Medical Physics 2.0: A Vision for Effective, Meaningful, and Value-Based Imaging Physics in the Clinical Environment

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ADVANCED
IMAGING
LABORATORIES

Medical Physics 2.0?

- A bold vision for an existential transition of clinical imaging physics
- 12 hrs didactic lectures on CT, MRI, NM, Fluoroscopy, Rad, Mammo, US, IT
  - **RSNA 2013**
  - **RSNA 2014**
  - **RSNA 2015**
  - **AAPM 2014**
  - **AAPM 2015**
  - **Clinical Imaging Physics.** Wiley and Sons, **2015**

Overarching presuppositions

- Imaging should render relevant state of health/disease accurately and precisely enough so that it can lead to definitive clinical decisions
- Images should be more reflective of the state of the patient than the technique used

Reality checks

Å Clinical activities are heterogeneous/compounded/complex operations

Å Increased scrutiny

Å Limited resources

Å How imaging physics can add value in the quality of imaging operation?

4 Key formative questions

1. Where is imaging in medicine enterprise?

Å Transformative technology

Å The “face” of modern medicine

2. Where medical imaging is going?

Å Evidence-based medicine

ï Practice informed by science

Å Precision medicine

ï Quantification and personalization of care

Å Value-based medicine

ï Scrutiny on safety, performance, consistency, stewardship, ethics

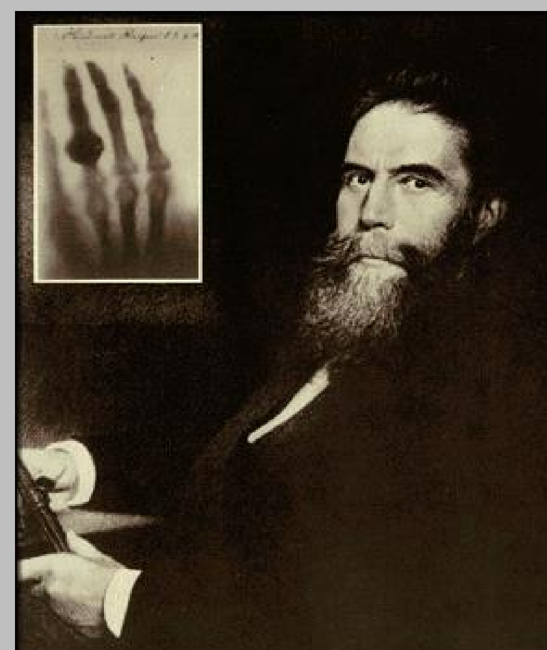
Å Comparative effectiveness and meaningful use

ï Enhanced focus on actual utility

3. What has been the role of imaging physics in medicine?

Å Remember Roentgen!

Å Medical physics is the foundational discipline behind Radiology and Radiation Oncology



4. What has been the clinical role of imaging physics?

Å Ensuing quality and safety of clinical imaging systems

Å We have done a GREAT job using engineering and physics concepts to

ï Design systems with superior performance

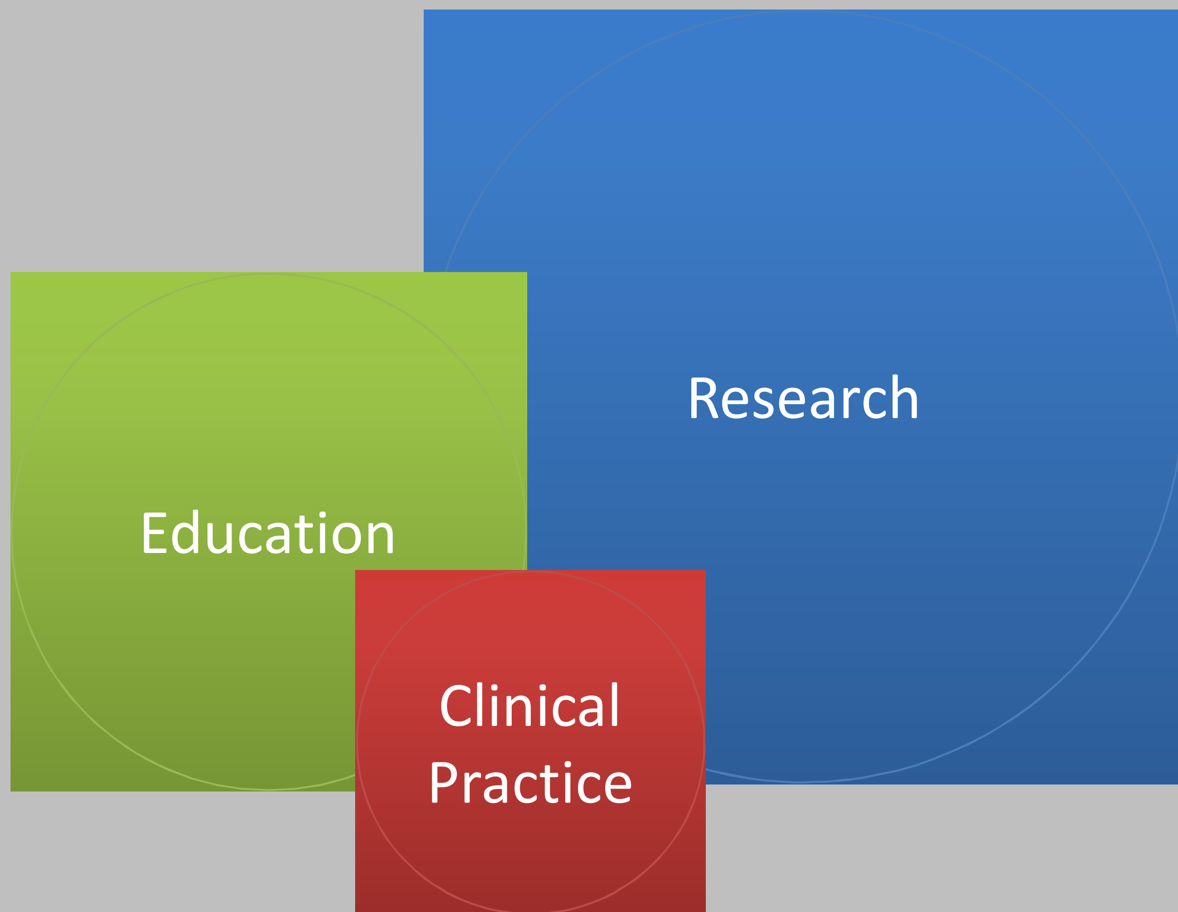
ï Ensure minimum intrinsic performance

ï Claim compliance

Å But…

Imaging physics enterprise

Imaging physics enterprise



Why 1.0 is not enough

Å **Not translatable**, historically, to clinical care, mostly equipment-focused

ï Relevance?

Å **Outdated science and technology**

ï Compliance lags behind clinical needs and innovations

Why 1.0 is not enough

Å Clinical performance?

Å Optimization of use?

Å Consistency of quality?

Å Changing technology?

Å Value-based healthcare?

1.0 to 2.0

Å Clinical imaging physics extending from

compliance	**to**	**excellence**
intrinsic	**to**	**extrinsic**
Equipment	**to**	**operation**
Specifications	**to**	**performance**
Quality	**to**	**consistency**
Assumption	**to**	**actual utility**
Promises	**to**	**implementation**

Inspiring practices of Medical Physics 2.0

1. Science: Practices that are scientifically-informed by latest findings and methods
2. Relevance: Objectives that are oriented towards the actual clinical practice
3. Stewardship: Approaches that are pragmatic in the meaningful and efficient use of resources
4. Integration: Solutions that are comprehensive and holistic in view of clinical operation
5. Empowerment: Education enabling others to be their best in their domain of care

Clinical role of medical physics

Applying the science of imaging physics

to ensure quality, safety,

consistency, and optimum utilization

in the clinical practice of medical imaging

Ensuring quality, safety, consistency, optimality

Ensuring quality, safety, consistency, optimality

Prospective performance assessment

Quality by inference

Prospective protocol definition

Quality by prescription

Retrospective quality assessment

Quality by outcome

Ensuring quality, safety, consistency, optimality

Prospective performance assessment

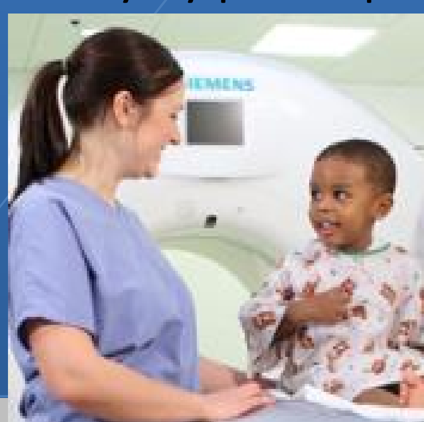
Quality by inference

Å **Devising better metrics**

Å **Automated characterization**

Prospective protocol definition

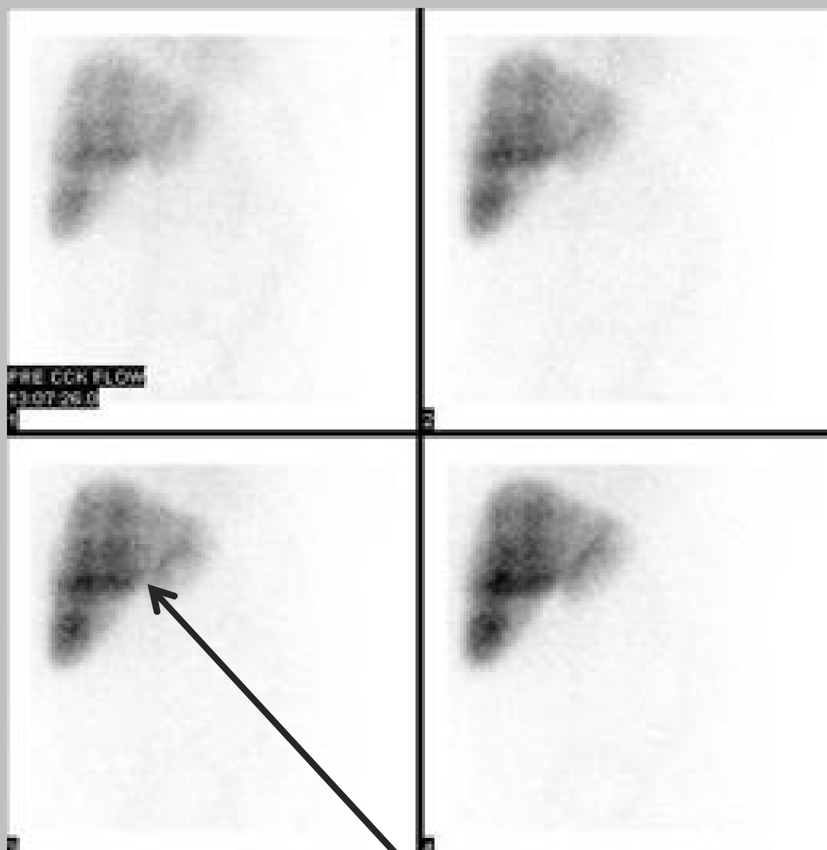
Quality by prescription

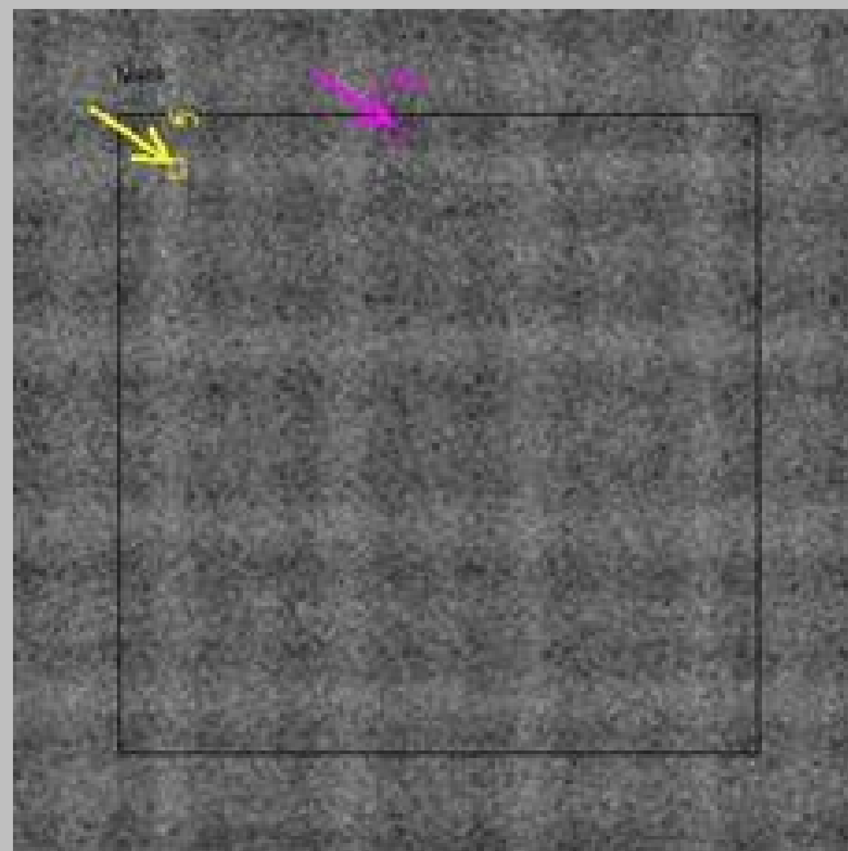


Retrospective quality assessment

Quality by outcome

Nuclear Medicine non-uniformity

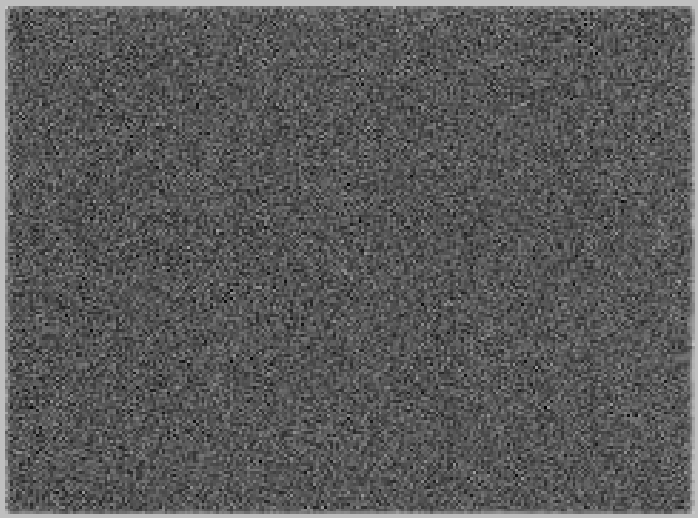




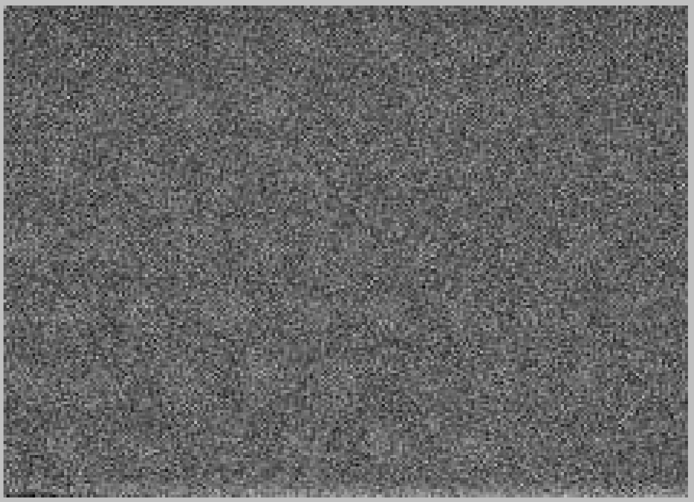
Crosshatched artifact pattern
(system has square PMT's)

Nuclear Medicine non-uniformity

$$\text{Integral Uniformity} = \frac{N_{\max} - N_{\min}}{N_{\max} + N_{\min}} \times 100\%$$



2.87%

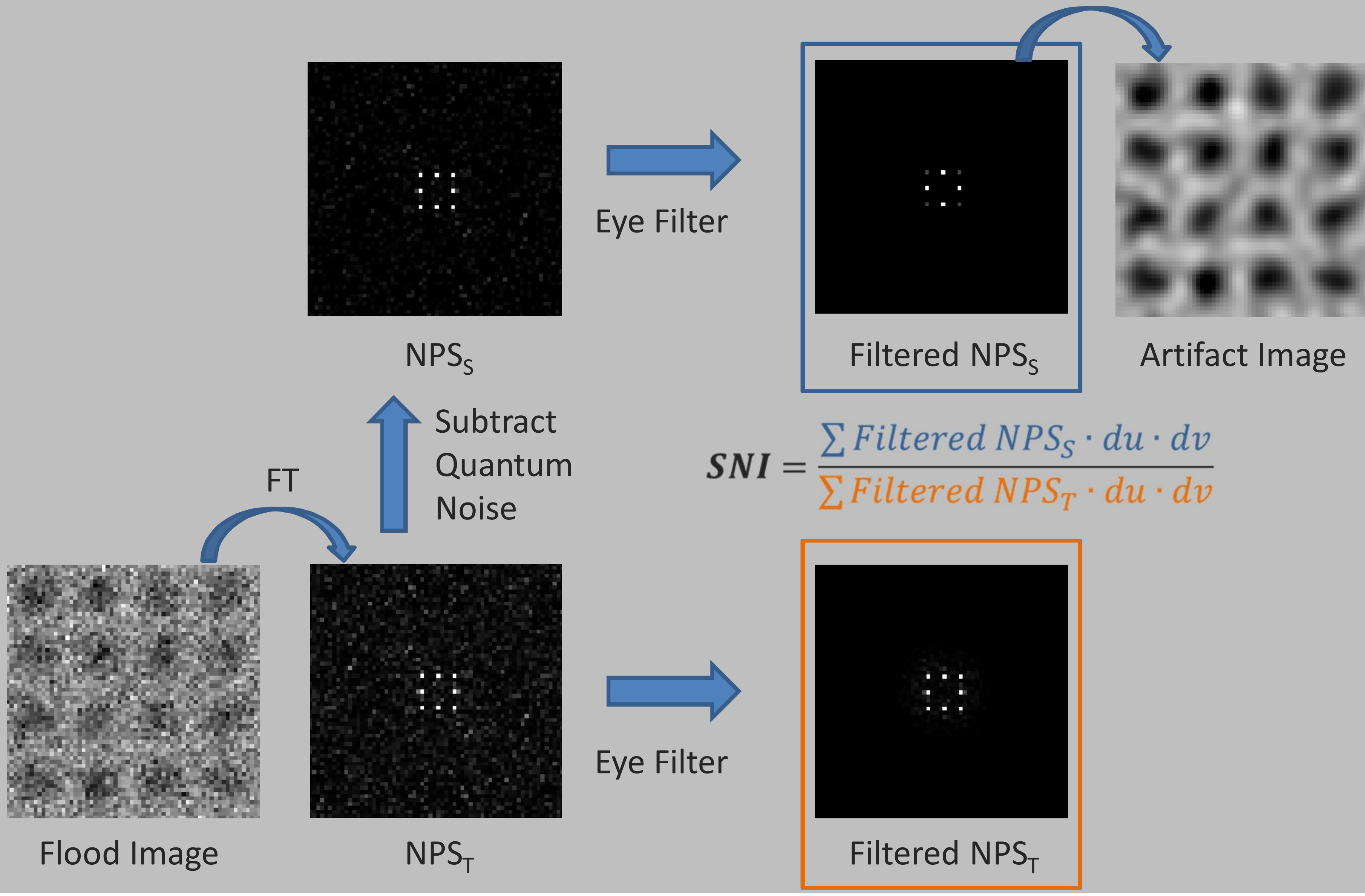


2.81%

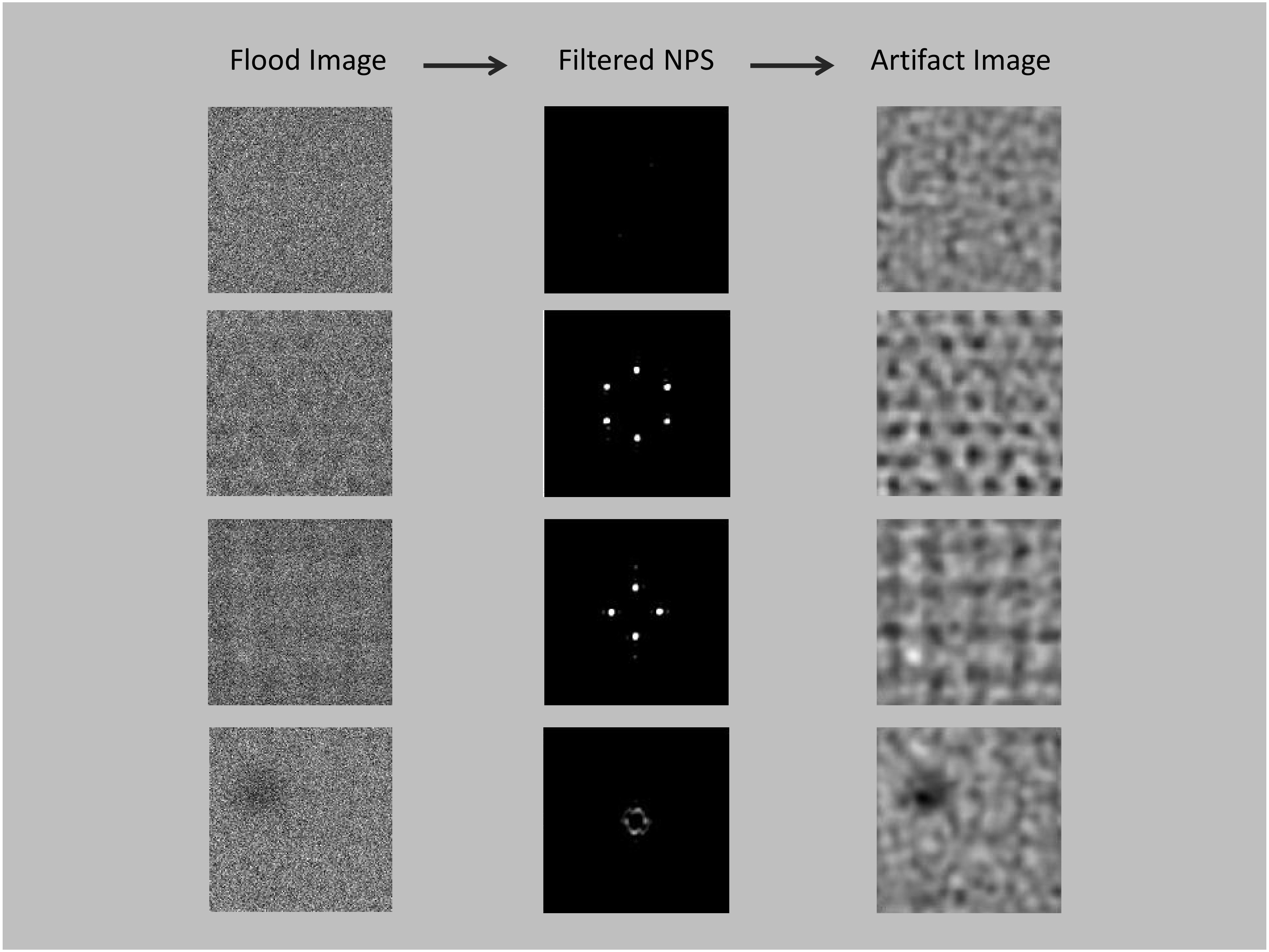
Action limit = > 5.00%

Nelson JS, et al, JNM, 2014

Structured Noise Index (SNI)



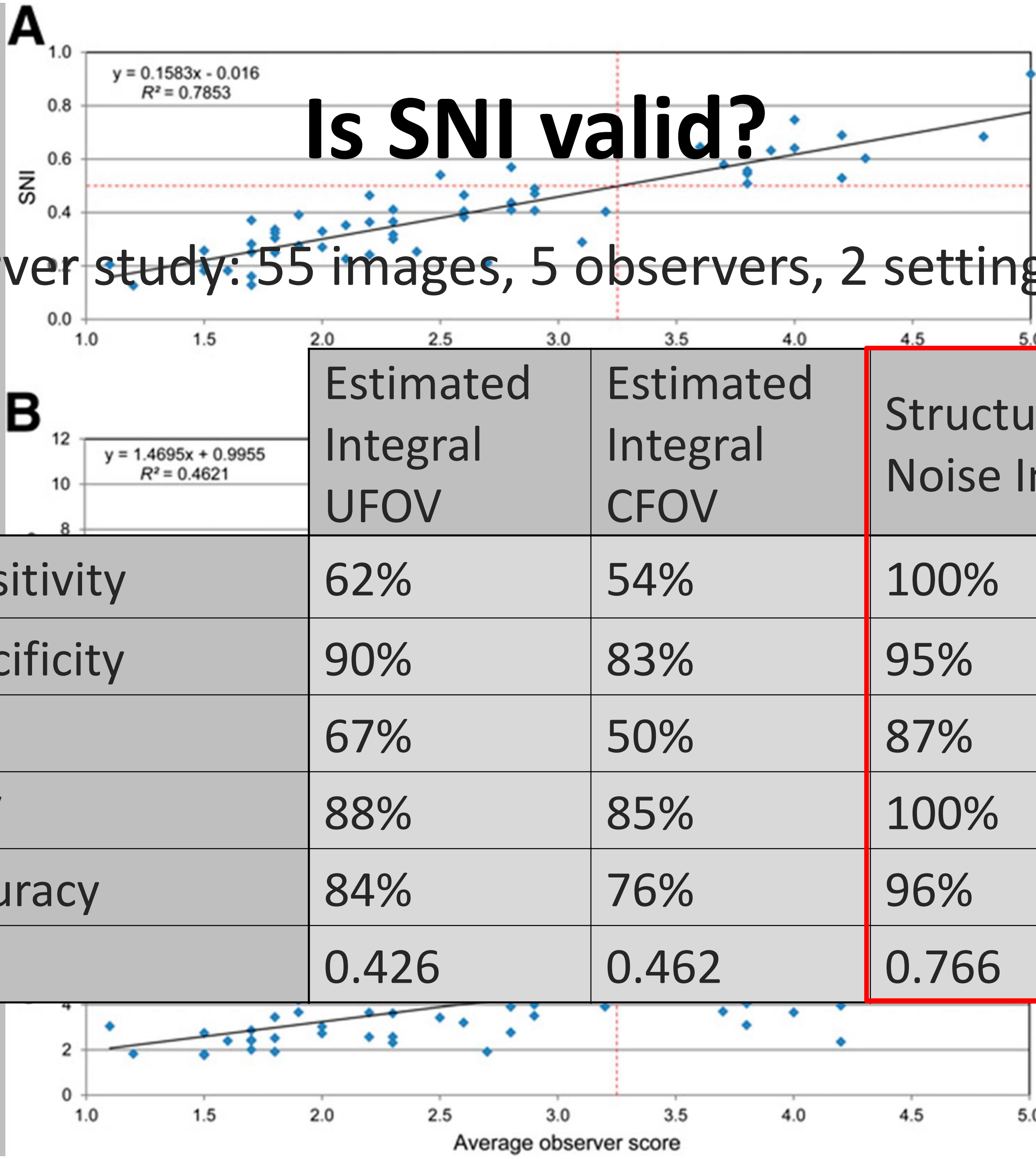
$$SNI = \frac{\sum Filtered\ NPS_S \cdot du \cdot dv}{\sum Filtered\ NPS_T \cdot du \cdot dv}$$



Flood Image
Filtered NPS
Artifact Image

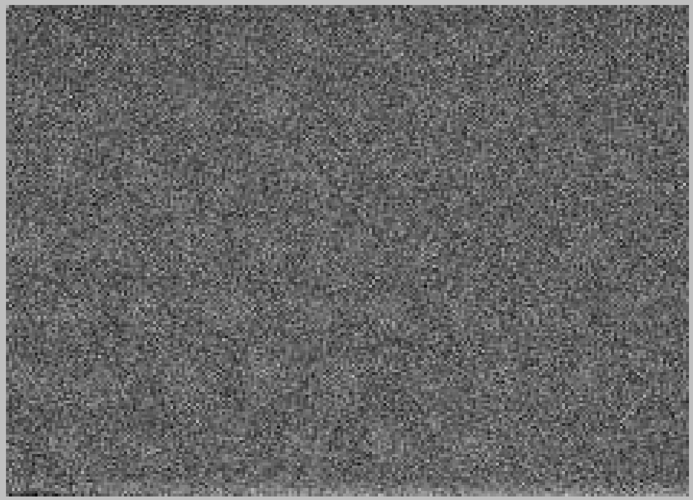
Is SNI valid?

