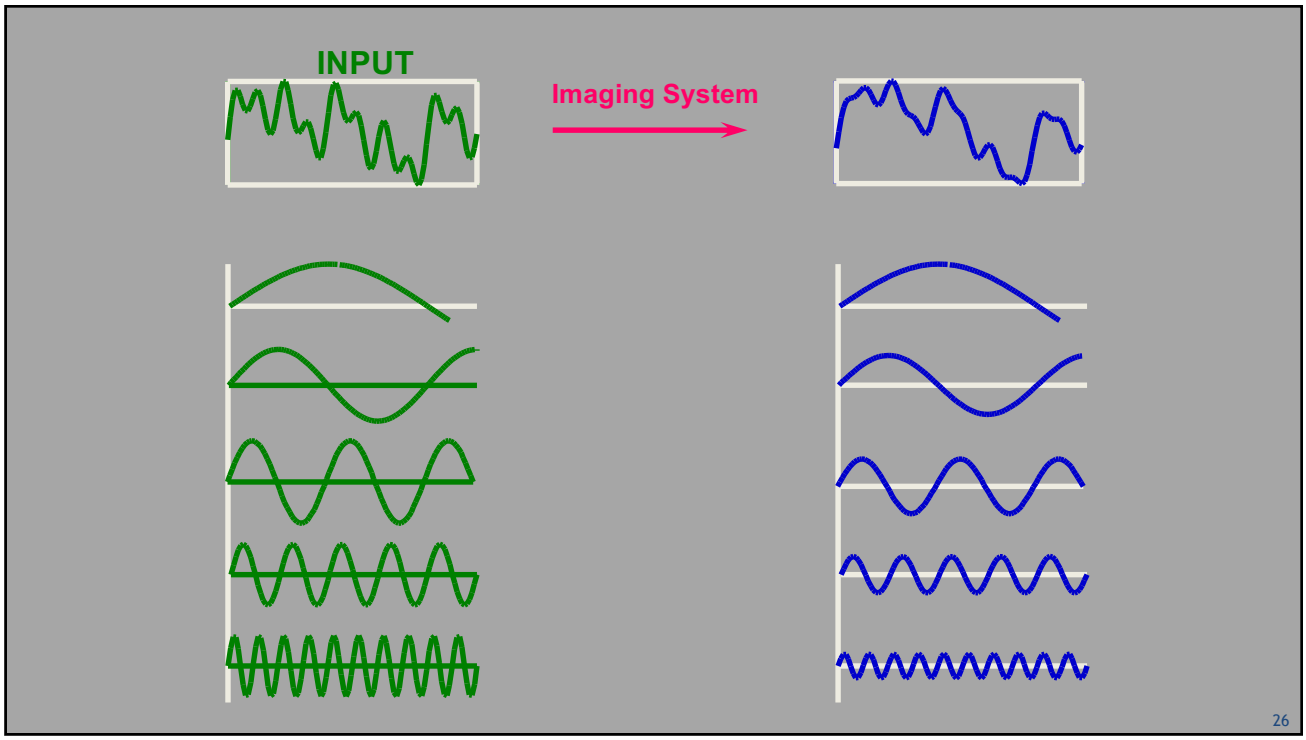
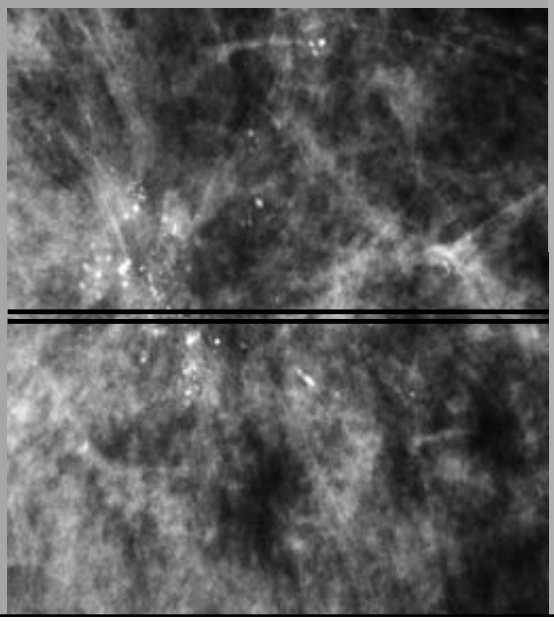
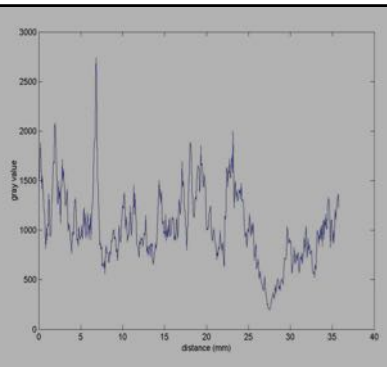
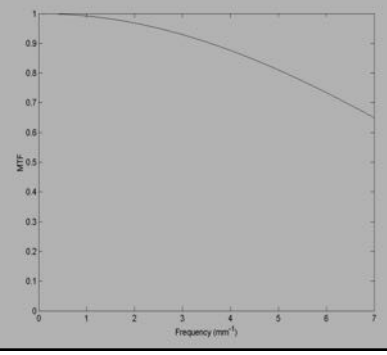




High MTF







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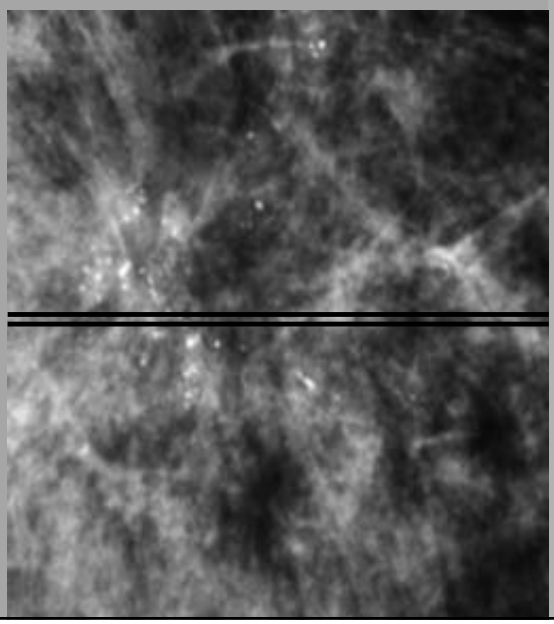
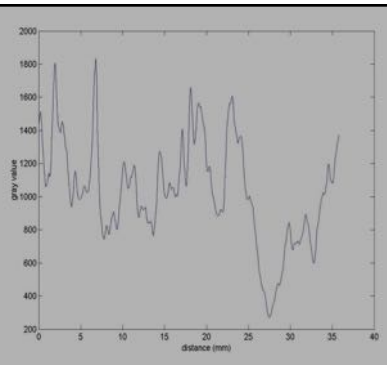
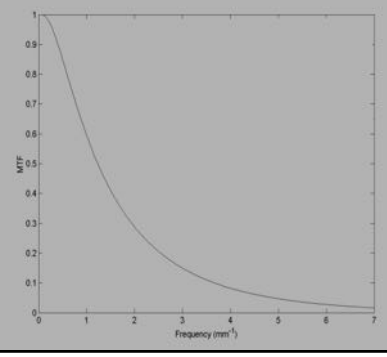
Low MTF







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MTF and limiting resolution

- Limiting resolution ~ Frequency at 10% MTF
- Mammography 5-10 lp/mm
- Radiography 2-5 lp/mm
- Fluoroscopy 1-2 lp/mm
- CT 0.5-1 lp/mm

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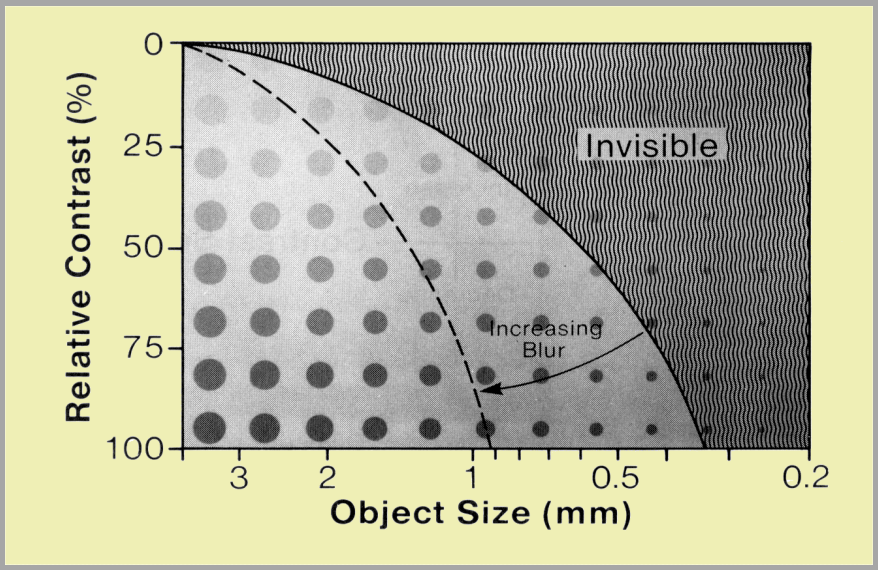
Effect of added blur



