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# Phantom-based Standardized Test Methods for Medical Imaging

## And Their Adaptation for Biophotonics

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**U.S. Food and Drug Administration**

Protecting and Promoting *Your* Health

*International Workshop on Tissue Phantoms and  
Standardization in Biophotonics  
May 21, 2014*



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# Overview

- Introduction
- Review of medical imaging consensus documents
  - Phantoms
  - Image quality issues
  - Methods
- Analogous OCT test methods
- Challenges



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# Motivation for Standardized Biophotonic Test Methods

- ❑ Objective, quantitative system evaluation
  - ❑ Facilitate device innovation, inter-comparison
  - ❑ Clinical trial standardization
  - ❑ Quality control, assurance
  - ❑ Rigorous, yet streamlined regulatory process
  - ❑ Standards documents are an indicator of the maturity of field
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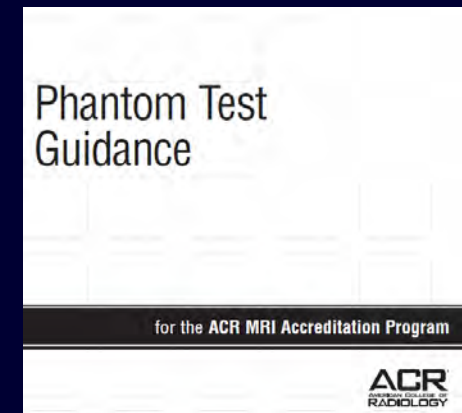
# Purpose

- Provide a foundation for the development of biophotonic imaging standards
- Help avoid...
  - Reinventing the wheel
  - Developing phantoms that do not adequately address relevant image quality issues



# Goals

- Review consensus documents
  - Standards organizations
  - Professional organizations
  - CT, MRI, ultrasound, etc.
- Identify
  - Performance characteristics
  - Test methods
    - Phantom design/materials
    - Measurement procedures
    - Figures of merit
  - Performance thresholds



# Key Documents Reviewed (of ~90)

## □ Computed tomography (CT)

- IEC 60601-2-44 Edition 3.0. Medical electrical equipment - Part 2-44:
- IEC 61223-2-6 Edition 2. Evaluation and routine testing in medical imaging departments – Part 2-6:
- IEC 61223-3-5. Edition 1. Evaluation and routine testing in medical imaging departments, Part 3-5:
- Computed tomography accreditation program, Phantom testing instructions, ACR, 2004.
- CT Accreditation Program Requirements, American College of Radiology, March 26, 2010.
- The phantom portion of the American College of Radiology (ACR)... Computed Tomography (CT) accreditation program: Practical tips, artifact examples, and pitfalls to avoid. *Med. Phys.* Volume 31, Issue 9, pp. 2423-2442
- CT Accreditation Program: Image Quality and dose measurement. C.H. McCollough source?
- The phantom portion of the ACR CT accreditation program: Practical tips, artifact examples, and pitfalls to avoid. Mc Collough et al., *Med. Phys.* Volume 31, Issue 9, pp. 2423-2442
- A. P. Reeves, et al., "On measuring the change in size of pulmonary nodules," *IEEE Trans. Med. Imaging* 25, 435-50 (2006).
- L. R. Goodman, et al., "Inherent variability of CT lung nodule measurements in vivo using semiautomated volumetric measurements," *Am. J. Roentgen*. 186, 989-94 (2006).

## □ Ultrasound

- IEC 61391-1 Ultrasonics – Pulse-echo scanners – Part 1: Techniques for calibrating spatial measurement systems and measurement of system point-spread function response
- IEC 61391-2 Ultrasonics – Pulse-echo scanners – Part 2: Measurement of maximum depth of penetration and local dynamic range
- IEC TS 61390 Ultrasonics - Real-time pulse-echo systems - Test procedures to determine performance specifications, 1996.
- Pulse echo ultrasound imaging systems: Performance tests and criteria, AAPM Report No. 8, General Medical Physics committee, ultrasound task group, Carson PL and Zagzebski JA, 1980.
- Real-time B-mode ultrasound quality control test procedures: Report of AAPM Ultrasound Task Group No. 1. Goodsitt et al., (*Med Phys* 25(8), 1385-1406, 1998).
- Pfeiffer D, Sutlief S, Feng W, Pierce HM, Kofler J. AAPM Task Group 128: Quality assurance tests for prostate brachytherapy ultrasound systems, *Med Phys* 35(12), 5471-5489, 2008.
- Ultrasound Accreditation Program Requirements, American College of Radiology, March 26, 2010

## □ MRI

- MRI accreditation program requirements, 2010.
- MRI Accreditation program – testing instructions
- Phantom Test Guidance for the ACR MRI accreditation program, 2005.
- Quality Assurance methods and phantoms for Magnetic Resonance Imaging, AAPM report #28, 1990.
- Quality assurance methods and phantoms for magnetic resonance imaging, AAPM Report No. 28, Task Group No. 1, Nuclear Magnetic Resonance Committee, 1990. (also Price et al., *Med Phys* 1990)IEC
- Magnetic resonance equipment for medical imaging – Part 1: Determination of essential image quality parameters, CEI/IEC 62464-1:2007.
- Practical aspects of functional MRI (NMR Task Group #8), Price et al., *Med Phys*, 29 (8), 2002.
- Overview of the ACR MRI Accreditation phantom, GD Clarke, MRI phantoms and QA testing

## □ X-ray

- Basic quality control in diagnostic radiology, AAPM Report No. 4, Diagnostic Radiology Committee, Task force on Quality Assurance Protocol. 1977.
- Performance Evaluation and Quality Assurance in Digital Subtraction Angiography, Diagnostic X-Ray Imaging Committee/Digital Radiography/Fluorography Task Group, High M, chairman, Report No. 15, AAPM, 1985.
- IEC 61223-3-3, Evaluation and routine testing in medical imaging departments – Part 3-3: Acceptance tests – Imaging performance of X-ray equipment for digital subtraction angiography (DSA), First edition, 1996.