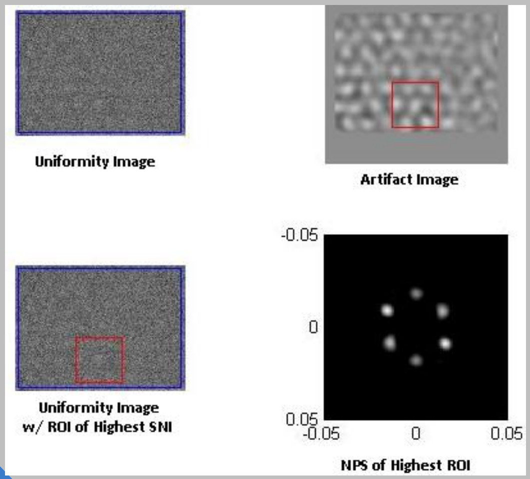
Å Observer study: 55 images, 5 observers, 2 settings



	Estimated Integral UFOV	Estimated Integral CFOV	Structured Noise Index
Sensitivity	62%	54%	100%
Specificity	90%	83%	95%
PPV	67%	50%	87%
NPV	88%	85%	100%
Accuracy	84%	76%	96%
R^2	0.426	0.462	0.766

Integral Uniformity vs SNI





CFOV IU = 2.81%

Action limit = > 5.00%

SNI= 0.78

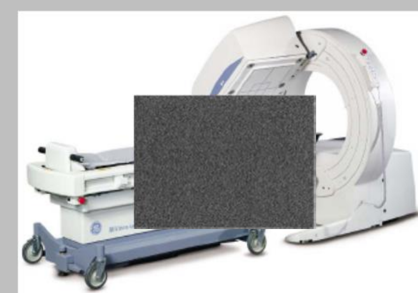
Action limit = > 0.5

SNI Tracking and Analytics

- **Scanners can send QC data to physics server**






SNI Tracking and Analytics

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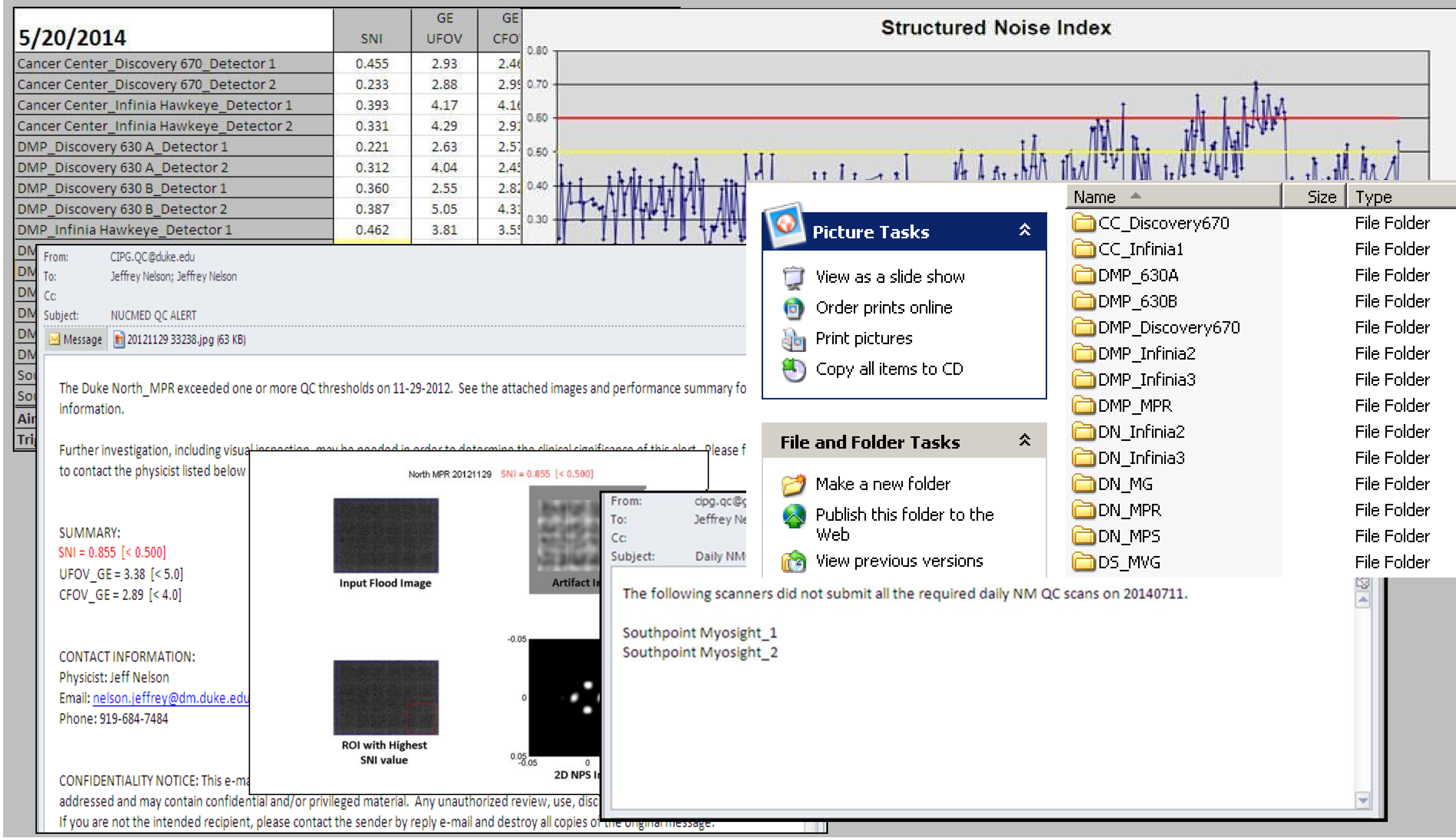
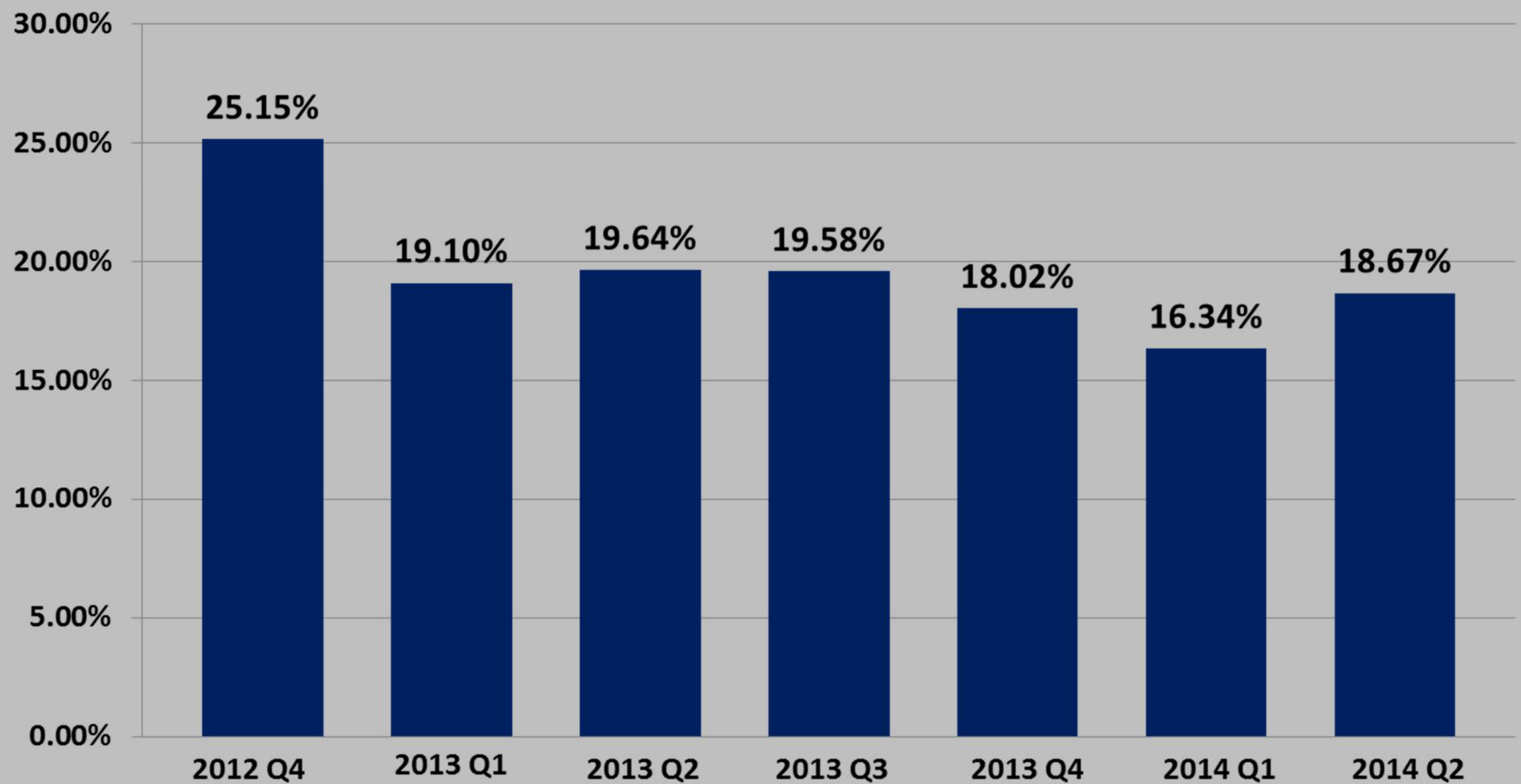


Improved consistency across NM fleet



SNI Tracking and Analytics

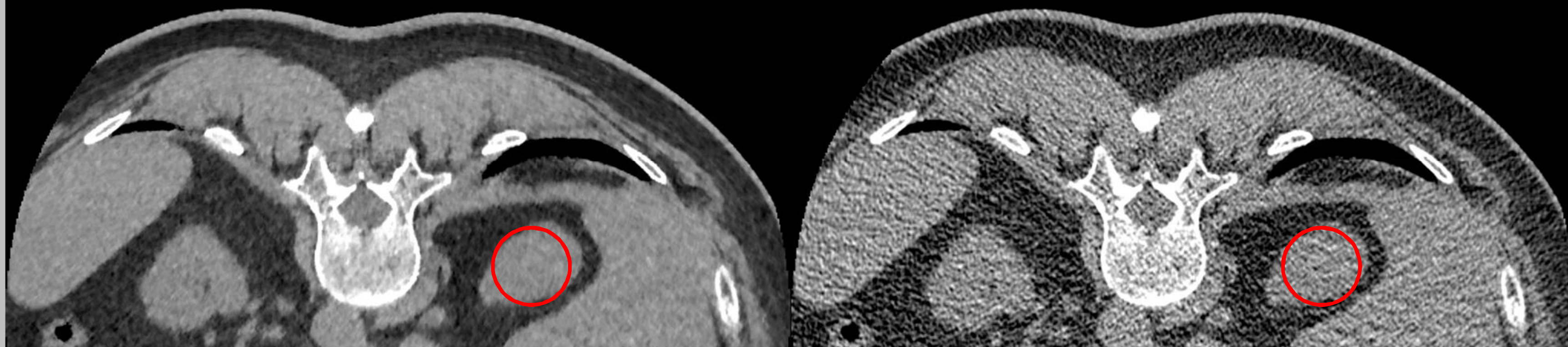
Å Improved consistency across systems

Å Decreased the time technologists and physicists spent analyzing QC

Å Successfully alerted staff to issues which would have been overlooked

Å Expedited communication between clinical staff, physicist, and clinical engineers

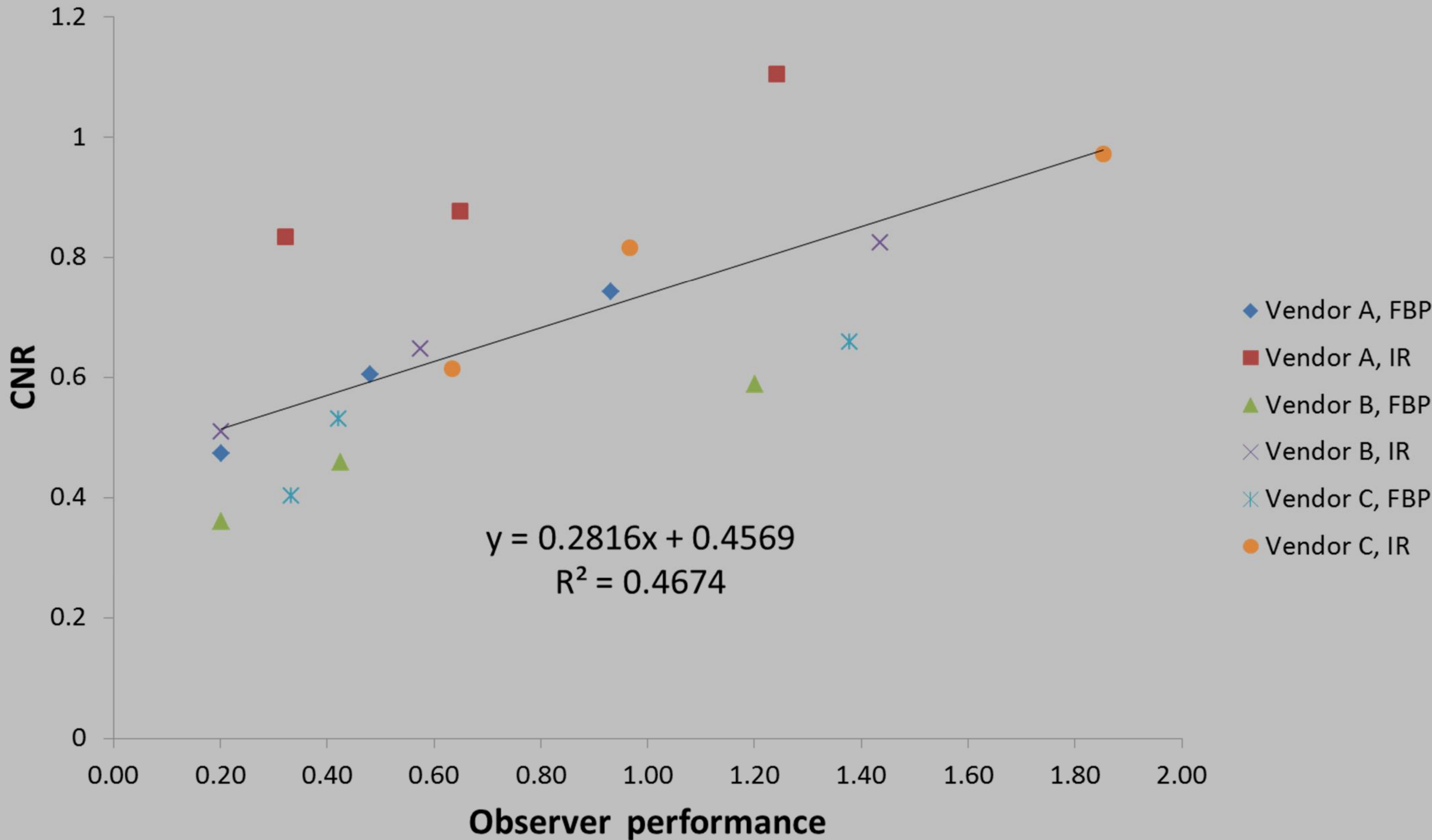
What is image quality?



ICRU Report 54, 1996

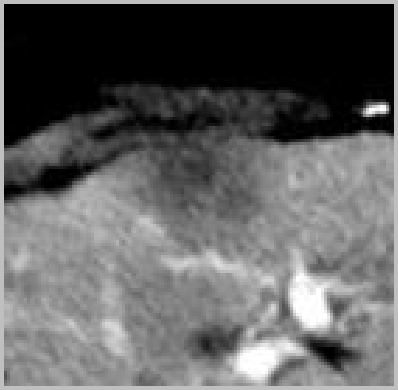
"Any general definition of image quality must address the effectiveness with which the image can be used for its intended task."

CNR vs observer performance



Christianson, et al, Radiology, 2015

Parameters that affect task-based image quality



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

Feature of interest

5. Resolution
6. Viewing distance
7. Display

Image details

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

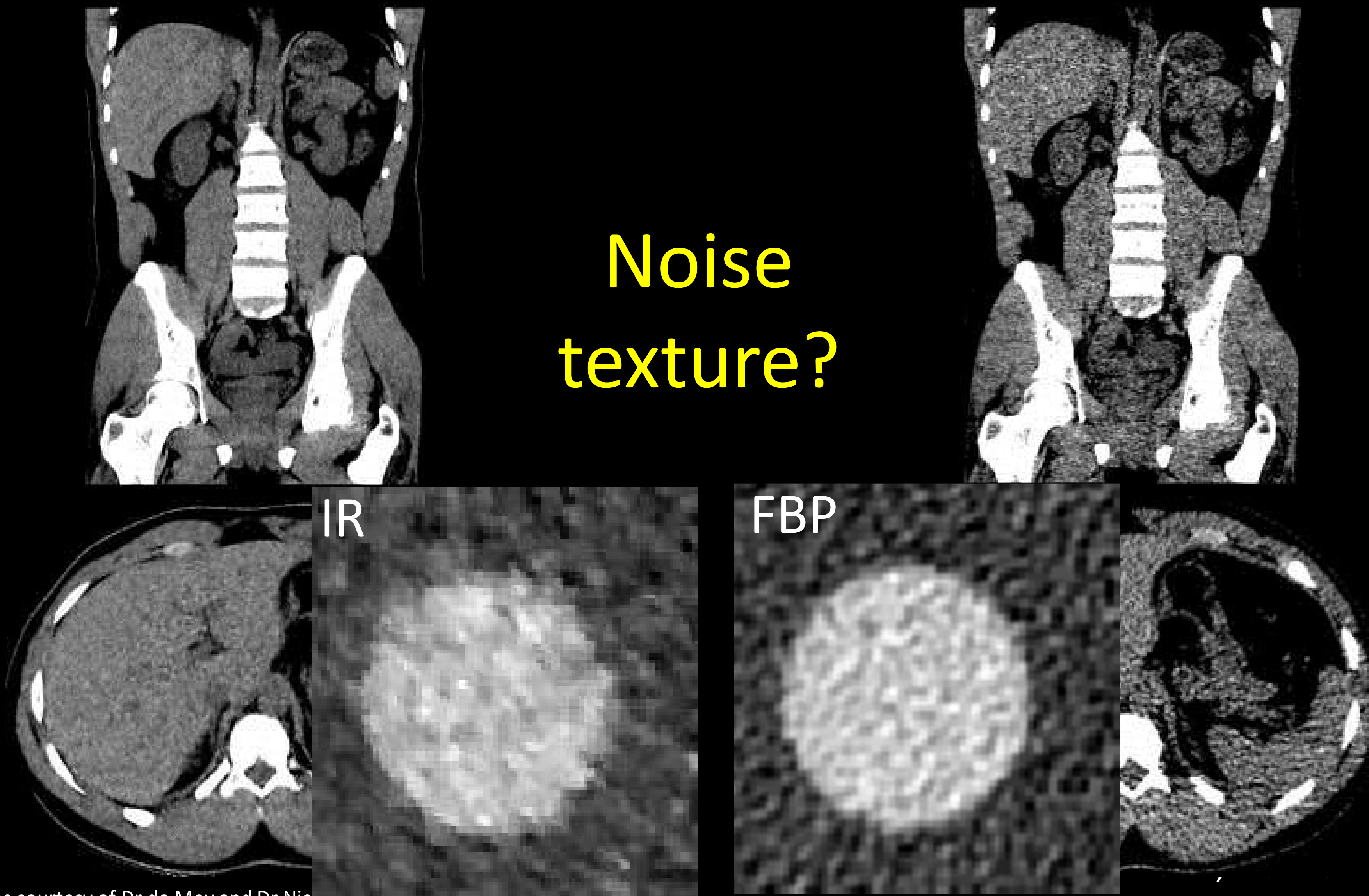
Distractors

Parameters that affect task-based image quality

		CNR
1. Contrast 2. Lesion size 3. Lesion shape 4. Lesion edge	Feature of interest	1. Contrast 2. Lesion size 3. Lesion shape 4. Lesion edge
5. Resolution 6. Viewing distance 7. Display	Image details	5. Resolution 6. Viewing distance 7. Display
8. Noise magnitude 9. Noise texture 10. Operator noise	Distractors	8. Noise magnitude 9. Noise texture 10. Operator noise

Iterative Reconstruction

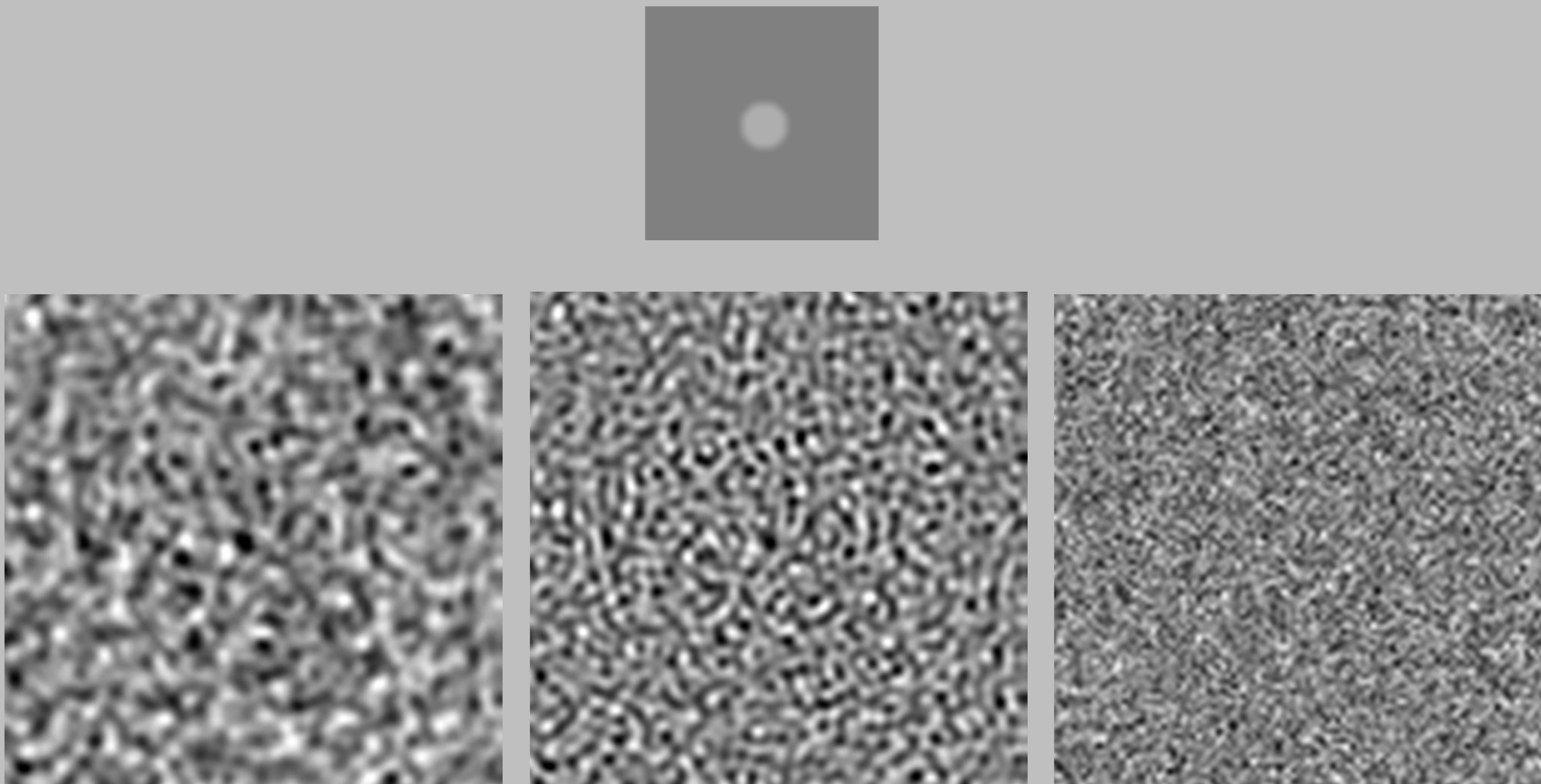
FBP Reconstruction

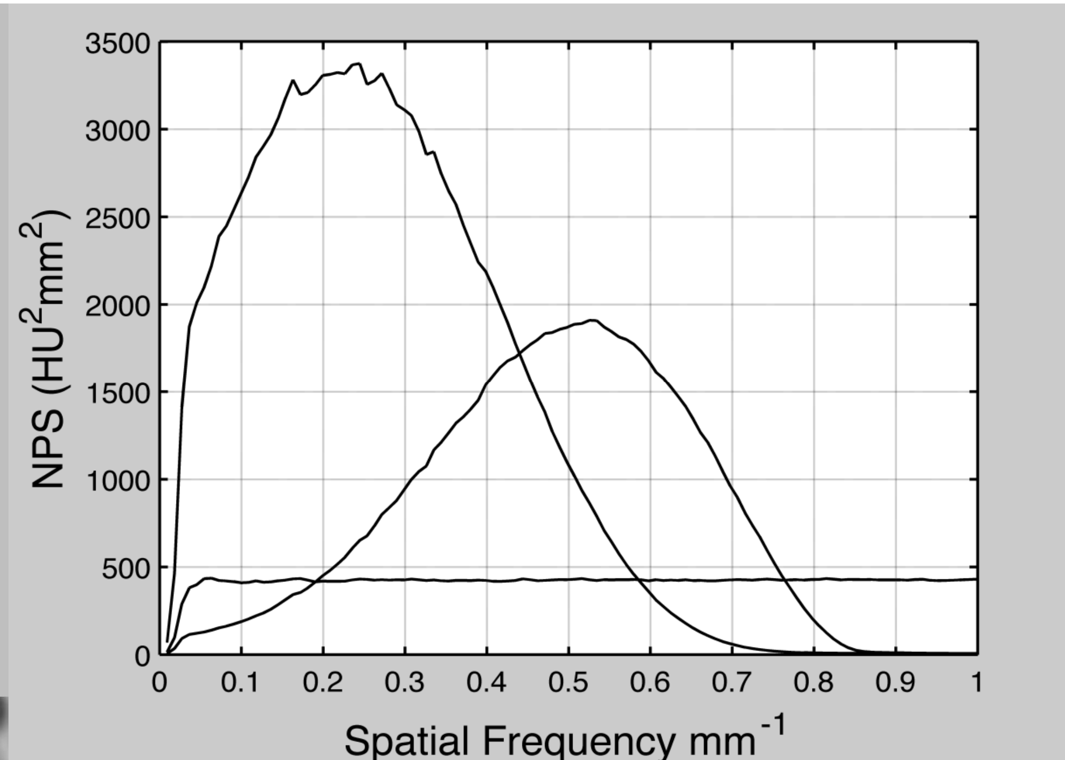


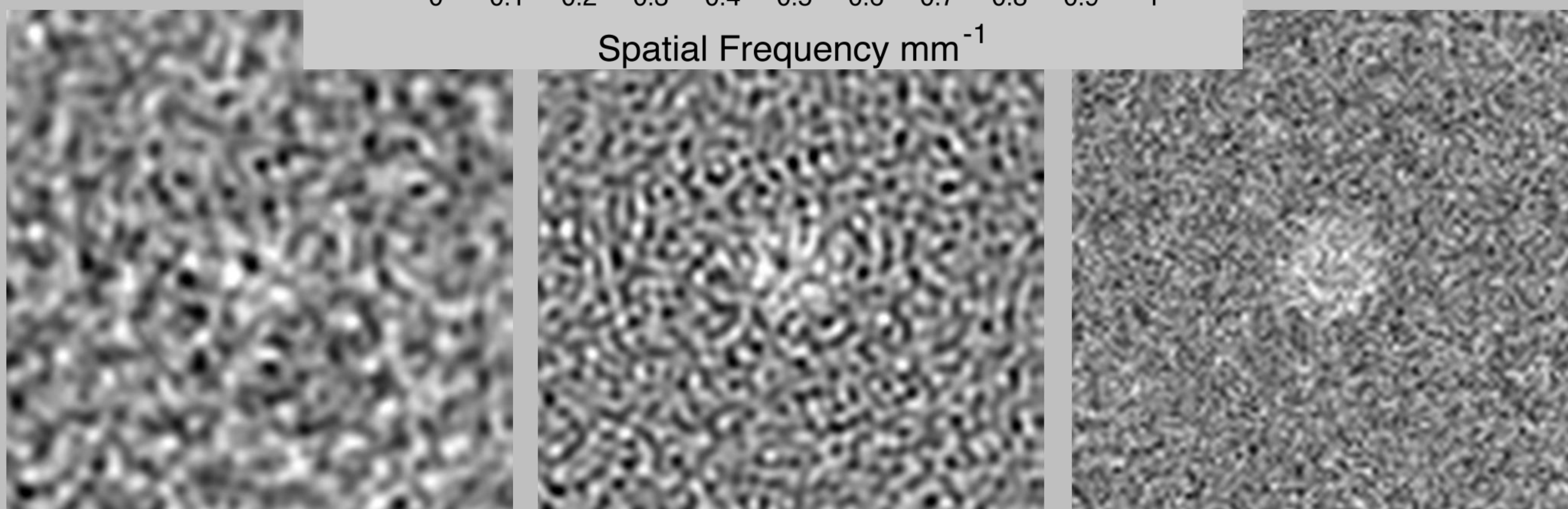
Noise texture?