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3. Noise

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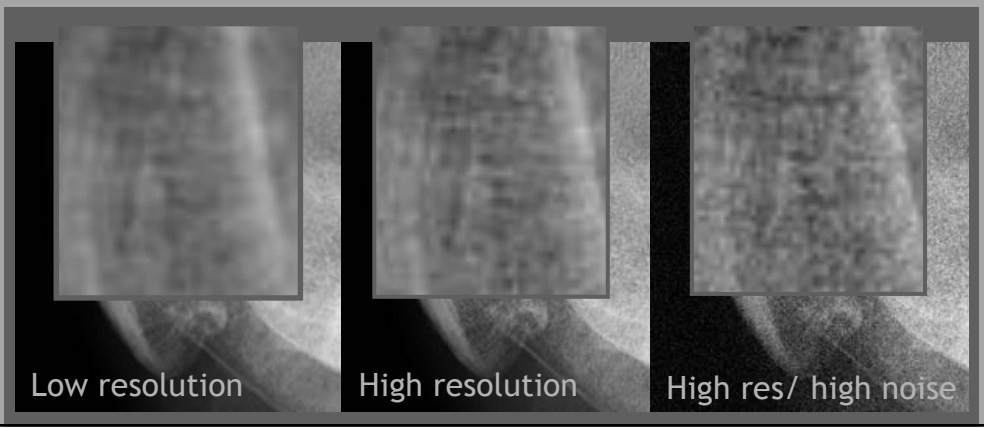
Noise

- Unwanted signals that interfere with interpretation



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An underexposed image is “too noisy”

Underexposure by 4x

Correct exposure

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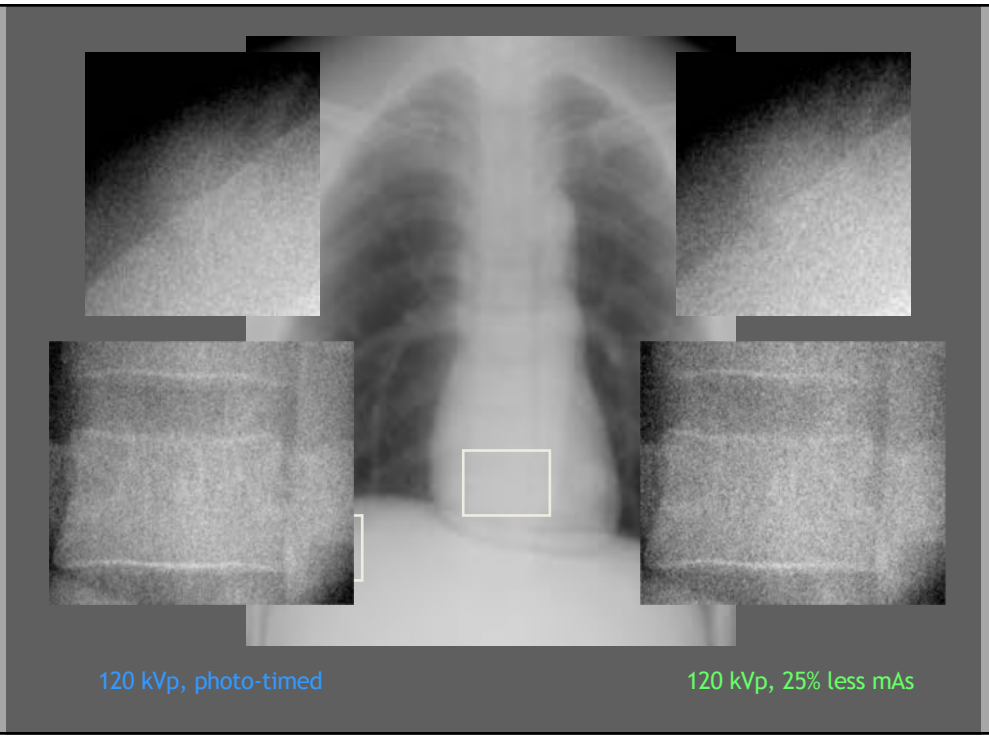

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Noise

- Best characterized by the noise power spectrum (NPS):
  - **The variance of noise in an image in terms of the spatial frequencies**

$$ACF(\chi,\eta) = \iint f(x,y) f(x+\chi, y+\eta) dxdy$$

$$NPS(f) = F\{ACF(x)\}$$

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Noise

- NPS

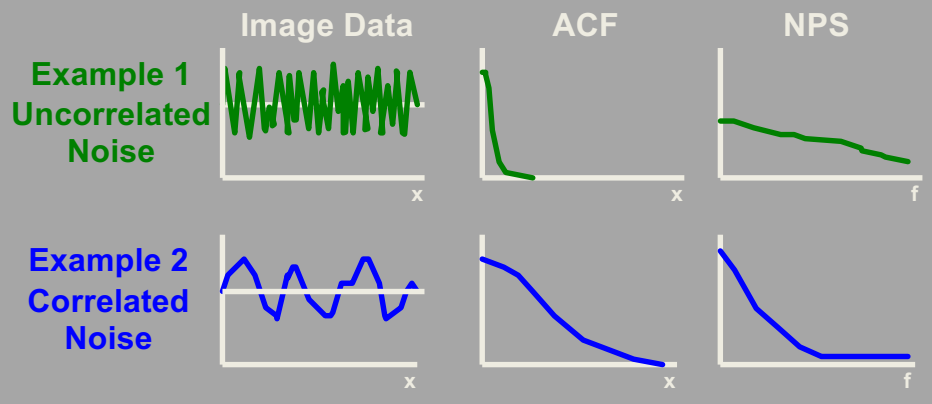

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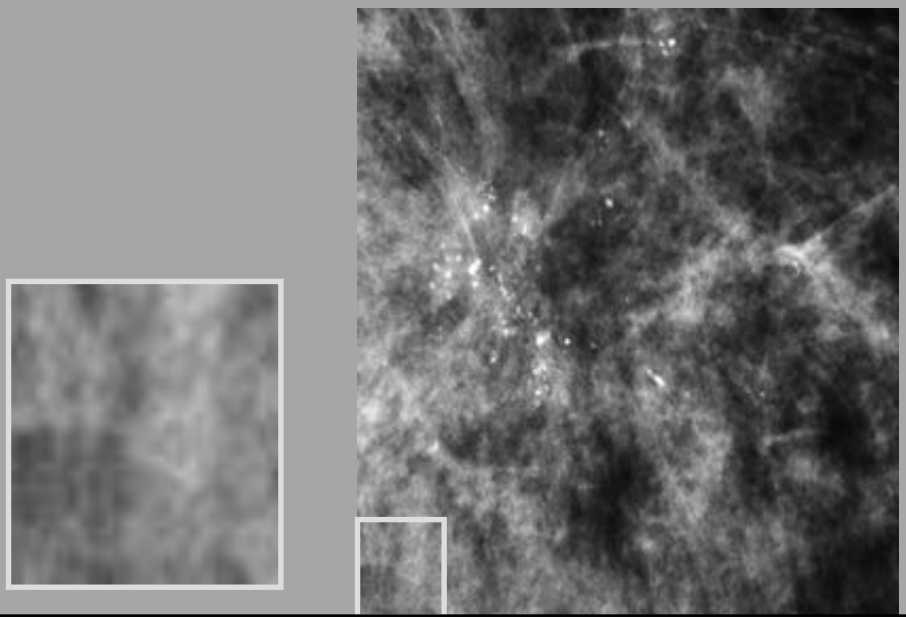
Image without noise



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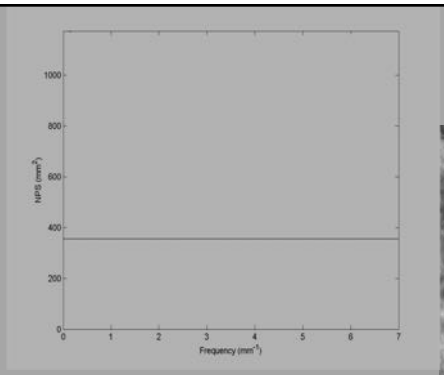
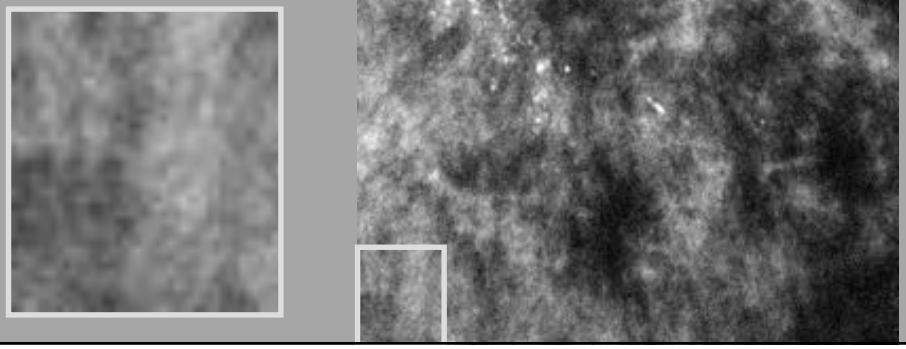
Uncorrelated noise





