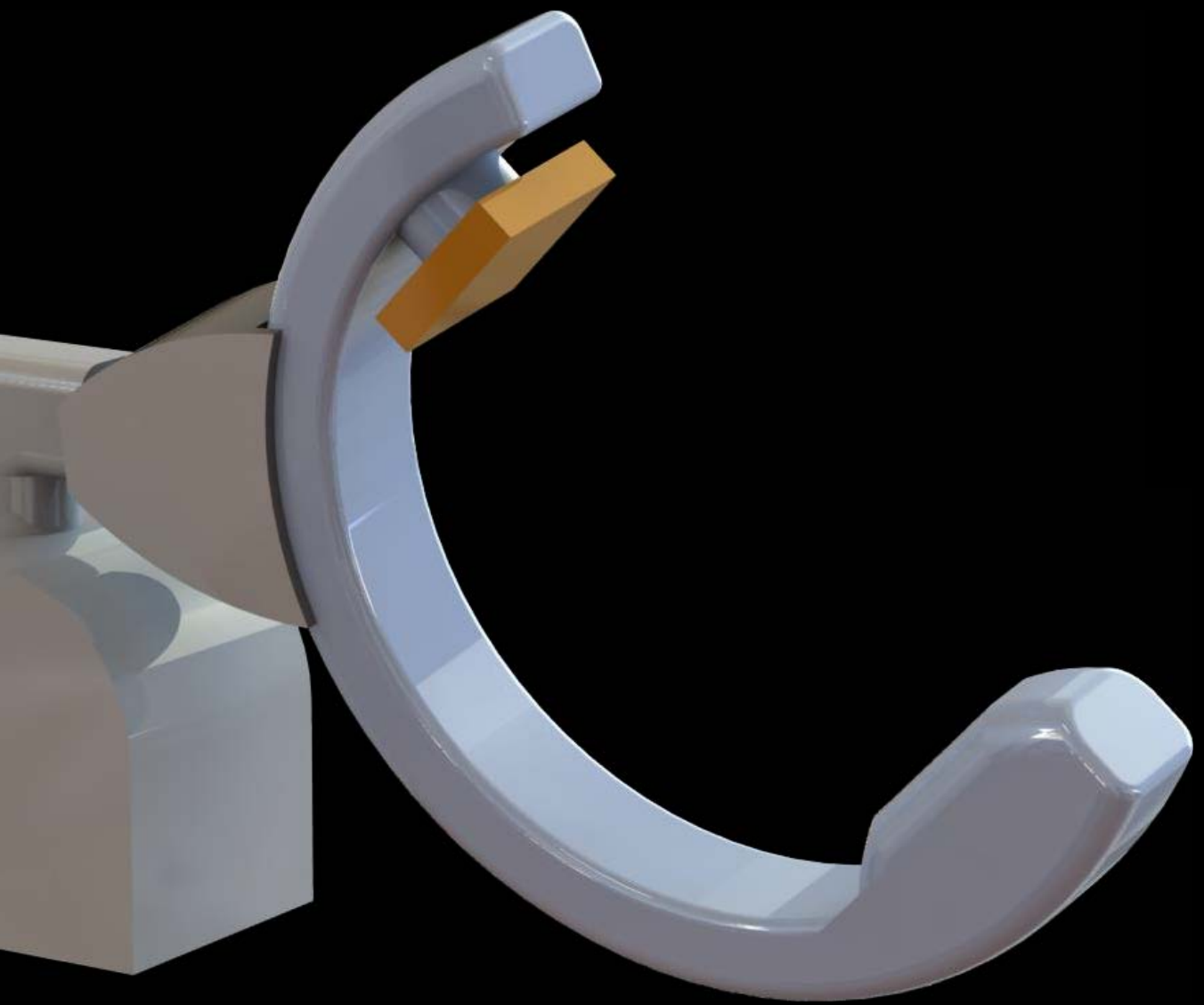
