MEDICAL PHYSICS 2.0
A NEW FRONTIER IN CLINICAL IMAGING PHYSICS

Questions, advise, comments:
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A NEW FRONTIER IN CLINICAL IMAGING PHYSICS

Ehsan Samei, PhD
Duke University

Medical Physics 2.0?

A vision for an existential transition in the field of clinical imaging physics

Med Phys 2.0 history

- **2011:** "The tenuous state of clinical medical physics in diagnostic imaging," Samei and Seibert, *Medical Physics* 38, 2011.
- **2012:** "The 2014 initiative can have potentially unintended negative consequences for medical physics in diagnostic imaging and nuclear medicine," Samei and Button, *Medical Physics* 39, 2012
- **2012:** "Quality, Safety and Compliance: How to address the triple challenge of modern imaging and therapy," Marks and Samei, SEAAPM Symposium
- John Weaver, Don Frey, Doug Pfeiffer

Med Phys 2.0 initiatives

- **RSNA 2013:** 12 hr course in CT, MRI, NM, Fluoroscopy, Rad, Mammo, US, IT:
  - **Mahesh, Martin, Barnes, Jones, Gingold, Schueler, Strauss, Pickens, Price, Carson, Lu, Hangiandreou, Flynn, Peck, Mawlawi, Nelson**
- **AAPM 2014:** 8 hr course and panel discussion
- **RSNA 2014:** 12 hr course
- **2015: "Clinical Medical Physics Primer,"** Wiley and Sons

Key formative questions

1. Where is imaging in medicine enterprise?
2. Where medical imaging is going?
3. What has been the role of imaging physics in medicine?
4. What is the clinical role of imaging physics?

Where is imaging in medicine enterprise?

- Transformative technology
- The “face” of modern medicine

Where medical imaging is going?

- Evidence-based medicine
  - Practice informed by science
- Quantitative medicine
  - Biometrics enabling precision medicine
- Value-based medicine
  - Scrutiny on safety, performance, consistency, stewardship, ethics
- Comparative effectiveness and meaningful use
  - Enhanced focus on actual utility

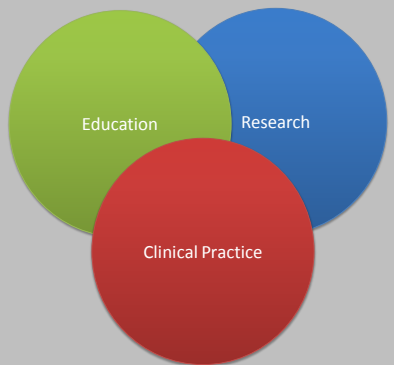
What has been the role of imaging physics in medicine?

- Remember Roentgen!

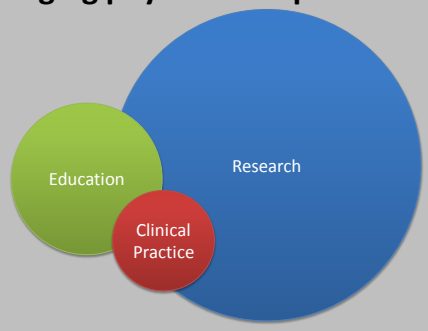
What is the clinical role of imaging physics?

- Ensuing quality and safety of clinical imaging systems
- Ensuring compliance
- Enabling accreditation

Imaging physics enterprise



Imaging physics enterprise



Medical Physics 1.0

- We have done a GREAT job using engineering and physics concepts to
  - Design systems with superior performance
  - Ensure minimum intrinsic performance
  - Claim compliance
- But…

Why 1.0 is not enough

- Most clinical physics work has been equipment-focused and not easily translatable to clinical care
  - Clinical relevance?
- Technology is changing
  - Compliance lags behind clinical needs

Why 1.0 is not enough

- Clinical performance?
- Optimization of use?
- Consistency of quality?
- Changing technology?
- Value-based healthcare?

1.0 to 2.0

- Clinical imaging physics extending from
  - intrinsic to extrinsic
  - Specs to performance
  - compliance to excellence
  - Quality to consistency
  - Equipment to operation

Clinical imaging physics 2.0

Operationalize relevant imaging physics science to ensure high quality, low-dose, efficient, and compliant setup and clinical operation of medical imaging systems, techniques, and applications

Clinical imaging physics 2.0

Operationalize relevant imaging physics science to ensure high quality, low-dose, efficient, and compliant setup and clinical operation of medical imaging systems, techniques, and applications

1. Scientifically-informed by findings and methods
2. Clinically-relevant to the operational practice
3. Pragmatic in the meaningful and efficient use of resources
4. Integrated in cooperation with scientific and clinical teams

Ensuring quality and safety:

3 spheres of quality assurance

System performance assessment

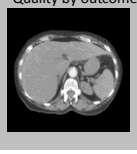
Quality by inference

Prospective protocol definition

Quality by prescription

Retrospective quality assessment

Quality by outcome



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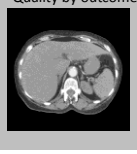

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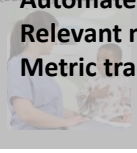
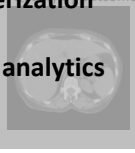
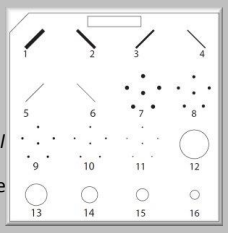
1. **Automated characterization**
2. **Relevant metrology**
3. **Metric tracking and analytics**





Automated characterization

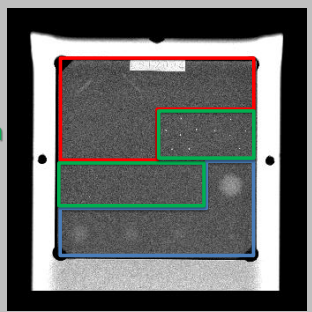
- ACR Mammography QC Phantom
  - Fibers
  - Calcification clusters
  - Spherical masses
- Automatic measurement based off work by Brooks *et al* (1997)
- Fourier convolution technique used to detect features
- CNR detection thresholds defined to match observer performance



http://www.coneinstruments.com/images/400/607096.jpg
http://www.gnwx.com/Accessories/Phantoms/Mammography/