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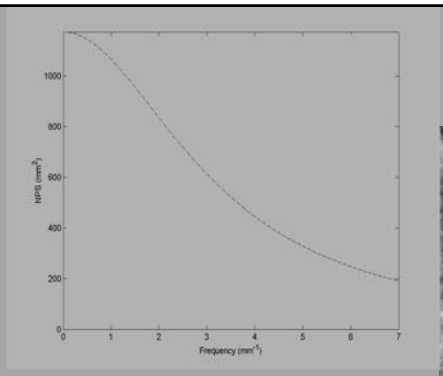
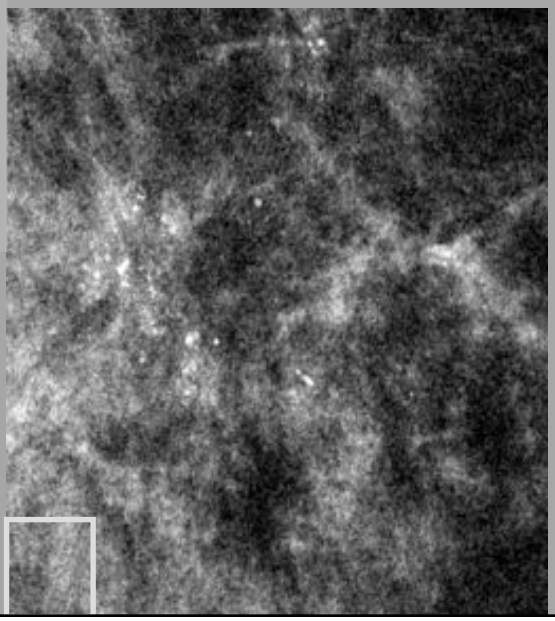
Correlated noise





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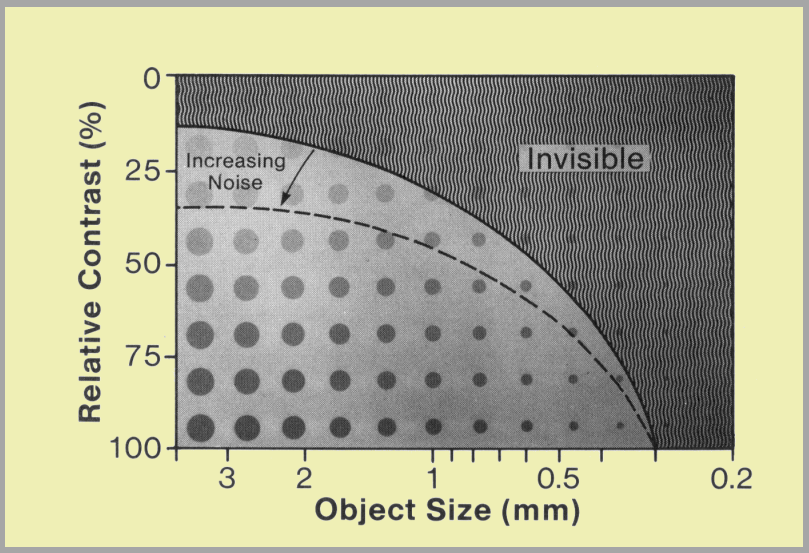
Effect of added noise



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4. SNR, CNR, SdNR

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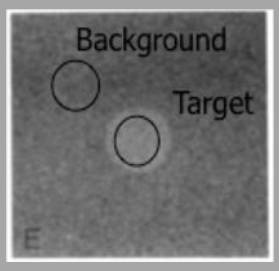
SNR

- Signal to noise ratio



$$SNR = \frac{I_{target}}{\sigma_{Background}}$$

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CNR and SdNR

$$CNR = \frac{\frac{I_{target} - I_{background}}{I_{background}}}{\frac{\sigma_{background}}{I_{background}}} = \frac{I_{target} - I_{background}}{\sigma_{background}} = SdNR$$

- In Linear systems:
  - N in CNR is relative noise
  - N in SdNR is noise
- In log systems, Sd in C and N in relative noise

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SNR(f)

- Noise Equivalent Quanta (NEQ) and frequency-dependent SNR
- Affected by the collective effects of resolution and noise and associated contributing factors

$$NEQ(f) = SNR^2_{actual}(f) = \frac{MTF^2(f)}{NPS(f)}$$

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CNR(f)

$$CNR^2(f) = \frac{C^2(f)MTF^2(f)}{NPS(f)} = C^2(f)SNR^2(f)$$

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5. DQE, eDQE, eDE

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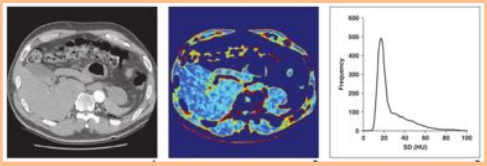
6. *In vivo* task-generic metrics

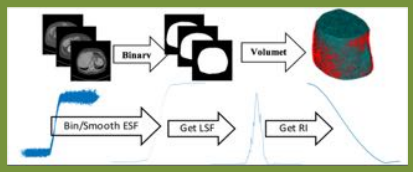
in vivo image quality

Noise



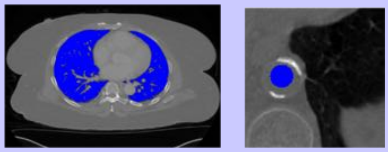
Christianson et al., AJR, 2014

Resolution



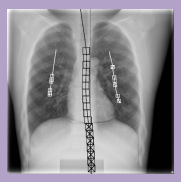
Sanders et al., Medical Physics, 2016

Organ-based HU



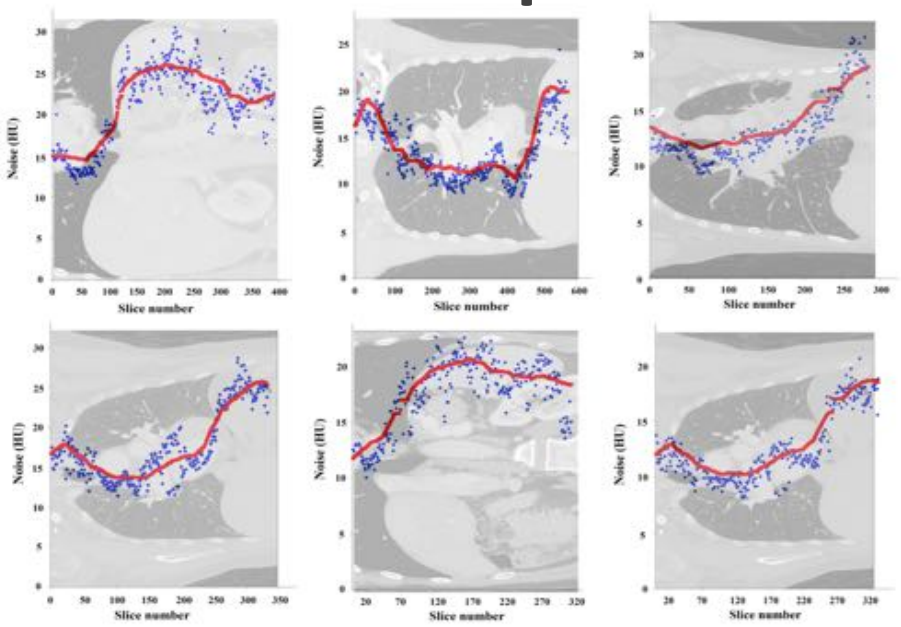
Abadi et al., Medical Physics, 2017

Perceptual Quality



Samei et al., Medical Physics, 2014

in vivo noise prediction



in vivo NPS

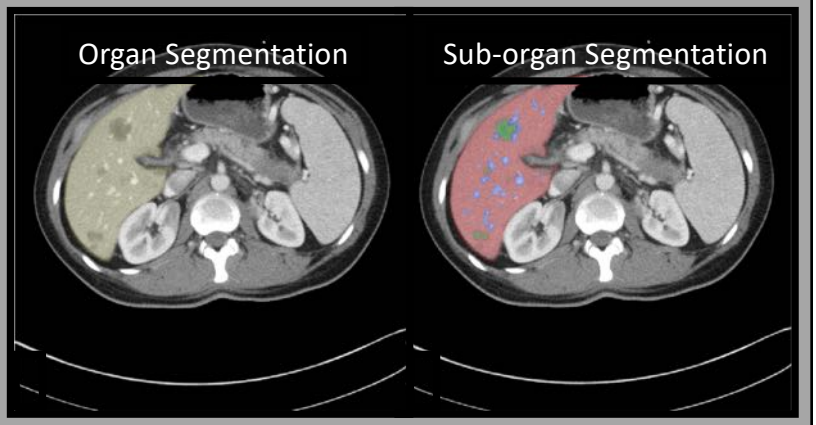
Segment the liver (Fu 2018)