## □ Mammography

- MQSA regulations
- Mammography accreditation program requirements, ACR, 2009.
- W. Huda, A. M. Sajewicz, K. M. Ogden, E. M. Scalzetti, and D. R. Dance, "How good is the ACR accreditation phantom for assessing image quality in digital mammography?" *Acad. Radiol.* 9, 764–772 (2002).
- J. A. Thomas, K. Chakrabarti, R. Kaczmarek, and A. Romanyukha, "Contrast-detail phantom scoring methodology," *Med. Phys.* 32(3), (2005).

## □ Nuclear Imaging (PET and SPECT)

- PET Phantom Instructions for Evaluation of PET Image Quality, ACR Nuclear Medicine Accreditation Program, PET Module, American College of Radiology. Feb 2010
- Site Scanning Instructions for the ACR Nuclear Medicine Phantom, ACR Nuclear Medicine Accreditation Program, American College of Radiology, March 2010
- Quantitation of SPECT performance, AAPM Report No. 52, Nuclear Medicine Committee Task Group 4, (*Med Phys* v., 22(4) 1995). 1995.

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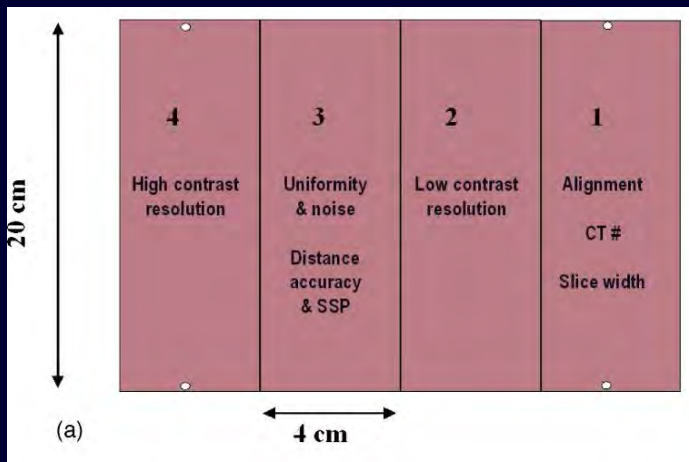
# Standard Phantoms for Medical Imaging

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# ACR CT Accreditation Phantom

American  
College of  
Radiology

Four-module  
phantom



## Phantom Construction

Matrix material . . . Solid Water<sup>®</sup>, 0 ±5 HU

**Epoxy**

Length. . . . . 16 cm (6.30 in)

Diameter . . . . . 20 cm (7.88 in)

Weight. . . . . 5.3 kg (11.75 lbs)

## Imbedded Test Objects

Water equivalent

linearity rod . . . . Solid Water<sup>®</sup>, 0 HU

Bone equivalent

linearity rod . . . . 915 HU Bone tissue equivalent material

Acrylic linearity

rod . . . . . Cast acrylic

Polyethylene

linearity rod . . . . Low density polyethylene

Low contrast

module matrix . . . Ciba Geigy CB4 epoxy or equivalent

Low contrast rods Ciba Geigy CB4 epoxy (density adjusted to yield 6 ±0.5 HU difference) or equivalent

Tungsten carbide

beads . . . . . 0.011 in diameter grade 25 tungsten carbide beads

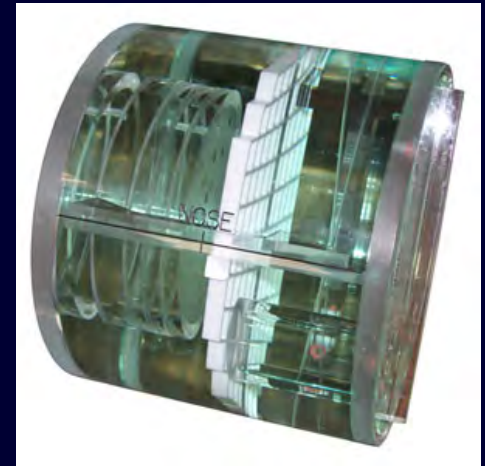
Line pair

material. . . . . 6061 Aluminum and Polystyrene

Steel beads . . . . 1.00 mm grade 25 chrome steel balls

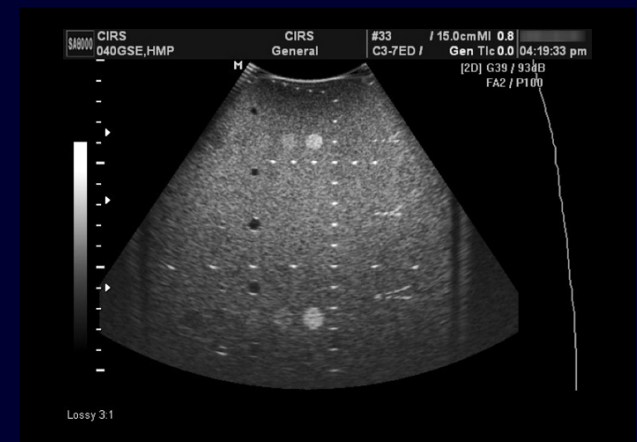
# ACR MRI Phantom

- Closed cylinder of acrylic
  - Length: 148 mm
  - Diameter: 190 mm
- Solutions
  - NaCl (conductivity)
  - NiCl<sub>2</sub> (T<sub>1</sub> relaxation times)
- Features enable measurement of 7 performance characteristics