Weekly ACR Mammo Phantom Image

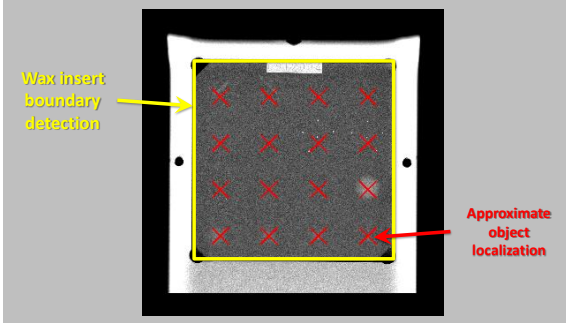
Calcification Clusters



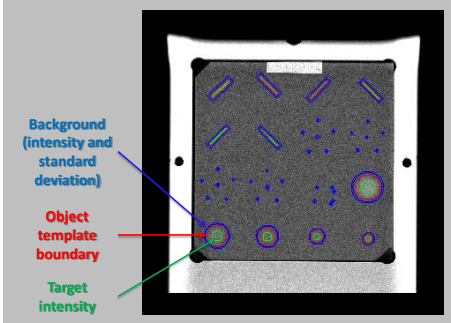
Nylon Fibers

Spherical Masses

Boundary Detection and Localization



Object Detection and Measurement



OBJECT	CNR
Fiber 1	1.45
Fiber 2	1.18
Fiber 3	0.93
Fiber 4	0.78
Fiber 5	0.54
Fiber 6	0.29
Calc 1	12.70
Calc 2	9.60
Calc 3	5.61
Calc 4	4.88
Calc 5	3.03
Mass 1	4.02
Mass 2	1.80
Mass 3	1.38
Mass 4	0.91
Mass 5	0.46

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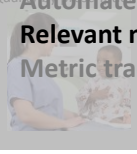


Parameters that affect IQ

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

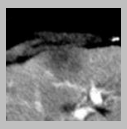
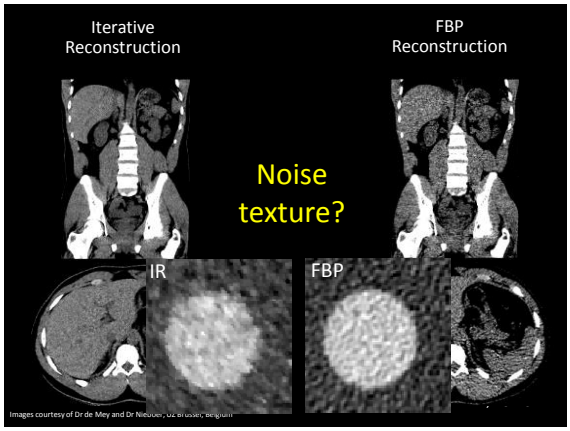
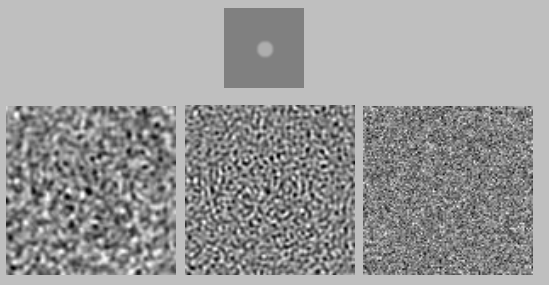


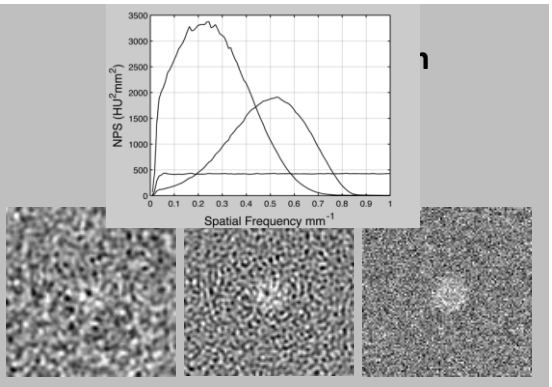
Image quality vs CNR

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



Noise Power Spectrum



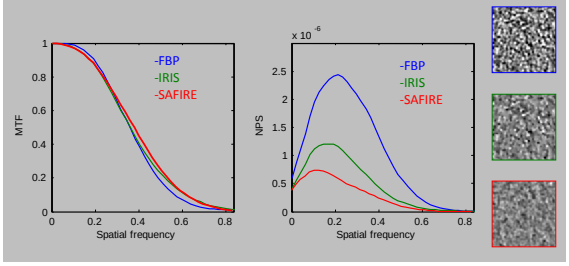


Solomon, Christianson, Samei, *Quantitative comparison of noise texture across CT scanners from different manufacturers.*, Medical physics, 39 (2012).

Resolution and noise, eg 1

Comparable resolution

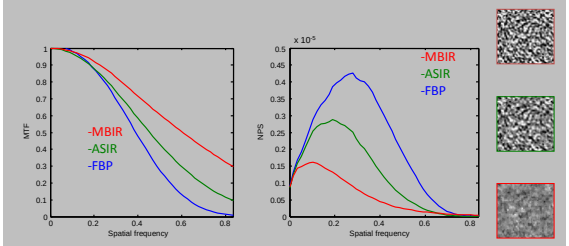
Lower noise but different texture



Resolution and noise, eg 2

Higher resolution

Lower noise but different texture



Task-based quality index

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

Task-based quality index

Fisher-Hotelling observer (FH)

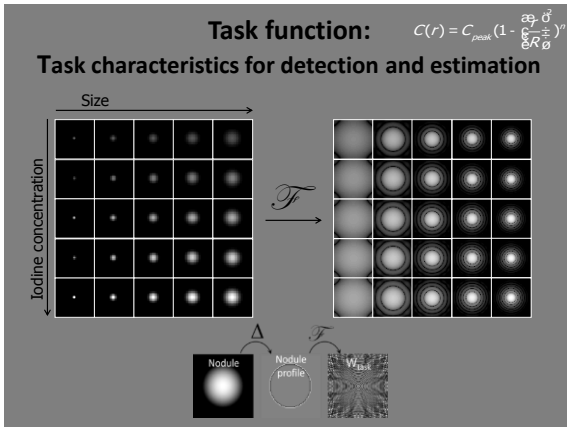
$$\left(d'_{FH}\right)^2 = \iint \frac{MTF^2(u,v)W_{Task}^2(u,v)}{NPS(u,v)}dudv$$