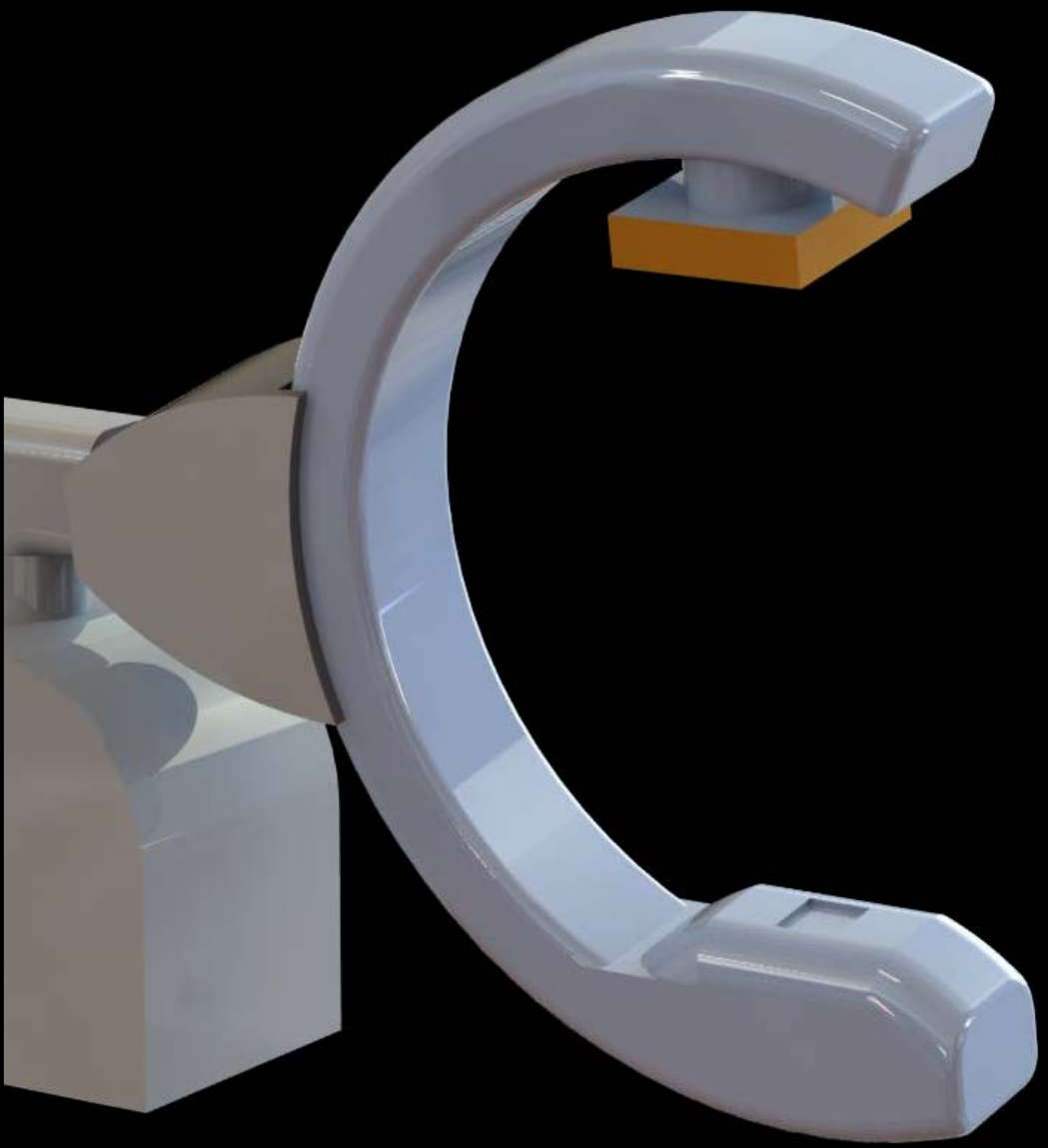