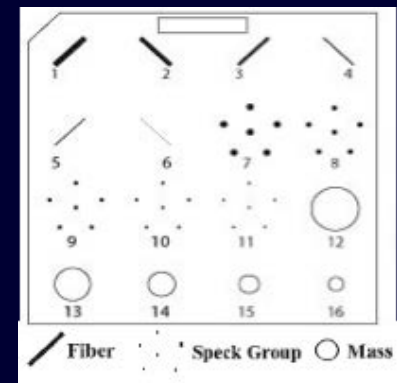
# Ultrasound

- Several commercially available
- Matrix material
  - Speed of sound  $1540 \pm 10$  m/s
  - Attenuation coefficient 0.5-0.7 dB/cm/MHz
  - Echogenicity and image texture similar to liver parenchyma
  - Zerdine™, CIRS
- Arrays of
  - Inclusions with positive and negative backscatter contrast
  - Nylon fibers



# ACR Accreditation Phantom for Mammography

- Matrix simulates adipose, glandular breast tissue (acrylic)
- Inclusions
  - Fibrous structures (nylon strands)
  - Microcalcifications (AlO<sub>2</sub> specks)
  - Tumor masses (acrylic disks)
- Task-based inclusion detection test method
- 4 largest fibers, 3 largest speck groups, and 3 largest masses must be visualized



Gammex.com

ACR Mammography Accreditation  
Prog. Requirements 2009

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# Performance Characteristics & Test Methods

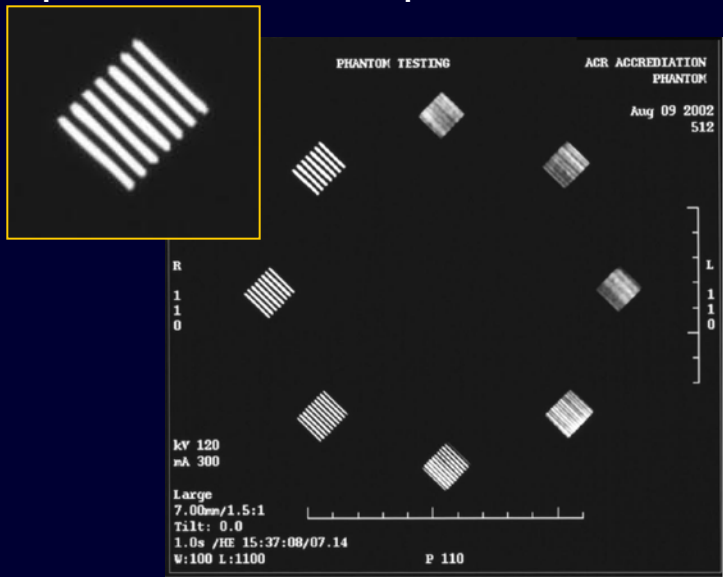
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# Spatial Resolution

## In-plane resolution

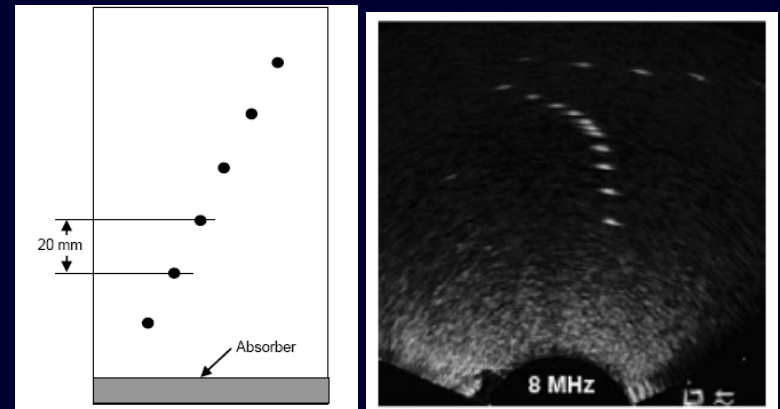
### CT

- Similar to USAF chart for MTF
- Qualitative (visual distinction)
- Aluminum bars with spatial frequencies of 4-12 lp/cm



### Ultrasound

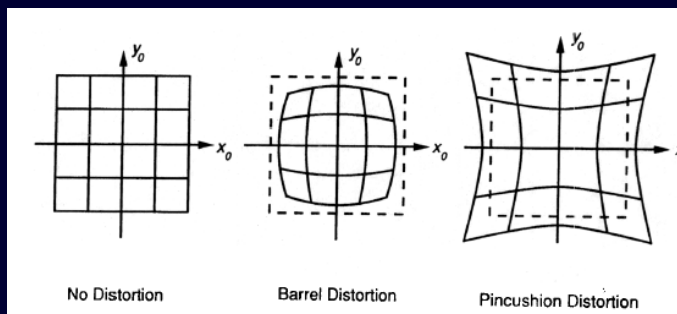
- Quantitative measurement of line spread function (LSF)
- Full-width-half-maximum (FWHM)
- Nylon or metal filaments