Identify liver parenchyma

- Avoid vasculature, fatty deposits

Sub-segment parenchyma and de-trend image data

- Use local polynomial fits for segment



Goal

~~1. Anatomical structure~~

~~2. Large scale trends~~

Wiener-Khinchin Theorem:

$NPS(\mathbf{u}) = FT\{R_N(\mathbf{x}_1;\mathbf{x}_2)\} = FT\{E[N(\mathbf{x}_1).N(\mathbf{x}_2)]\}$

Estimate NPS from non-square patches in the liver

in vivo resolution

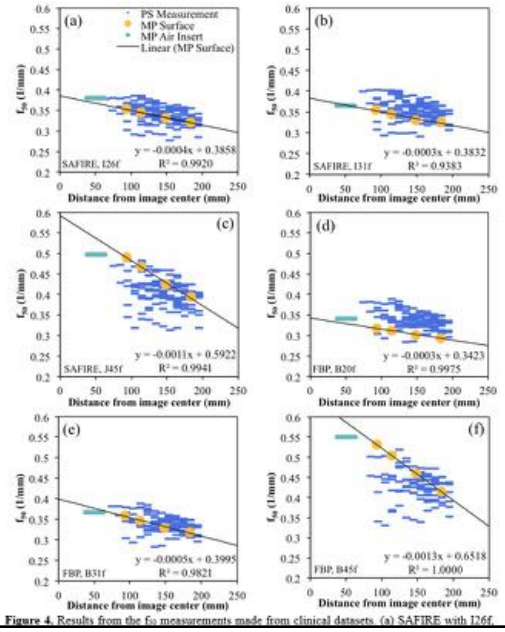
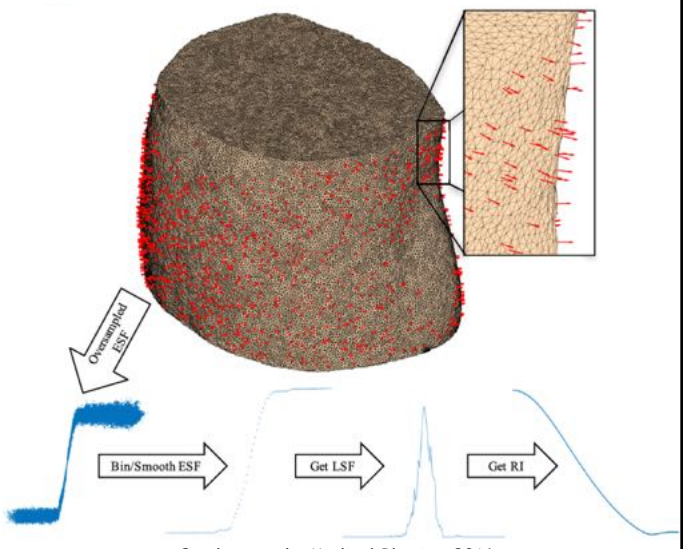
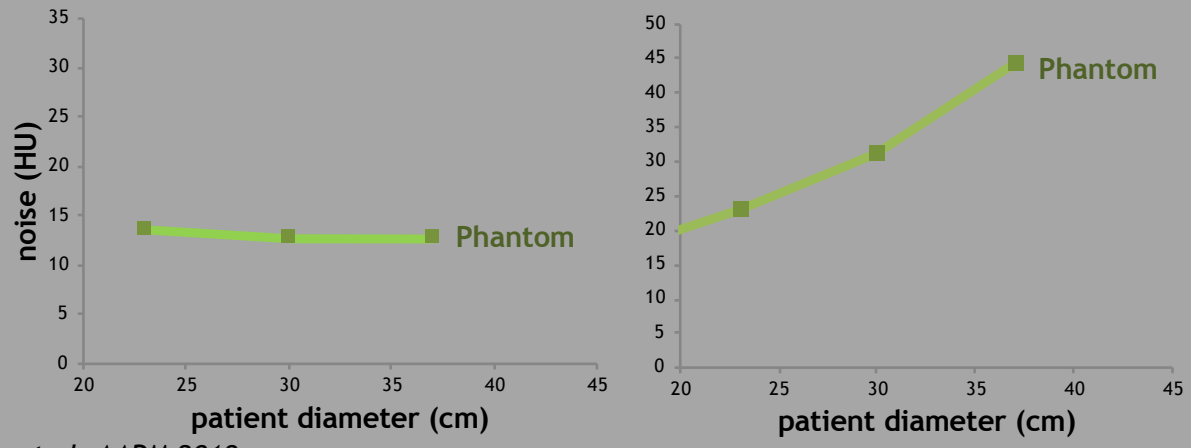


Figure 4. Results from the f_{50} measurements made from clinical datasets. (a) SAFIRE with I26f.

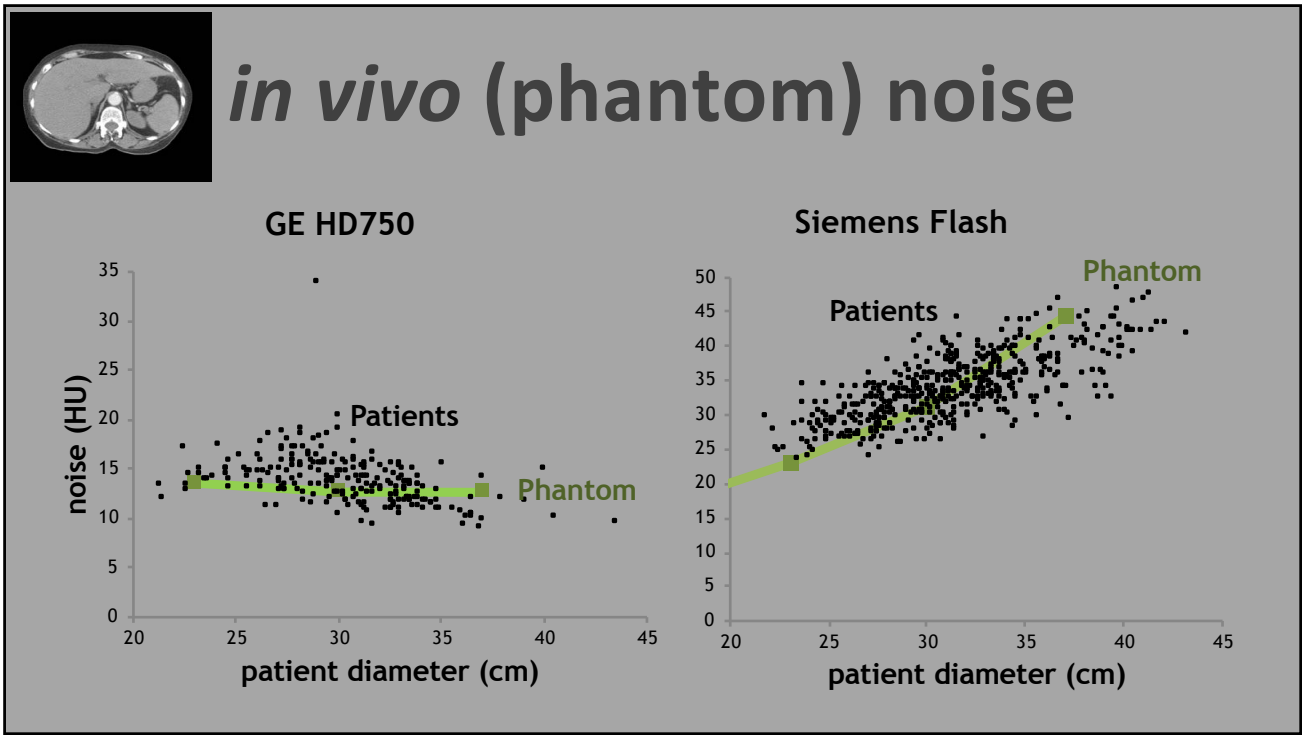


Sanders et al., Medical Physics, 2016

in vitro (phantom) noise



Ria et al, AAPM 2018



Task-based metrics

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Task-based indicators

- Direct measures of task performance
- Direct measures of task-like performance
- Derivatives of task performance from generic indicators

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Direct measures of task performance

- Most reliable
- $ and time-consuming
- Not translatable to other tasks or conditions

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Direct measures of task-like performance

- Often based on simplistic tasks
- Most $ and time requirement
- Not translatable to other tasks or conditions

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Derivatives of task performance from generic indicators