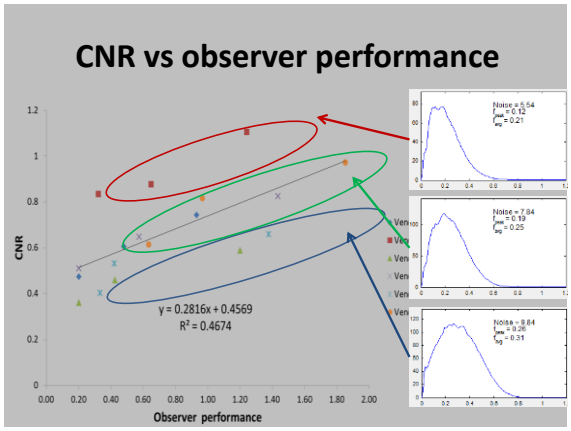
Non-prewhitening observer (NPW)

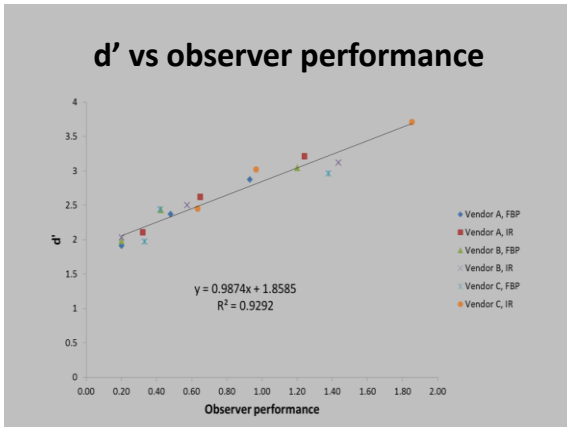
$$\left(d'_{NPW}\right)^2 = \frac{\left[\iint MTF^2(u,v)W_{Task}^2(u,v)dudv\right]^2}{\iint MTF^2(u,v)W_{Task}^2(u,v)NPS(u,v)dudv}$$

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 function:
$C(r) = C_{peak}(1 - \left(\frac{r}{R}\right)^2)^n$
Task characteristics for detection and estimation
Size
Iodine concentration
Nodule
Nodule profile


CNR vs observer performance
CNR
Observer performance
y = 0.2816x + 0.4569
R² = 0.4674

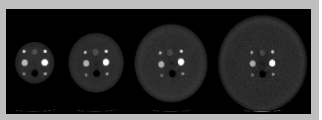

d' vs observer performance
d'
Observer performance
y = 0.9874x + 1.8585
R² = 0.9292
Vendor A, FBP
Vendor A, IR
Vendor B, FBP
Vendor B, IR
Vendor C, FBP
Vendor C, IR

Quality index phantom
Duke Mercury 3.0



Mercury Phantom





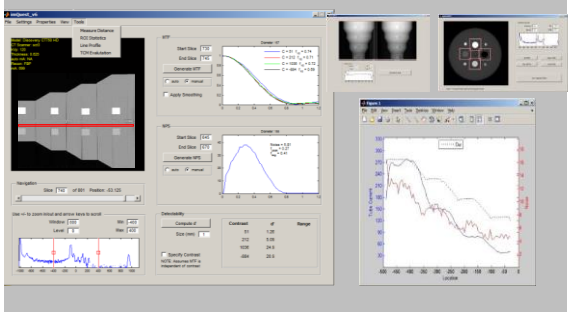
- Three tapered, four cylindrical regions of polyethelene (Diameters: 16, 23, 30, 37 cm)
- Cylindrical inserts
  - air, polystyrene, acrylic, teflon
  - different concentration iodinated

Wilson, AAPM 2012
Winslow, AAPM 2012

imQuest

(image quality evaluation software)

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



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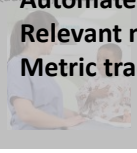
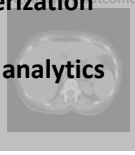
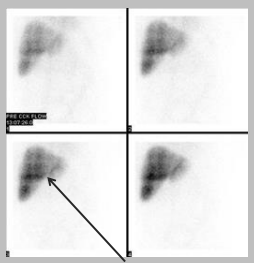
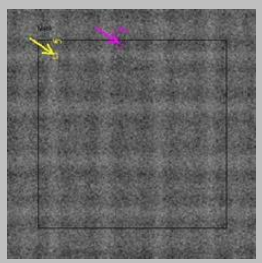




Nuclear Medicine non-uniformity





Crosshatched artifact pattern
(system has square PMT's)

Nuclear Medicine non-uniformity

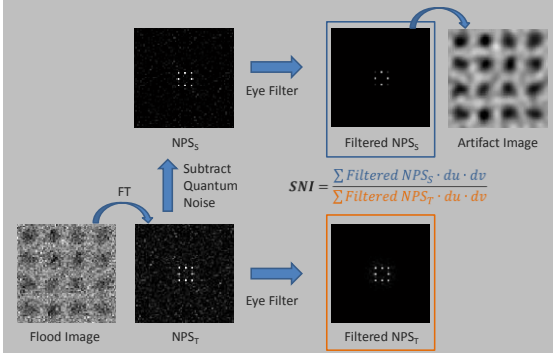
$$\text{Integral Uniformity} = \frac{N_{max} - N_{min}}{N_{max} + N_{min}} \times 100\%$$

