NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

National Institute of Biomedical Imaging and Bioengineering

Metrology for Computed Tomography:

Lessons from the Past, Needs for the Future

John M. Boone, Ph.D.
Distinguished Professor of Radiology
& of Biomedical Engineering
University of California Davis
Editor-in-Chief, Medical Physics

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Disclosures

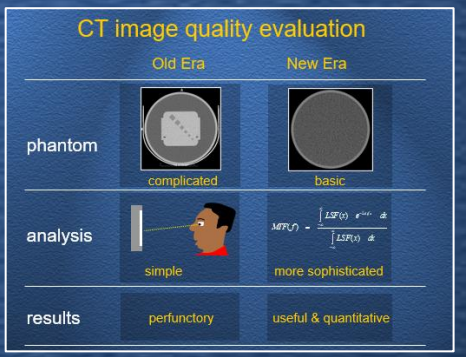
JM Boone (with JH Siewerdsen) have a patent on the Corgi phantom, which is licensed to The Phantom Lab

ChatGPT was used for data collection and image generation in some instances for this presentation

RSNA Categorical Course
2008 – 2009 - 2010

Image Quality Metrics in CT

John M. Boone, Ph.D., FAAPM, FSBI, FACR
Department of Radiology
University of California Davis

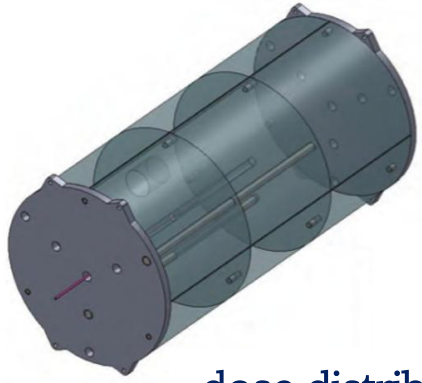


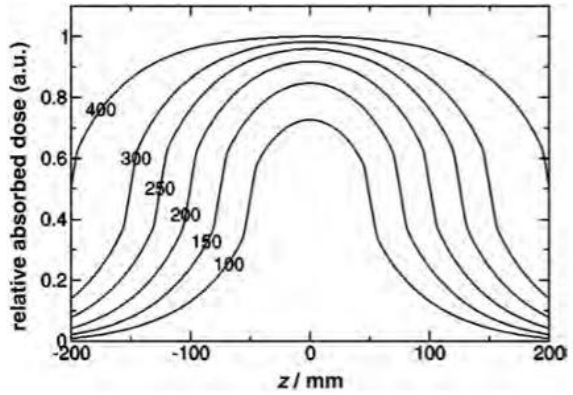
RADIATION DOSE AND IMAGE-QUALITY ASSESSMENT IN COMPUTED TOMOGRAPHY

Report Committee

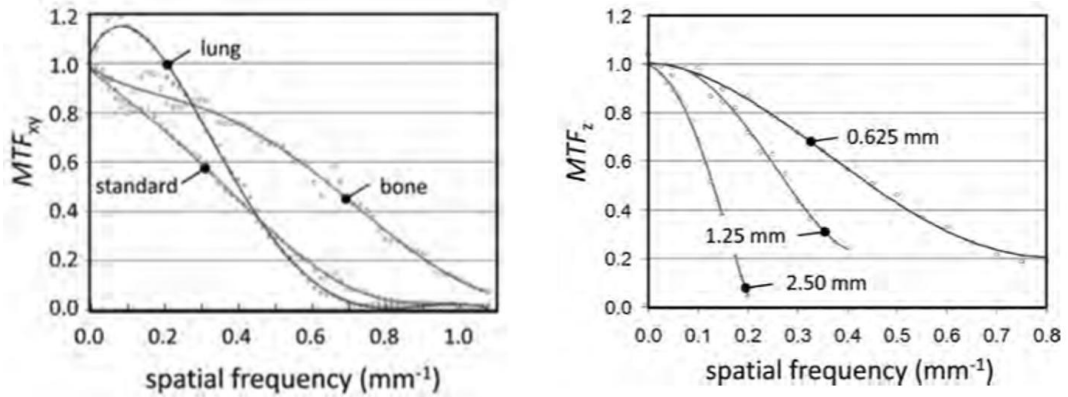
J. M. Boone (Chair), University of California Davis, Sacramento, California, USA
J. A. Brink, Massachusetts General Hospital, Boston, Massachusetts, USA
S. Edyvean, Public Health England, Oxfordshire, UK
W. Huda, Medical University of South Carolina, Charleston, South Carolina, USA
W. Leitz, Swedish Radiation Protection Authority, Stockholm, Sweden
C. H. McCollough, Mayo Clinic, Rochester, Minnesota, USA
M. F. McNitt-Gray, University of California Los Angeles, Los Angeles, California, USA



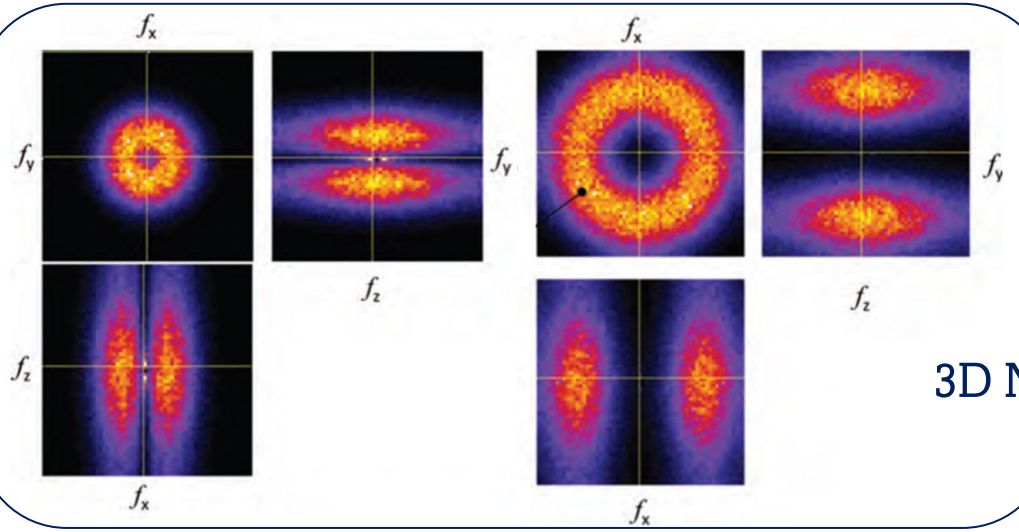




dose distributions



3D MTF(f)



3D NPS(f)

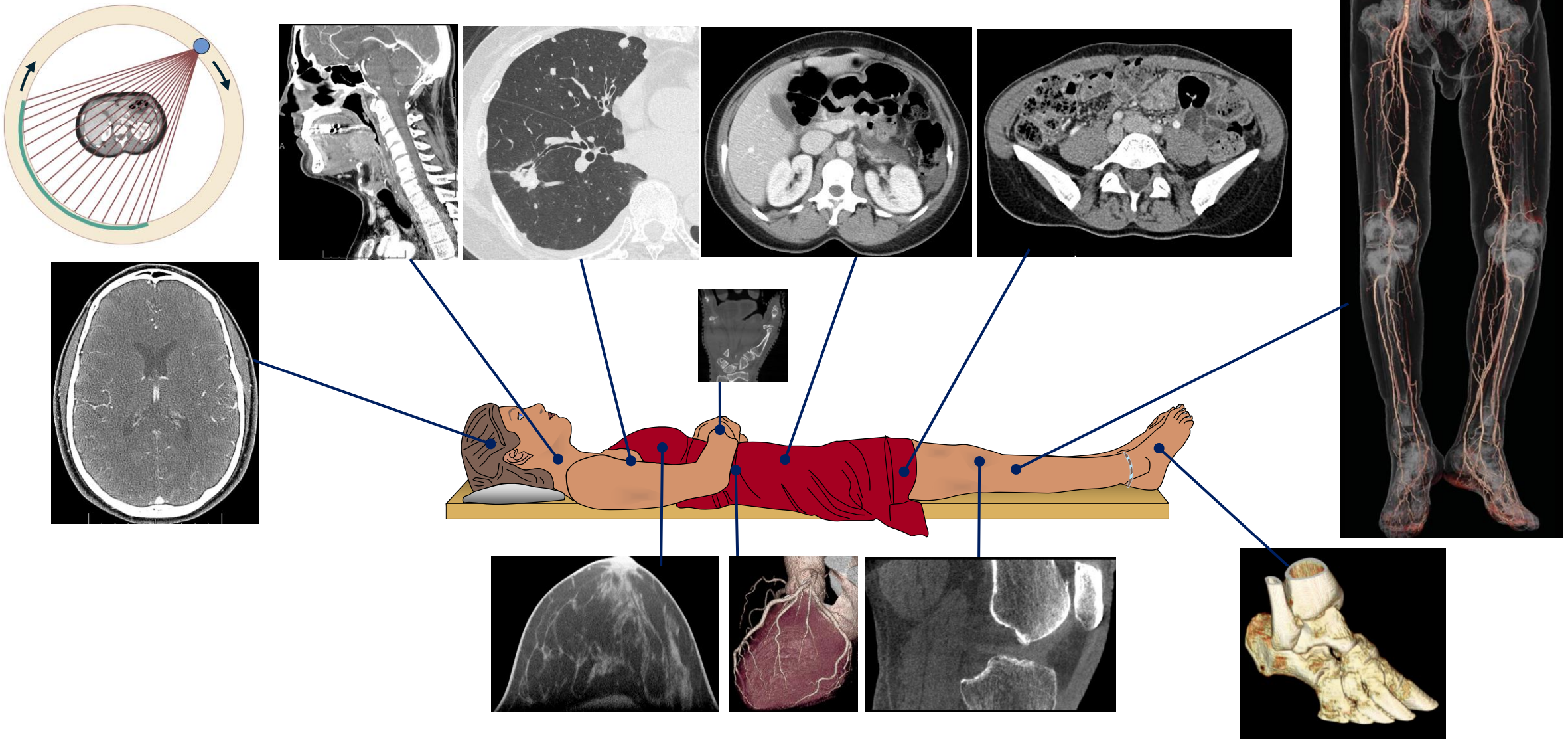
CT Metrology: Past and Future



- About CT
  - Radiation Dosimetry in CT
  - CT Image Quality Metrics (past)
  - CT Image Quality Metrics (current)
  - CT Image Quality Metrology (future needs)
  - Summary

CT Metrology

About CT



CT Metrology

Abou

The radiation levels from CT caught the eye of the media

CT scans in children linked to cancer

By Steve Sternberg, USA TODAY

Each year, about 1.6 million children in the USA get CT scans to the head and abdomen — and about 1,500 of those will die later in life of radiation-induced cancer, according to research out today.