- Most practical method to assess task performance
- Subject to linearity constraints of generic indicators
- Observer models

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Threshold Contrast

- Fundamental ability to be able to see things in images
- Rose model:

$$C_{threshold} = \frac{k}{\sqrt{AN}} = \frac{k}{\sqrt{A}} \frac{1}{SNR}$$

C = threshold contrast
k = constant (3-5)
A = area of signal
N = number of photons
SNR = signal-to-noise ratio

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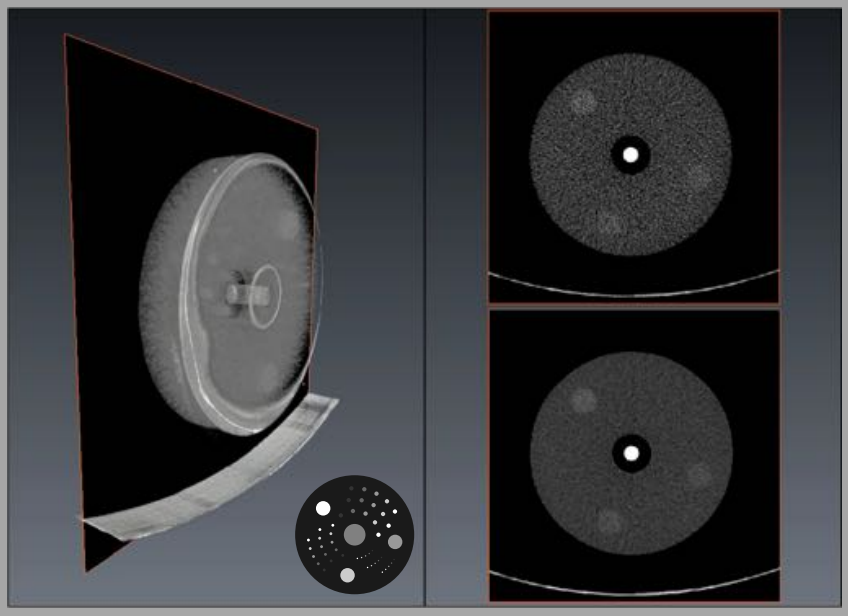
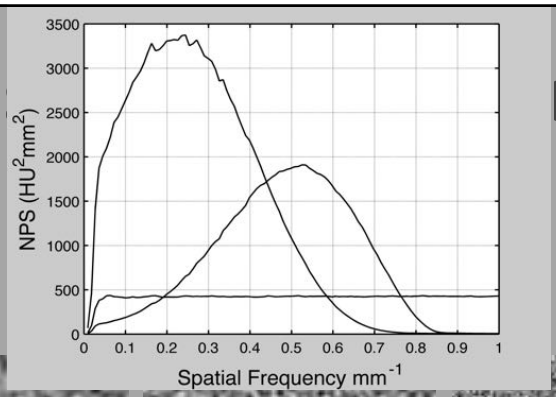
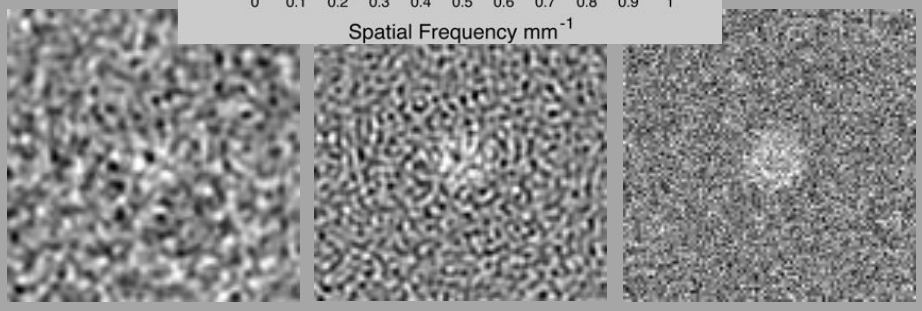
CT images of the low-contrast phantom

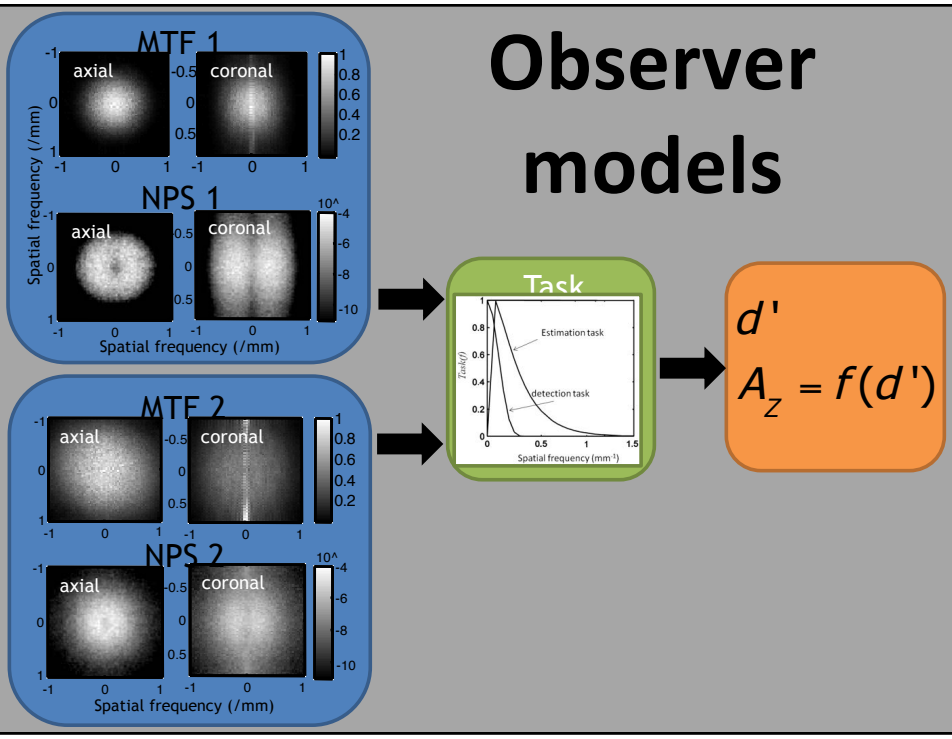


Noi rum





Observer models



Observer models

- Mathematical descriptions of how human visual system processes medical images for an interpretive task

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Measuring image quality

Factors that affect task performance

1. Contrast
2. Lesion size
3. Lesion shape
4. Lesion edge profile

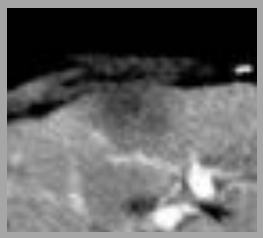
Feature of interest

5. Resolution
6. Viewing distance
7. Display

Image details

8. Noise magnitude
9. Noise texture
10. Operator noise

Distractors



Observer models

Resolution and contrast transfer × Attributes of image feature of interest

Image noise magnitude and texture

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

Richard, and E. Samei, Quantitative breast tomosynthesis: from detectability to estimability. Med Phys, 37(12), 6157-65 (2010).
Chen et al., Relevance of MTF and NPS in quantitative CT: towards developing a predictable model of quantitative... SPIE2012

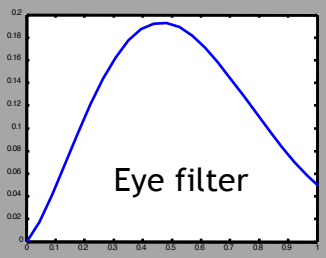
Observer models

Fisher-Hotelling observer (FH)

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

Non-prewhitening observer (NPW)

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

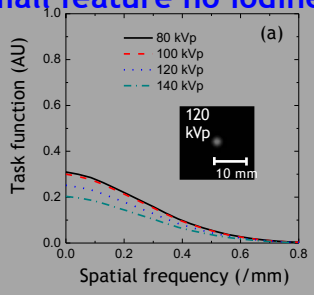


NPW observer with eye filter (NPWE)

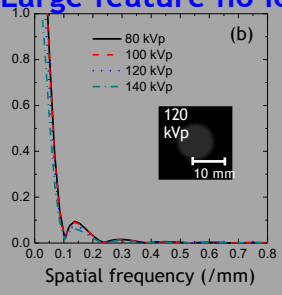
$$\left(d'_{NPWE}\right)^2 = \frac{\left[\iint MTF^2(u,v)W_{Task}^2(u,v)E^2(u,v)dudv\right]^2}{\iint MTF^2(u,v)W_{Task}^2(u,v)NPS(u,v)E^4(u,v) + MTF^2(u,v)W_{Task}^2(u,v)N_i\,dudv}$$