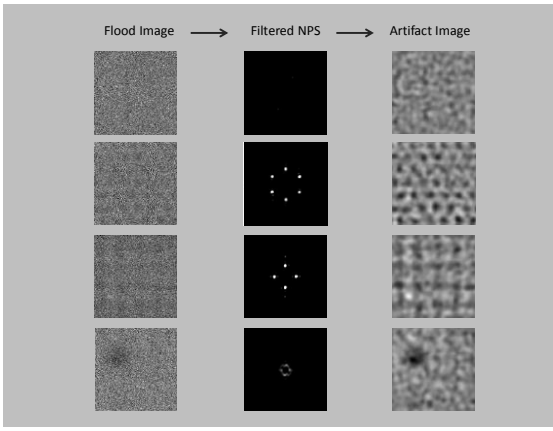
2.87%

Action limit = > 5.00%

2.81%

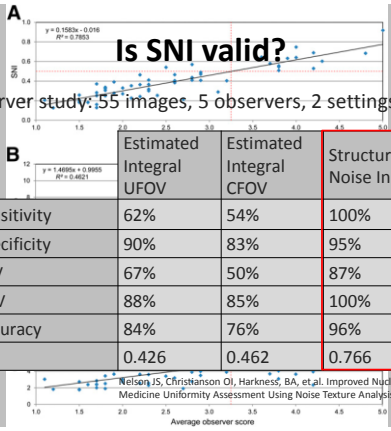
Structured Noise Index (SNI)





Is SNI valid?

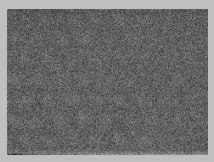
- Observer study: 55 images, 5 observers, 2 settings

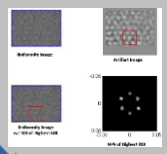


	Estimated Integral UFOV	Estimated Integral CFOV	Structured Noise Index
Sensitivity	62%	54%	100%
Specificity	90%	83%	95%
PPV	67%	50%	87%
NPV	88%	85%	100%
Accuracy	84%	76%	96%
R^2	0.426	0.462	0.766

Nelson JS, Christianson OI, Harkness, BA, et al. Improved Nuclear Medicine Uniformity Assessment Using Noise Texture Analysis. JNM

Integral Uniformity vs SNI

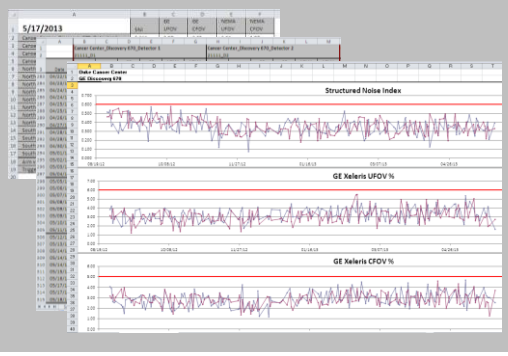


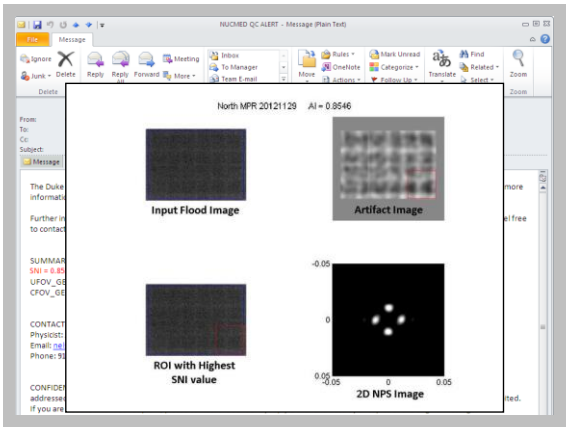


CFOV IU = 2.81%
Action limit = > 5.00%

SNI= 0.78
Action limit = > 0.5

SNI tracking and analytics





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2. **Quality consistency**

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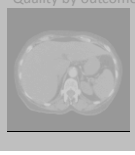
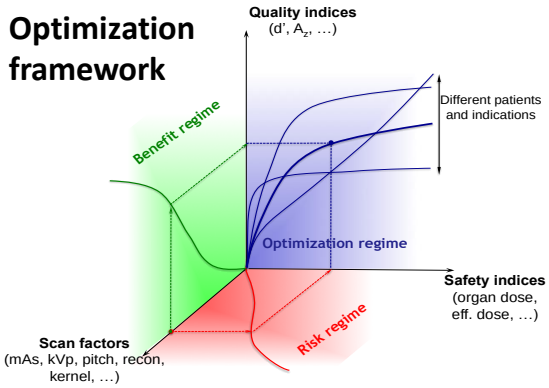
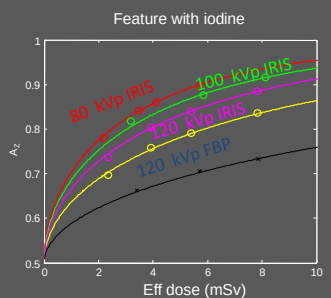


Optimization framework



Quality-dose dependency

Siemens IRIS/kVp optimization

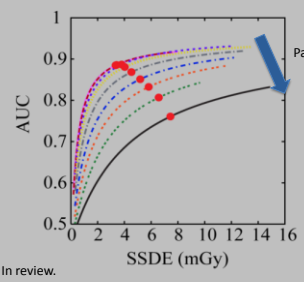


Samei, Richard, Med Phys, in press, 2014

Quality-dose dependency

Patient size effect

Iso-gradient optimization points to define ALARA

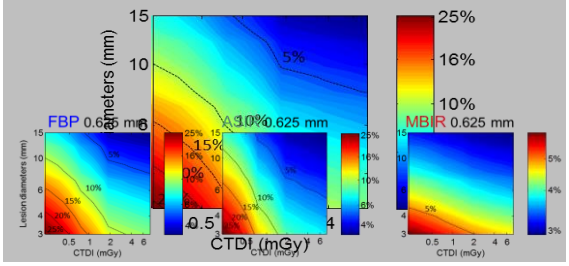


Li et al, Med Phys, In review.