What's more, CT or computed tomography scans given to kids are typically calibrated for adults, so children absorb two to six times the radiation needed to produce clear images , a second study shows. These doses are "way bigger than the sorts of doses that people at Three Mile Island were getting," David Brenner of Columbia University says. "Most people got a tenth or a hundredth of the dose of a CT."

FDA Public Health Notification:
Reducing Radiation Risk from Computed Tomography for Pediatric and Small Adult Patients

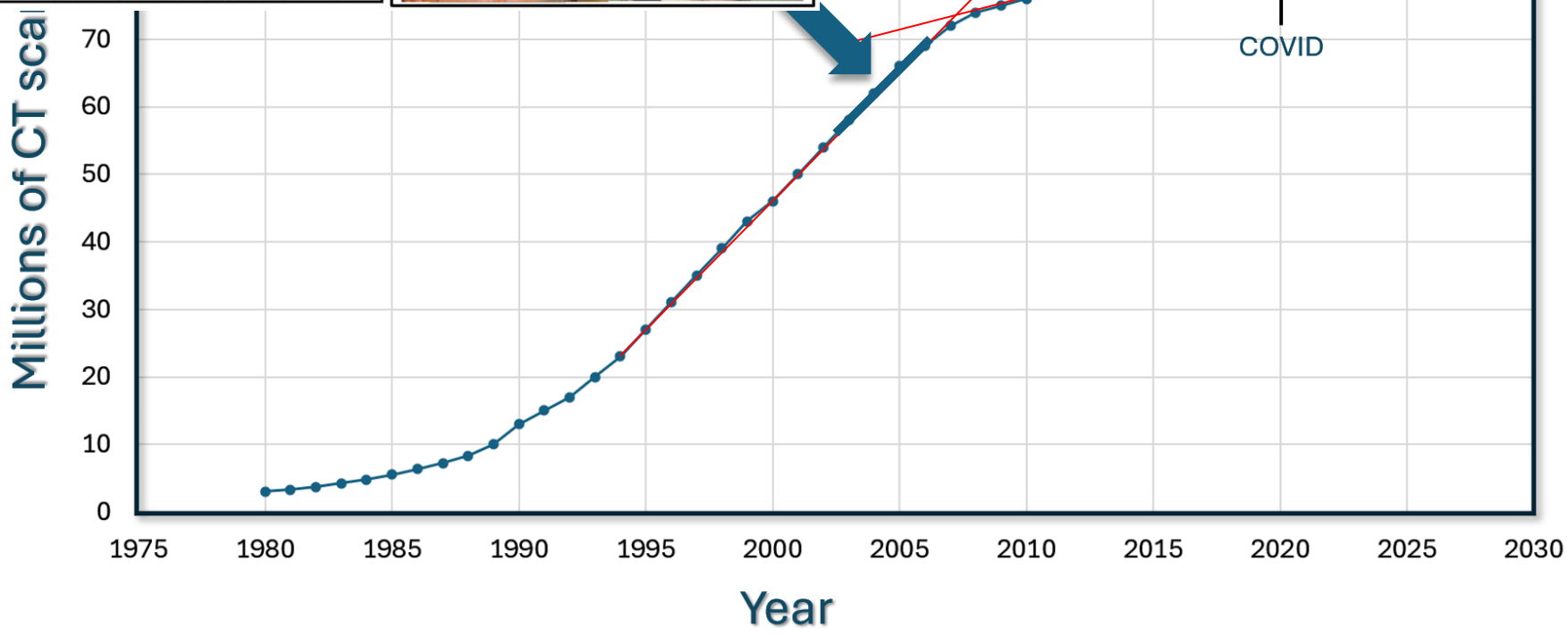
Radiation-induced temporary hair loss as a radiation damage only occurring in patients who had the combination of MDCT and DSA

Eur Radiol (2005) 15:41–46



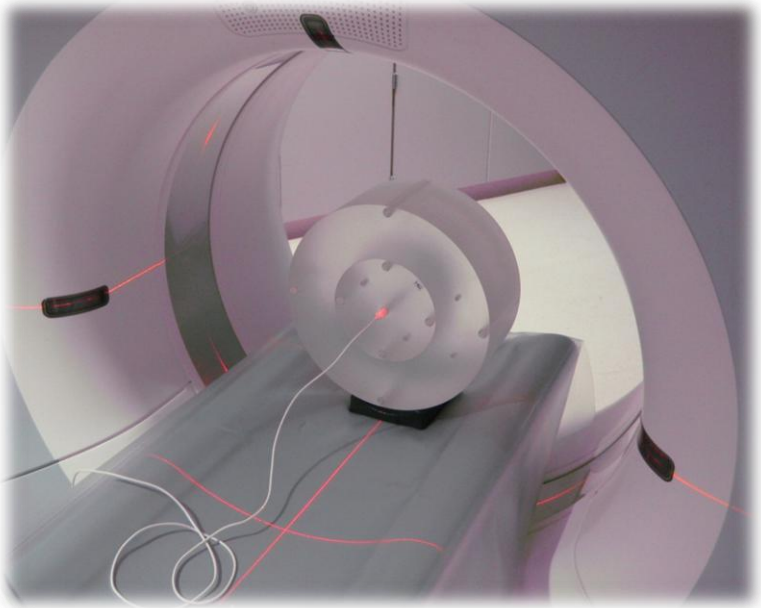
Cedars-Sinai Medical Center
Los Angeles, California • Over 260 cases of epilation





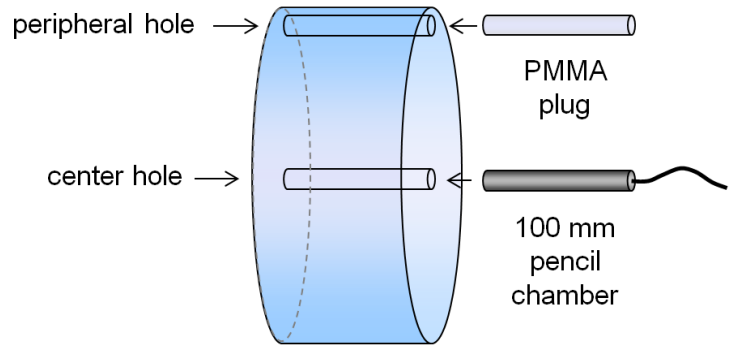
Radiation Dosimetry in CT

- About CT
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Volume CT Dose Index ($CTDI_{vol}$)