Images courtesy of Dr de Mey and Dr Nieboer, UZ Brussel, Belgium

Noise Power Spectrum



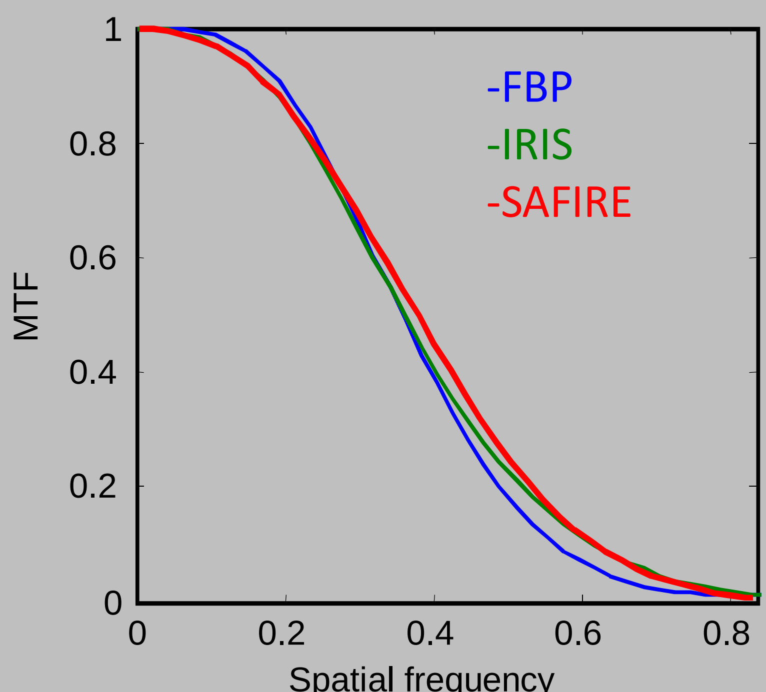

NPS (HU^{2}mm^2)
3500
3000
2500
2000
1500
1000
500
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Spatial Frequency mm^{-1}

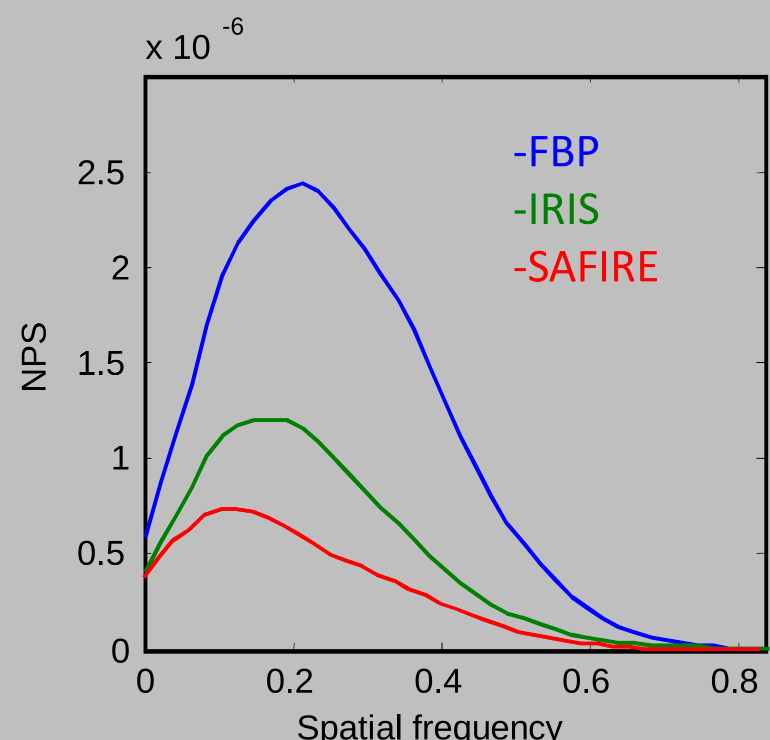


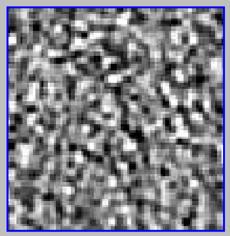
Resolution and noise, eg 1

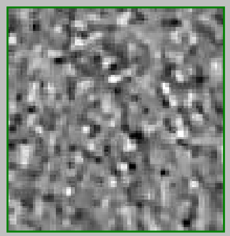
Comparable resolution

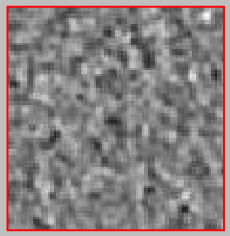
Lower noise but different texture







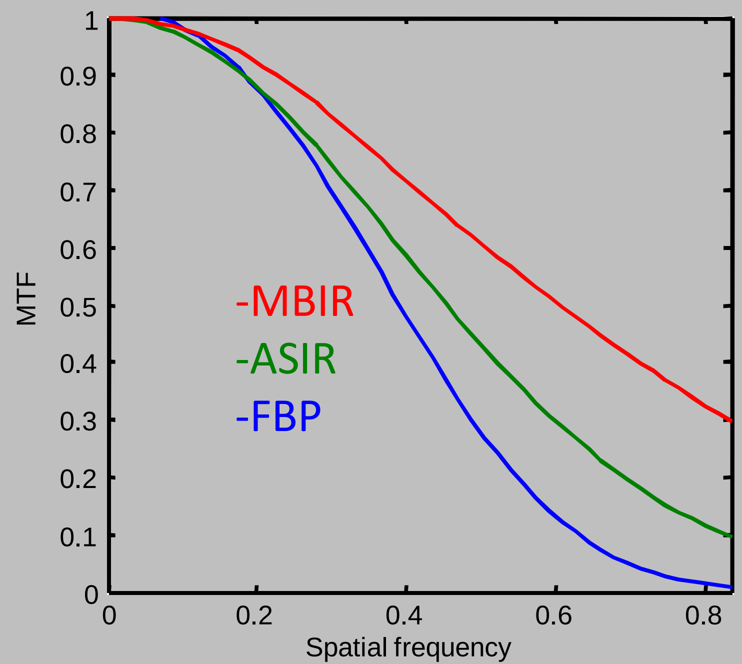


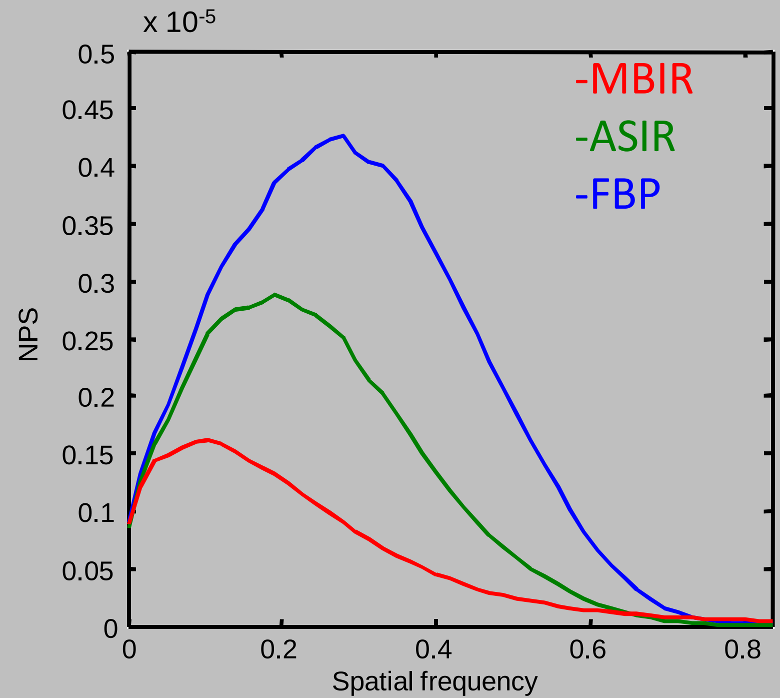


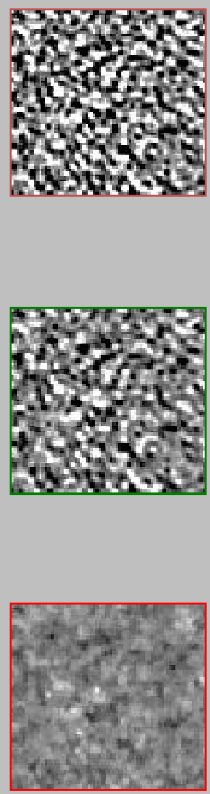
Resolution and noise, eg 2

Higher resolution

Lower noise but different texture







Task-based quality index

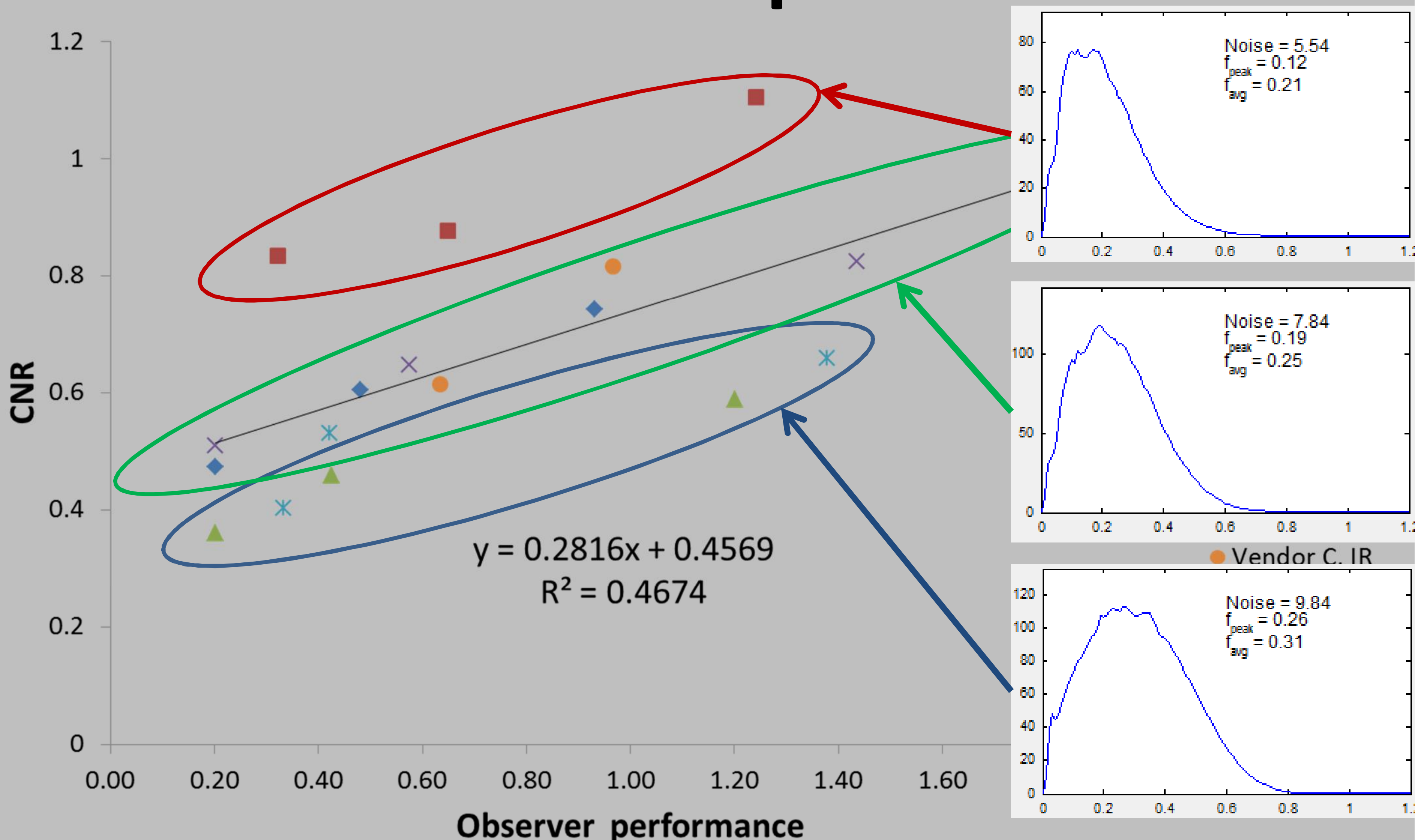
$$\frac{\text{Resolution and contrast transfer} \times \text{Attributes of image feature of interest}}{\text{Image noise magnitude and texture}}$$

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

Richard, and E. Samei, Quantitative breast tomosynthesis: from detectability to estimability. Med Phys, 37(12), 6157-65 (2010).

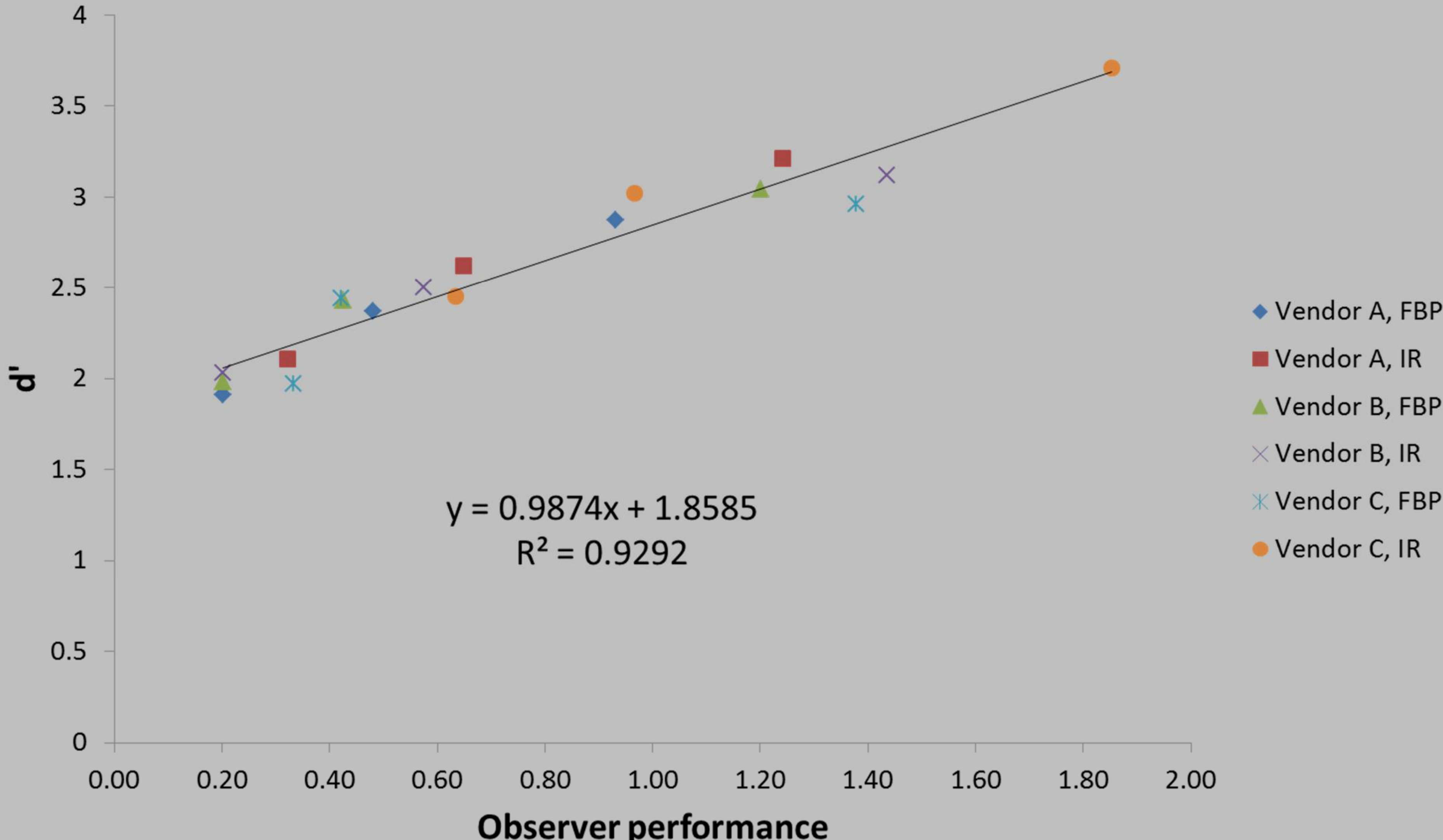
Chen et al., Relevance of MTF and NPS in quantitative CT: towards developing a predictable model of quantitative... SPIE2012

CNR vs observer performance

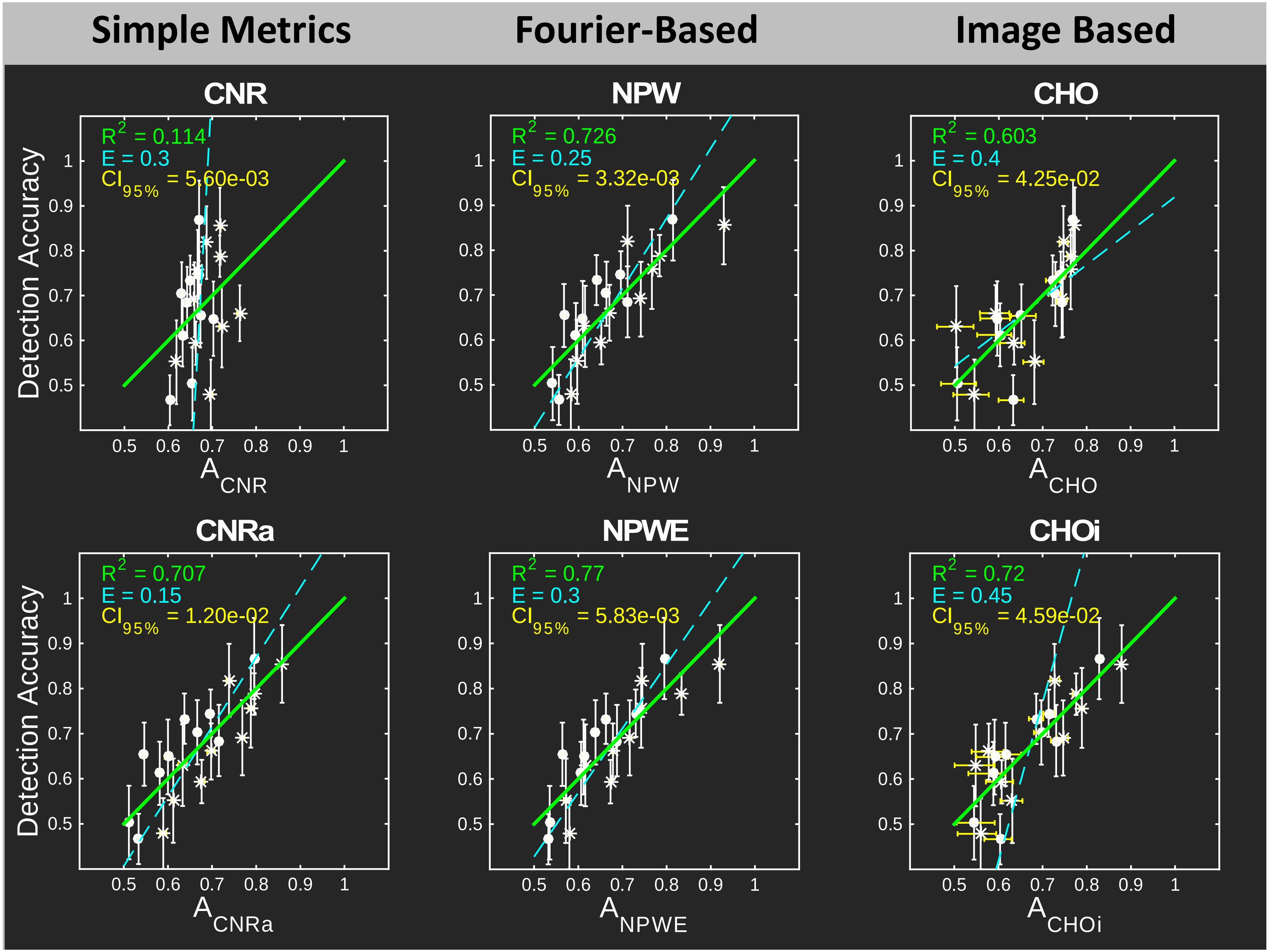


Christianson, et al, Radiology, 2015

d’ vs observer performance



Christianson, et al, Radiology, 2015



Simple Metrics
Fourier-Based
Image Based
CNR
NPW
CHO
CNRa
NPWE
CHOi
R2 = 0.114
E = 0.3
CI95% = 5.60e-03
R2 = 0.726
E = 0.25
CI95% = 3.32e-03
R2 = 0.603
E = 0.4
CI95% = 4.25e-02
R2 = 0.707
E = 0.15
CI95% = 1.20e-02
R2 = 0.77
E = 0.3
CI95% = 5.83e-03
R2 = 0.72
E = 0.45
CI95% = 4.59e-02
Detection Accuracy
ACNR
ANPW
ACHO
ACNRa
ANPWE
ACHOi