Quality-dose dependency

Quantitative volumetry via CT

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



Patient-specific protocoling

Radiography technique chart

Patient categorization

- Neonate
- One year old
- Five year old
- 15 year old
- Small adult
- Average adult
- Large 1 adult
- Large 2 adult

Transmission factor assessments

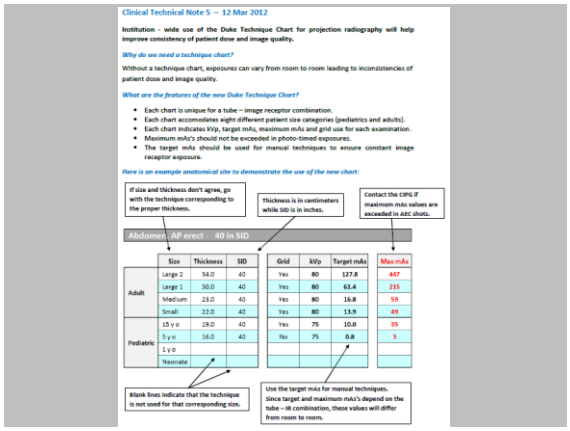
- FS = 5 x 5 in, 10 x 10 in, 14 x 14 inches
- kVp = 60 , 80, 100, 120
- SID = 40, 48, 72 inches
- Selected thicknesses:
  - 2 cm to 16 cm for no grid
  - 16 cm to 33 cm for grid TF's

Transmission Factor (TF) coefficients: Grid number 1, SID = 40 inches				
TF = $(C_1 * kVp^2 + C_2 * kVp + C_3) * \exp(- C_4 * \text{Thickness})$				
Field size (at SID) [in]	C_1	C_2	C_3	C_4
5 x 5	-1.652E-06	0.007343	-0.2357	0.2143
10 x 10	2.288E-06	0.005843	-0.2026	0.1948
14 x 14	3.522E-06	0.004838	-0.1631	0.1837

mAs to obtain targeted mR

Facial bones: Lateral position

	Size	Thickness	SID	Grid	kVp	Target mAs	Max mAs
Adult	Large 2	17.0	40	Yes	80	14.8	40
	Large 1	16.0	40	Yes	80	12.2	34
	Medium	15.5	40	Yes	80	11.0	31
	Small	15.0	40	Yes	80	10.0	28
Pediatric	15 y o	14.8	40	Yes	70	16.1	36
	5 y o	14.5	40	Yes	70	15.2	34
	1 y o	12.0	40	No	60	4.9	30
	Neonate	10.0	40	No	60	3.5	22



Clinical Technical Note 5 – 12 Mar 2012

Institution - wide use of the Duke Technique Chart for projection radiography will help improve consistency of patient dose and image quality.

Why do we need a technique chart?

Without a technique chart, exposures can vary from room to room leading to inconsistencies of patient dose and image quality.

What are the features of the new Duke Technique Chart?

- Each chart is unique for a tube – image receptor combination.
- Each chart accomodates eight different patient size categories (pediatrics and adults).
- Each chart indicates kVp, target mAs, maximum mAs and grid use for each examination.
- Maximum mAs's should not be exceeded in photo-timed exposures.
- The target mAs should be used for manual techniques to ensure constant image receptor exposure.

Here is an example anatomical site to demonstrate the use of the new chart:

If size and thickness don't agree, go with the technique corresponding to the proper thickness.

Thickness is in centimeters while SID is in inches.

Contact the CIPS if maximum mAs values are exceeded in AEC shots.

Abdomen AP erect - 40 in SID

	Size	Thickness	SID	Grid	kVp	Target mAs	Max mAs
Adult	Large 2	34.0	40	Yes	80	127.8	447
	Large 1	30.0	40	Yes	80	61.4	215
	Medium	23.0	40	Yes	80	16.8	59
	Small	22.0	40	Yes	80	13.9	49
Pediatric	15 y o	19.0	40	Yes	75	10.0	35
	5 y o	16.0	40	No	75	0.8	3
	1 y o						
	Neonate						

Blank lines indicate that the technique is not used for that corresponding size.

Use the target mAs for manual techniques. Since target and maximum mAs's depend on the tube – IR combination, these values will differ from room to room.

Ensuring quality and safety:

3 spheres of quality assurance

System performance assessment

Quality by inference

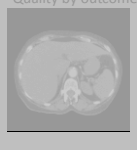
1. Patient-specific protocoling
2. **Quality consistency**

Prospective protocol definition

Quality by prescription

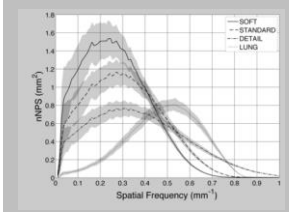
Retrospective quality assessment

Quality by outcome

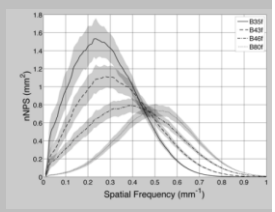


Noise texture vs kernel

GE

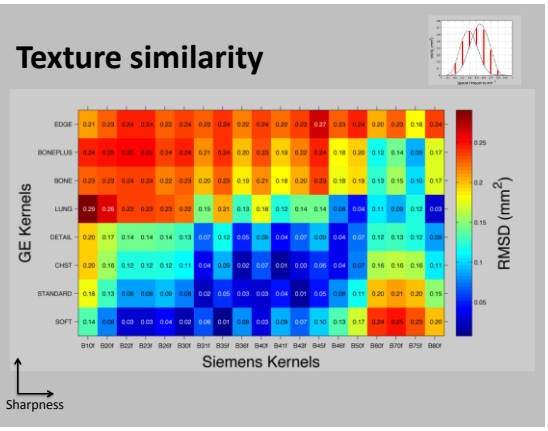


Siemens



Solomon et al, Med Phys 2012

Texture similarity

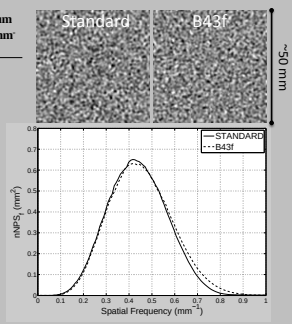


Results

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

Results

GE	Siemens	Minimum RMSD (mm^2)	Minimum |PFD| (mm^{-1})
STANDARD	B43f	0.01	0.00



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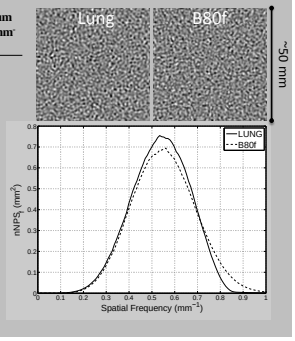
LUNG	B80f	0.03	0.00