CT Metrology



Volume CT Dose Index Measurement

Early Foundation in 1980 by FDA scientists

$$\text{Dose} = \frac{\text{Energy Absorbed}}{\text{Mass}}$$

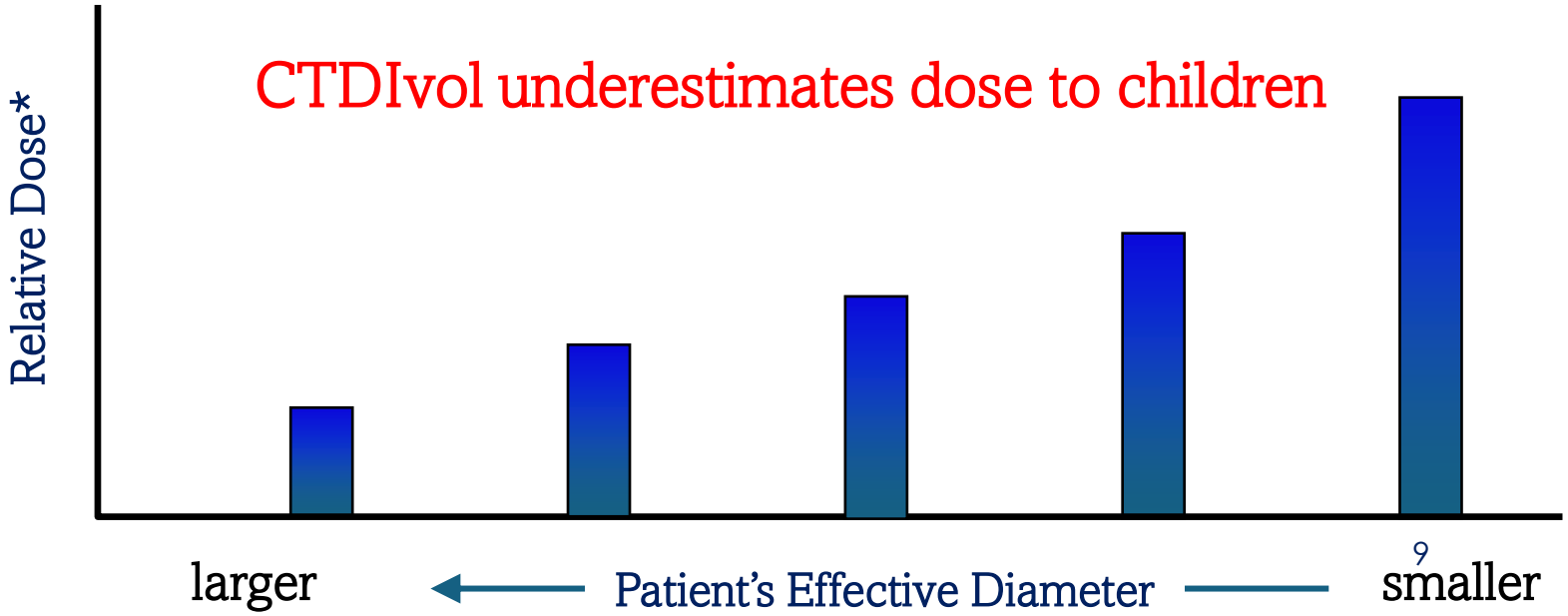
*for the same CT technique

ADULT CHILD



$CTDI_{vol}$

CTDIvol underestimates dose to children



CT Metrology

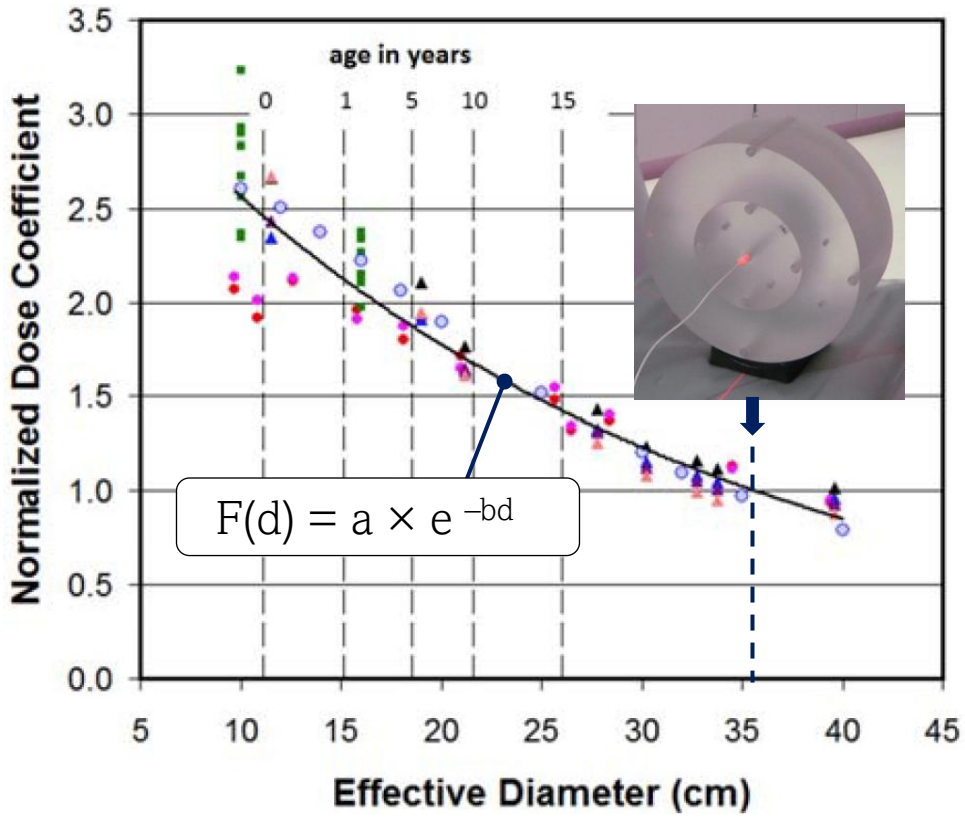
AAPM Report 204

John M. Boone
Keith J. Strauss
Dianna D. Cody
Cynthia H. McCollough
Michael F. McNitt-Gray
Thomas L. Toth

Size Specific Dose Estimates (SSDE) in Pediatric and Adult Body CT Examinations

image gently℠

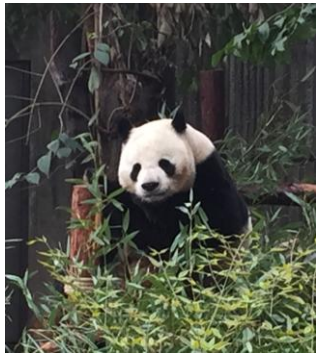
Dose (mGy) = CTDIvol (mGy) × F(d)



Size-Specific Dose Estimate (SSDE)

AAPM TG-204 (body)
AAPM TG-293 (head)

CT Metrology





Chengdu China
2018



Tel Aviv
2019

International Electrotechnical Commission (IEC)



Seoul Korea
2019

IEC Subcommittee
62B (on CT)

SSDE is now an Industry Standard in CT (IEC 62985:2019)

"… standardized methods for calculating, displaying and recording SSDE on CT scanners…"

Past CT Image Quality Metrics



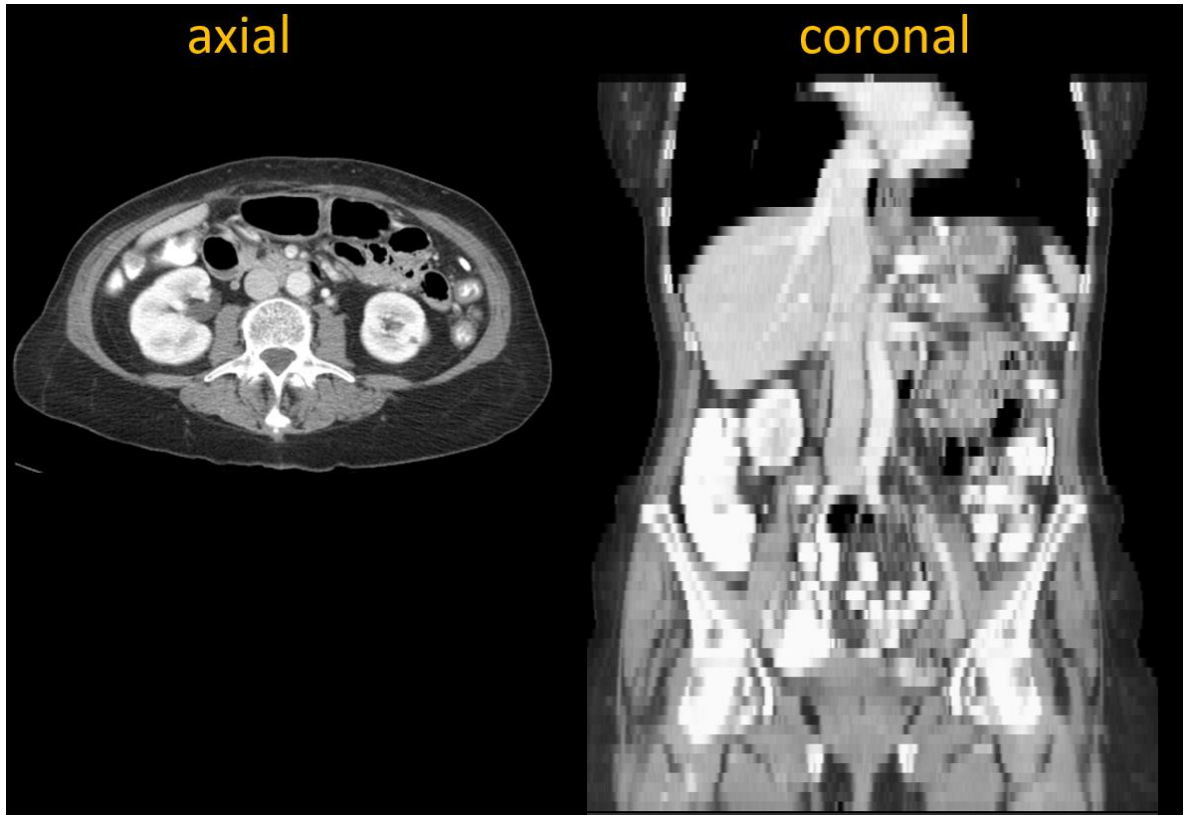
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CT Metrology