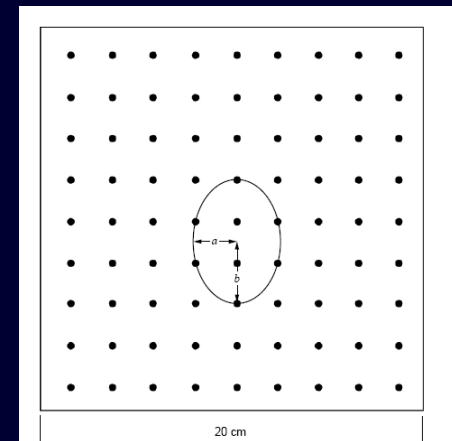
# Geometric Distortion

- Variation in geometric linearity (i.e., magnification) across an image

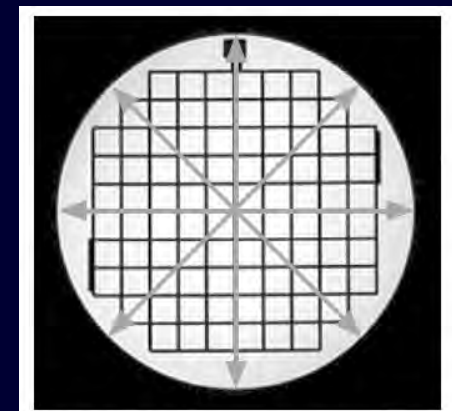


$$\%GD = 100 * \frac{D_{actual} - D_{measured}}{D_{measured}}$$

Ultrasound  
Filament  
array



MRI  
Grid  
target

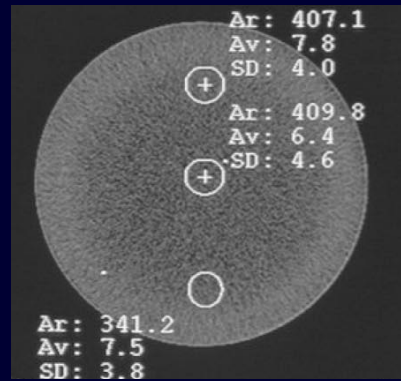
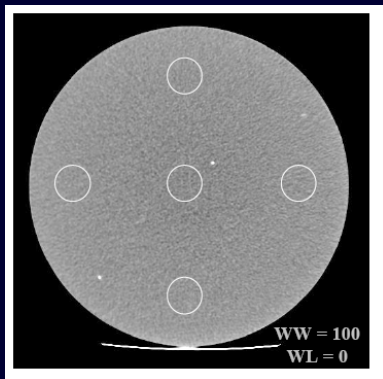


# Signal Uniformity

- Spatial variation in sensitivity
- Due to illumination and/or detection
- Homogeneous phantoms common

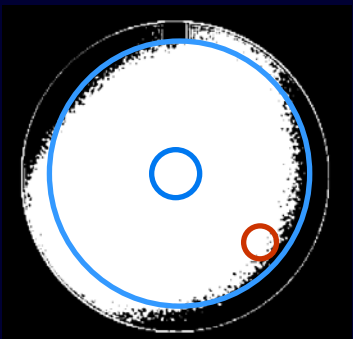
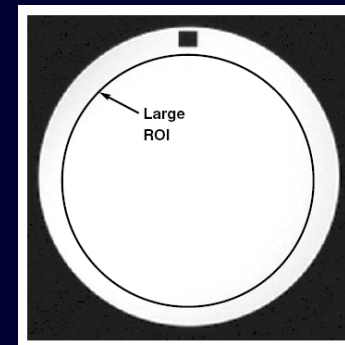
## CT

- Mean at center and 3, 6, 9, 12:00
- Difference between center, edge
- Threshold: Diff < 5 HU



## MRI

$$100 * \left[ 1 - \left( \frac{high - low}{high + low} \right) \right]$$



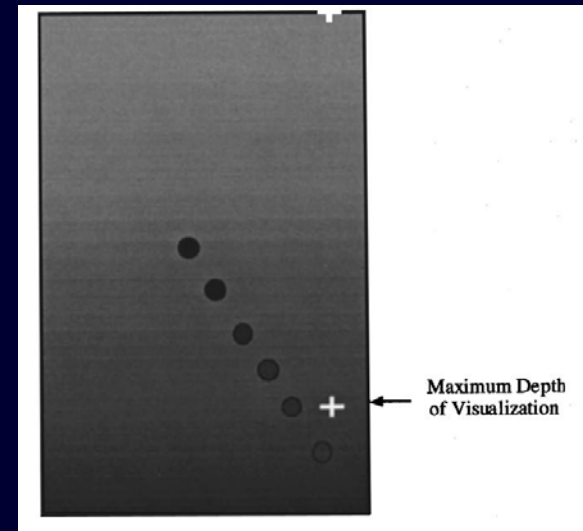
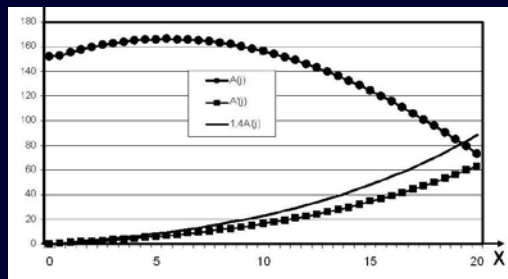
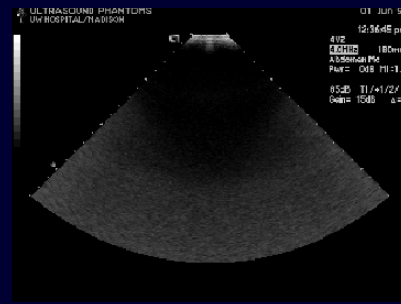
# Visualization Depth