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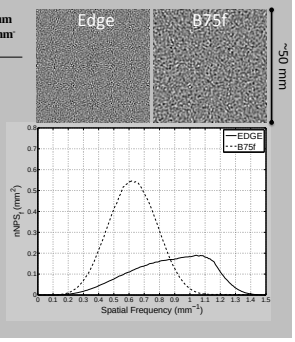


Ensuring quality and safety:

3 spheres of quality assurance

System performance assessment

Quality by inference

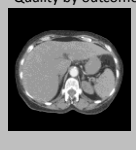
1. **Protocol tracking**
2. **Dose monitoring and analytics**
3. **Quality tracking and analytics**

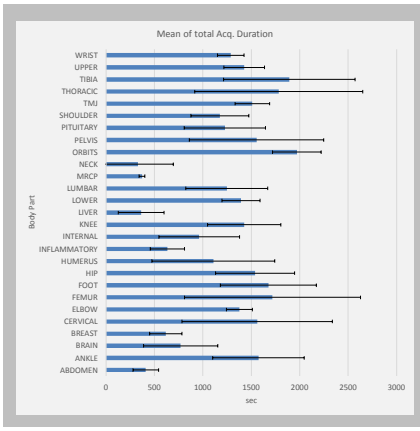
Prospective protocol definition

Quality by prescription

Retrospective quality assessment

Quality by outcome





1832 exams
40 days

Josh Wilson, PhD

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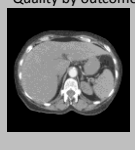
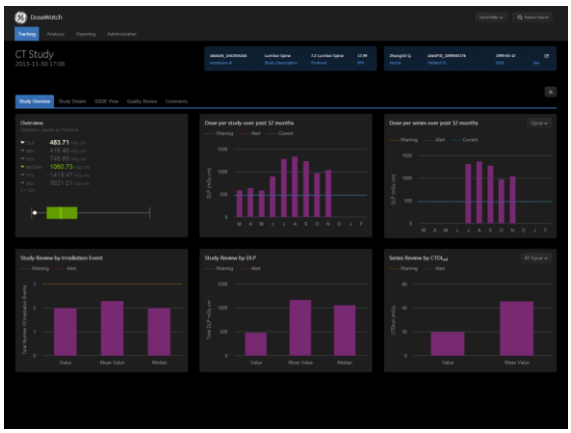
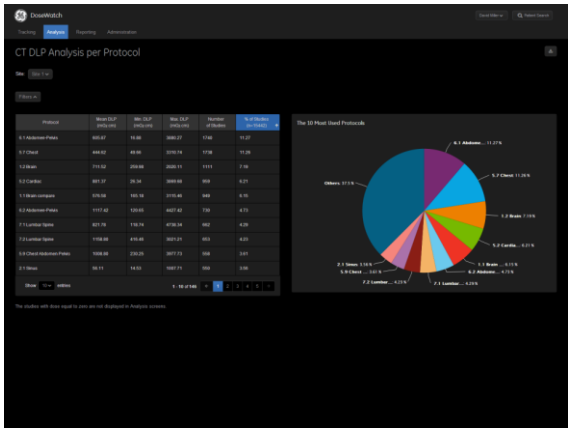






4 goals of dose monitoring

1. How?
   - Recalling early days of PACS
2. What?
   - Meaningful metrics to track
   - Patient-specific metrics, organ dose
3. So what?
   - Analytics and follow up
4. Standardization
   - Systematic implementation of the process

JACR, August 2014

Dose Index Analytics: More Than a Low Number

Ehsan Samei, PhD, Olav Christianson, MS

What do we know about CT dose, what is its variability across medical practices, and how can we ensure that our patients are safe, considering the complexities and heterogeneity of clinical care within and across medical facilities? The foun-

The ACR initiated the CT Dose Index Registry® in 2011 as an effort to monitor CT radiation dose. Since then, hundreds of facilities have registered with the Dose Index Registry, leading to millions of collected dose data. Although this

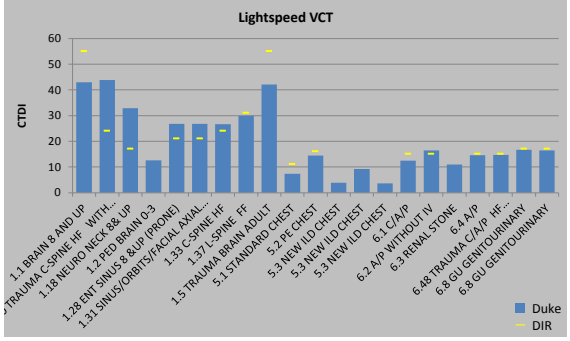
a few analytic methods that can be applied to the dose data to extract meaningful knowledge toward quality improvement.

Dose-monitoring data can be used to establish most meaningful reference and alert levels. Contrary to

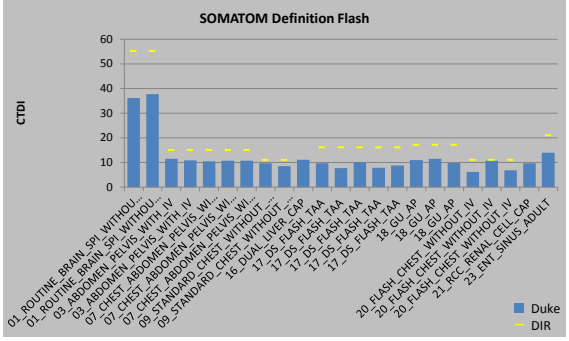
Dose analytics

1. Benchmark doses against national references
2. Establish diagnostic reference levels
3. Identify mis-dose conditions
4. Evaluate and enhance operational consistency

DIR Comparison



DIR Comparison



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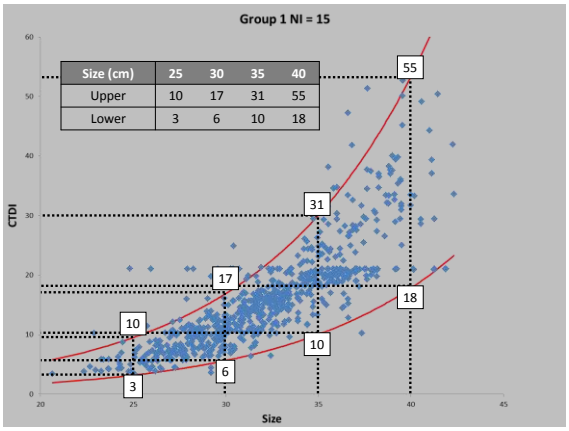