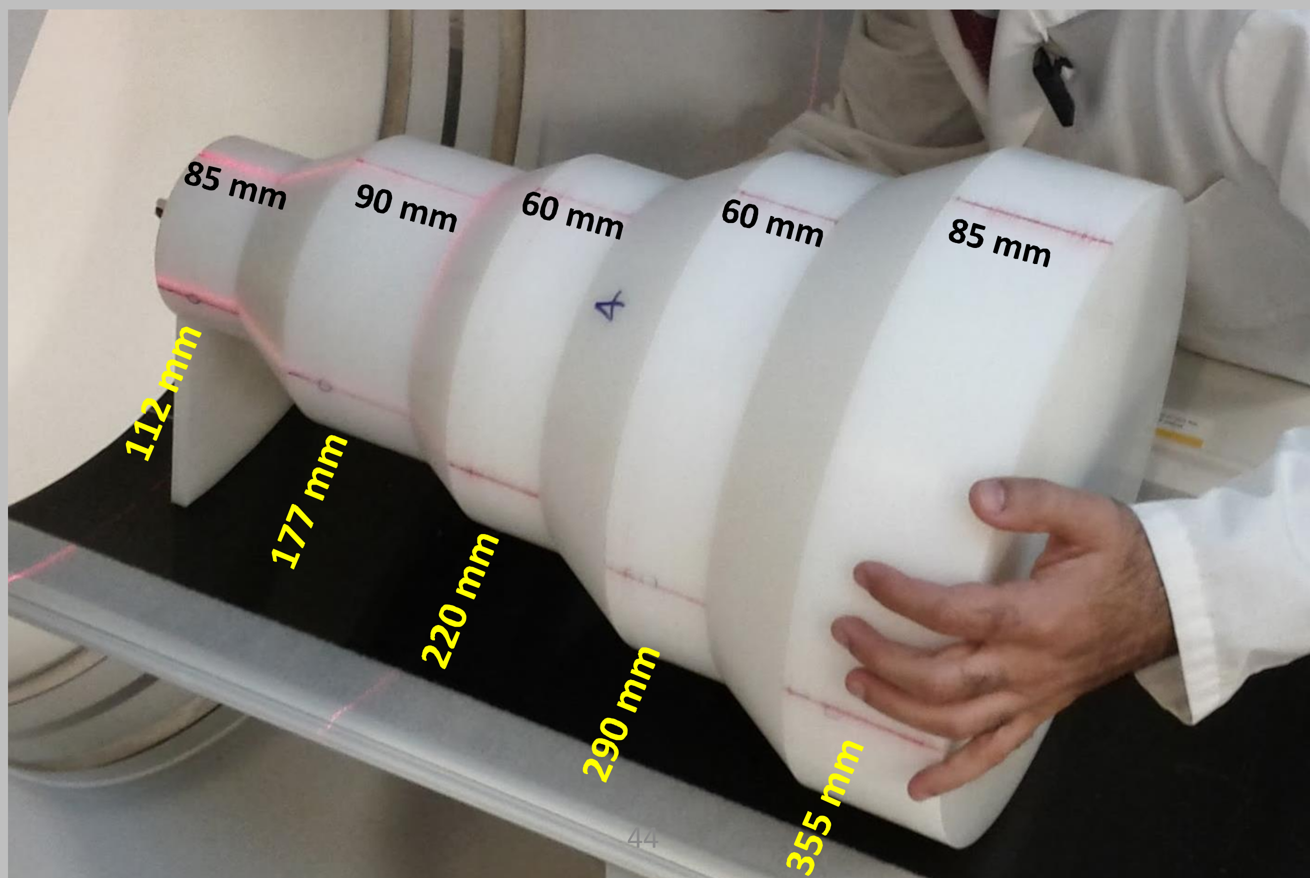
Task-based measurements

Mercury Phantom 3.0

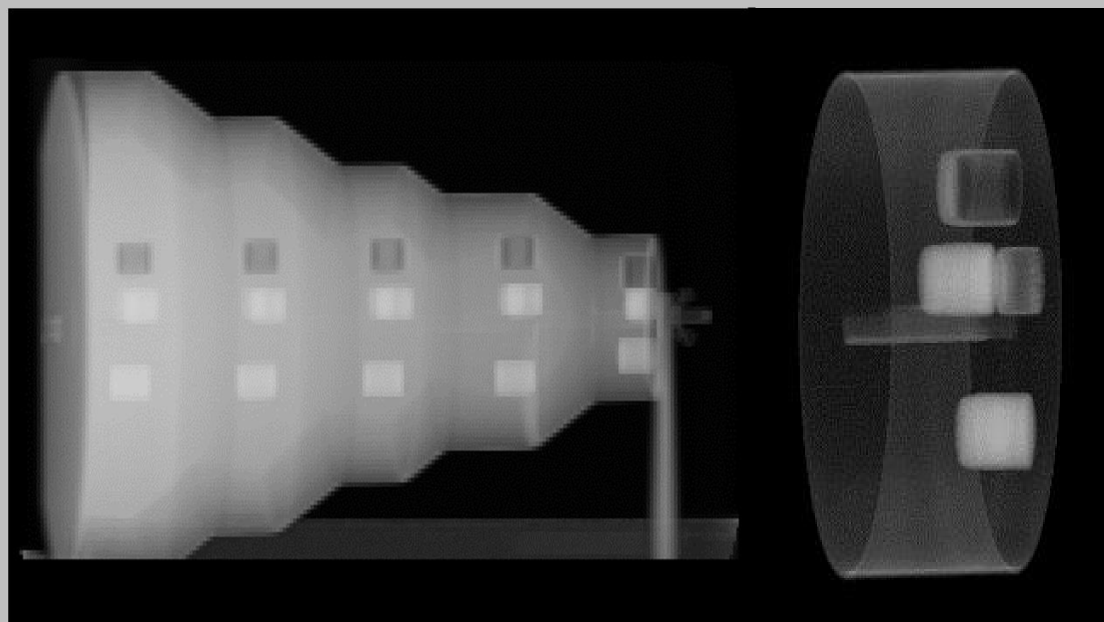
Å Diameters matching population cohorts

Å Depths consistent with cone angles

Å Designed for size, AEC, and d’ evaluations



Design: Resolution, HU, noise



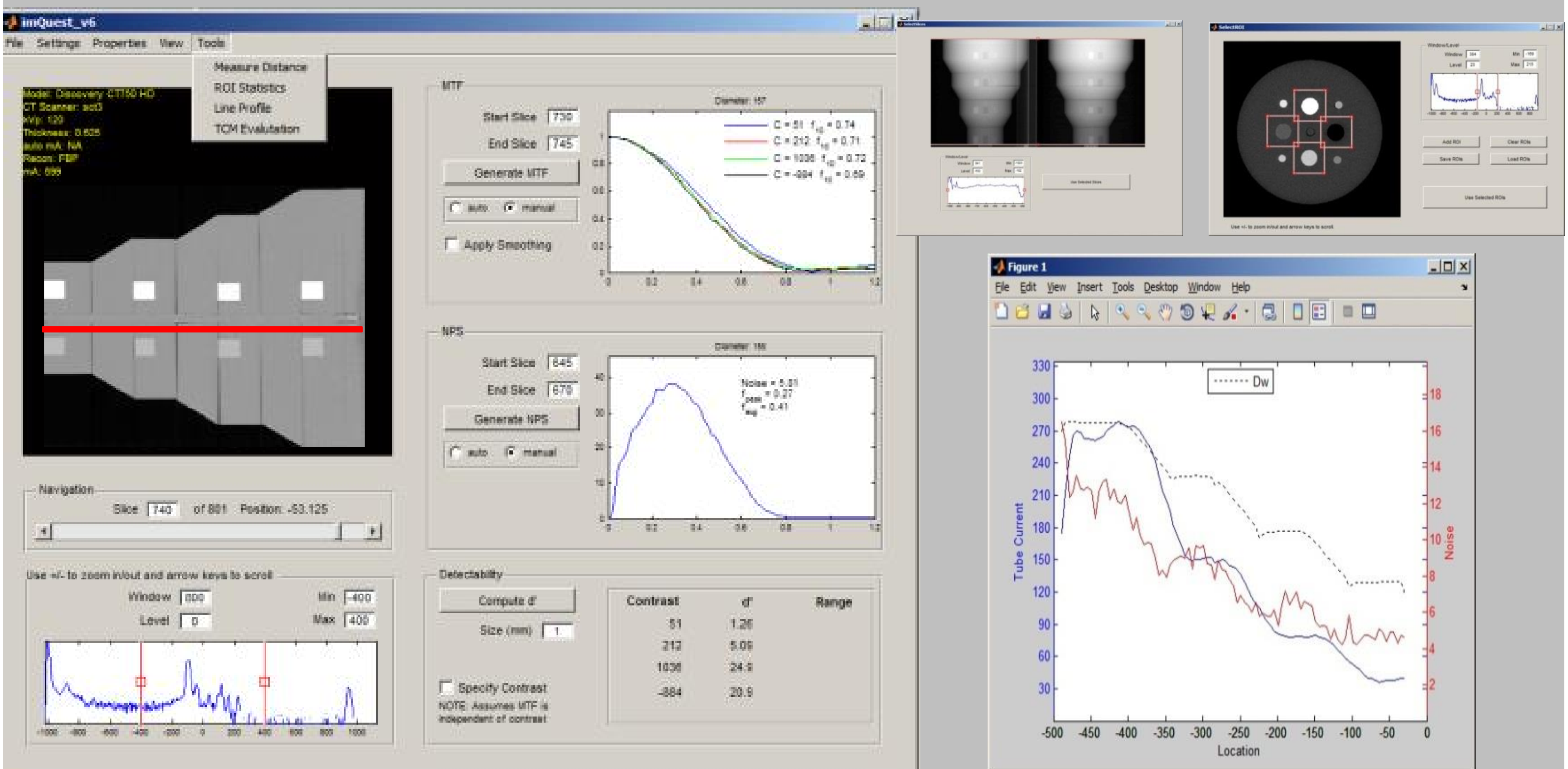
- **Representation of abnormality-relevant HUs**
- **Sizes large enough for resolution sampling**
- **Maximum margin for individual assessment**
- **Iso-radius resolution properties**
- **Matching uniform section for noise assessment**

Wilson et al, MedPhys 2012

imQuest

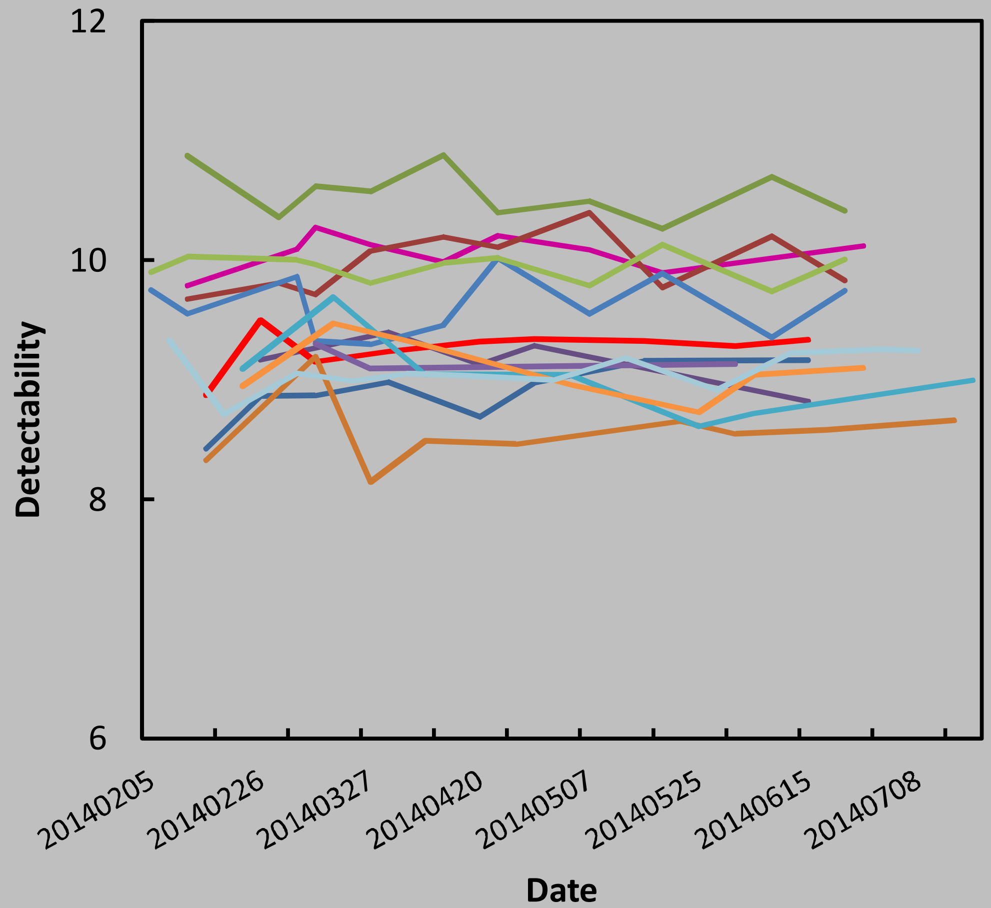
(image quality evaluation software)

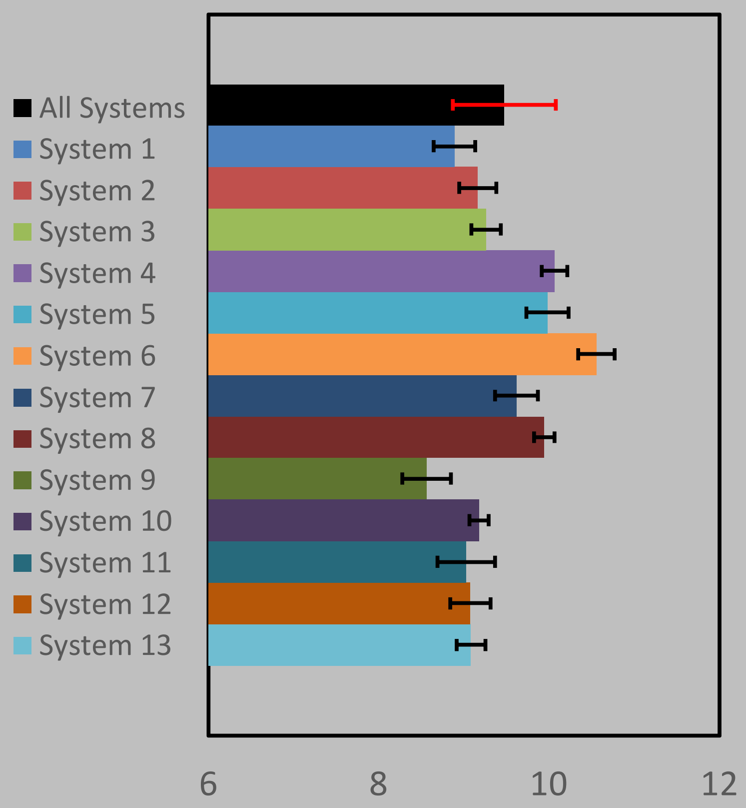
HU, Contrast, Noise, CNR, MTF, NPS, and d’ per patient size, mA modulation profile