Axial (depth-wise) non-uniformity

## Ultrasound

- Phantom vs. air (noise only)
- Depth where  $UP=1.4*NP$

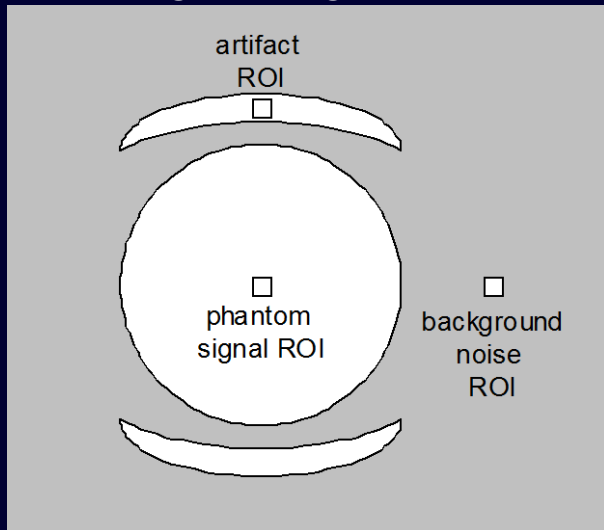
- Anechoic inclusions 15 dB lower than background



# Artifacts

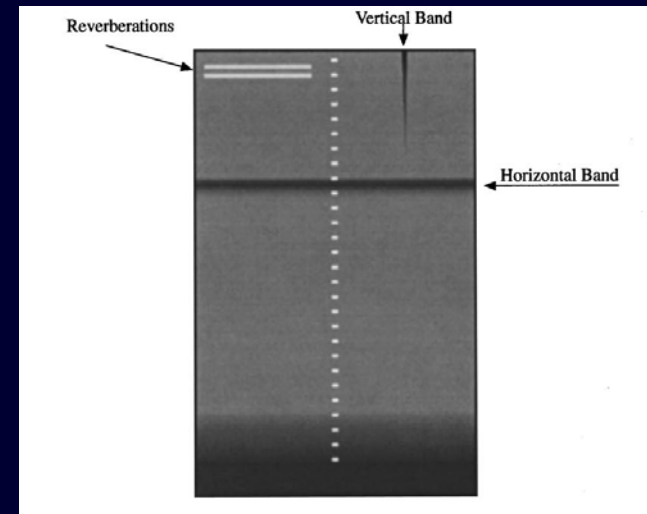
- Non-uniformity in signal distribution
- Homogeneous phantom region
- Qualitative or quantitative

## MRI (ghosting)



- Ghost-to-signal ratio
- Ghost-to-noise ratio

## Ultrasound

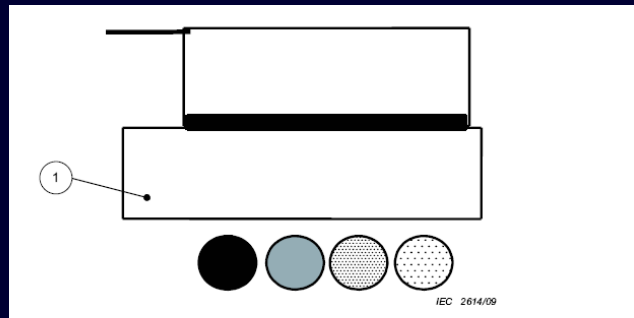


- Qualitative analysis

# Dynamic Range and Linearity

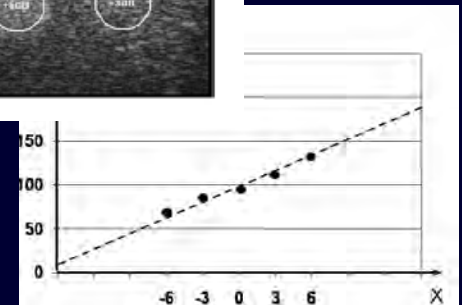
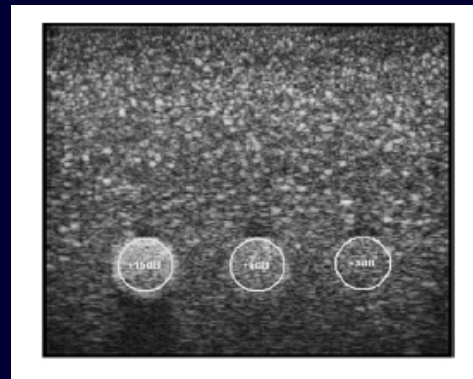
- Dynamic Range
  - Ratio of the highest to lowest signal intensities
  - Range of physical properties measurable (e.g., backscatter coef)