Task functions

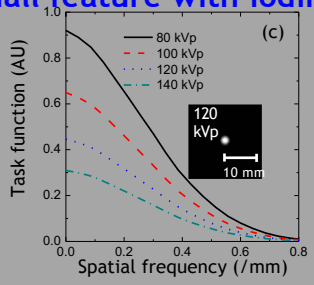
Small feature no iodine



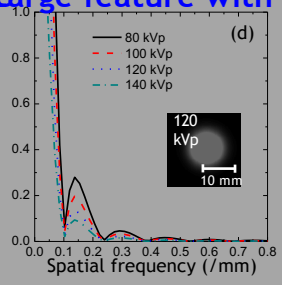
Large feature no iodine



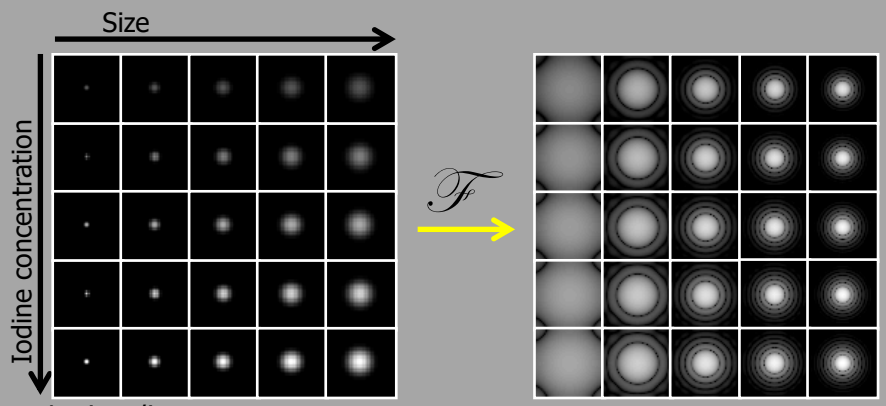
Small feature with iodine



Large feature with iodine



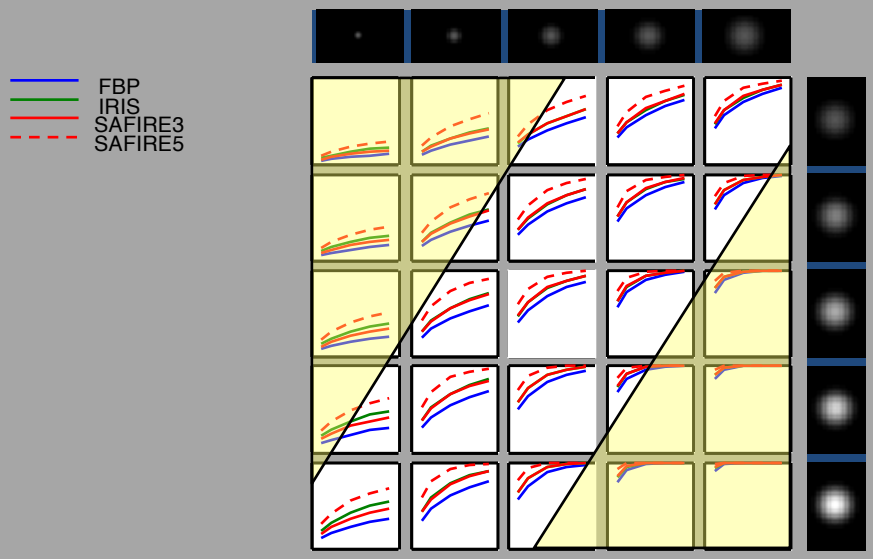
Task function (W_{task})



Lesion diameter =
{5, 7.5, 10, 12.5, 15 mm}
Lesion contrast =
{100, 150, 200, 250, 300 HU}

Task function (W_{task})