CT technology 1986



CT images were displayed using analog film

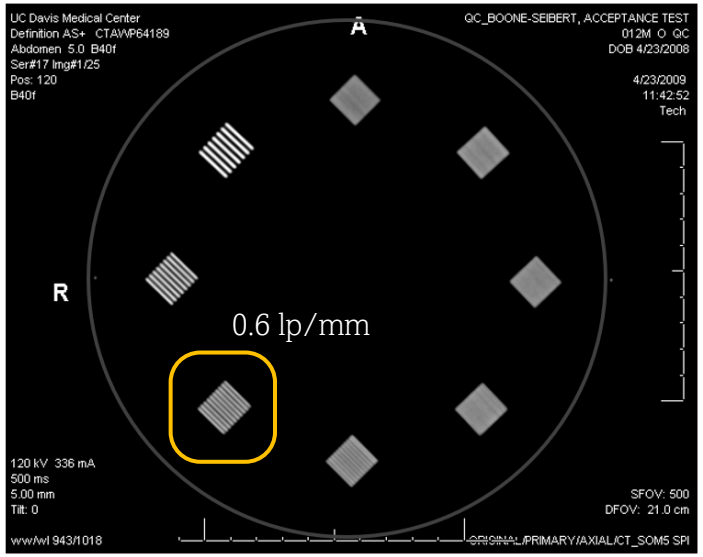


Typical CT slice thickness was ~5 – 7 mm

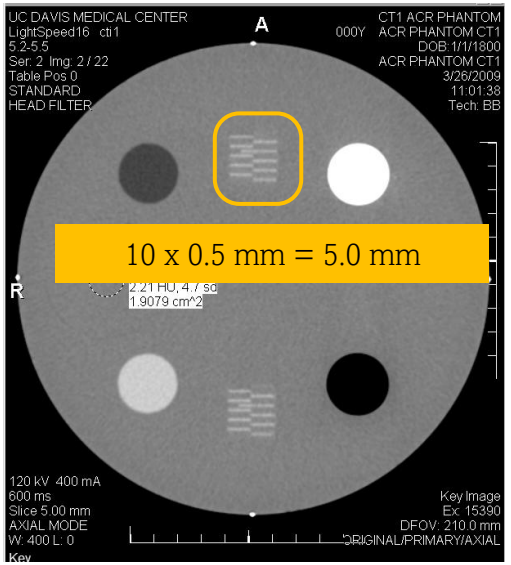
CT Metrology



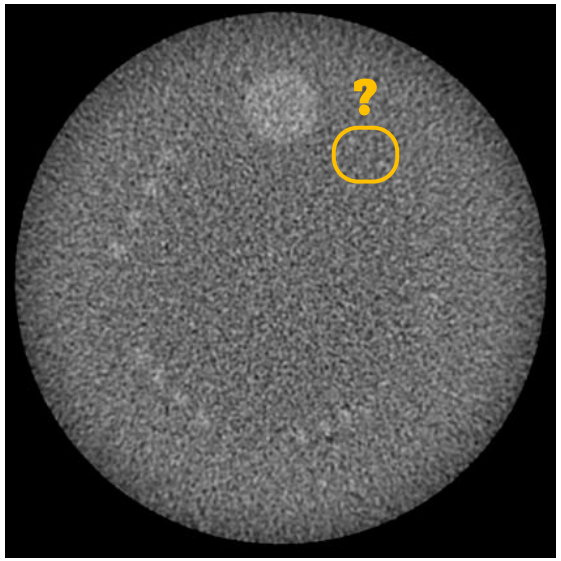
ACR CT accreditation phantom



spatial resolution assessment



CT slice thickness assessment



contrast resolution assessment

CT Accreditation Program: Image Quality and Dose Measurements

1997

Cynthia H. McCollough, Ph.D.
Department of Radiology
Mayo Clinic
Rochester, MN

In 1997, the ACR approved the development of an Accreditation Program for CT. Since that time, many knowledgeable and dedicated individuals have volunteered countless hours towards the development of the CT Accreditation Program, including radiologists, medical physicists, and ACR staff members. The CT Accreditation committee is chaired by Robert Zeman, M.D. I was pleased to be asked to chair the Physics subcommittee, which includes fellow physicists Mike McNitt-Gray Ph.D., Tom Payne Ph.D., Tom Ruckdeschel M.S., and physics-savvy radiologist, James Brink, M.D. I am particularly pleased to report that the

MEDICAL PHYSICS
The International Journal of Medical Physics Research and Practice

Educational treatise

The phantom portion of the American College of Radiology (ACR) Computed Tomography (CT) accreditation program: Practical tips, artifact examples, and pitfalls to avoid

Cynthia H. McCollough, Michael R. Bruesewitz, Michael F. McNitt-Gray, Krista Bush, Thomas Ruckdeschel, J. Thomas Payne, James A. Brink, Robert K. Zeman

First published: 19 August 2004 | https://doi.org/10.1118/1.1769632 | VIEW METRICS



CT Metrology

Current CT Image Quality Metrics



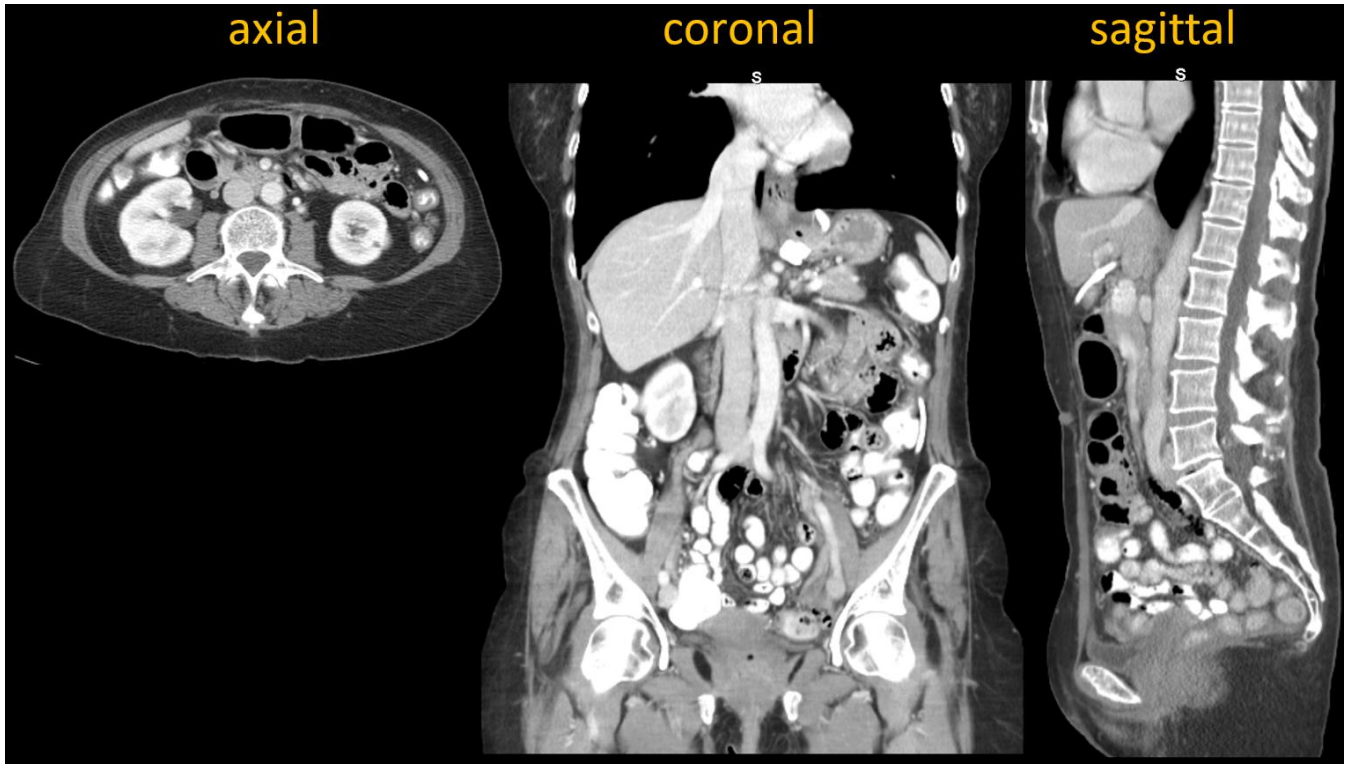
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CT Metrology

CT technology 2026



CT images are displayed on interactive monitors



Typical CT slice thickness is 1-3 mm

CT Metrology



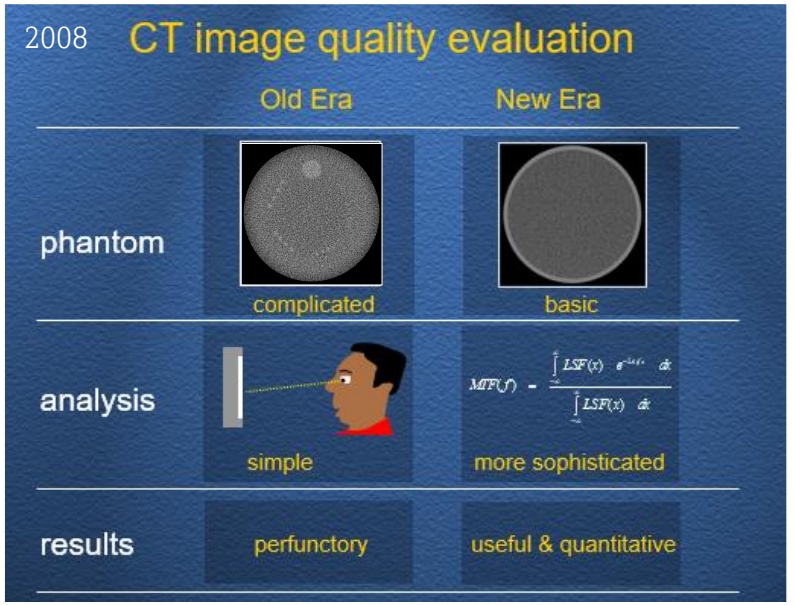
ACR CT accreditation

Current CT Image Quality Assessment

There are approximately 15,000 CT scanners now in clinical service

From the ACR (2024):
ACR Accredited CT Facilities: 7013
ACR Accredited CT scanners: 10,190

68% of all CT scanners are currently accredited by the ACR

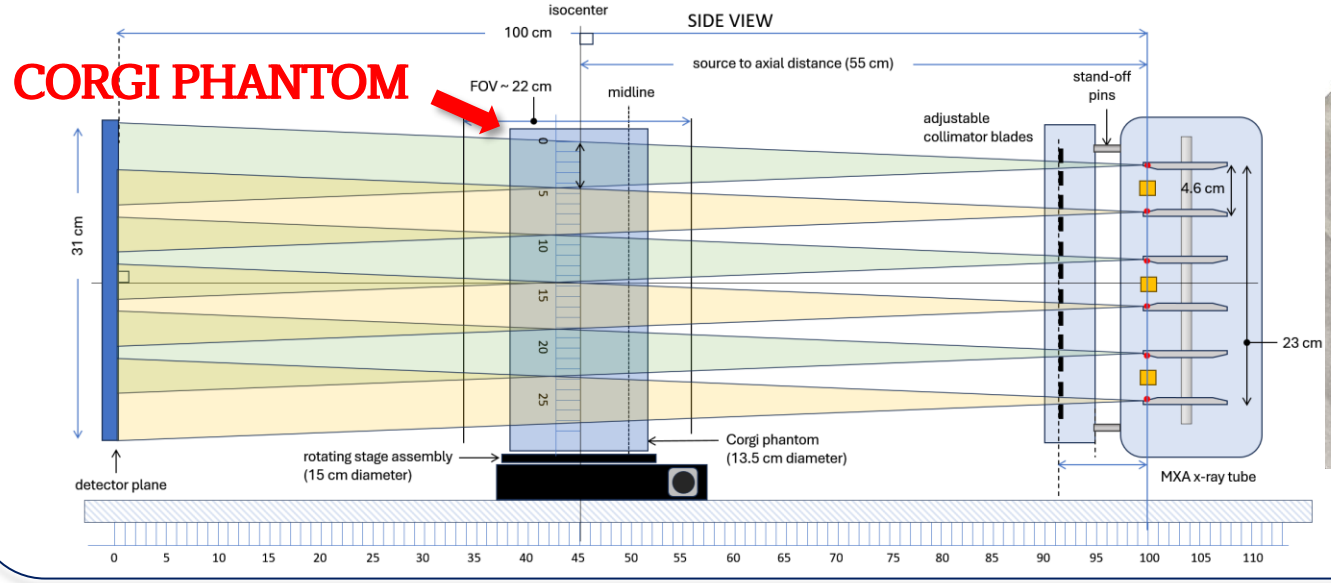


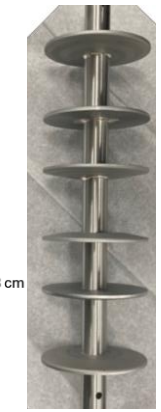
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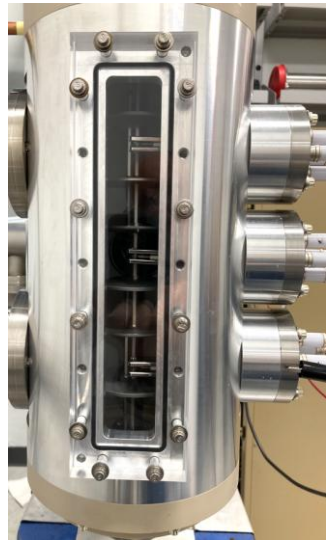
CT Metrology