*Specular reflecting surfaces*



- Linearity
  - Physical property value vs. signal intensity

Ultrasound

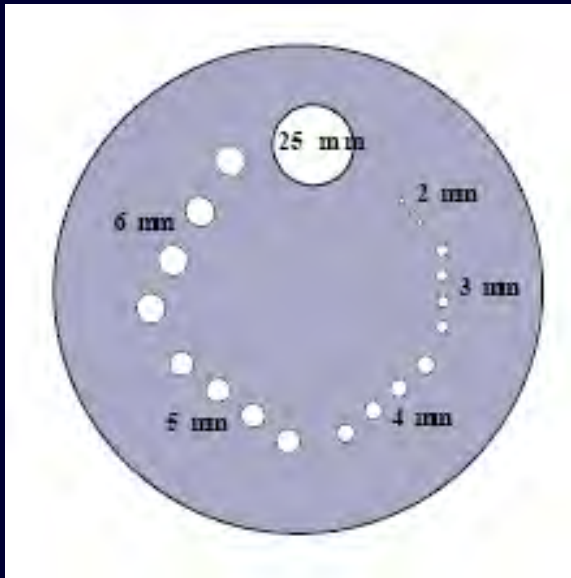


# Low Contrast Detectability

## Task-based test method

### CT

- Inclusions of single scattering level, varying size
- Qualitative visualization of all 4 inclusions in array
- Performance threshold: visualization of 6 mm rods

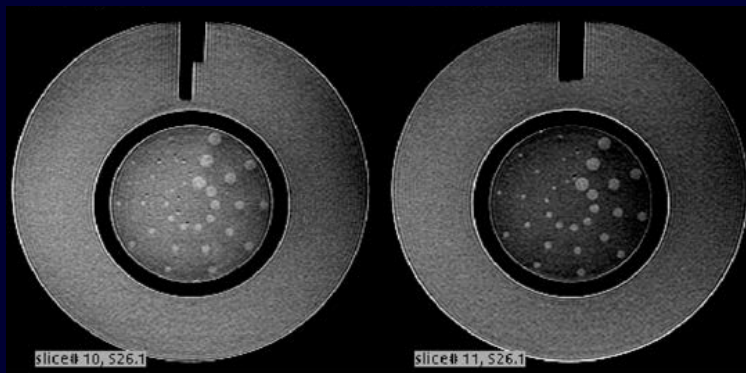


# Contrast-Detail Analysis

## Task-based test method

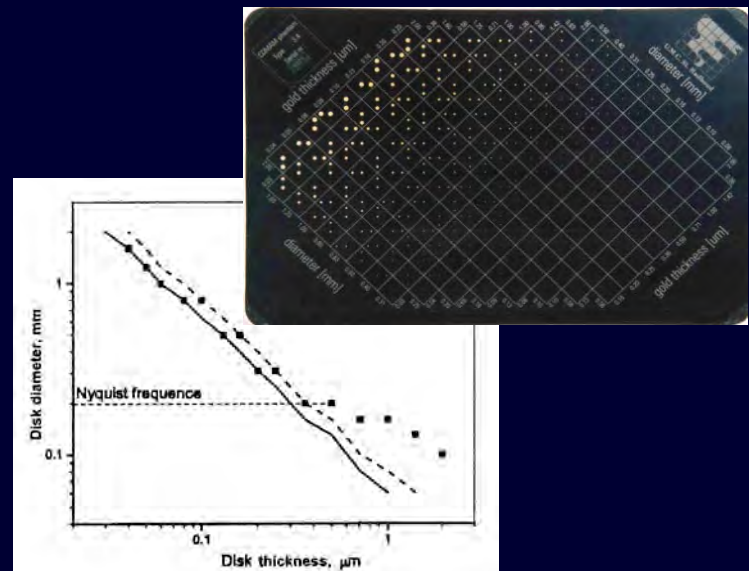
### MRI

- Sections with increasing contrast levels
- “Spokes” with increasing inclusion sizes
- Smallest inclusion size visible for each contrast level



### Mammography

- Aluminum plate with gold disks of varying diameter and thickness
- Smallest disk thickness that is visible for each diameter

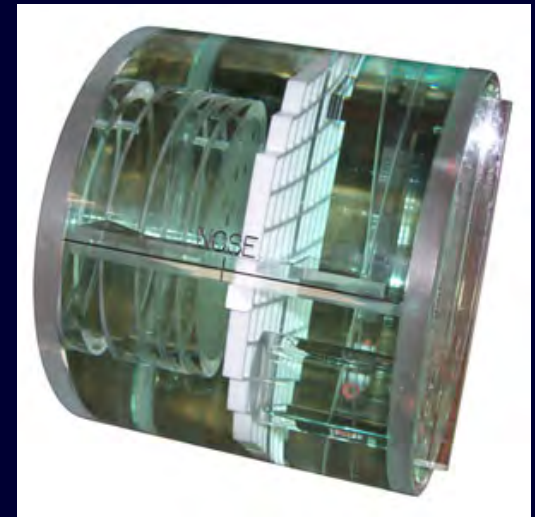


# Summary of Performance Characteristics

	Ultrasound	CT	MRI
Sharpness / Spatial Resolution	X	X	X
Section Thickness	X	X	X
Spatial Meas. Accuracy	X	X	X
Distortion	X		X
Uniformity	X	X	X
Visualization Depth	X		
Artifacts	X		X
Contrast: low contrast resolution, contrast-detail analysis	X	X	X
Material Property Meas. Accuracy	X	X	
Sensitivity/Noise/SNR	X	X	X
Dynamic Range	X		
Linearity	X		

# Medical Imaging Phantoms

- Enable determination of metrics for specific performance characteristics
- Morphology
  - Idealized, not highly anthropomorphic
  - Basic geometrical shapes (e.g., fibers, cylinders)
  - Accurate, repeatable morphology
- Material properties
  - Well-characterized, stable values
  - Biologically relevant, not tissue-specific
  - Background/matrix materials: Low contrast
  - Feature materials provide high (e.g., metals), low or negative contrast (non-scattering)