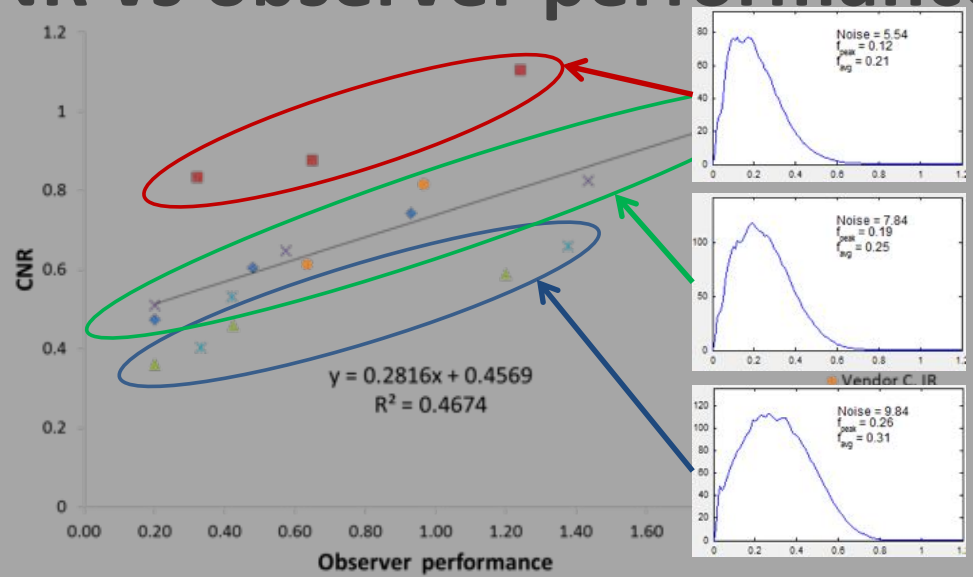
AUC vs. dose



$A_z = f(d')$

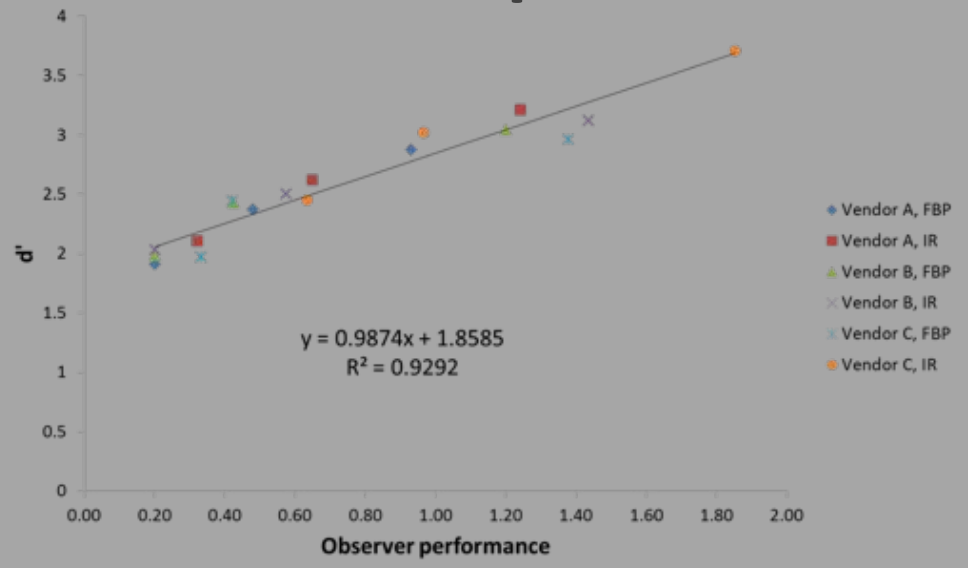
Chen, SPIE, 2013

CNR vs observer performance



Christianson et al, Radiology, 2015

d' vs observer performance

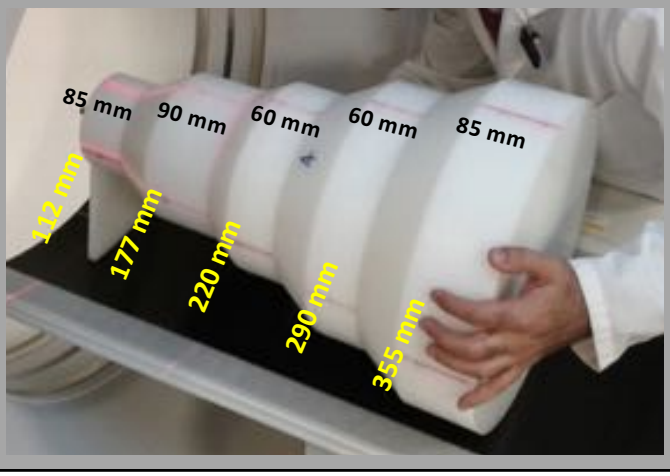


Christianson et al, Radiology, 2015

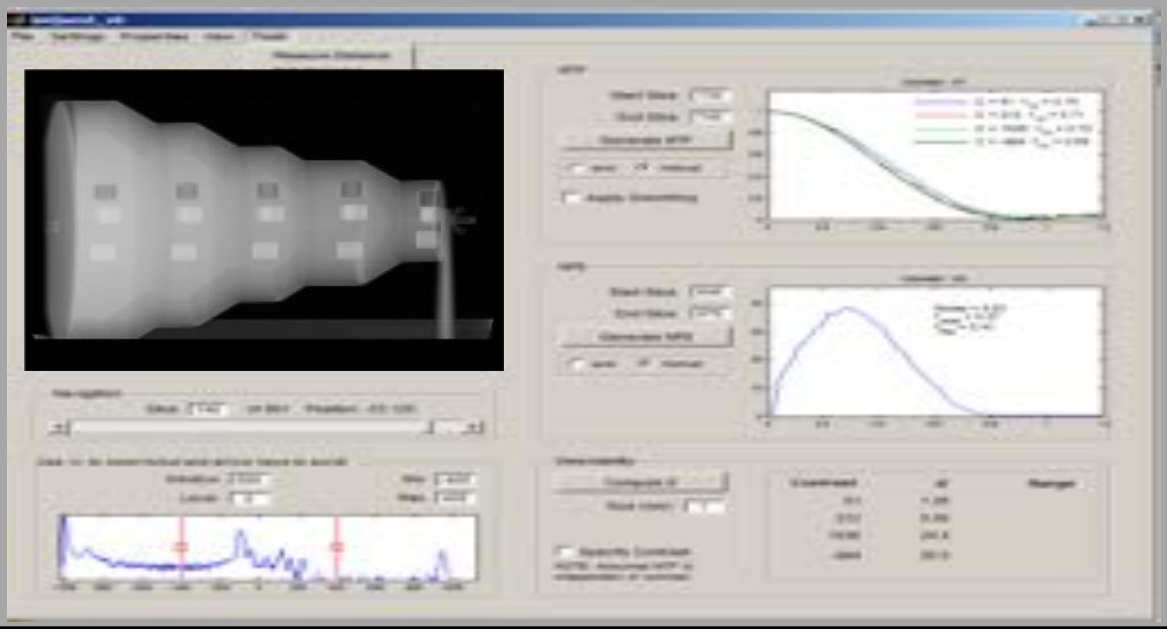
Mercury Phantom

Detectability (d'), resolution, and noise per size

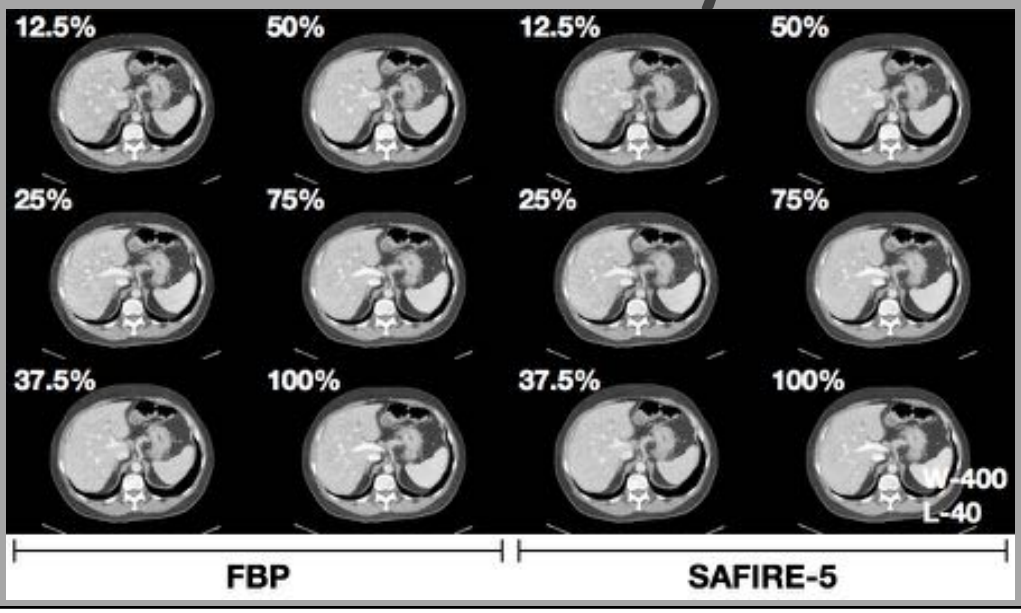
AAPM 233: https://www.aapm.org/pubs/reports



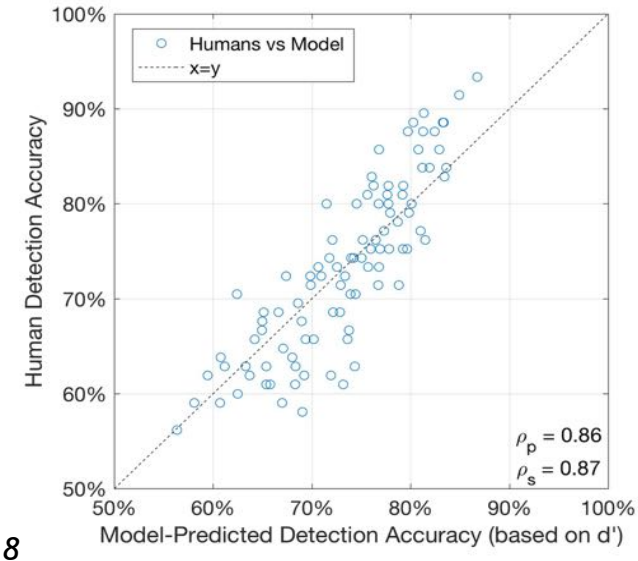
Automated Characterization



in vivo detectability index

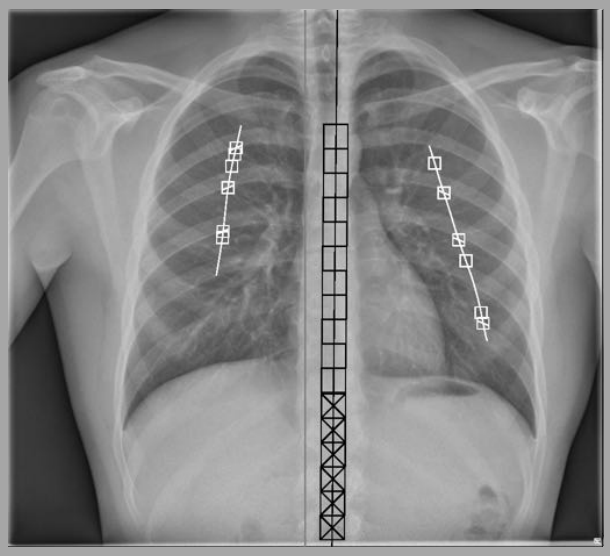


in vivo detectability index



Smith et al, JMI 2018

in vivo chest image quality



IQ Parameters
Lung Grey level
Lung Detail
Lung Noise
Rib-Lung Contrast
Rib Sharpness
Mediastinum Detail
Mediastinum Noise
Mediastinum Alignment
Subdiaphragm-Lung Contrast
Subdiaphragm Area

Lin et al, Medical Physics 2012; Samei et al, Medical Physics 2014

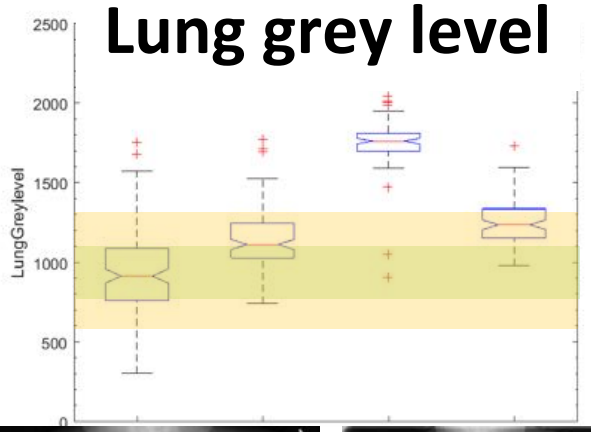
Published consistency and quality ranges

TABLE III. Summary of the minimum, median, and maximum values from the overall observer results, and the derived consistency and quality ranges across all observers. Unilateral metrics were labeled in bold.