Wilson et al, MedPhys 2012

Detectability index across systems



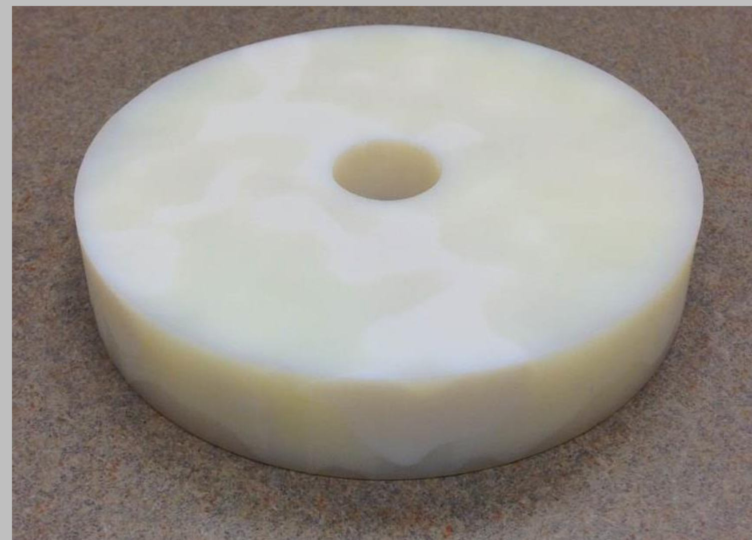


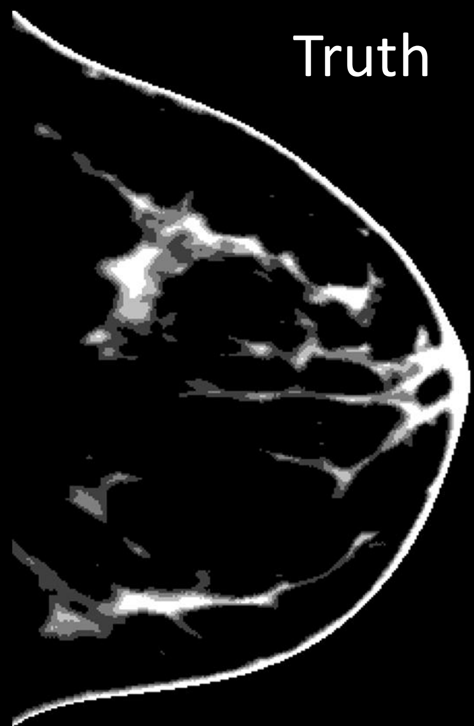
Intra system variability: 1-4%

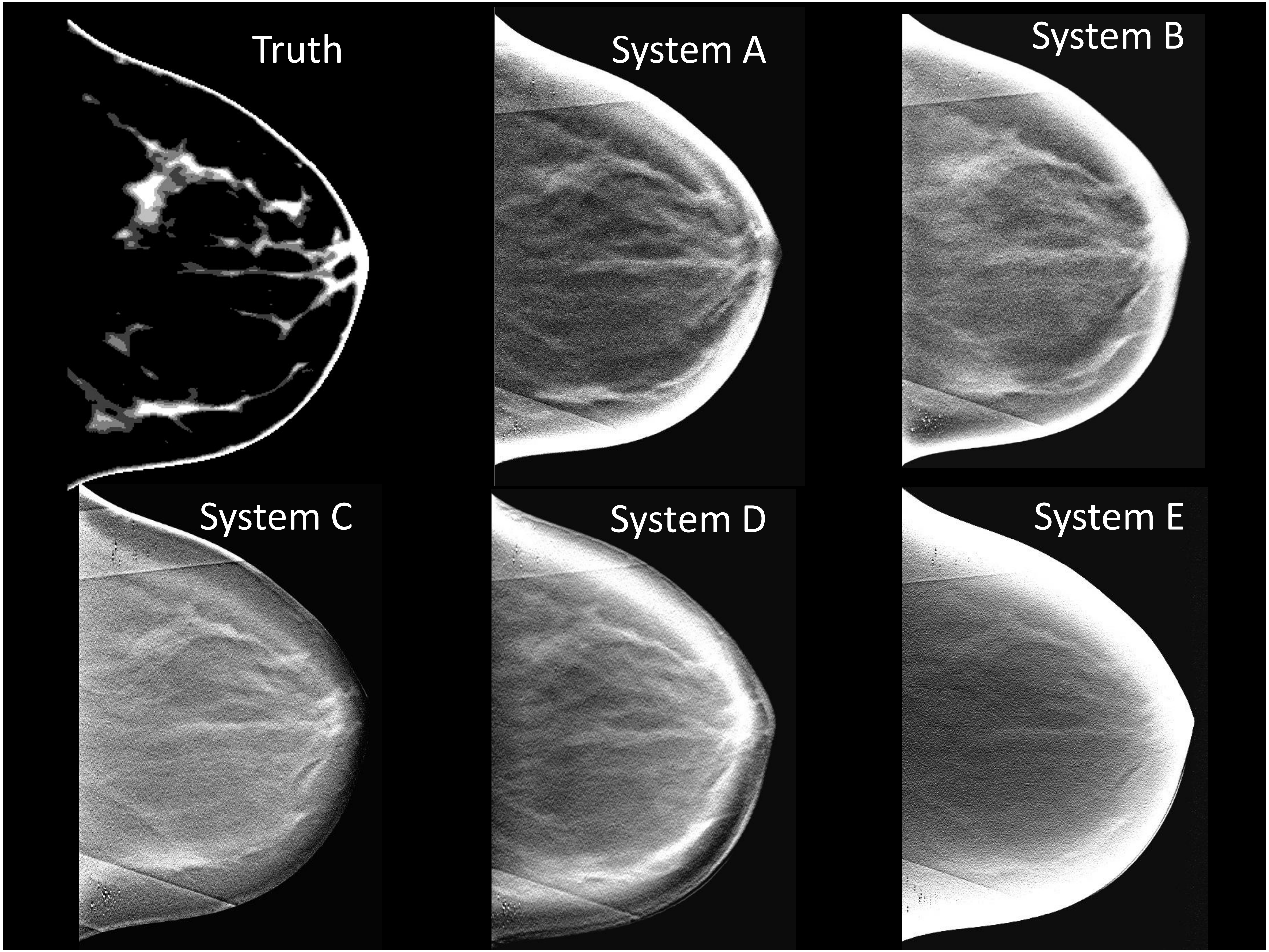
Inter system variability: 6%

Winslow et al, AAPM, 2014

Image quality in the presence of anatomical heterogeneity




Truth


Truth
System A
System B
System C
System D
System E

Ensuring quality, safety, consistency, optimality

Prospective performance assessment

Quality by inference

Å **Protocol optimization**
Å **Protocol consistency**

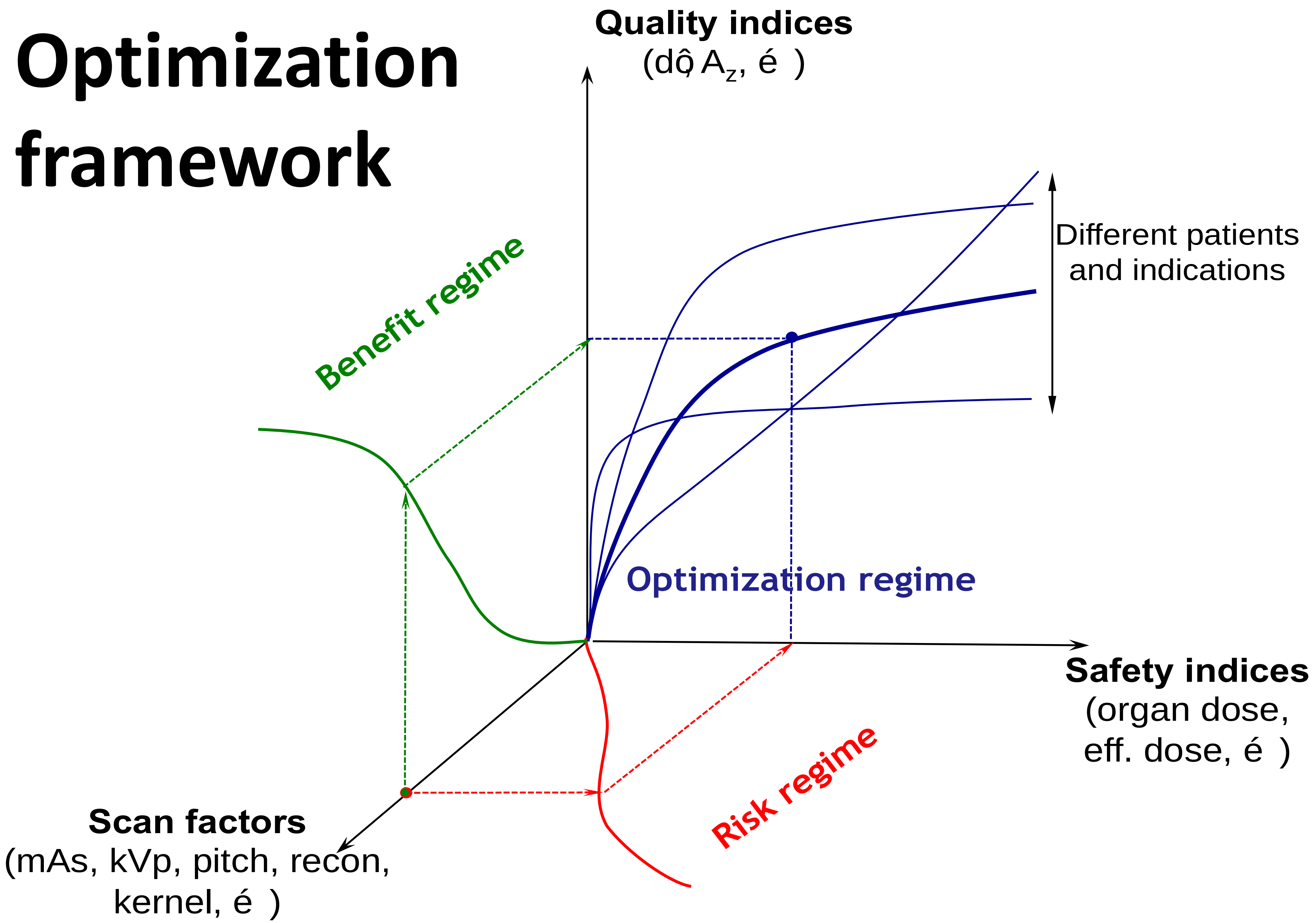
Prospective protocol definition

Quality by prescription

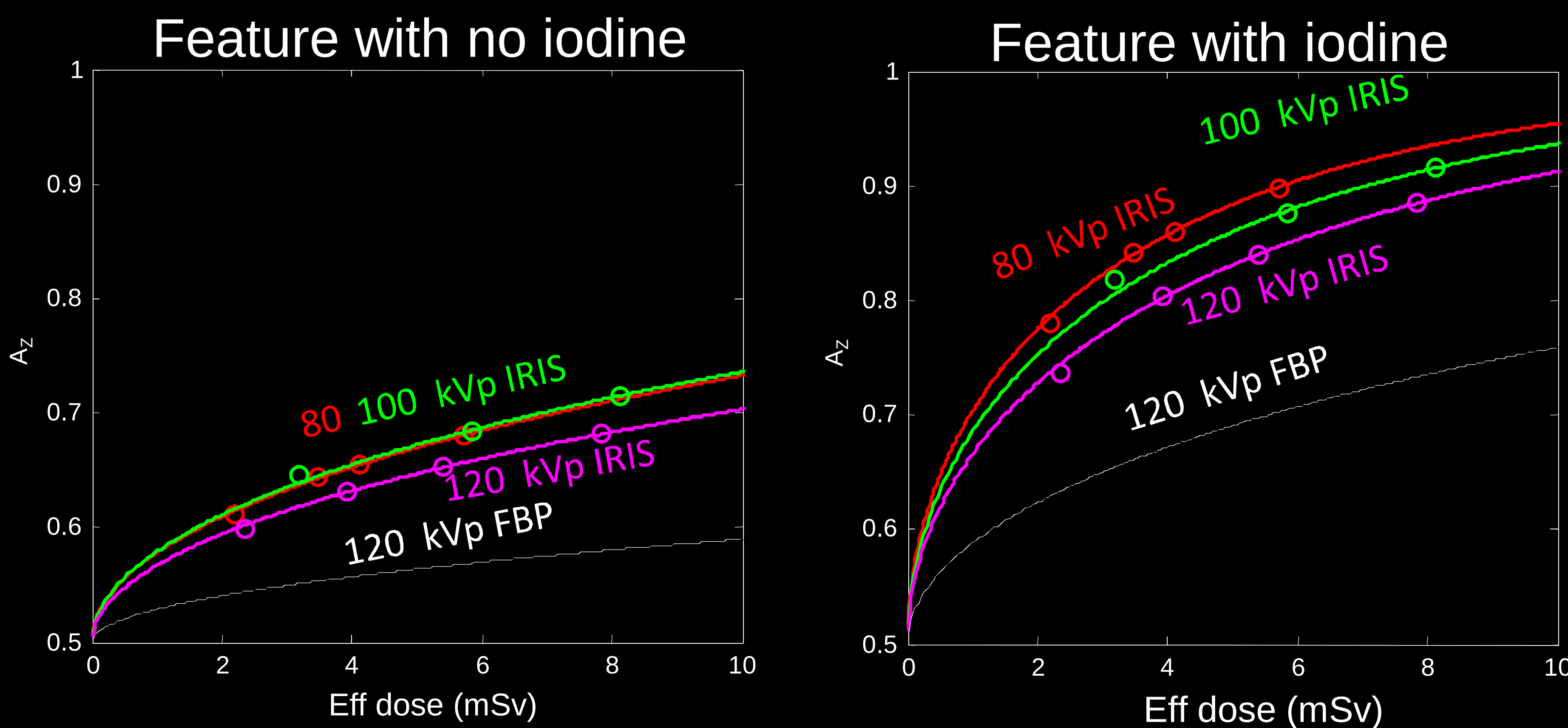
Retrospective quality assessment

Quality by outcome

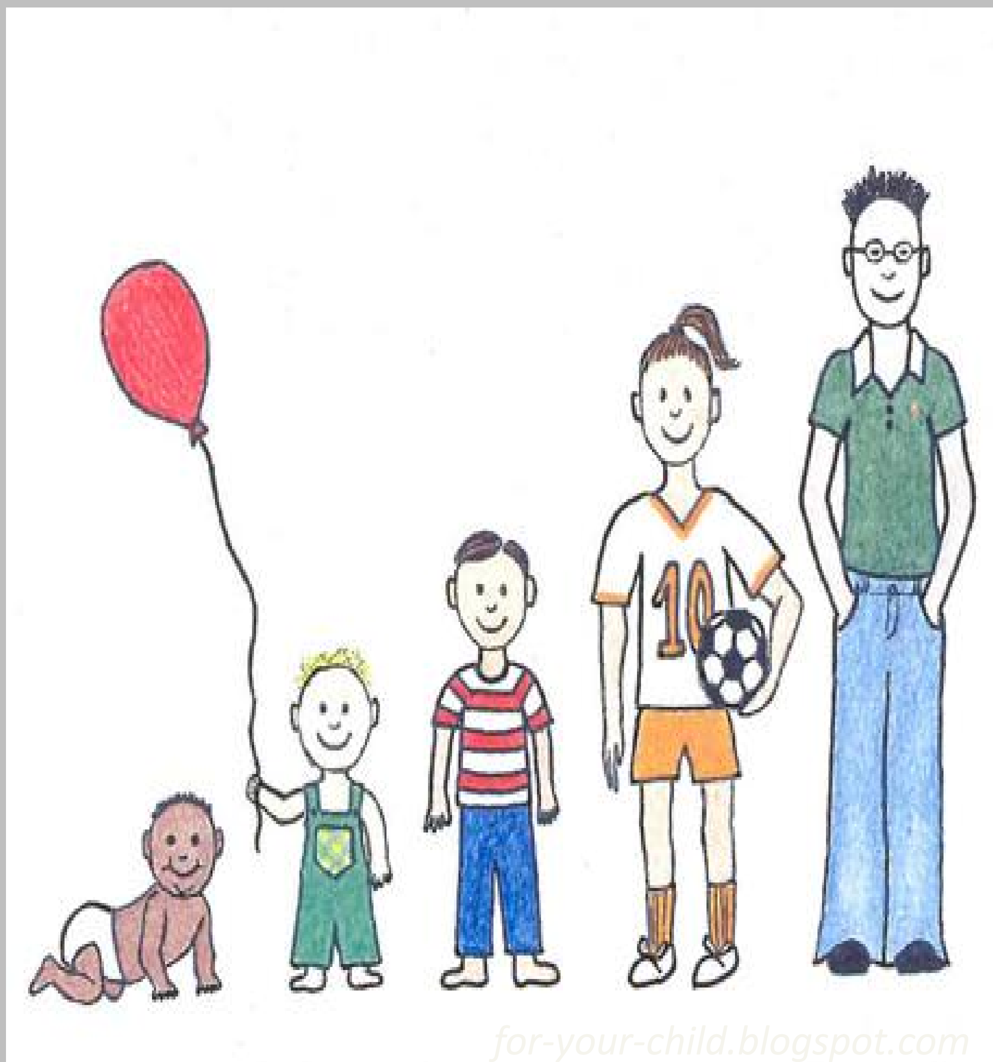
Optimization framework



Optimization of kVp-recon

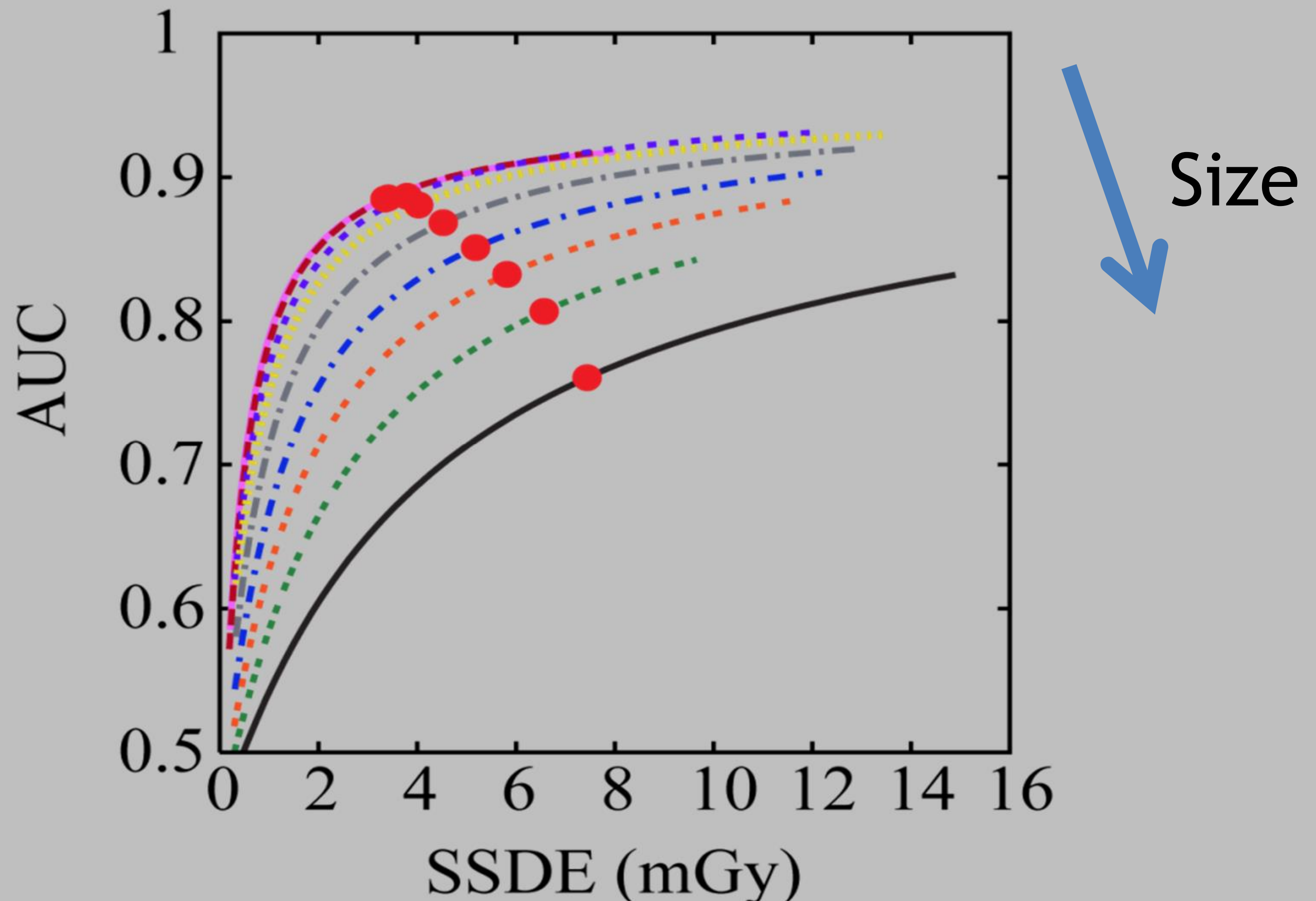


Patient size?



Optimization of dose per size

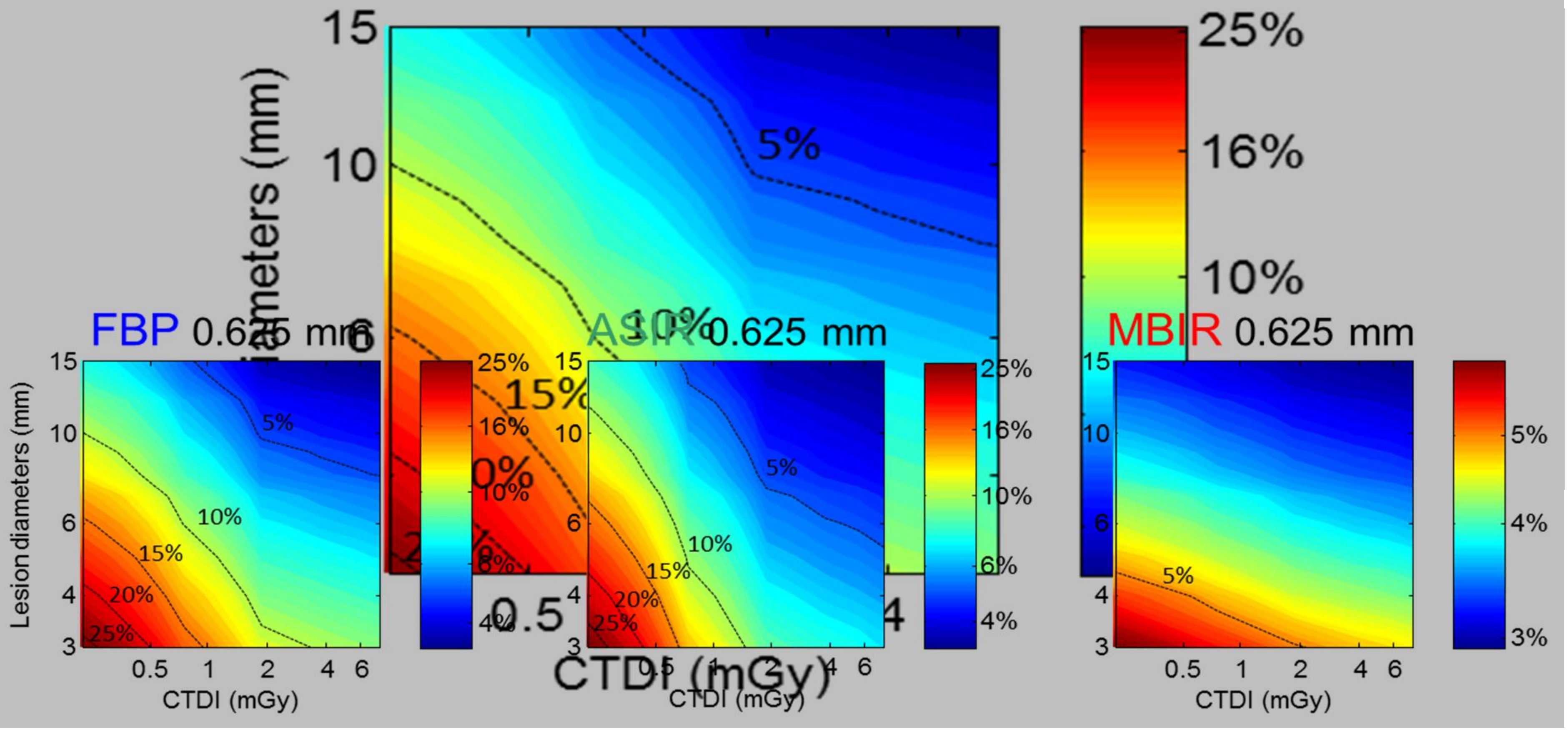
Iso-gradient optimization points to define ALARA



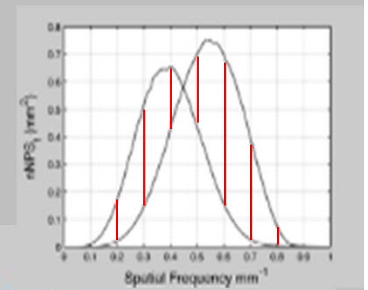
Optimization for quantification

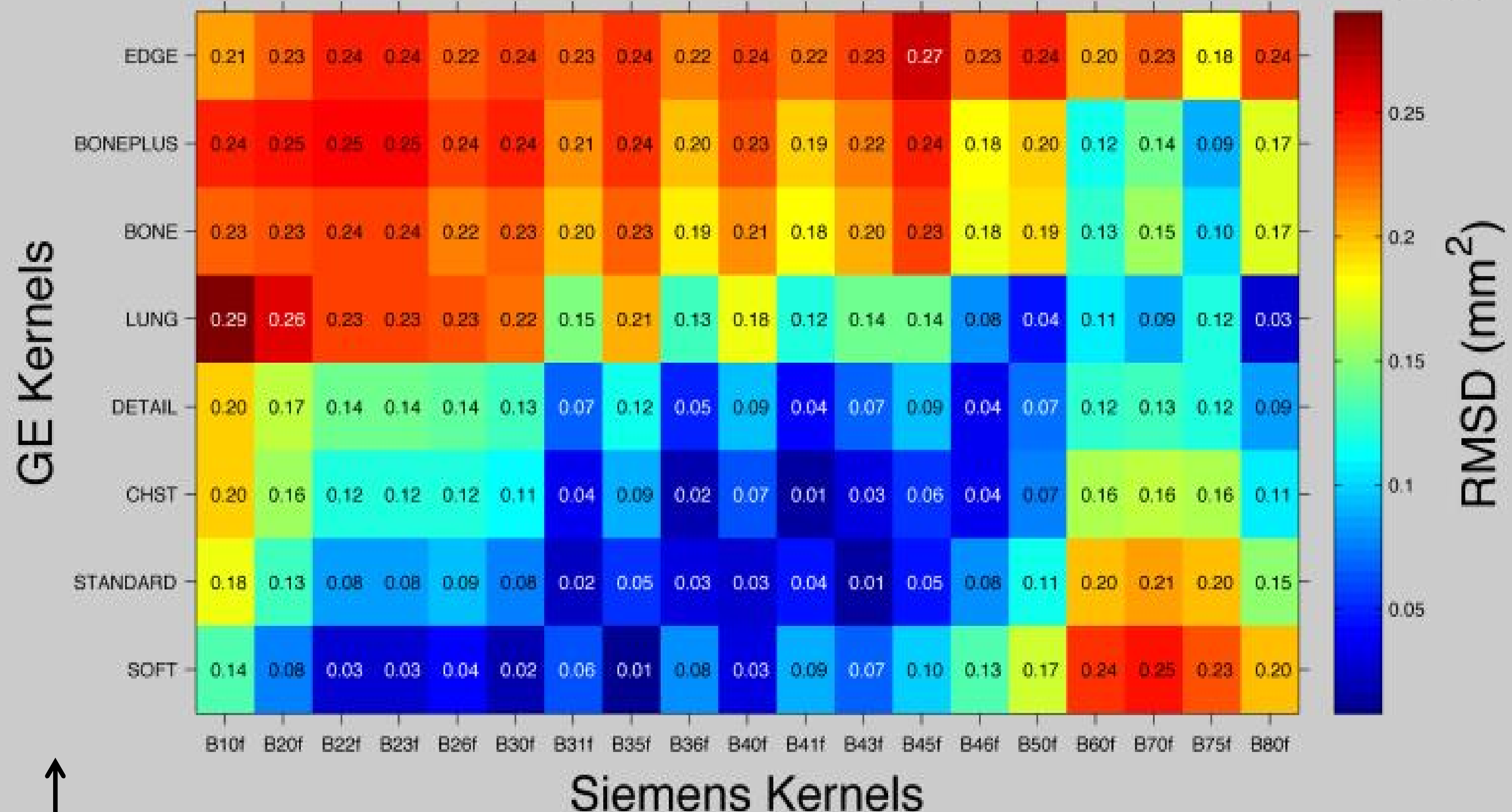
Quantitative CT volumetry

PRC: Relative difference between any two repeated quantifications of a nodule with 95% confidence



Texture similarity





Sharpness

Solomon, Samei, Med Phys, 2012

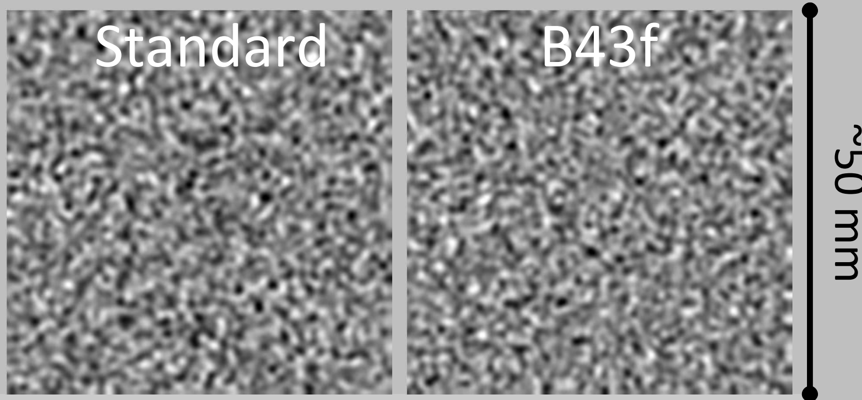
Texture similarity – matched recons

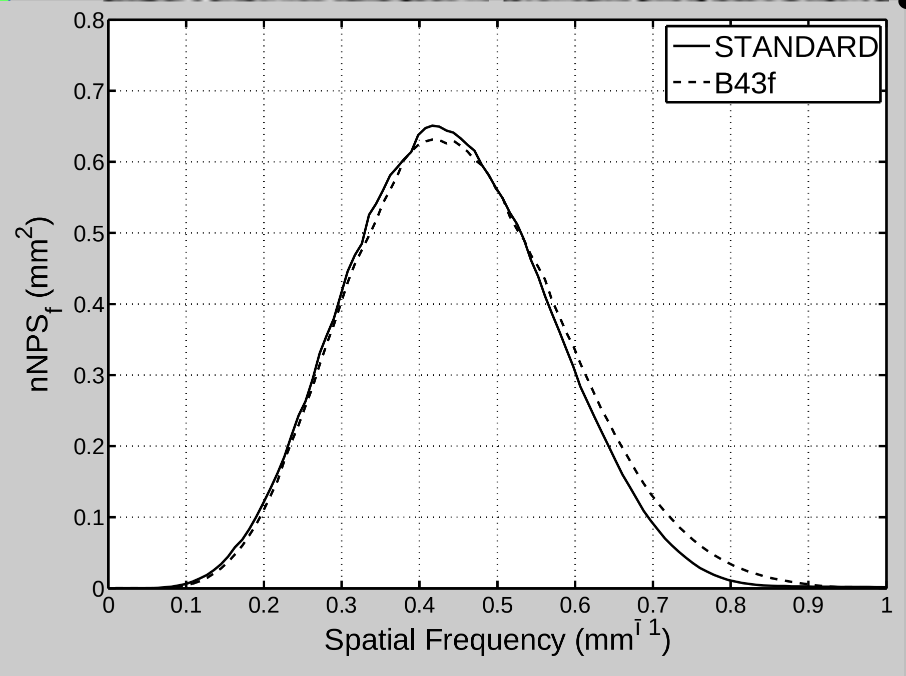
GE	Siemens	Minimum RMSD (mm^2)	Minimum |PFD| (mm^{-1})
SOFT	B35f	0.01	0.00
STANDARD	B43f	0.01	0.00
CHEST	B41f	0.01	0.01
DETAIL	B46f	0.04	0.01
LUNG	B80f	0.03	0.00
BONE	B75f	0.10	0.13
BONE+	B75f	0.09	0.12
EDGE	B75f	0.18	0.41

Solomon, Samei, Med Phys, 2012

Texture similarity – matched recons

GE	Siemens	Minimum RMSD (mm^2)	Minimum |PFD| (mm^{-1})
SOFT	B35f	0.01	0.00
STANDARD	B43f	0.01	0.00
CHEST	B41f	0.01	0.01
DETAIL	B46f	0.04	0.01
LUNG	B80f	0.03	0.00
BONE	B75f	0.10	0.13
BONE+	B75f	0.09	0.12
EDGE	B75f	0.18	0.41

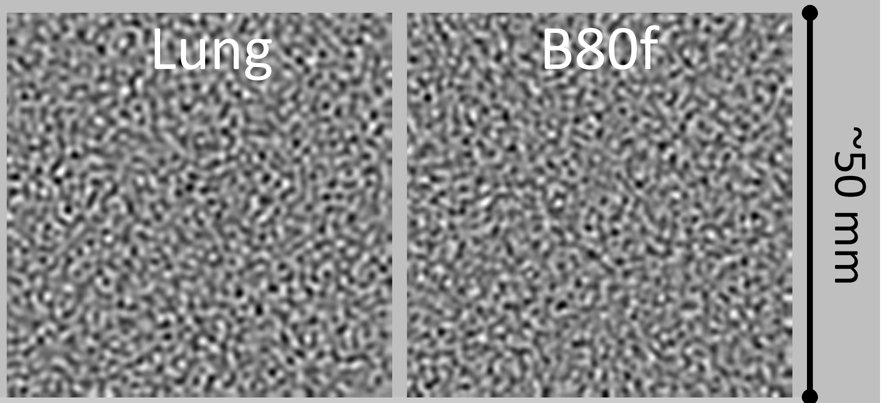


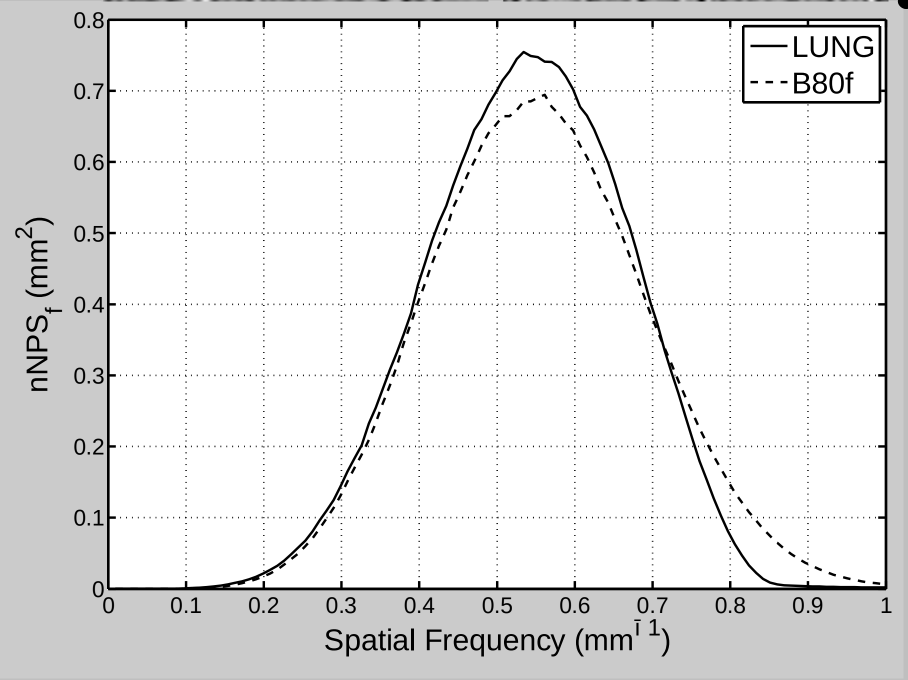


Solomon, Samei, Med Phys, 2012

Texture similarity – matched recons

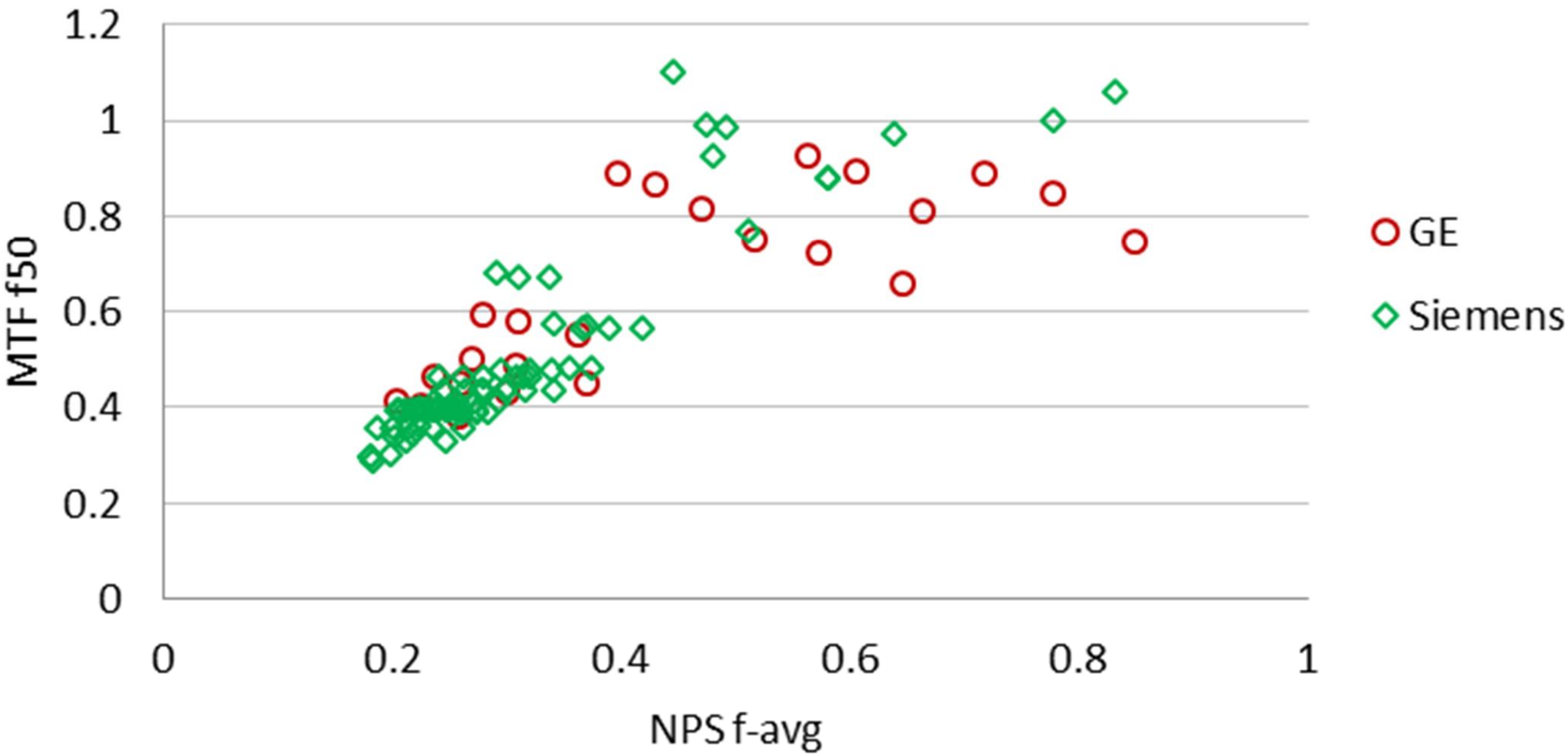
GE	Siemens	Minimum RMSD (mm^2)	Minimum |PFD| (mm^{-1})
SOFT	B35f	0.01	0.00
STANDARD	B43f	0.01	0.00
CHEST	B41f	0.01	0.01
DETAIL	B46f	0.04	0.01
LUNG	B80f	0.03	0.00
BONE	B75f	0.10	0.13
BONE+	B75f	0.09	0.12
EDGE	B75f	0.18	0.41