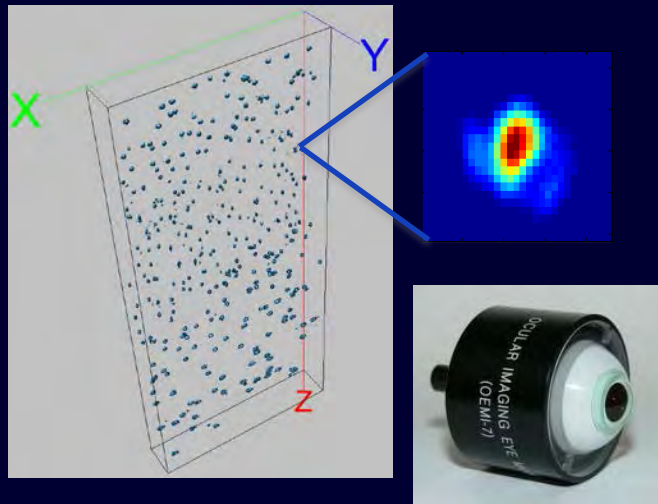
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How can we adapt these approaches for  
biophotonic imaging?

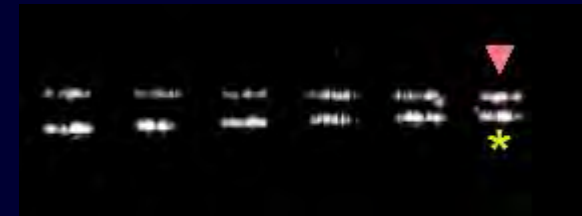
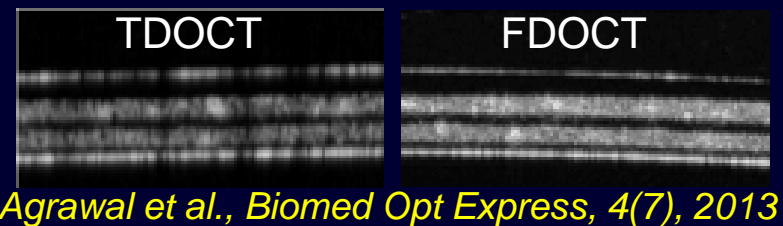
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# OCT Spatial Resolution

## PSF-nanoshell Phantoms



## Bar Chart Phantoms



*Gu et al., Biomed Opt Express, 3(9), 2014*

- Analogous to LSF filament phantoms for ultrasound

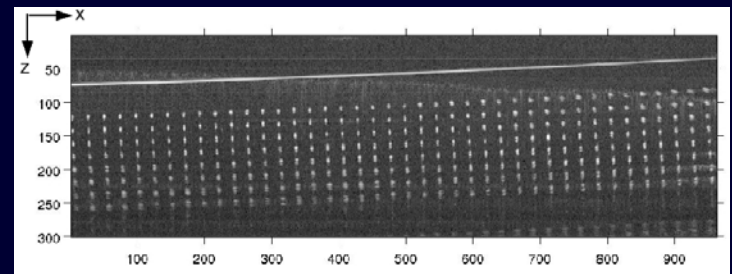
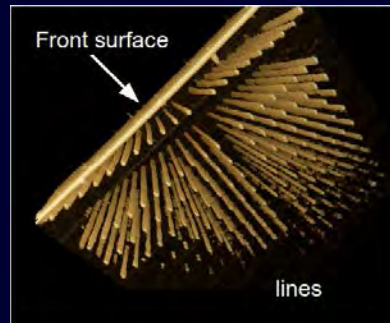
*Agrawal et al., Opt Lett, 35(13), 2010*

*Agrawal et al., Biomed Opt Express, 3(5), 2012*

- Analogous to USAF and CT bar chart approaches

# OCT Distortion, Spatial Measurement Accuracy

Laser-inscribed fused silica phantom



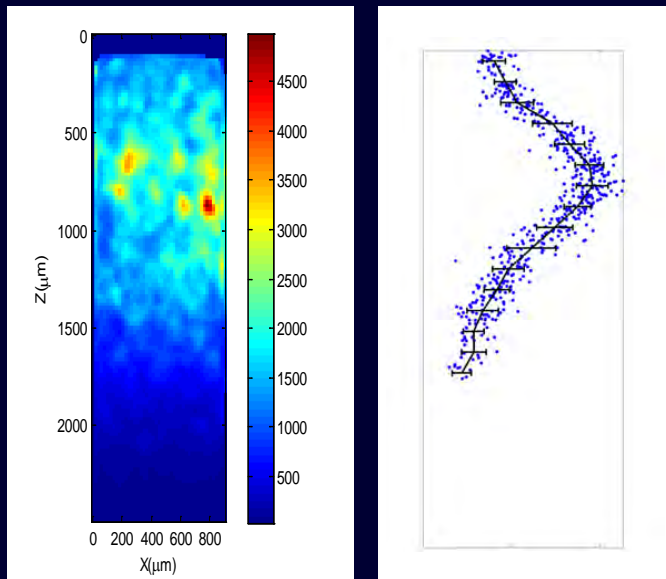
- Analogous to filament phantoms for ultrasound
- May also be useful for resolution, sensitivity
- Commercially available (Arden Photonics Ltd., UK)