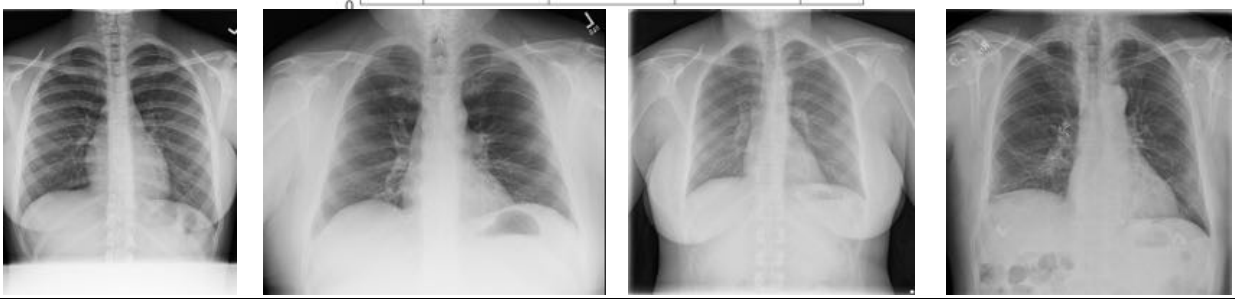
Metric	Min	Median	Max	Consistency range		Quality range		Quality range (from Ref. 1)	
$L_{\text{graylevel}}$	331.6	913.5	1308.0	543	1308	731	1082	706.7	1112.7
L_{detail}	13.9	25.3	42.3	14	42	19	31	20.9	+∞
L_{noise}	**13.9**	**21.4**	**36.7**	**0**	**34**	**0**	**21**	**0.0**	**28.7**
RL_{contrast}	0.16	0.36	0.63	0.2	0.6	0.28	0.44	0.25	0.45
$R_{\text{sharpness}}$	**87.9**	**89.0**	**89.9**	87.9	90.0	89.0	90.0	**88.6**	**90.0**
M_{detail}	4.2	12.2	18.7	4.2	18.7	9.2	15.3	5.3	13.2
M_{noise}	**22.2**	**31.3**	**45.2**	**0**	**45**	**0**	**31**	**0.0**	**37.2**
$M_{\text{alignment}}$	**6.0**	**121.6**	**298.6**	**0**	**267**	**0**	**122**	**0.0**	**109.0**
SL_{contrast}	0.88	1.2	1.6	0.9	1.6	1.1	1.3	1.1	1.4
S_{area}	0.03	0.18	0.51	0.08	0.49	0.17	0.27	0.10	0.36

Samei et al, Medical Physics 2014

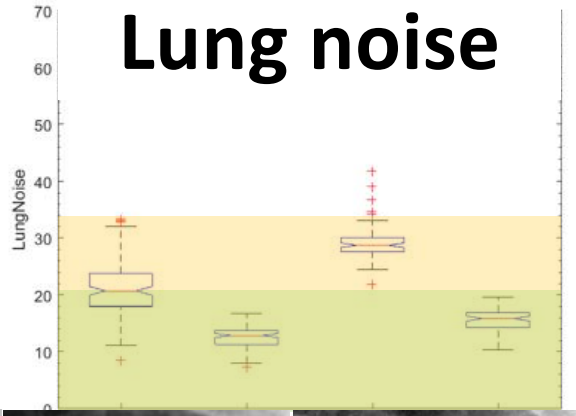
Lung grey level

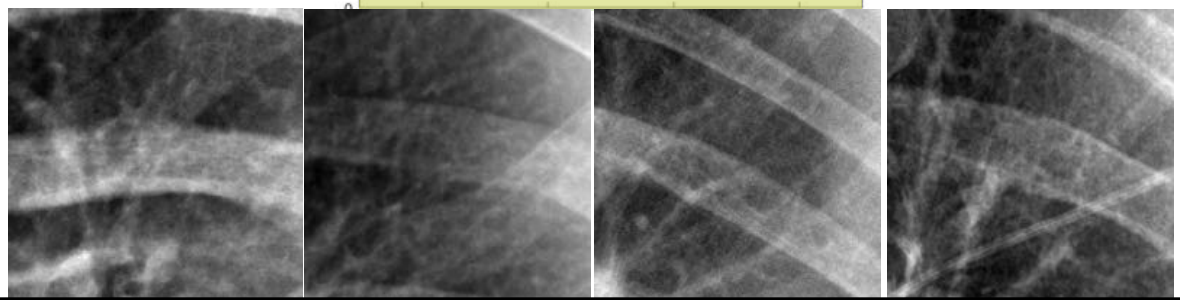


Consistency
Quality

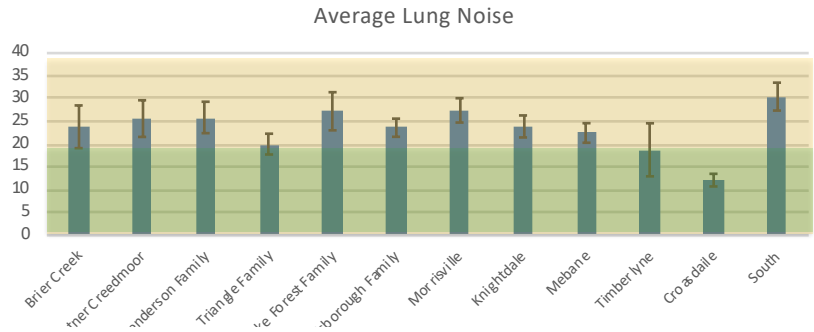


Lung noise

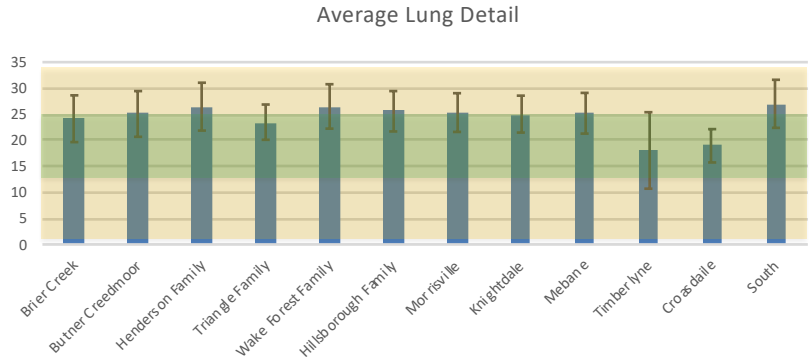




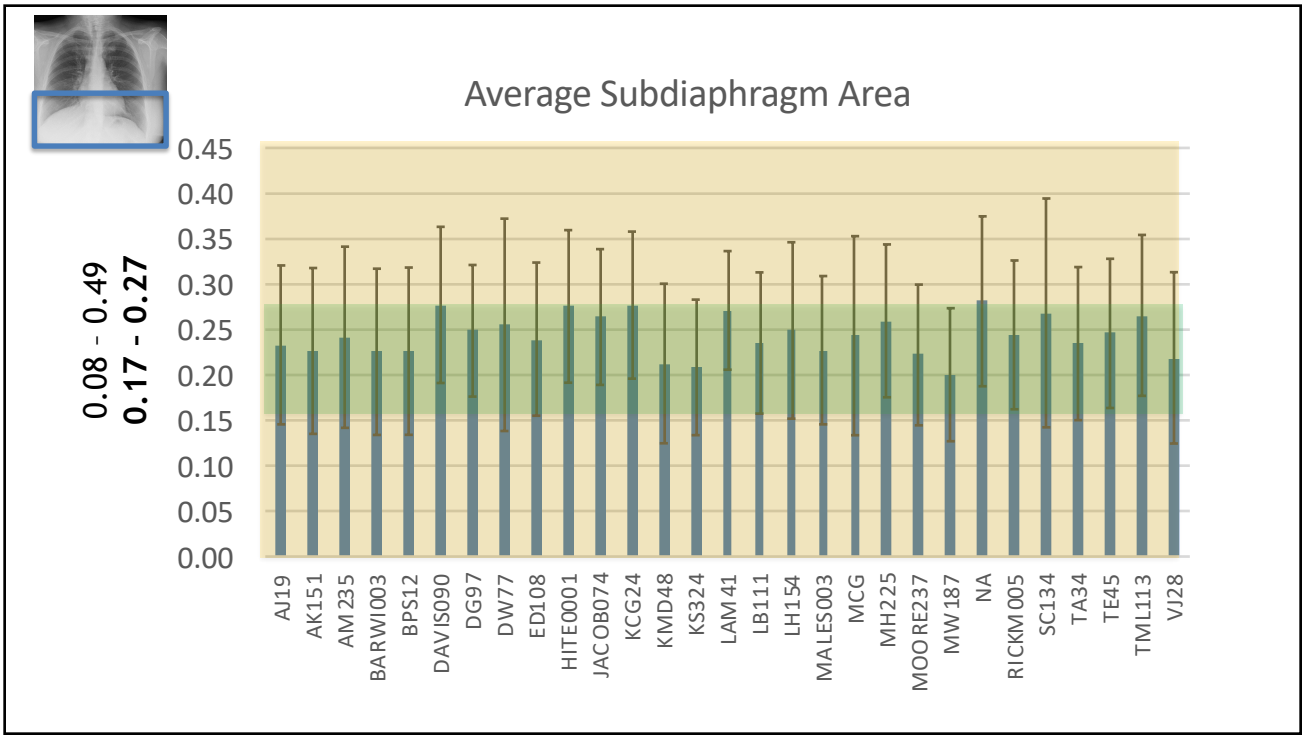
Consistency
Quality



Consistency
Quality



13 - 42
19 - 31



Take-home Points

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Take-home points

- The point of having image quality metrics is to have such metrics relatable to the purpose of imaging => clinical image quality
- C, MTF, NPS offer generic indicators relatable to task-specific metrics of Contrast Threshold, Detectability, Estimability
- *in vivo* measures provide a window into image quality across patient cases

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Questions?

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