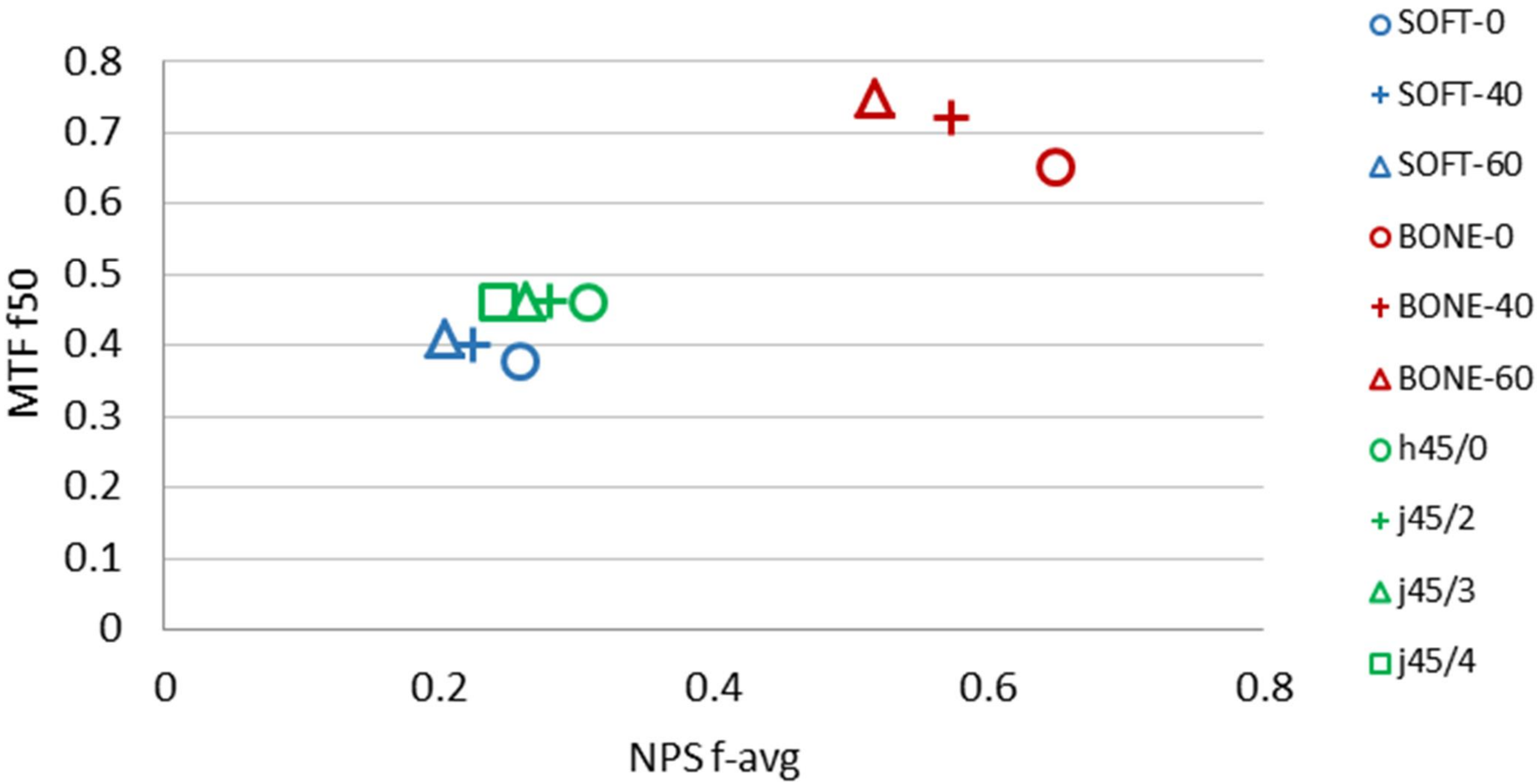


Solomon, Samei, Med Phys, 2012

Resolution/noise across recons



Resolution/noise across recons



Ensuring quality, safety, consistency, optimality

Prospective performance assessment

Quality by inference

Å **Dose monitoring - analytics**

Å **Quality tracking - analytics**

Prospective protocol definition

Quality by prescription

Retrospective quality assessment

Quality by outcome

Dose monitoring components

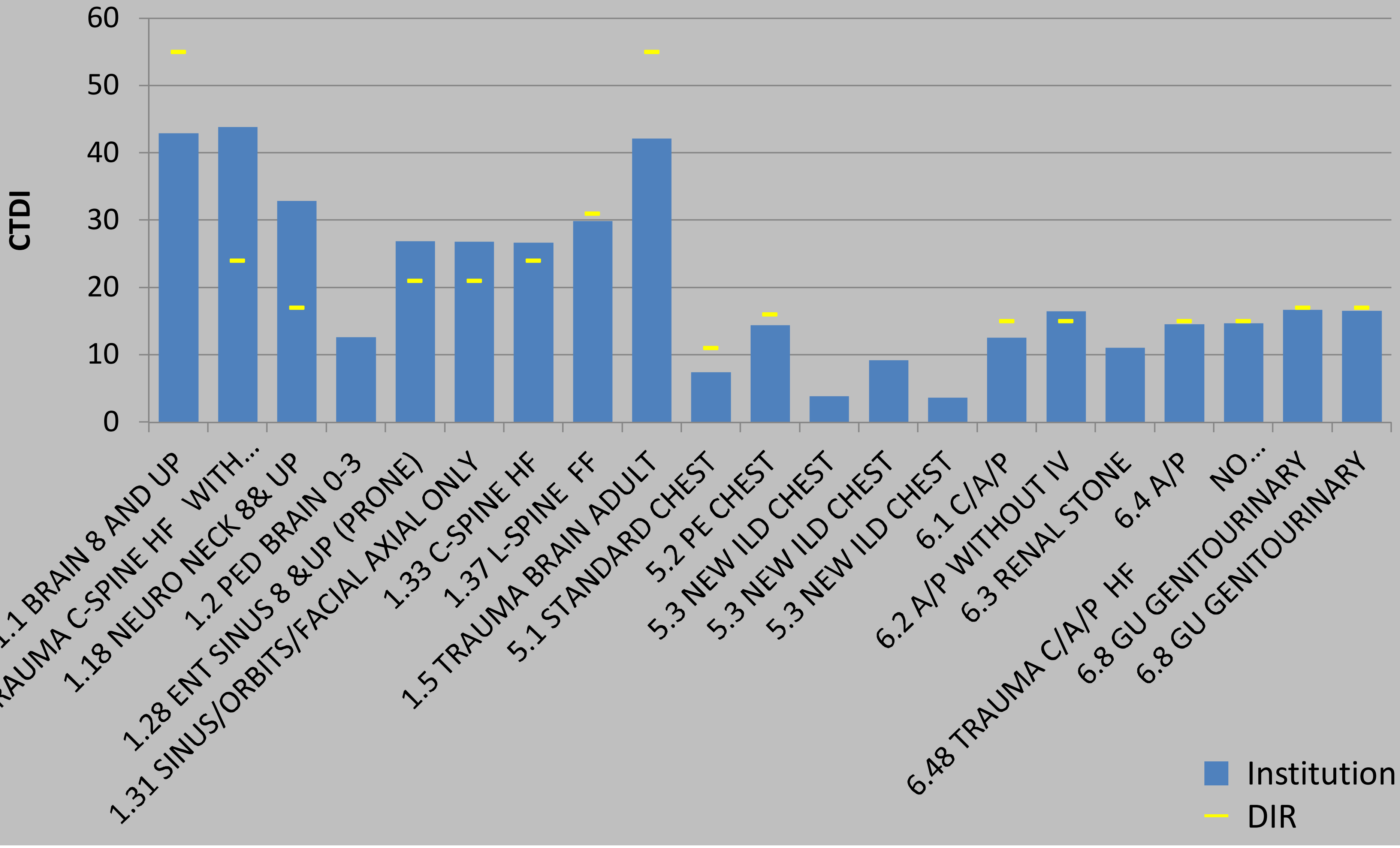
A. **Access**: Connection and collection of dose-relevant data
B. **Integrity**: Data quality and accuracy
C. **Metrology**: Meaningful quantities to monitor
D. **Analytics**: From data to knowledge
E. **Informatics**: Dose monitoring as a secure, integrated solution

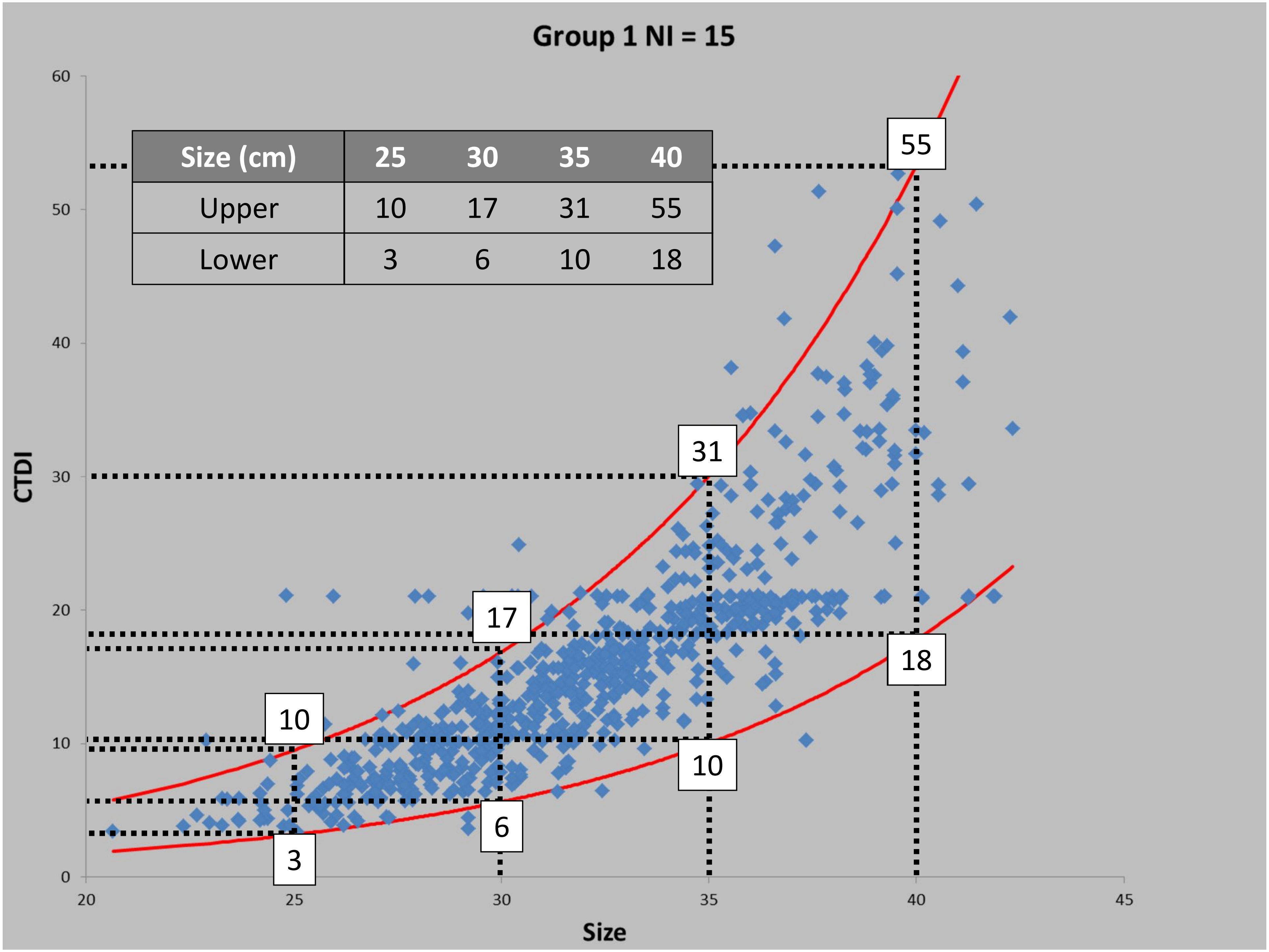
Dose analytics

1. Benchmarking institution against national DRLs
2. Defining protocol- and size-specific DRLs
3. Identifying outliers
4. Ascertaining trends over time
5. Ascertaining inter-system variability
6. Tracking protocol discrepancy
7. Investigating individual doses
8. Improving operational consistency

Frush, Samei, Medscape Radiology, in print 2015

Benchmarking institution against national DRLs




Group 1 NI = 15
CTDI
Size
0
10
20
30
40
50
60
20
25
30
35
40
45
Size (cm) 25 30 35 40
Upper 10 17 31 55
Lower 3 6 10 18
55
31
17
10
18
10
6
3

max mA						700		
DFOV (cm)						per patient	per patient	
Iterative Reconstruction						40%	40%	
Recon Algorithm						Standard	Standard	
Recon Mode						Full	Plus	
AUTO APPS DMPR						N/A	Yes/Coronal	
CTDI Patient Width 25cm								
CTDI Patient Width 30cm								
CTDI Patient Width 35cm								
CTDI Patient Width 40cm								
	Target					17		
	Lower Guideline					8		

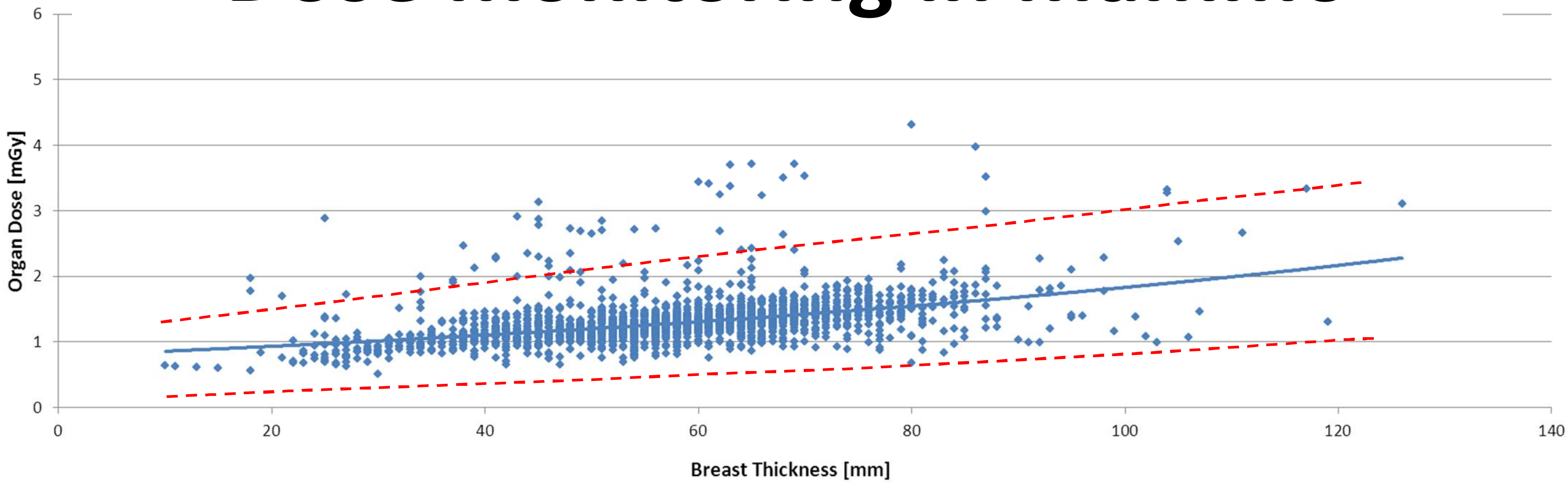
Upper Guideline	9
Target	6
Lower Guideline	3

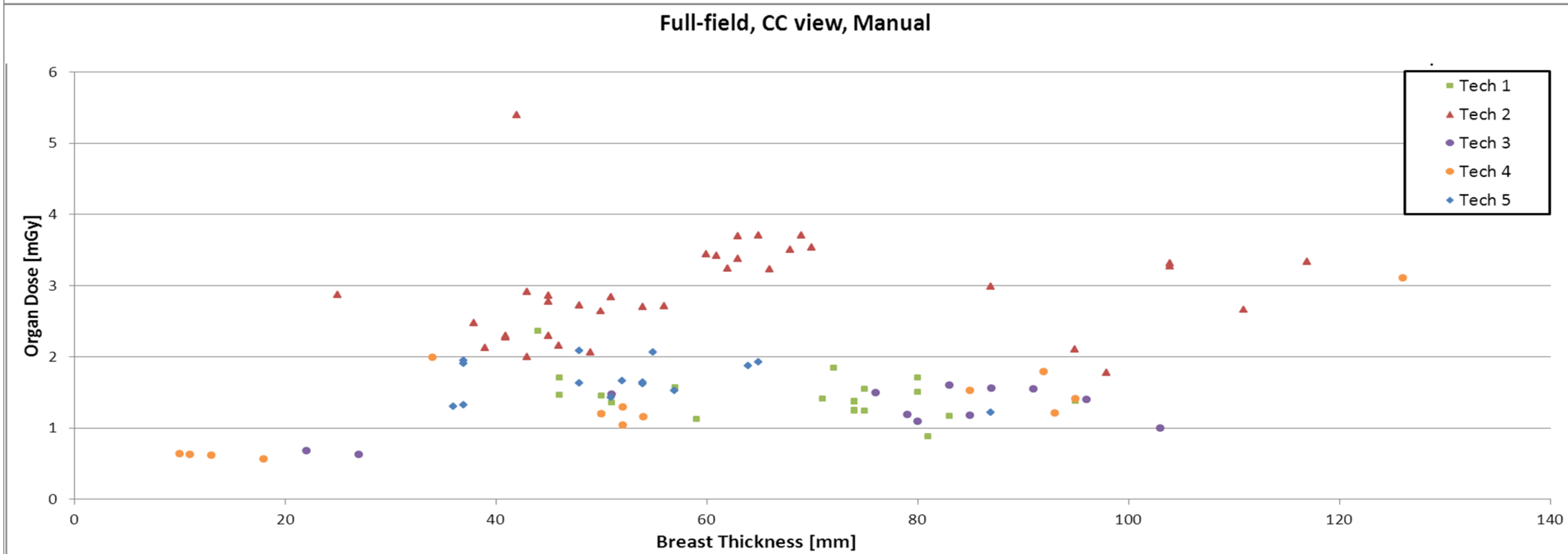
Notes

r/o abcess always MD check
If abcess radiologist to stipulate if oral is needed

Contrast Contraindications:

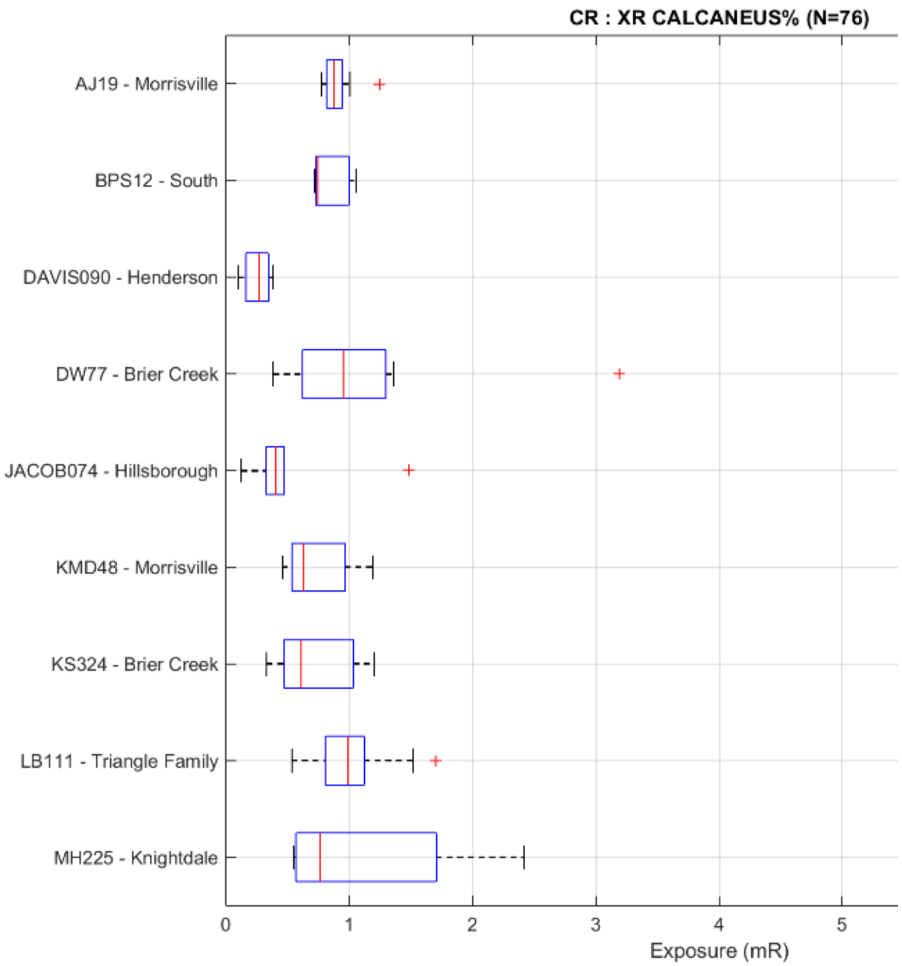
Dose monitoring in mammo



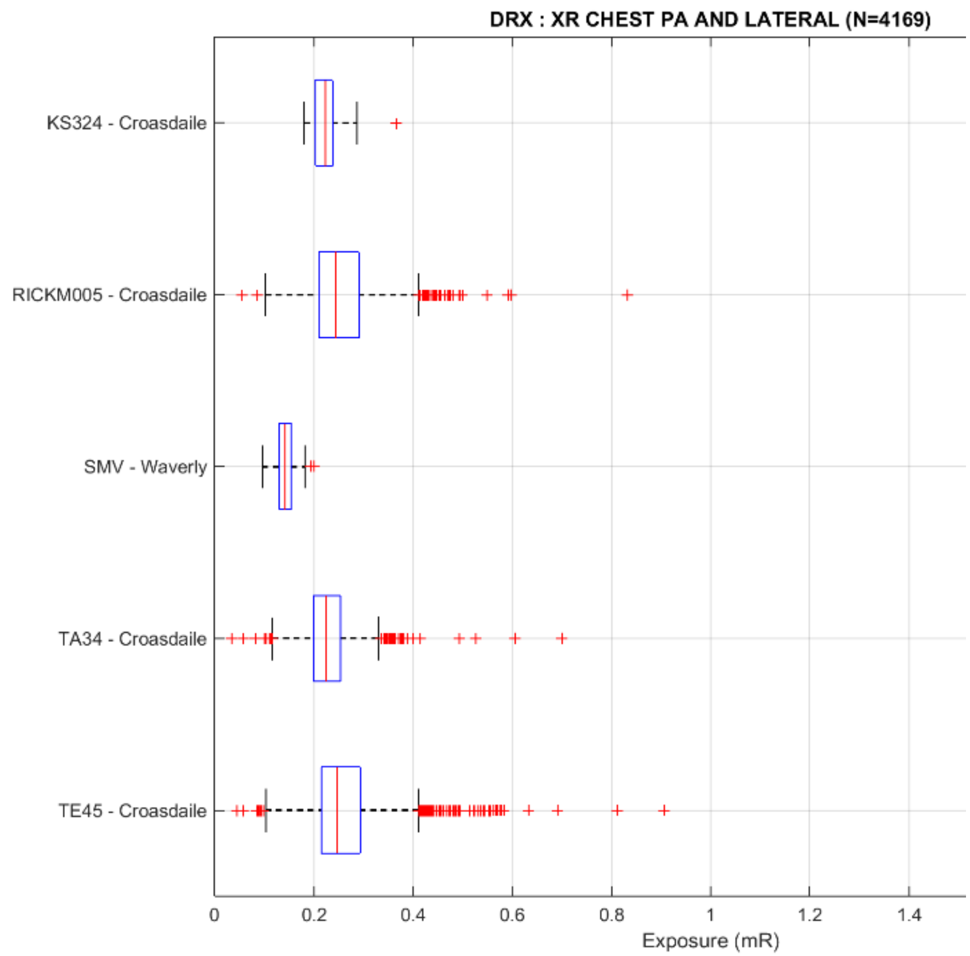


Chest exposures by operator and Clinic

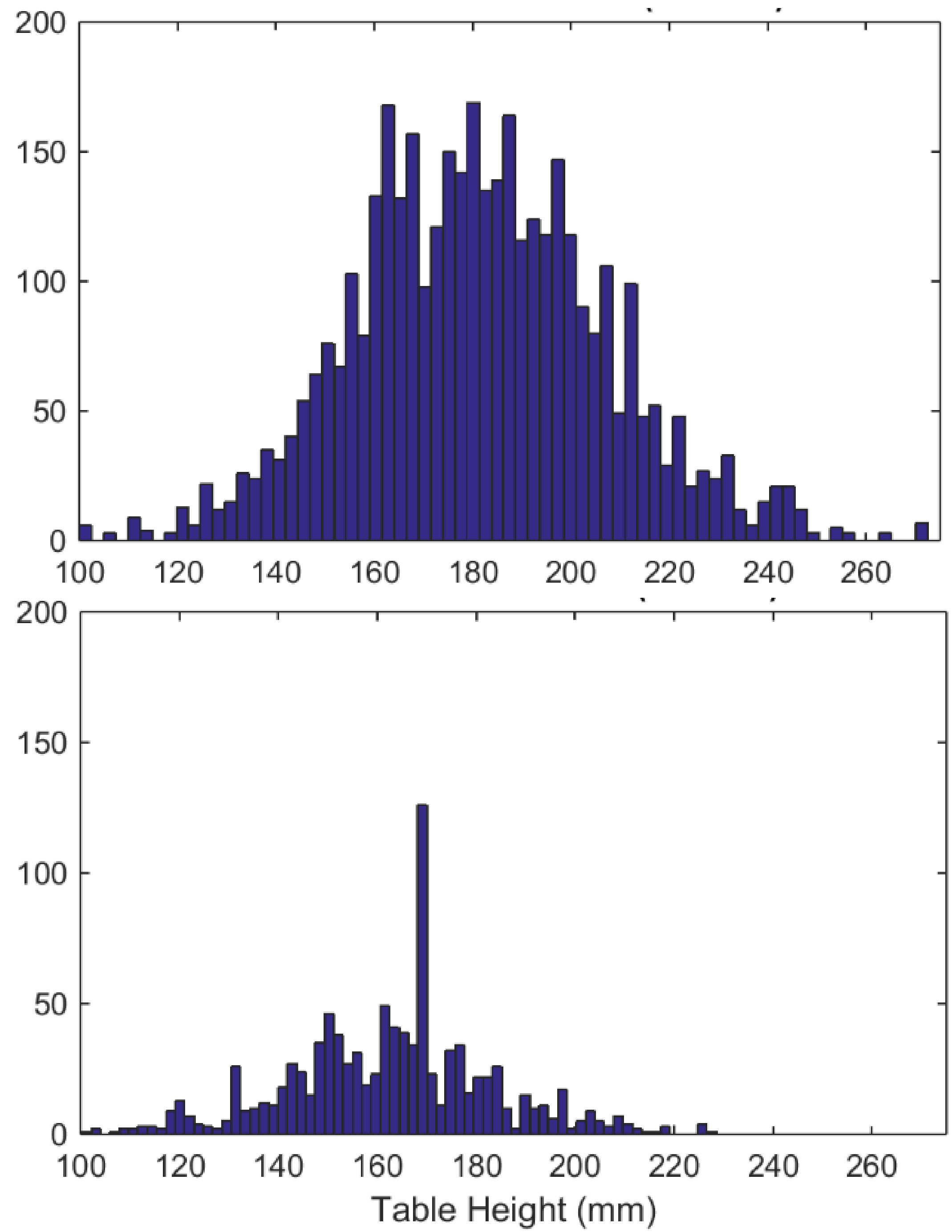
CR

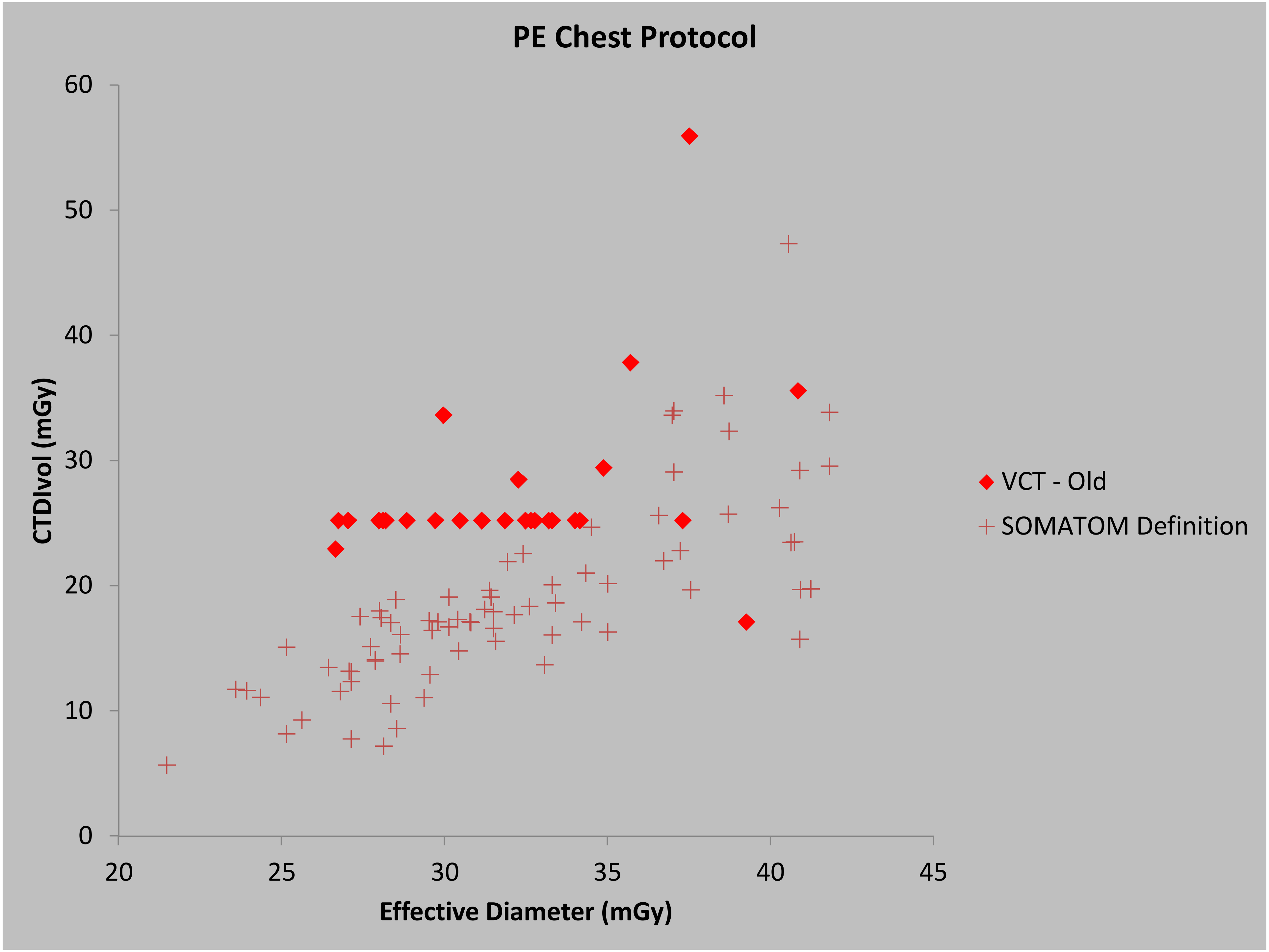


DR

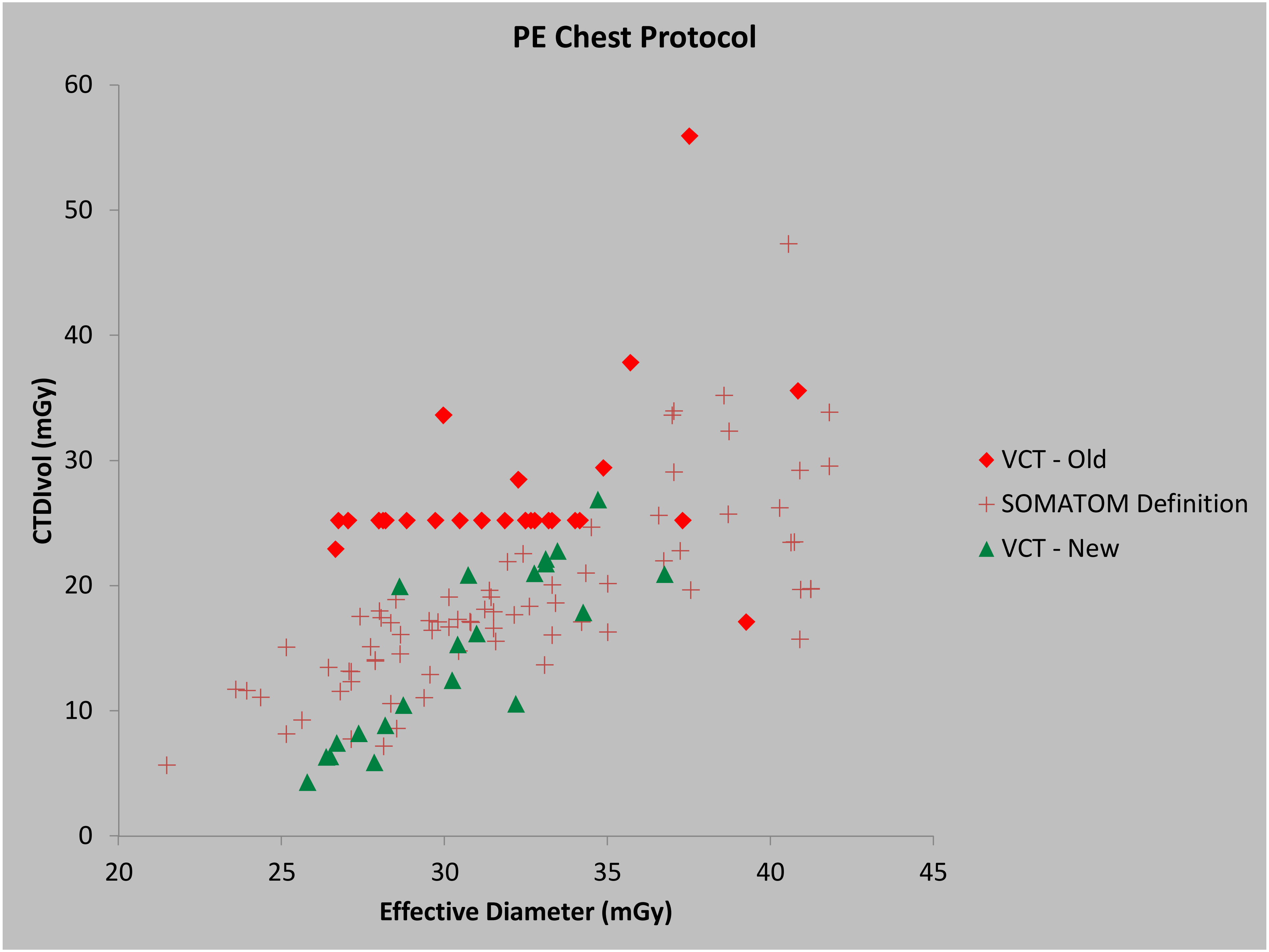


CT Table Height

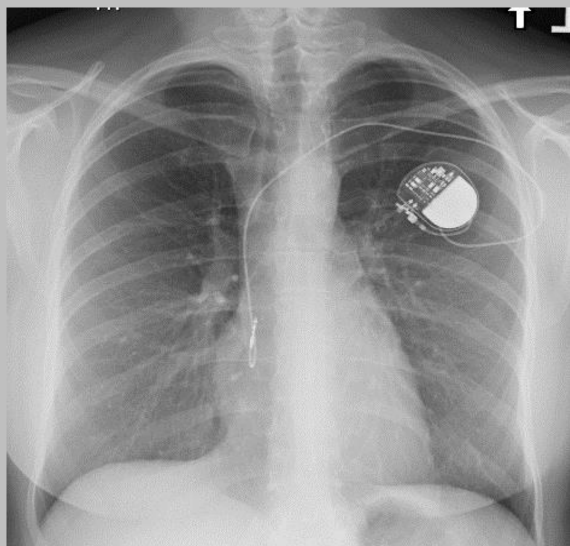


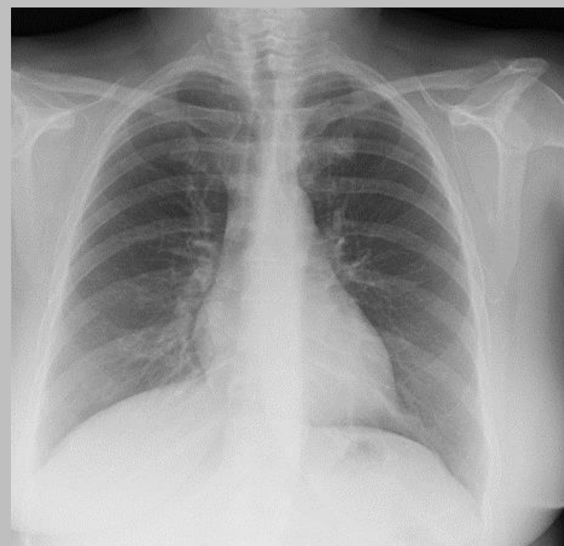


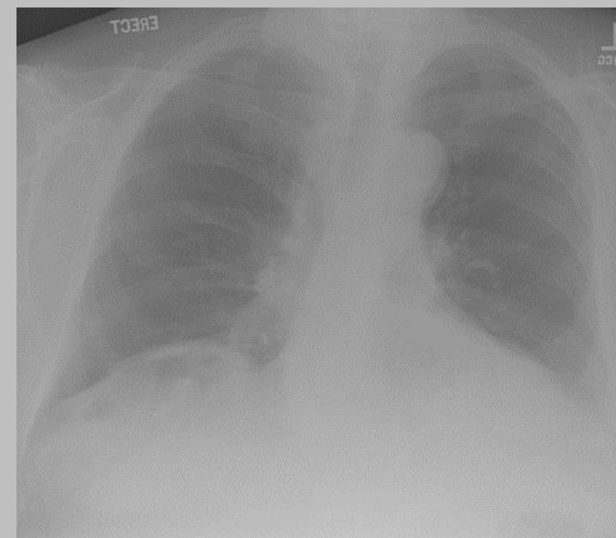
PE Chest Protocol
60
50
40
30
20
10
0
20
25
30
35
40
45
CTDIvol (mGy)
Effective Diameter (mGy)
VCT - Old
SOMATOM Definition

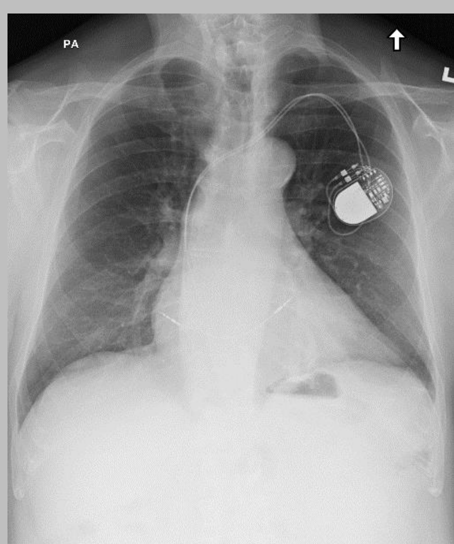

PE Chest Protocol
60
50
40
30
20
10
0
CTDIvol (mGy)
20
25
30
35
40
45
Effective Diameter (mGy)
VCT - Old
SOMATOM Definition
VCT - New

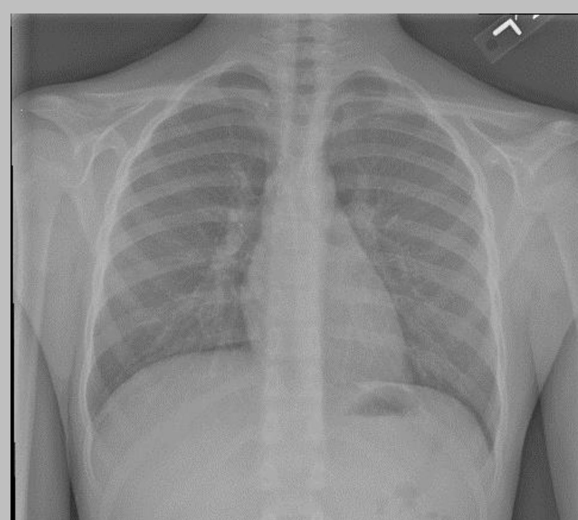
Clinical image quality?

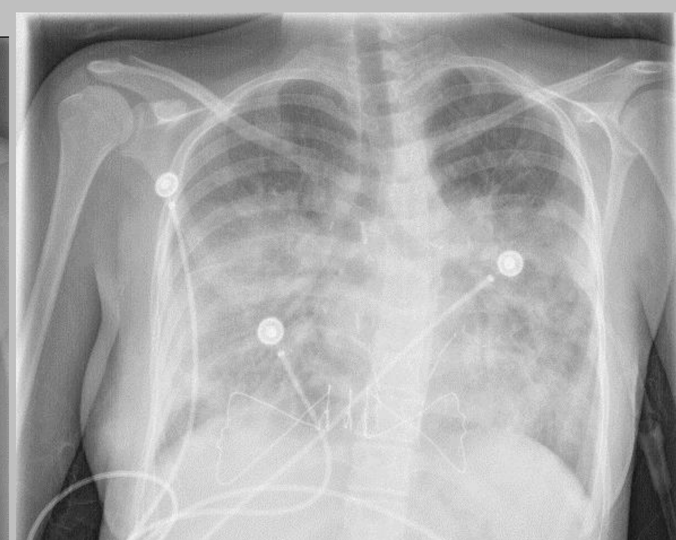






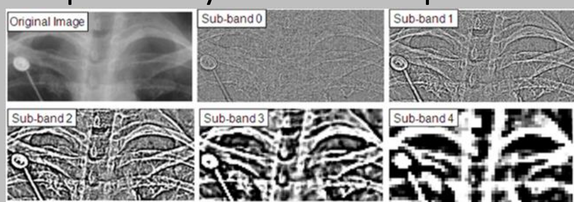


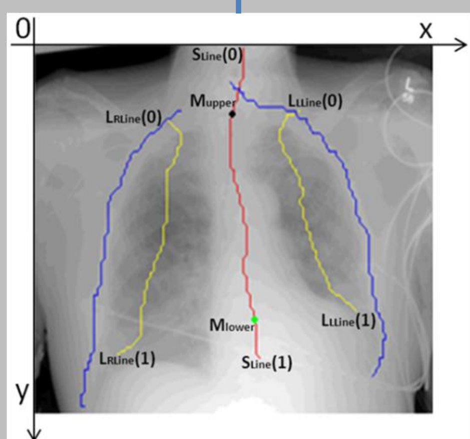




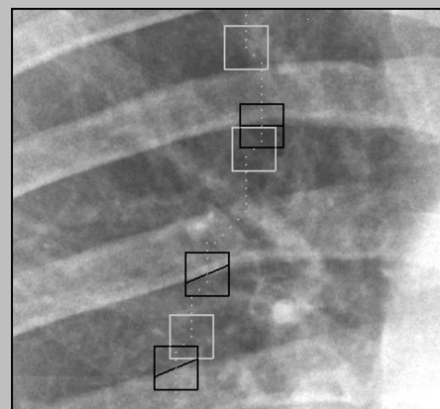
Clinical image quality monitoring

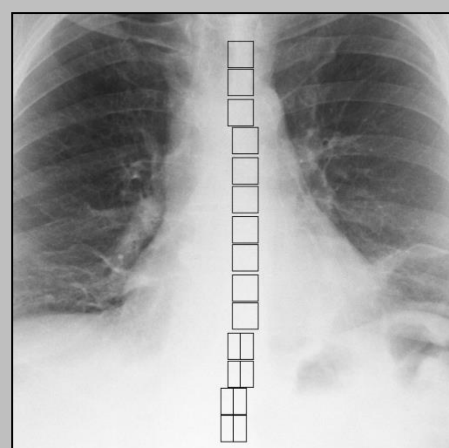
Laplacian Pyramid Decomposition

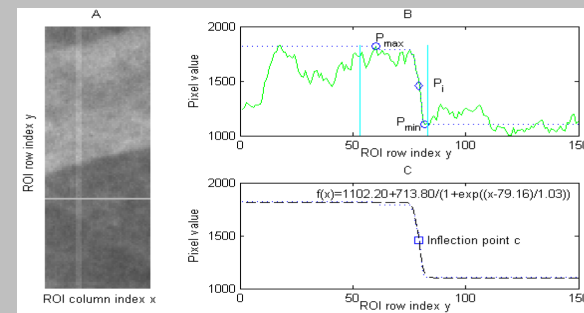




Thorax linear landmark detection







1. Lung grey level
2. Lung detail
3. Lung noise

4. Rib-lung contrast
5. Rib sharpness

6. Mediastinum detail
7. Mediastinum noise
8. Mediastinum alignment

9. Subdiaphragm-lung contrast
10. Subdiaphragm area

Lin et al, Med Phys 2012
Samei et al, Med Phys 2014

Mediastinum noise

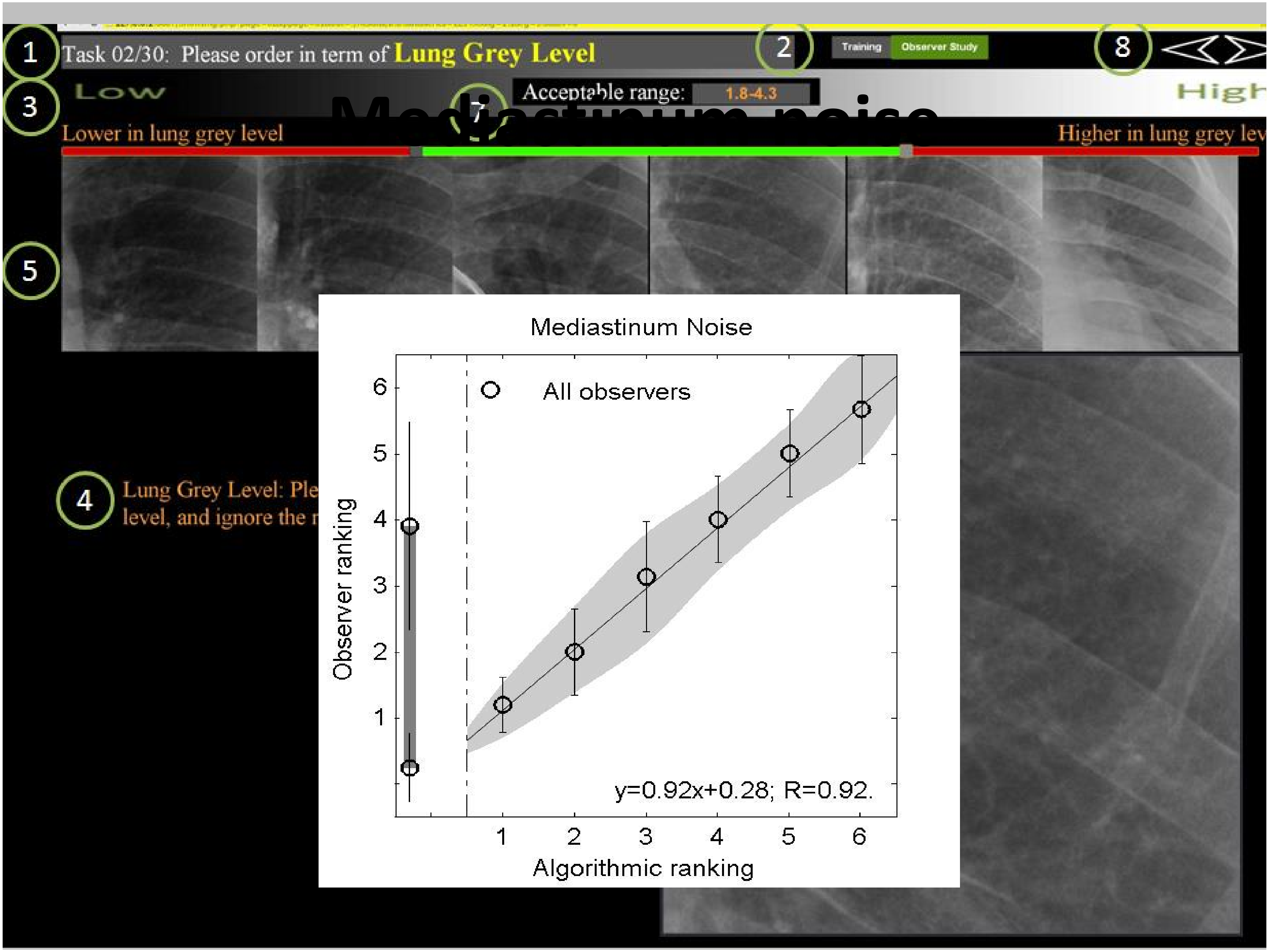
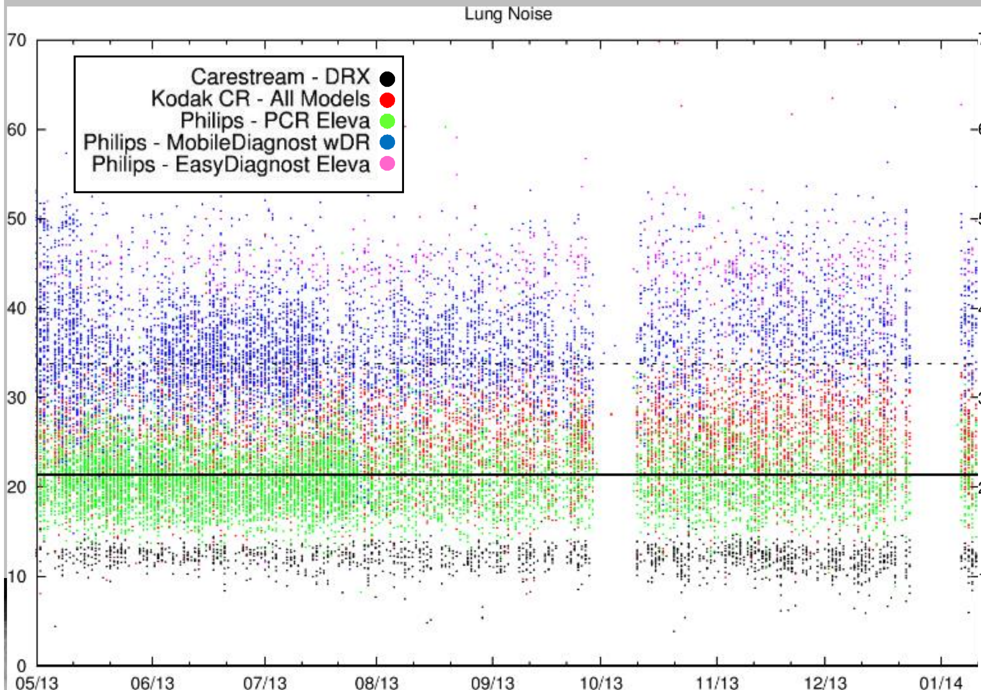
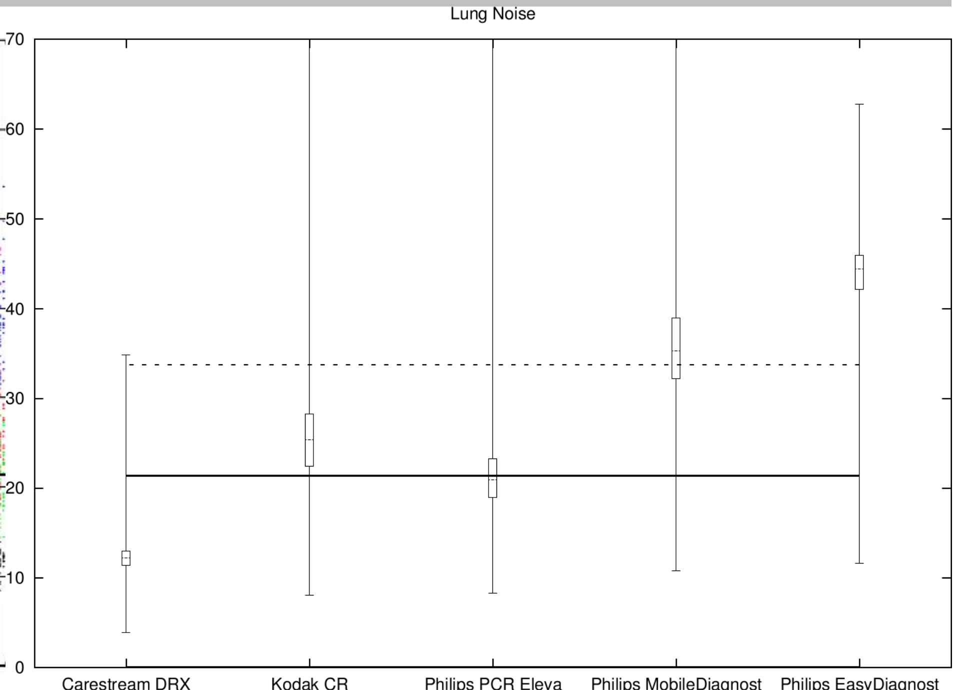
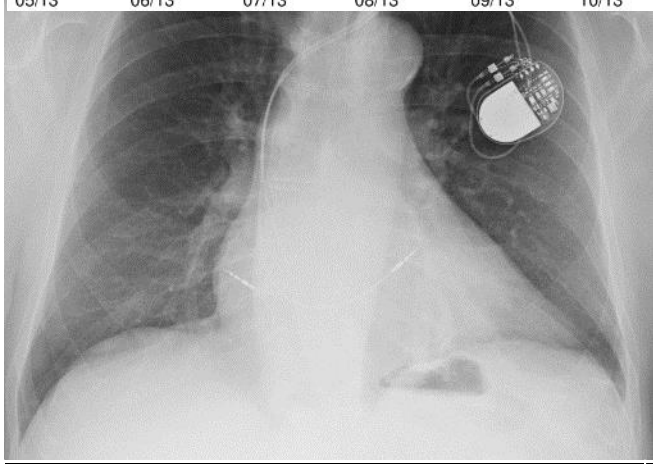
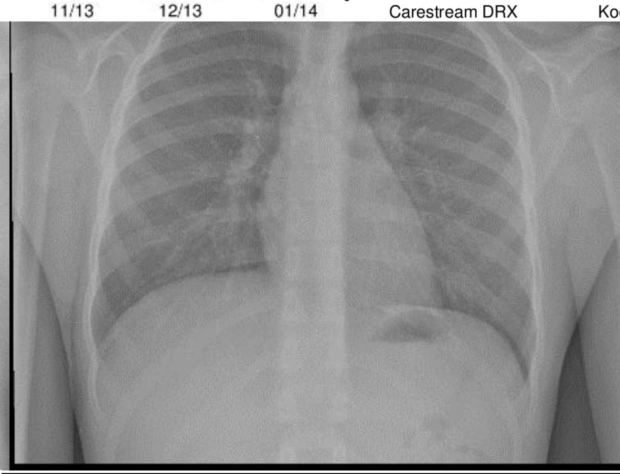


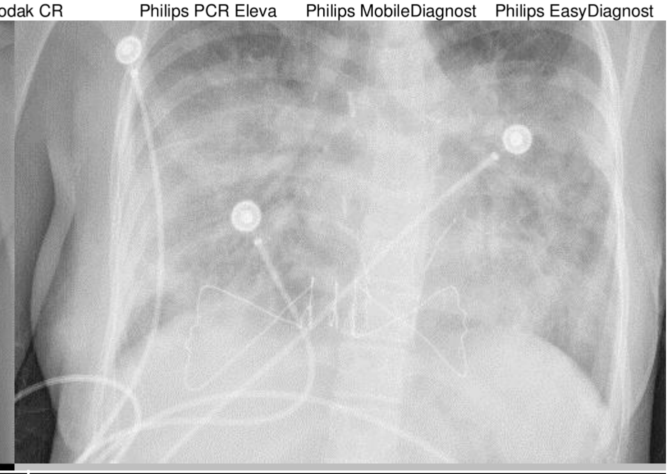
Image quality reference levels – lung noise