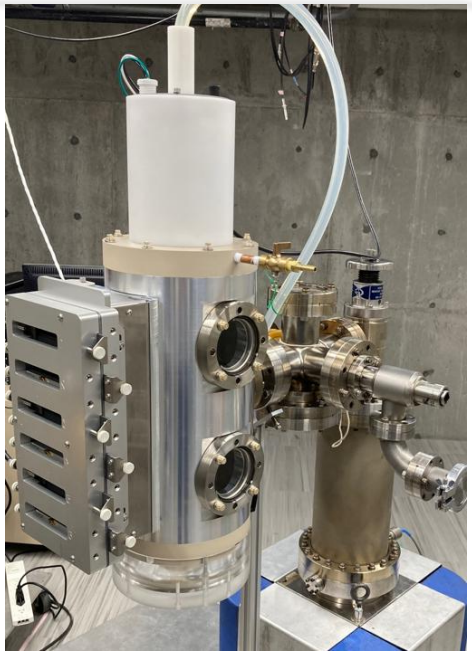
National Institute of Biomedical Imaging and Bioengineering

U01: Multiple X-ray Source Array (MXA) Computed Tomography









Notice of Special Interest (NOSI): Administrative Supplements for Supporting the Optimization, Calibration, and Dissemination of Imaging Phantoms

Notice Number:
NOT-EB-24-009

➡ NIST / NIBIB Phantom Library

U01S: Phantom and Automated Analysis for Advanced Computed Tomography Systems



Cone-beam CT dose and imaging performance evaluation with a modular, multipurpose phantom

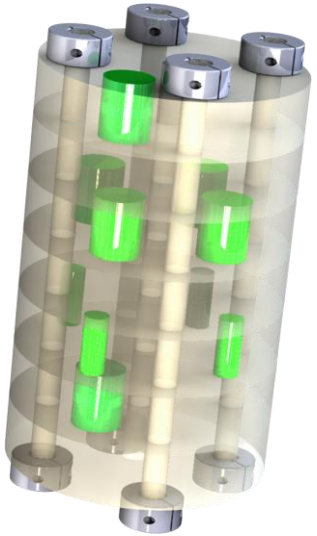
J. H. Siewerdsen[a)] and A. Uneri
Department of Biomedical Engineering, Johns Hopkins University, Baltimore, MD 21205, USA

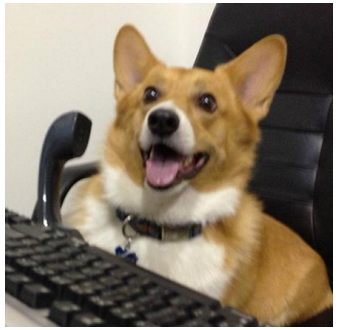
A. M. Hernandez, G. W. Burkett, and J. M. Boone
Department of Radiology, University of California – Davis, Sacramento, CA 95817, USA

(Received 5 September 2019; revised 18 November 2019; accepted for publication 23 November 2019; published 25 December 2019)

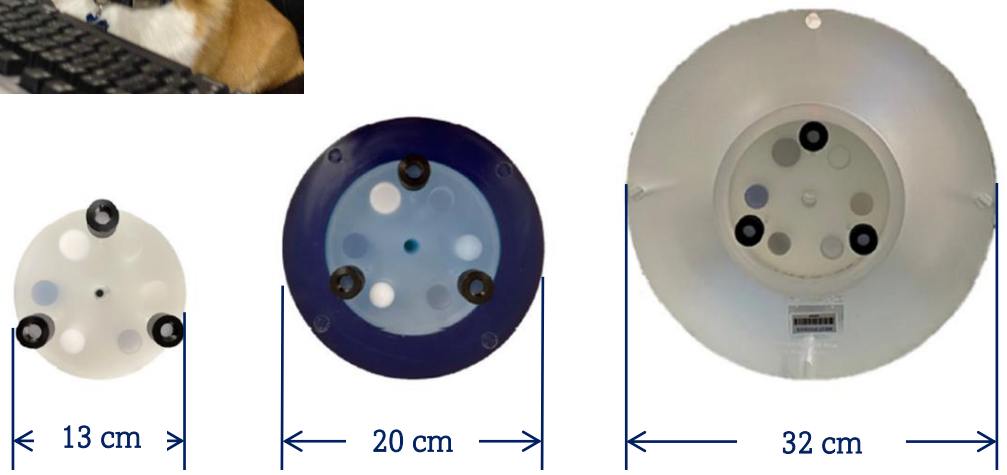








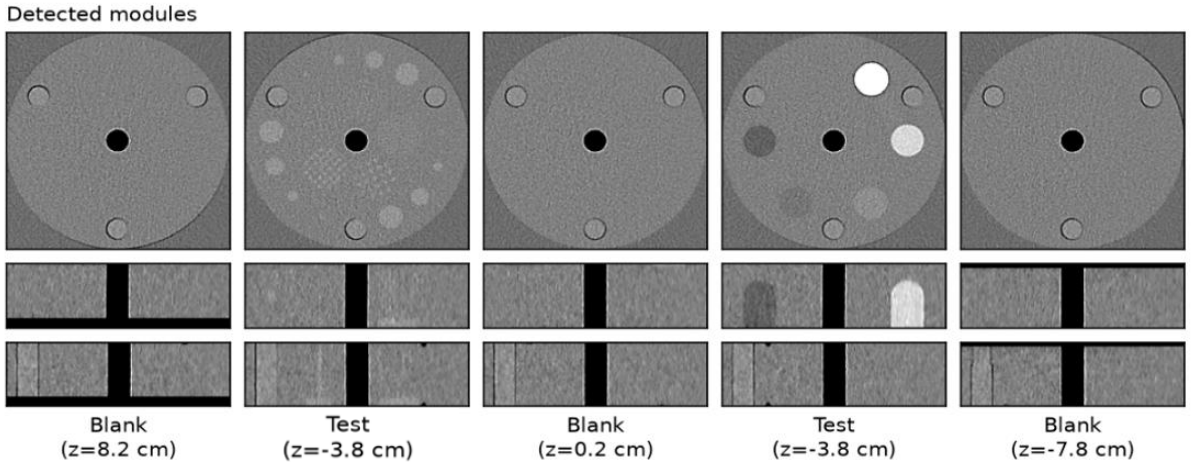
CORGI PHANTOM



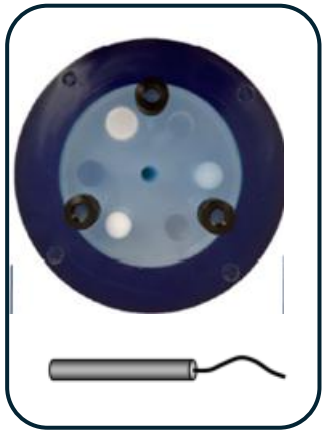
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CT Metrology

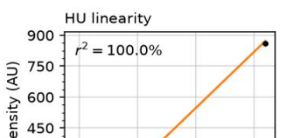
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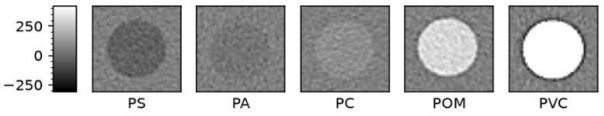
- HU linearity
- Contrast-to-Noise
- Edge Spread Function
- Modulation Transfer Function
- Axial Noise Power Spectrum (1D)
- Noise Power Spectrum (2D)
- Cone Beam Artifact