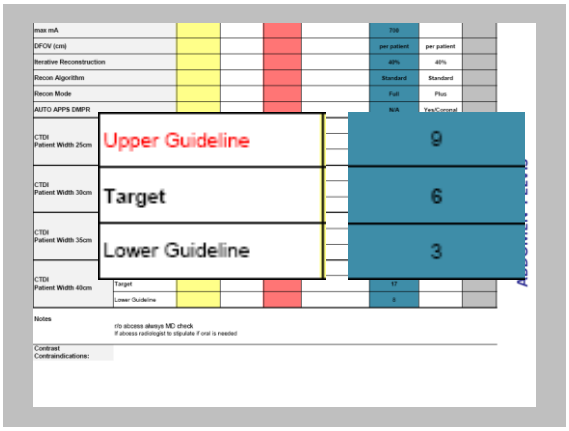

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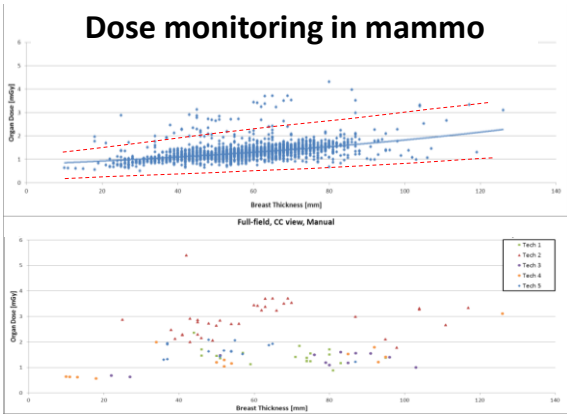
Dose monitoring in mammo



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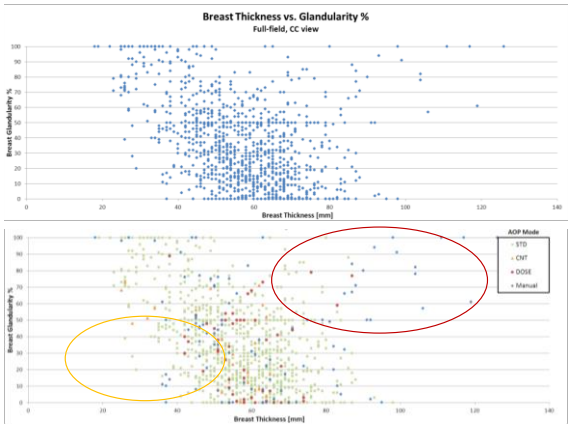

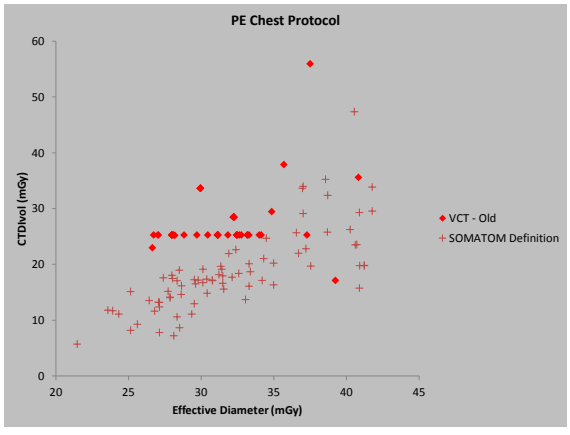

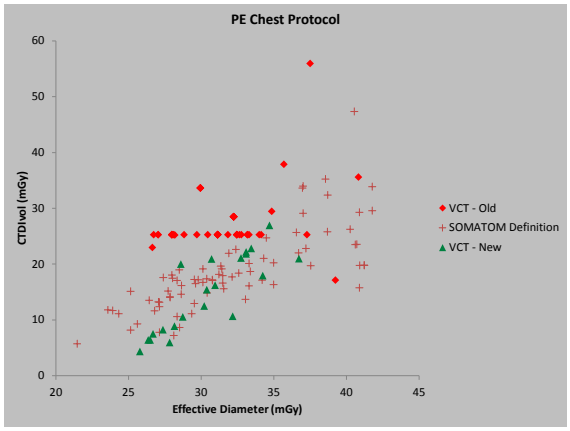

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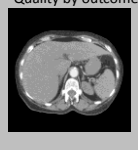
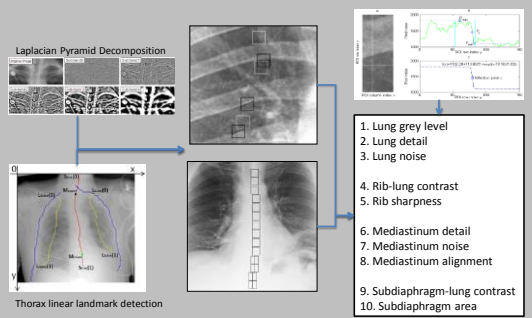
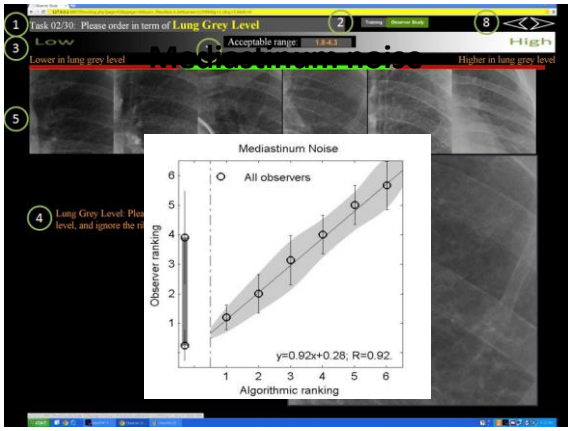