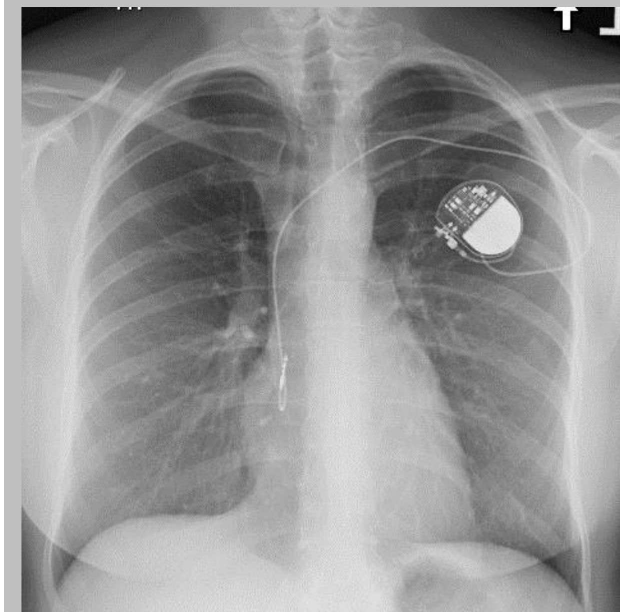


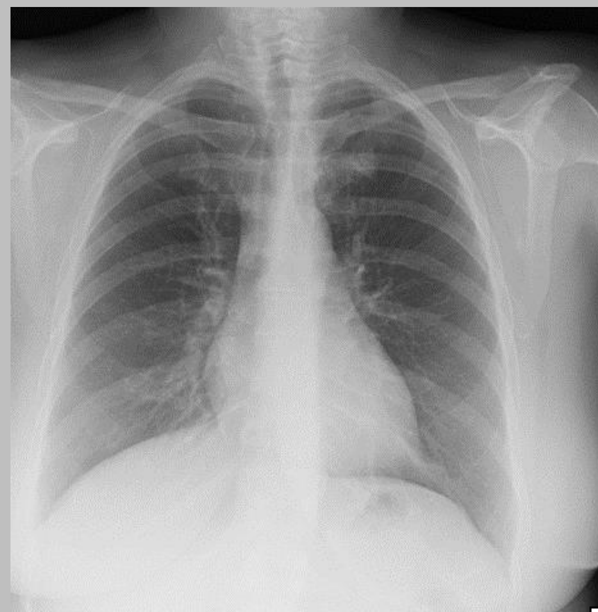


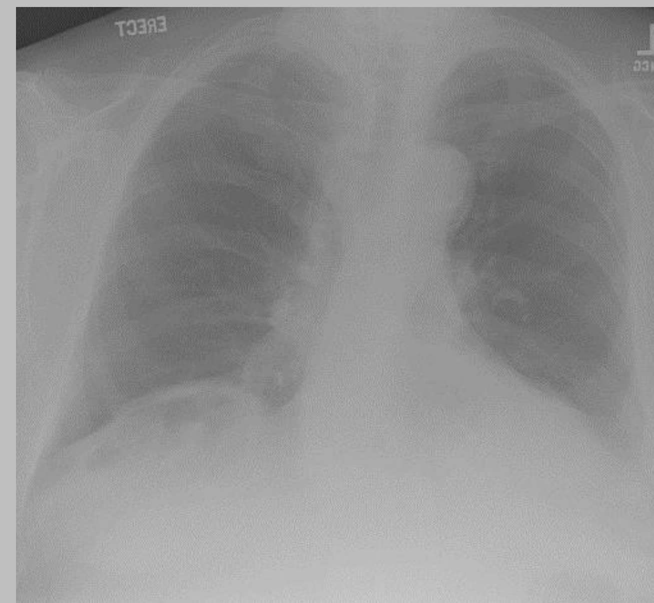


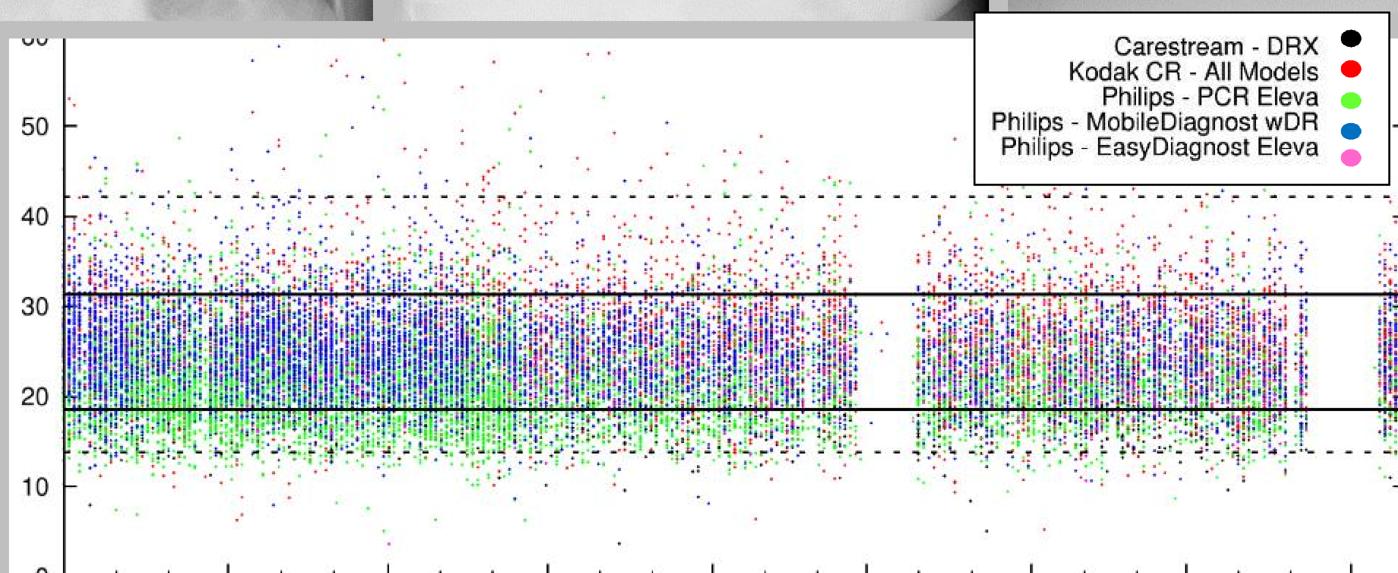
Quality	Acceptable	Poor

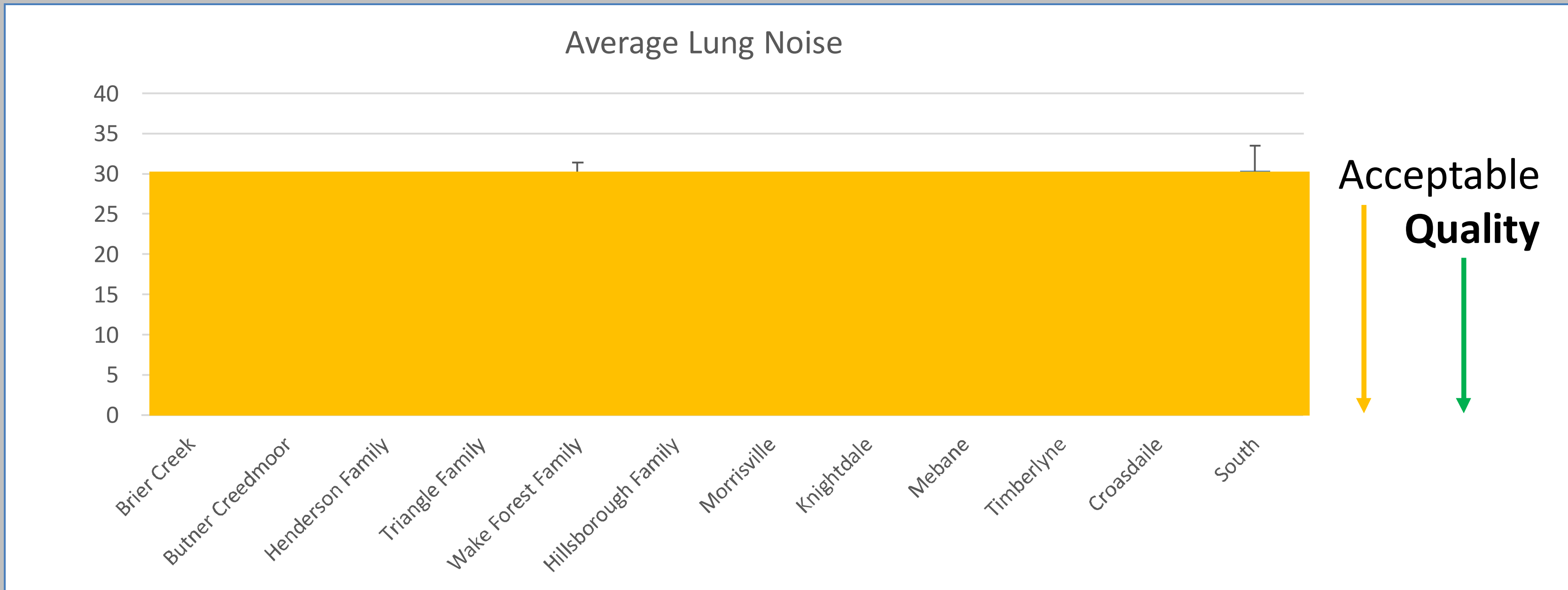
Lung detail



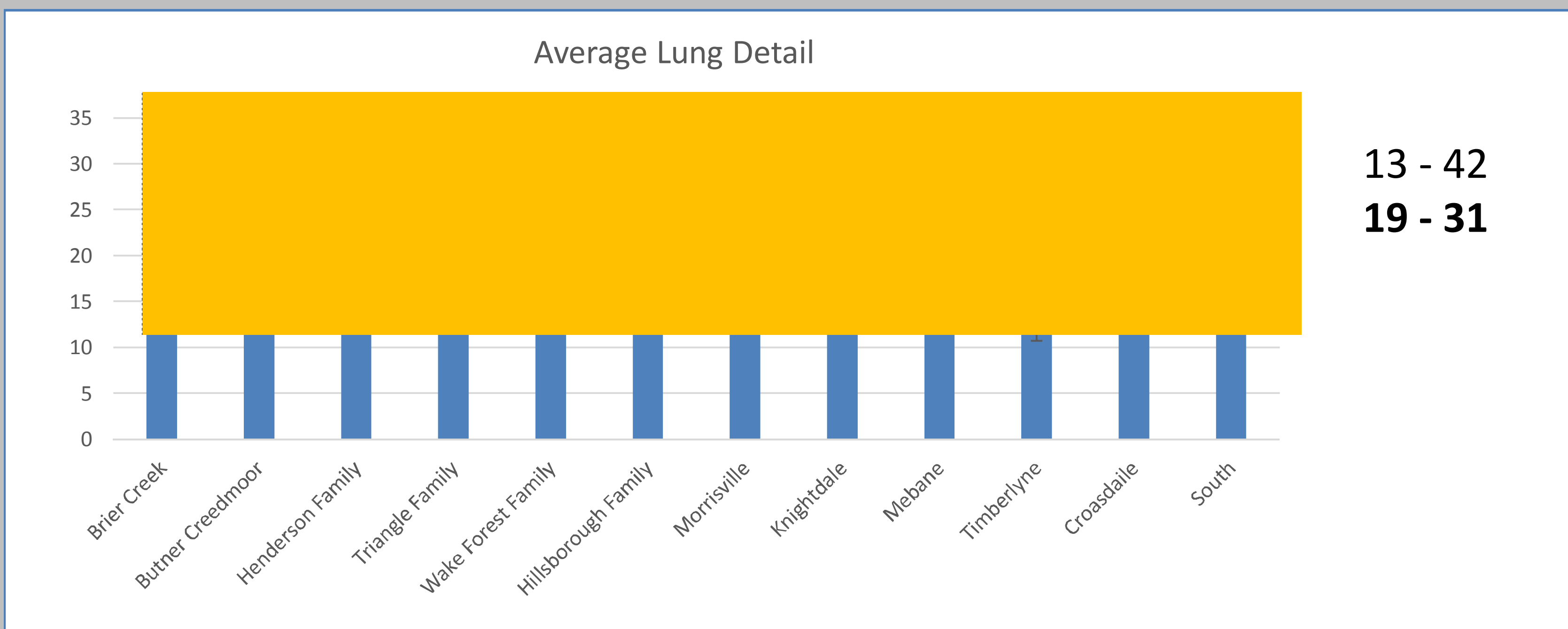




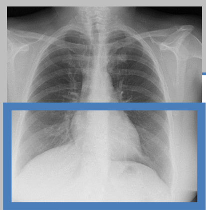

Carestream - DRX
Kodak CR - All Models
Philips - PCR Eleva
Philips - MobileDiagnost wDR
Philips - EasyDiagnost Eleva
50
40
30
20
10
0



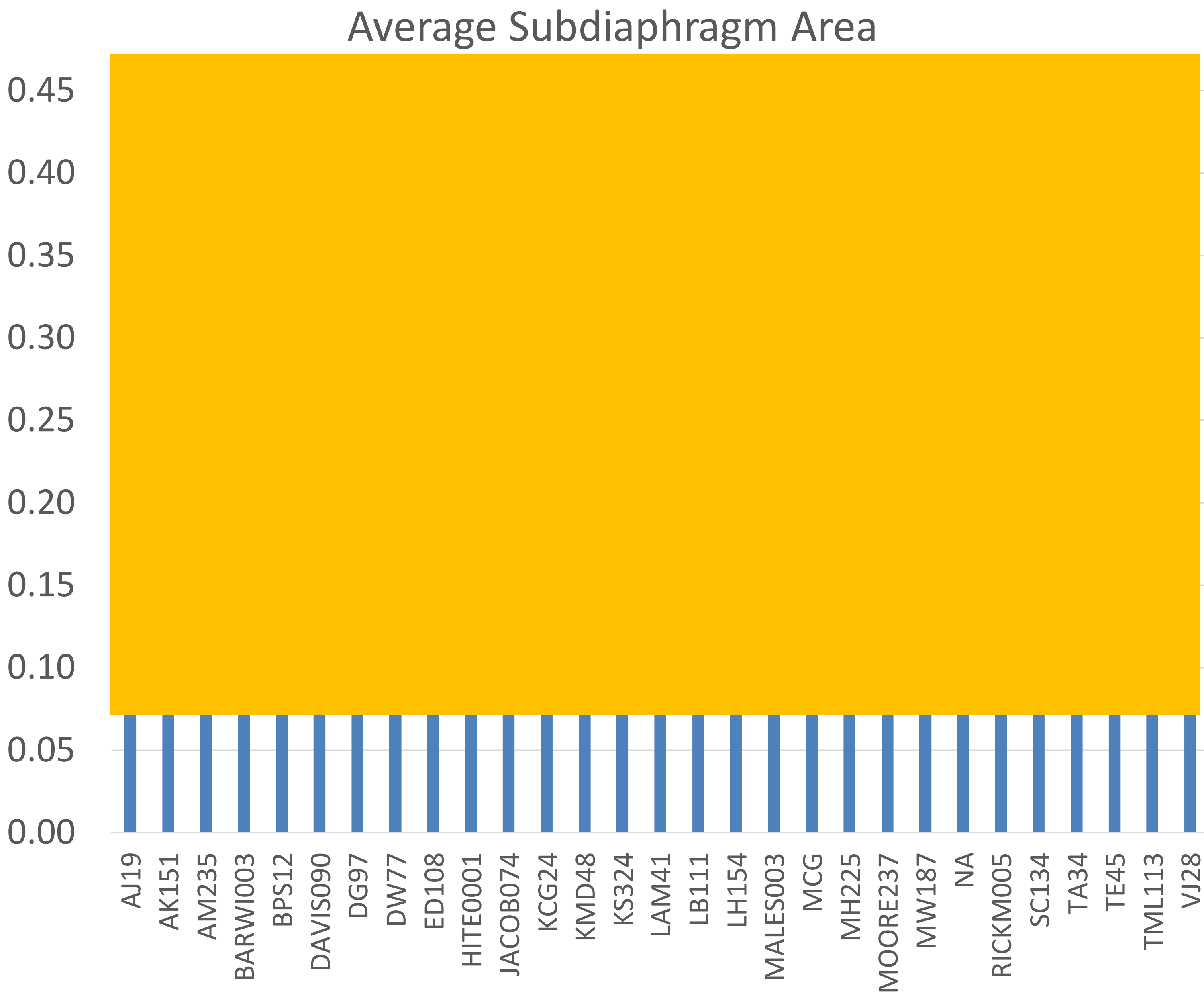
Average Lung Noise
40
35
30
25
20
15
10
5
0
Brier Creek
Butner Creedmoor
Henderson Family
Triangle Family
Wake Forest Family
Hillsborough Family
Morrisville
Knightdale
Mebane
Timberlyne
Croasdaile
South
Acceptable
Quality



Average Lung Detail
35
30
25
20
15
10
5
0
Brier Creek
Butner Creedmoor
Henderson Family
Triangle Family
Wake Forest Family
Hillsborough Family
Morrisville
Knightdale
Mebane
Timberlyne
Croasdaile
South
13 - 42
19 - 31

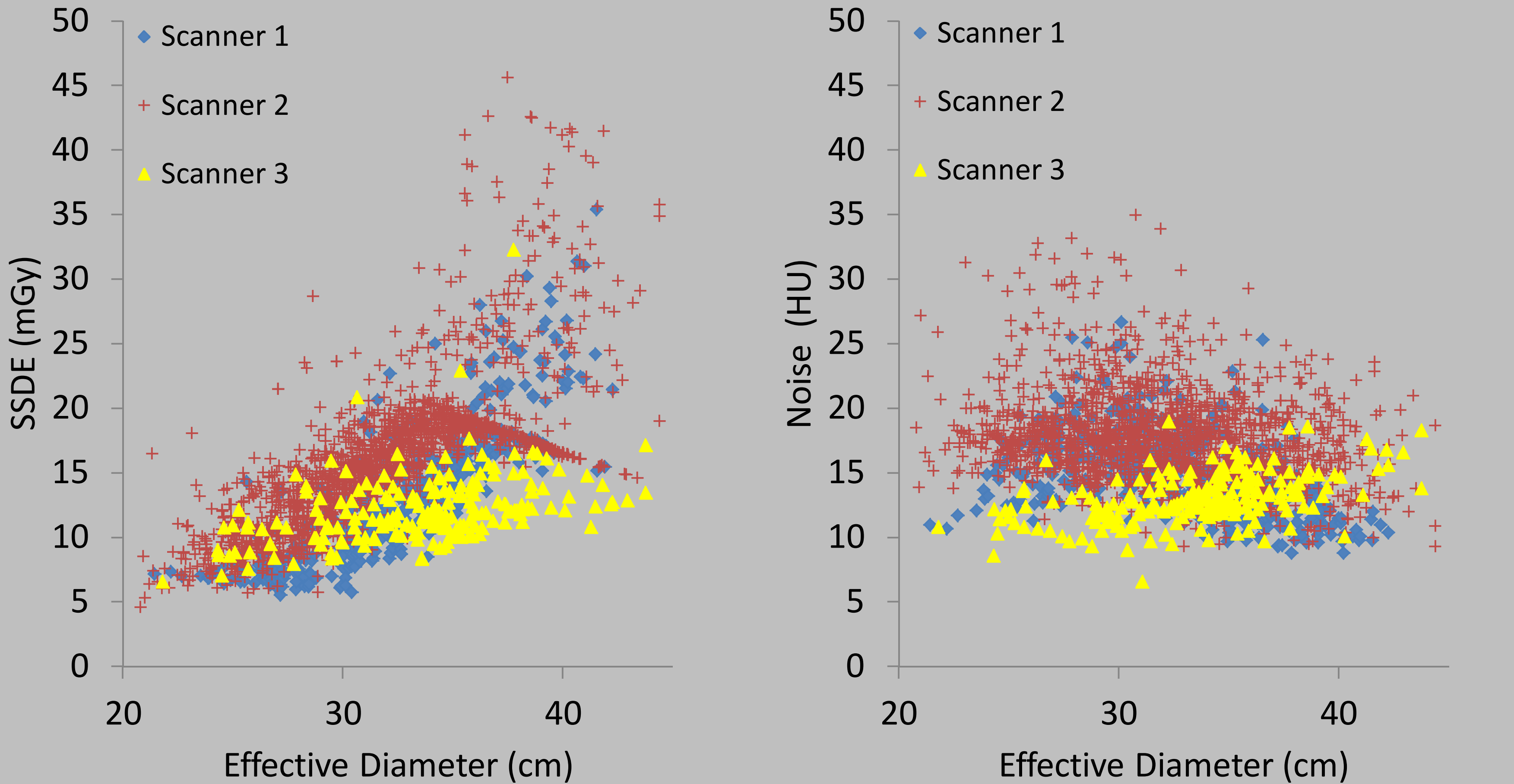


0.08 – 0.49
0.17 – 0.27



Overall operational consistency - CT

Abdomen Pelvis Exams (n=2358)



Christianson et al, AAPM, 2014

Protocol Report Cards

STANDARD CHEST 5 mm

n = 4229 annually

Protocol Definition

Scan parameter	Definition	Flash	750 HD	VCT	LS 16
Protocol name	23_STANDARD_CHEST_WITHOUT_IV	22_FLASH_PE_CHEST	5.1STANDARD CHEST	5.1STANDARD CHEST	5.1STANDARD CHEST
Scan type	Helical	Helical	Helical	Helical	Helical
Rotation time	0.5	0.285	0.4	0.4	0.5
Pitch	0.8	3	1.375	1.375	1.375
Table speed	61.4	404.2	137.5	137.5	55
Beam width	38.4	38.4	40	40	20
kVp	120	120	120	120	120
Slice thickness	5	5	5	5	5
Auto mA	On	On	On	On	On
mA/NI/mAsref	150	150	19.2	16	16
SFOV	Wedge_3	Wedge_2	Body	Body	Body
Kernel	B31f	B31f	Standard	Standard	Standard
Iterative Level	FBP	FBP	ASiR 30%	FBP	FBP
Matches e-protocol	Yes	No	Yes	Yes	Yes
% of STANDARD CHEST exams	14.3%	27.4%	47.9%	5.3%	5.2%

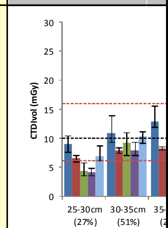
Image Quality (Prospective)

	Kernel/IR	NPSavg	MTF50	d' (5mm)	5% Match
Target (CT 750HD)	STD/40%	0.261	0.45	40	N/A
Current Flash	B31/0	0.293	0.412	33.2	No
Current VCT	STD/0	0.3	0.43	35.6	No
Current LS16	STD/0	0.3	0.43	35.6	No
Recommended Flash	i40/3	0.265	0.432	40.7	Yes
Recommended VCT	STD/0	0.3	0.43	35.6	No
Recommended LS16	STD/0	0.3	0.43	35.6	No

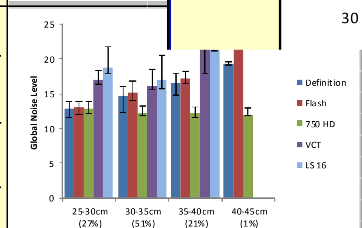
To match noise magnitude of 750HD, increase ref mAs to 155

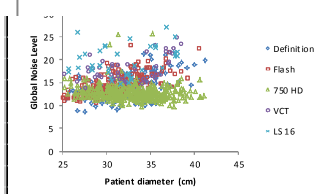
If STD behaves on VCT as on 750HD, , decrease VCT NI to 11.8

Radiation Dose

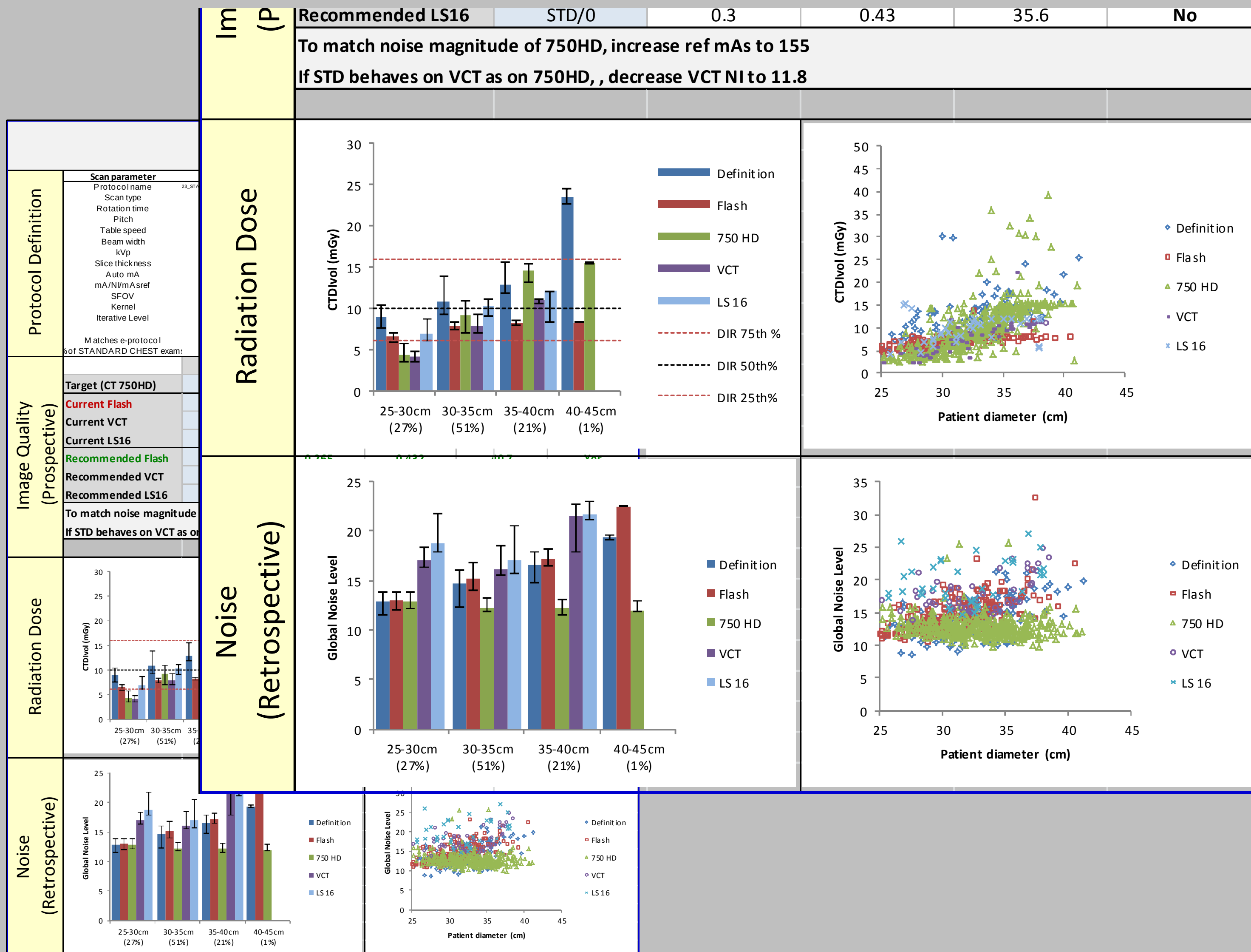


Noise (Retrospective)





Protocol Report Cards



Challenges on the path to MP2.0

Å Cultural inertia

Å Availability of effective tools

Å Availability of QA informatics

Å Lagging guidelines, accreditations, regulations

Å Lagging certification requirements

Å Lagging education

Å Effective model(s) of practice

Conclusions 1

- Clinical Imaging physics is a severely untapped resource insufficiently integrated into the patient care process.
- We need a new paradigm to define and enact how the clinical physicist can engage as an active, effective, and integral member of the clinical team.

Medical Physics 2.0

- An existential transition of clinical physics in face of the new realities of value-based, evidence-based, personalized medicine.
- Clinical imaging physics expanding beyond insular models of inspection and acceptance testing, oriented toward compliance, towards
  - Team-based models of operational engagement
  - Prospective assurance of effective use
  - Retrospective evaluation of clinical performance

Conclusions 3

- Skilled expertise in imaging physics is needed to understand the nuances of modern imaging equipment to
  - Ensure quality (with relevant metrology)
  - Ensure consistency
  - Define and ensure conformance
  - Inform effective use, at outset and continually
  - Optimize quality and safety
  - Monitor and ensure their continued performance
  - Enable quantitative and personlized utilization