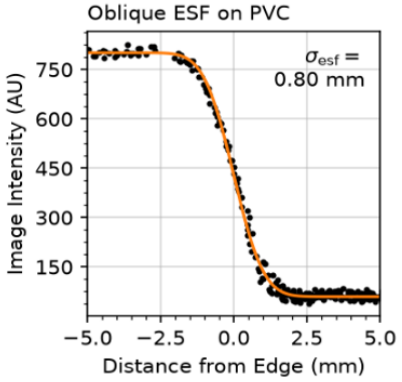


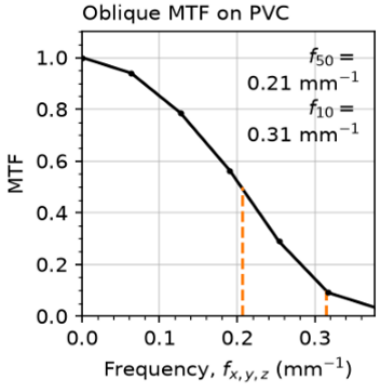
At the same dose

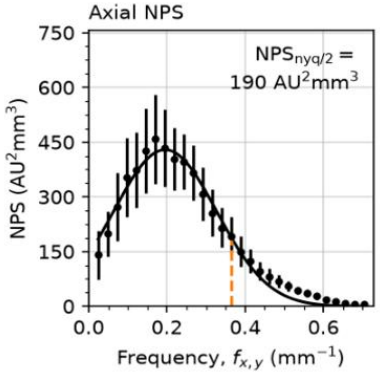


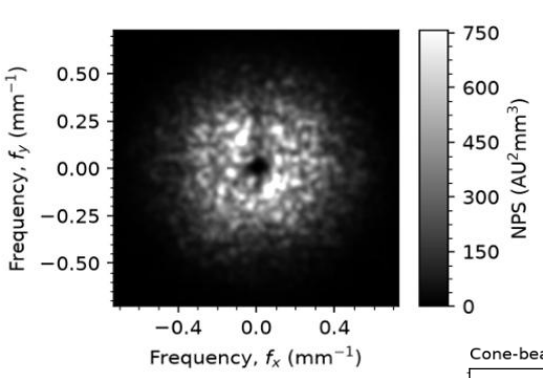


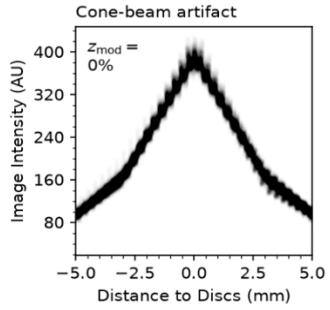












delivers quantitative metrics for a more precise understanding of CT performance

Future CT Image Quality Metrics



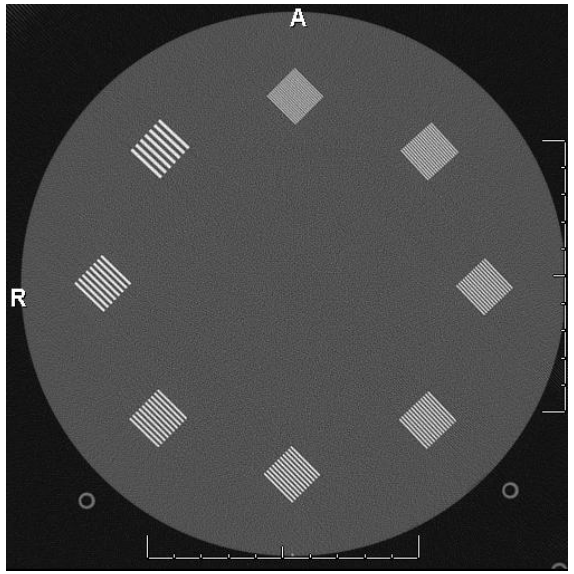
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New CT applications: Unmet metrology needs

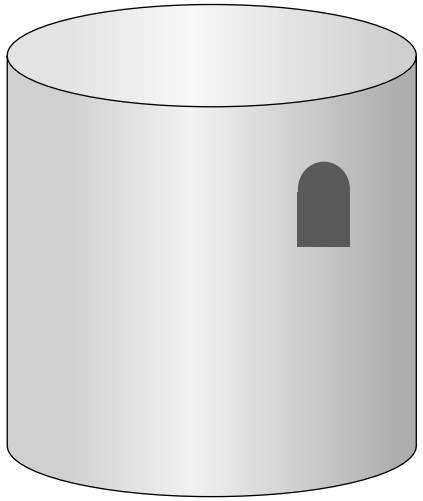
- Most new CT scanners have high spatial resolution
- Photon Counting CT systems (multi-energy) are here
- Radiomics is a promising new area but needs standardization
- Tumor volumetric analysis is needed
- AI reconstruction methods can create images which defy Fourier based analysis

CT Metrology

Spatial Resolution



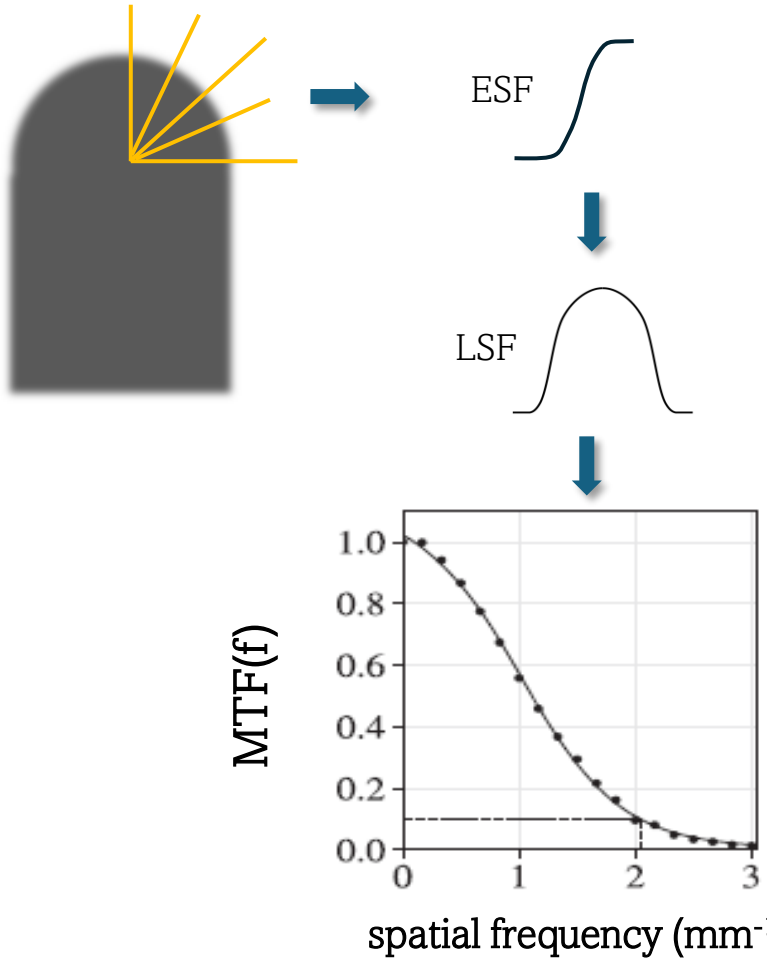
ACR phantom
(can resolve all l/p modules)



Corgi Phantom
(measures MTF)

MTF is robust across over all spatial resolutions

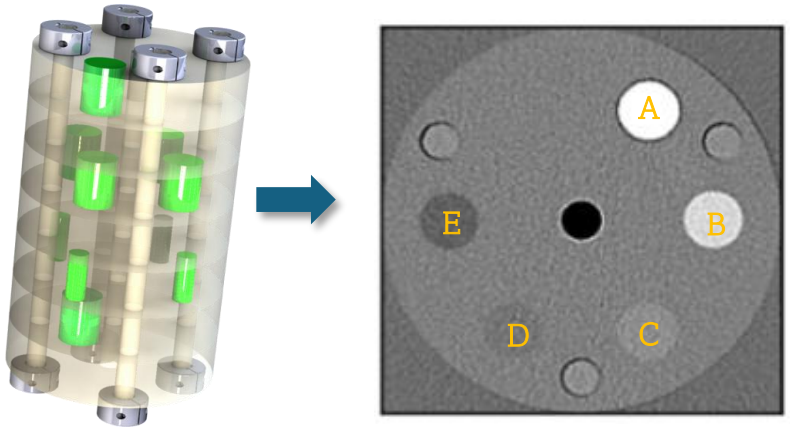
Modulation Transfer Function

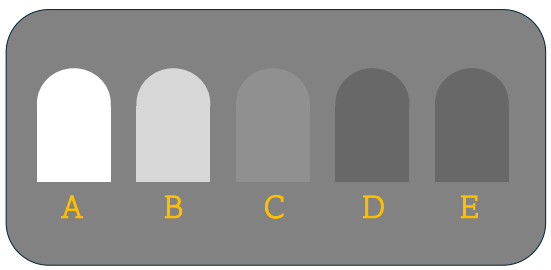


CT Metrology

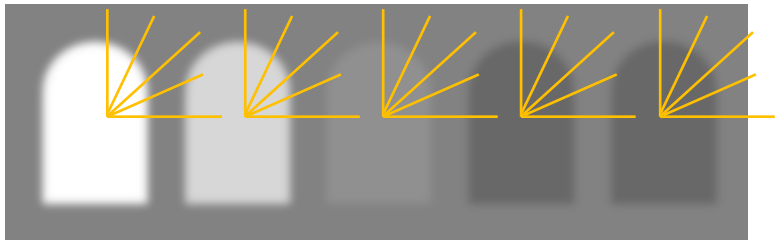
AI & IR reconstruction

…where spatial resolution is generally contrast dependent

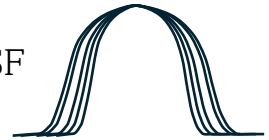


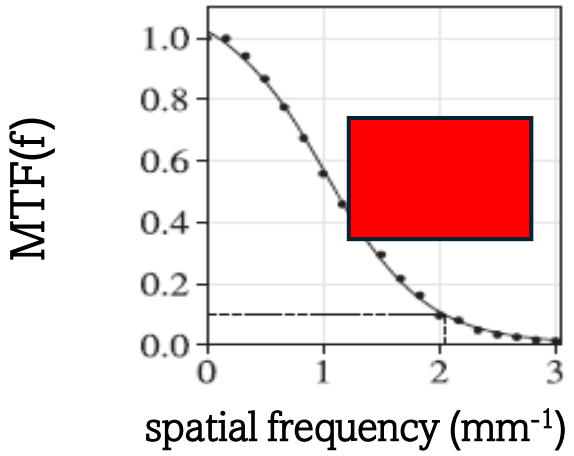


Modulation Transfer Function





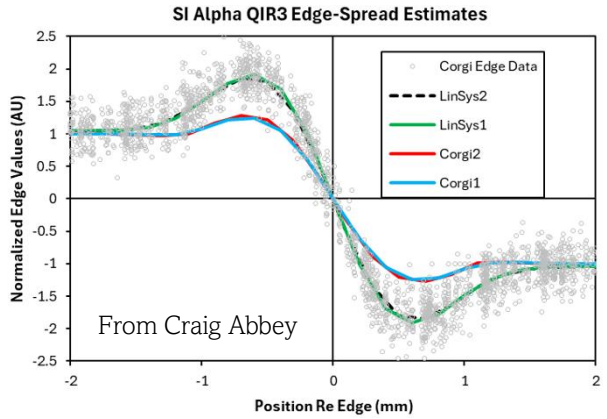




CT Metrology

Potential NIST standardization projects:

Spatial Resolution



What metrics?

2D (axial plane spatial resolution)

Slice thickness (outdated, still needs a metric)

3D spatial resolution

IR and AR (non-linear) resolution metrics?

Contrast dependent?

What to measure?

Modulation Transfer Function

Full width at half-max of LSF?

How to measure?