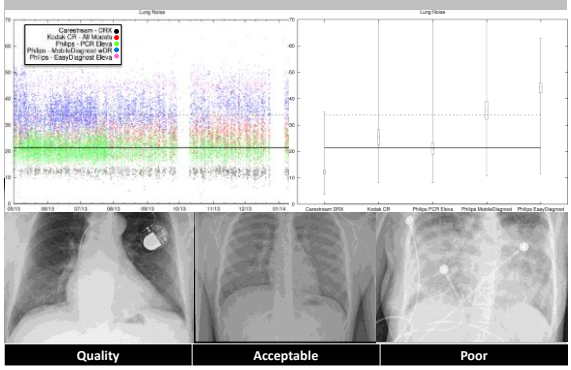
Automated Image Quality Assessment of Computed Radiography

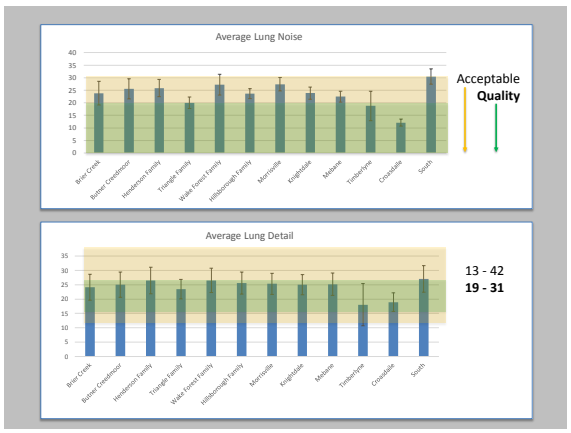


Y Lin, E Samei, *An image-based technique to assess the perceptual quality of clinical chest radiographs.*, Medical physics, 39 (2012).

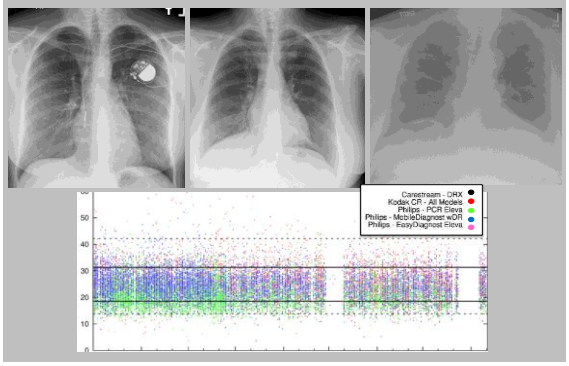


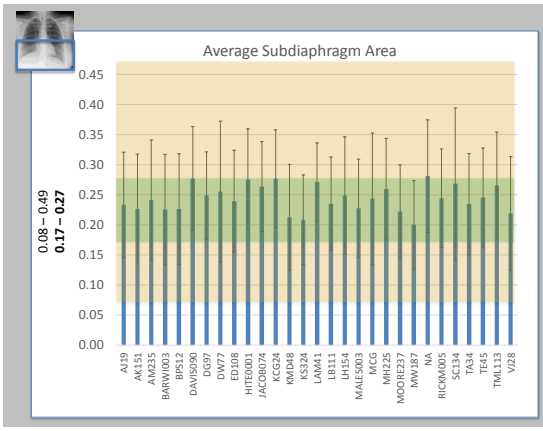
Establish Image Quality Reference Levels





For Example, Lung Detail





Challenges on the path to MP2.0

- Availability of effective tools
- Availability of QA informatics
- Cultural inertia
- Lagging guidelines, accreditations, regulations
- Lagging certification requirements
- Effective model(s) of practice
- Education

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

- A bold vision for an existential transition of clinical imaging physics in face of the new realities of value-based and evidence-based medicine, comparative effectiveness, and meaningful use.
- Clinical imaging physics expanding beyond traditional insular models of inspection and acceptance testing, oriented toward compliance, towards
  - team-based models of operational engagement
  - prospective definition and 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 sustained performance
  - Enable quantitative utilization

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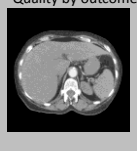

Medical Physics 2.0

CT, MRI, NM, Fluoro
Rad, Mammo, US, IT

- **AAPM 2014:** 6 hr of modality specific lectures
- **RSNA 2014:** 12 hr course
- **Book in 2015:** Wiley and Sons

MEDICAL PHYSICS 2.0

PANEL DISCUSSION

Questions, advise, comments:

Tweet #medphys2.0

Panelists

- Doug Pfeiffer, Boulder Community Hospital
- Paul Carson, University of Michigan
- Bob Dixon, UNC
- Don Frey, MUSC
- Nick Hangiandrou, Mayo Clinic
- David Jordan, University Hospitals Case
- Elizabeth Krupinski, Univ of Arizona
- Mahadevappa Mahesh, Johns Hopkins
- Bob Pizzutiello, Landauer

Question 1

- What are the tools needed to bring forth Med Phys 2.0 to practice?

Question 2

- What are the successes and failures per modality in defining what is needed and implementing that for med phys 2.0?

Question 3

- What new modalities should be incorporated in med phys 2.0?

Question 4

- What are the political/professional means to bring forth Med Phys 2.0 to practice?
  - Administrative “buy”?
  - Regulatory requirement?
  - Endorsement of guidelines (AAPM)?
  - Requirement of accreditation bodies (ACR, IAC)?
  - Practice models?
    - Departmental physicists
    - Institutional physicists
    - Consulting physicists

Question 5

- What are the manpower means to bring forth med phys 2.0 to practice?
  - Economics and needed manpower
  - Education
    - Elite education: Medical physics leadership institute
      - Clinical
      - Administrative: project management
      - Research: skills, innovation, forsight
      - Communication: teaching, writing, speaking
    - Graduate and residency education
    - Certification

Question 6

- What would you like to do? What would you suggest AAPM to do to advance this effort?
  1. Nothing, we like the world as is. Please pass the slide rule.
  2. Ask the BOD to support this using Strategic Planning funds
  3. Form a Task Force or WG to define goals, process and educational/training requirements
  4. Support an AAPM Summer School
  5. Ask each of the Council Chairs to consider this as part of their priorities
  6. Open up an AAPM Web discussion on the subject
  7. Other (write)