*Tomlins et al., Biomed. Opt. Express, 2(5), 2011*

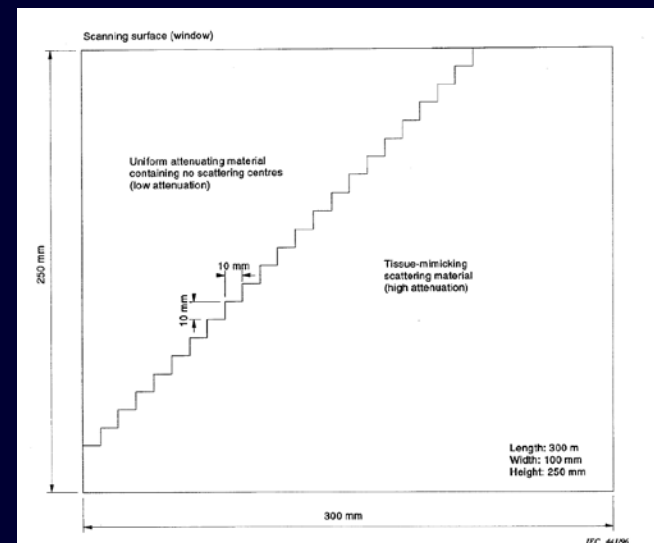
*Lee et al., Proc. SPIE 8427, 2012*

# OCT Uniformity/Penetration Depth

Nanoshell uniformity phantom



Stair-step penetration phantom



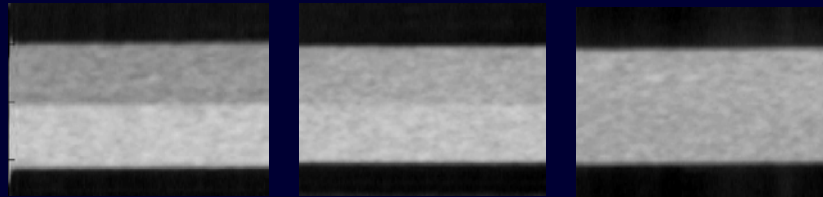
- Analogous to homogeneous uniformity phantoms, no bulk attenuation

- Stair-step design analogous to IEC TS 1390 (ultrasound)

# OCT Low Contrast Detectability

## Task-specific Approach

Layer  
detectability



- Spin coated PDMS layers

Inclusion  
detectability



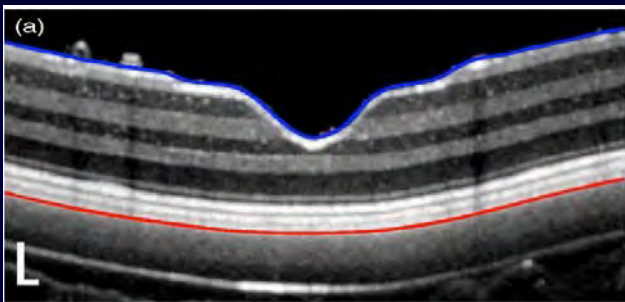
- PDMS with intralipid inclusion

- Analogous to LCD / C-D test methods for CT and MRI
- Minimum detectable difference in  $\mu_s'$

# OCT Anthropomorphic Phantoms

For Task-specific Test Methods

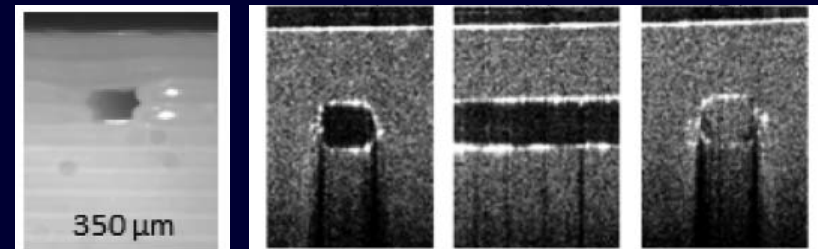
Retina-simulating Phantoms



- FDA-designed phantom
  - 13 spin-coated layers
  - Evaluation of feature measurements (device, algorithm)

*Baxi et al., J Biomed Opt 19(2), 2014*
- Rowe Technical Design, Inc.
  - 6-layer retinal phantom

3D Printed Phantoms



- *Potential to revolutionize phantom fabrication*
  - Ideal and realistic geometries
  - Rapid dissemination of standard phantom designs

*Wang et al., Optics Letters 39(10), 2014*

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# Challenges

- Need for well-validated phantoms
    - Performance characterization analogous to that described in medical imaging standards
    - Key clinically-relevant tasks
  - Additional work to develop/optimize/validate test methods
    - Robust materials that simulate/incorporate tissue chromophores
    - Repeatable fabrication approaches
    - *In vivo* studies to evaluate relevance of specific performance characteristics
    - Phantom comparisons: multi-lab, round-robin testing
  - Establish consensus
    - Most important performance characteristics
    - Optimal phantom-based test methods, metrics
  - Incorporate consensus methods into standards and guidance documents
  - Translate to commercial products
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- For more info on test methods, phantoms and regulatory issues...
    - A review of consensus test methods for established medical imaging modalities and their implications for optical coherence tomography, Pfefer J and Agrawal A. Proc. SPIE 82150D, 2012.
    - Regulatory perspectives and research activities at the FDA on the use of phantoms with diagnostic devices. Agrawal A, Gavrielides M, Weininger S, Chakrabarti K, Pfefer J, Proc. SPIE 6870-05, 2008.
    - “Regulation and regulatory science for optical imaging,” Pfefer TJ and Drum BA, Chap. 15 in Translational Multimodality Optical Imaging, F. S. Azar and X. Intes, Eds., pp. 299-325, Artech House, Boston, Mass, 2008.

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