Edge Spread Function

Line Spread Function

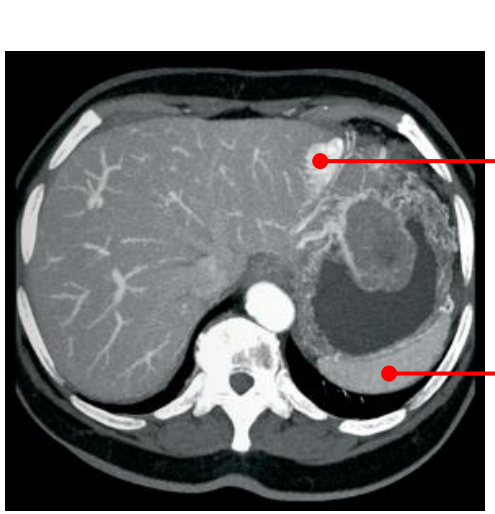
Point Spead Function

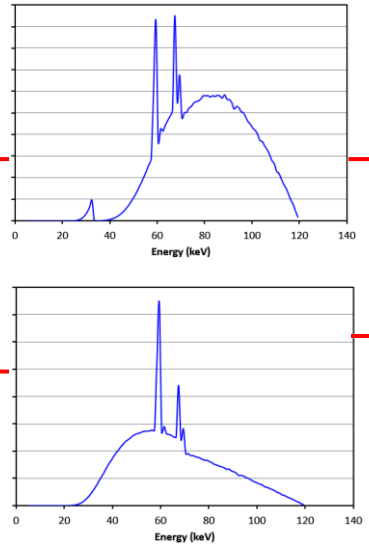
Measurement location in field of view?

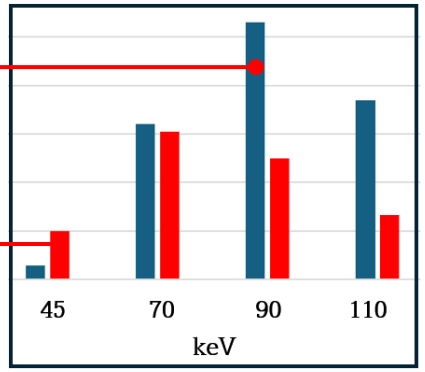
System stationarity (PSF versus position)

CT Metrology

Photon Counting CT







Spectral Imaging in each voxel

5 or 6 bins / "multi-energy"

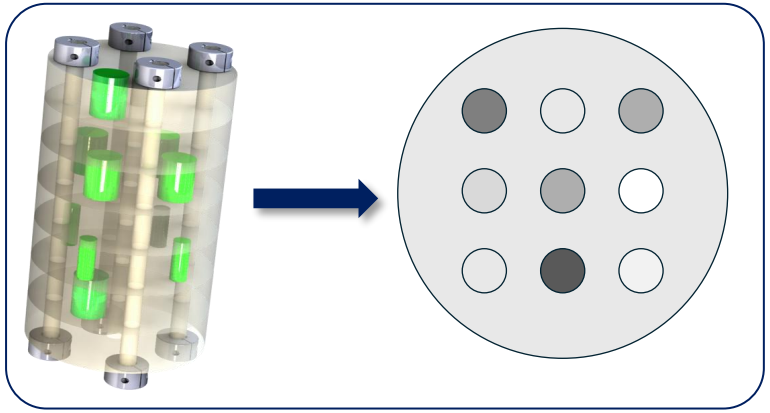
Effective Atomic Number

Soft Tissue	7.6
Bone (Ca)	13
Titanium	22
Iodine	53
Gadolinium	64

Basis Decomposition

soft tissue / bone
soft tissue / iodine
bone / iodine
etc.

Add a module to Corgi for basis decomposition



Potential NIST standardization projects:

Photon Counting

How to measure (with tolerances)?

Effective atomic number

Virtual monoenergetic CT numbers

Electron density

Iodine / Calcium concentration

Basis decomposition exemplars

Phantom Design for PCCT

Calcium inserts [n]

Iodine inserts [n]

Metallic inserts [n]

Metal artifact reduction

New metrics to be developed

Thanks to:
Norbert Pelc
Guang-Hong Chen

CT Metrology

Radiology

Breast Imaging

Zhimin Huo, PhD
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Dulcy E. Wolverton, MD
Barbara L. Weber, MD
Charles E. Metz, PhD
Weiming Zhong, MS
Shelly A. Cummings, MS

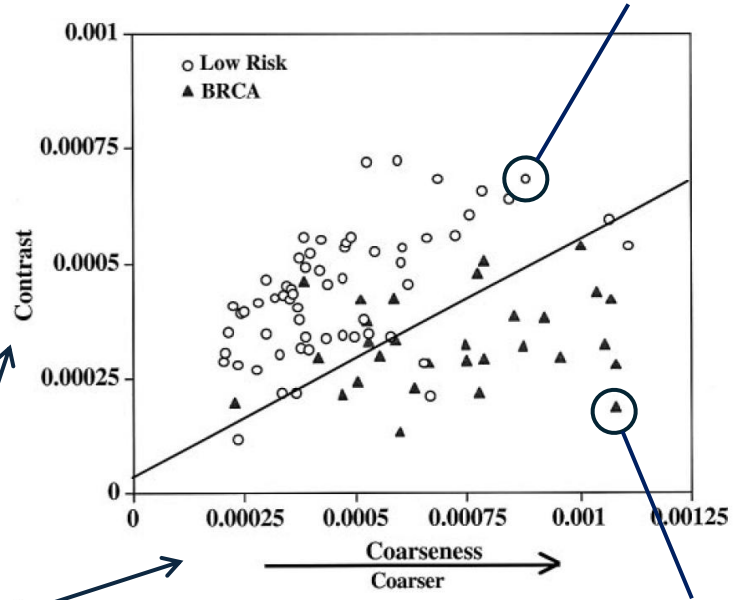
Index terms:

Computerized Analysis of Digitized Mammograms of BRCA1 and BRCA2 Gene Mutation Carriers[1]

The birth of……

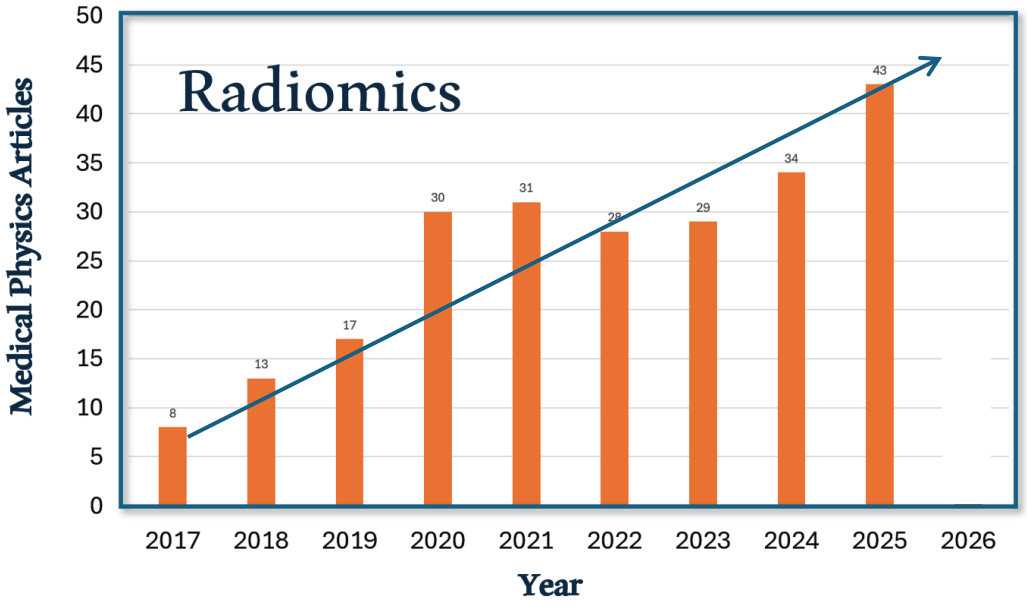
Radiomics

normal risk women



metrics computed from digital mammograms

high risk women



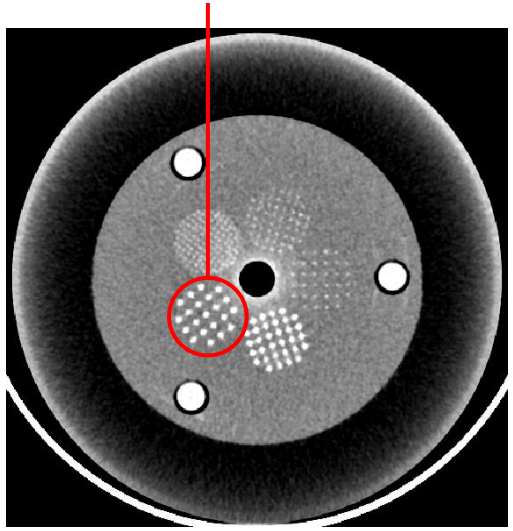
CT Metrology

Radiomics Module

gray level co-occurrence matrix (GLCM)



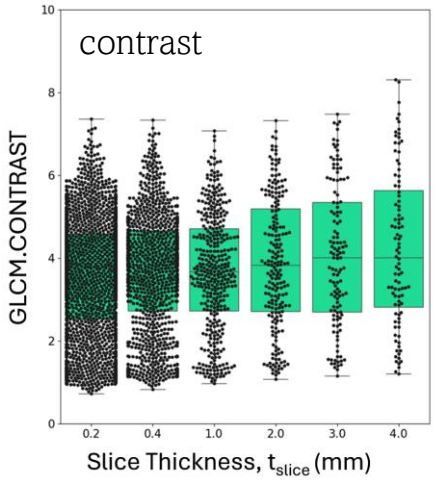
Corgi phantom insert

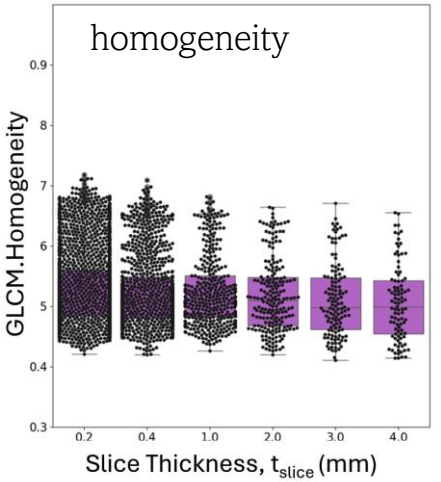


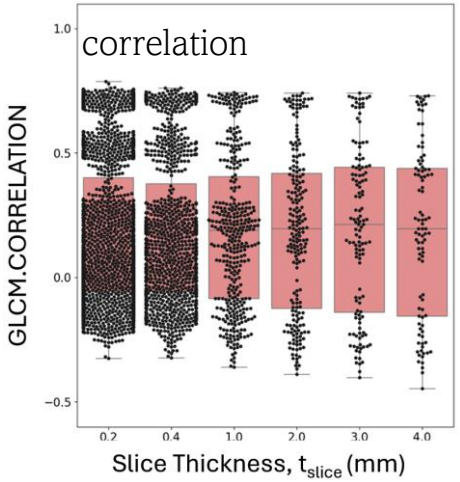
CT scan of it

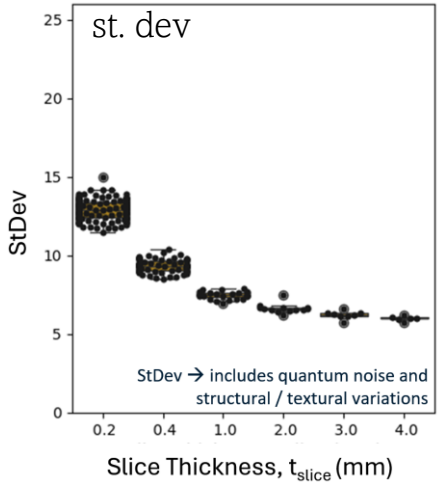
A module has been developed and is under comprehensive analysis in our U01 supplement

radiomic features









Potential NIST standardization projects:

Radiomics

What metrics?

Standard GLCM metrics

- Contrast
- Correlation
- Energy
- Homogeneity
- Entropy

Etcetera

Phantom Development

What structures and how many?

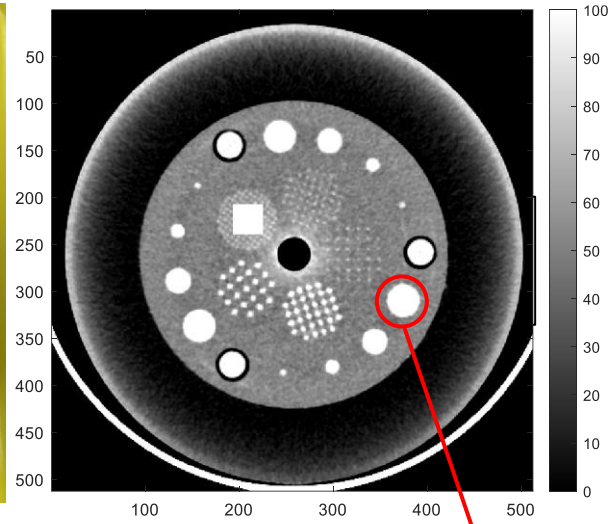
How to measure?

Radiomic algorithms

CT Metrology

Volumetry Module





Corgi phantom insert CT scan of it

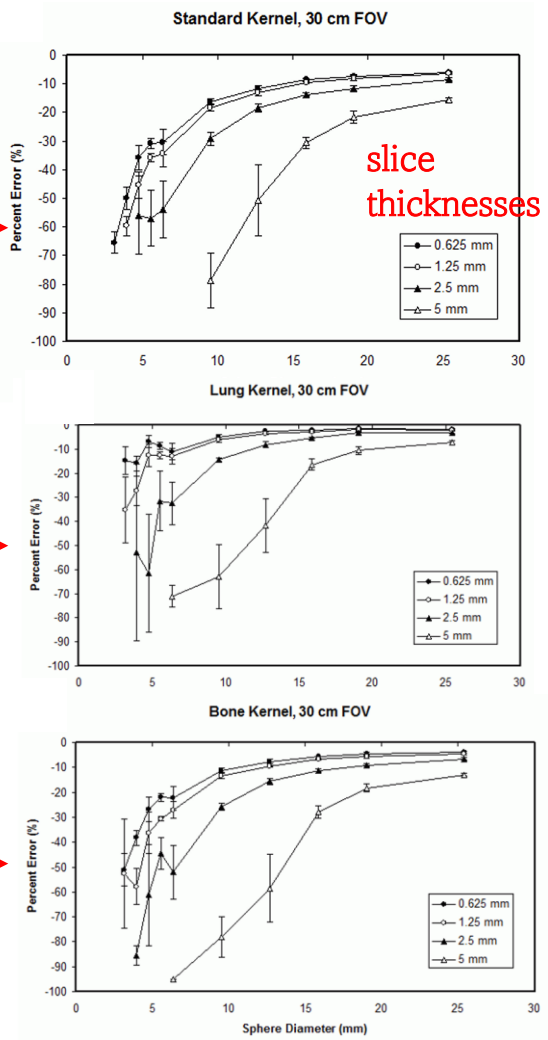
3 replicates of 4 sphere diameters

A module has been developed and is under comprehensive analysis in our U01 supplement

volume analysis

kernels

slice thicknesses



CT Metrology

Potential NIST standardization projects:

Volume Accuracy

The metric is Volume – cm^3 or ml

How to measure?

segmentation algorithms

Over what range to measure?

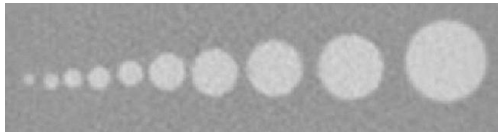
3 ml to 1000 ml?

Organ Volumes?

Phantom Development

What structures, how many, what contrast,

what background, how big, ….?



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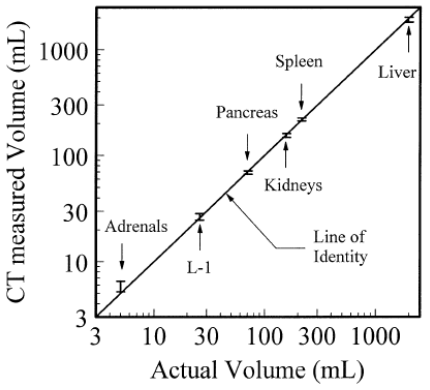
Volume assessment accuracy in computed tomography: a phantom study

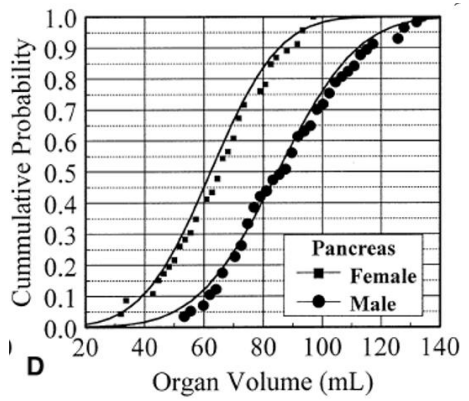
Nicolas D. Prionas,[a] Shonket Ray, John M. Boone
Department of Radiology, University of California Davis Medical Center, Sacramento,

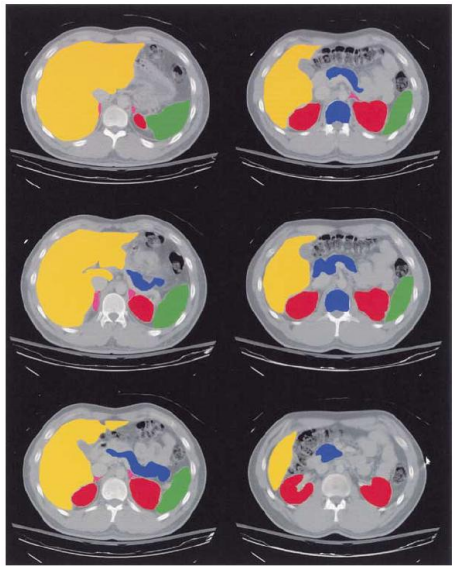
Normal organ volume assessment from abdominal CT

E. M. Geraghty, J. M. Boone, J. P. McGahan, K. Jain

Department of Radiology, University of California, Davis, Medical Center, Research Imaging Center, 4701 X Street, Sacramento, CA 95817, USA

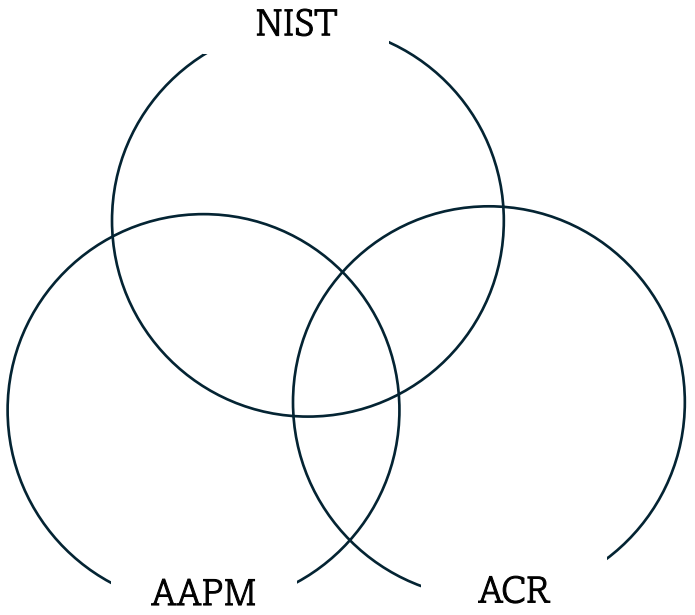






Summary

- Quantitative CT Image Quality Metrics are sorely needed
- Comprehensive new approaches which address non-linear recon
- CT Vendors need to be engaged
- Phantoms – so many phantoms – but we need more!
- Phantom Vendors need to be engaged
- Collaboration across disciplines & organizations will be required



NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

National Institute of Biomedical Imaging and Bioengineering

Metrology for Computed Tomography:

Lessons from the Past, Needs for the Future

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