# Open Gantry Cone-Beam CT

## *Now You C It*

**Jeff Siewerdsen, PhD**
Department of Biomedical Engineering
Department of Computer Science
Russell H. Morgan Department of Radiology
Department of Neurosurgery
Armstrong Institute for Patient Safety and Quality
Johns Hopkins University

The I-STAR Lab / **istar.jhu.edu**
Carnegie Center for Surgical Innovation / **carnegie.jhu.edu**



# Disclosures

## Funding Support

National Institutes of Health
- R01-EB-017226 (Imaging for OR Safety and QA)
- R01-CA-112163 (Dual-Energy CT)
- R01-EB-018896 (High-Resolution CBCT – W Zbijewski, PI)
- U01-EB-018758 (Sub-mSv CT – JW Stayman, PI)

Siemens Healthineers (XP, AT)
- Mobile and Robotic C-arm CBCT

Medtronic
- Intraoperative 3D Imaging and Registration

Carestream Health
- Extremity CBCT
- Point-of-Care CBCT of the Head

## Advisory Board

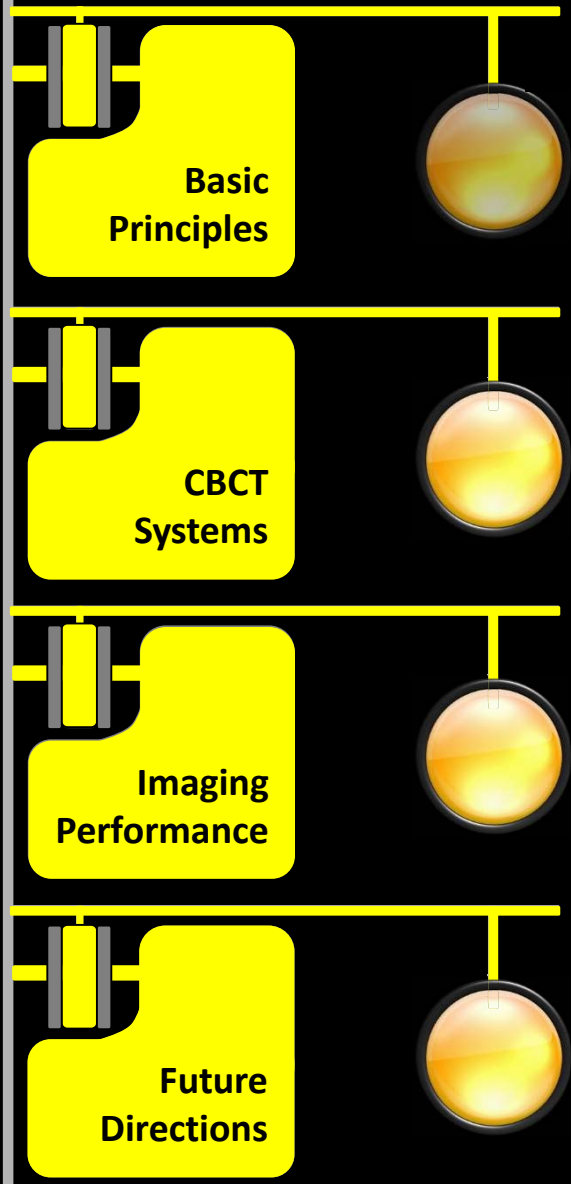
Siemens Healthineers
Carestream Health

## Licensing Agreement

Carestream Health
Elekta Oncology

*This presentation includes research systems and off-label use.

# Overview / Learning Objectives




Physical configurations
Image acquisition and reconstruction

Diversity of system platforms
Diversity of applications – from IGRT to diagnostic imaging

Spatial resolution, contrast resolution, …
Artifacts
Radiation dose

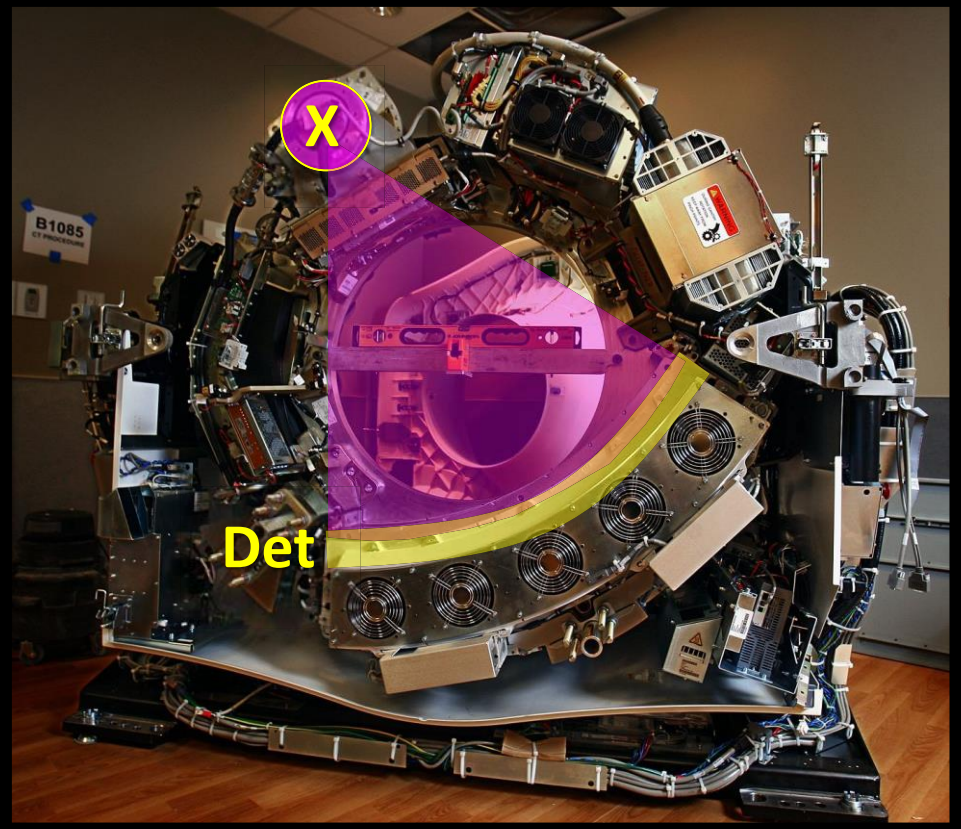
New systems and applications
Advanced imaging techniques

Handouts for this presentation available after RSNA at:
http://istar.jhu.edu/talks

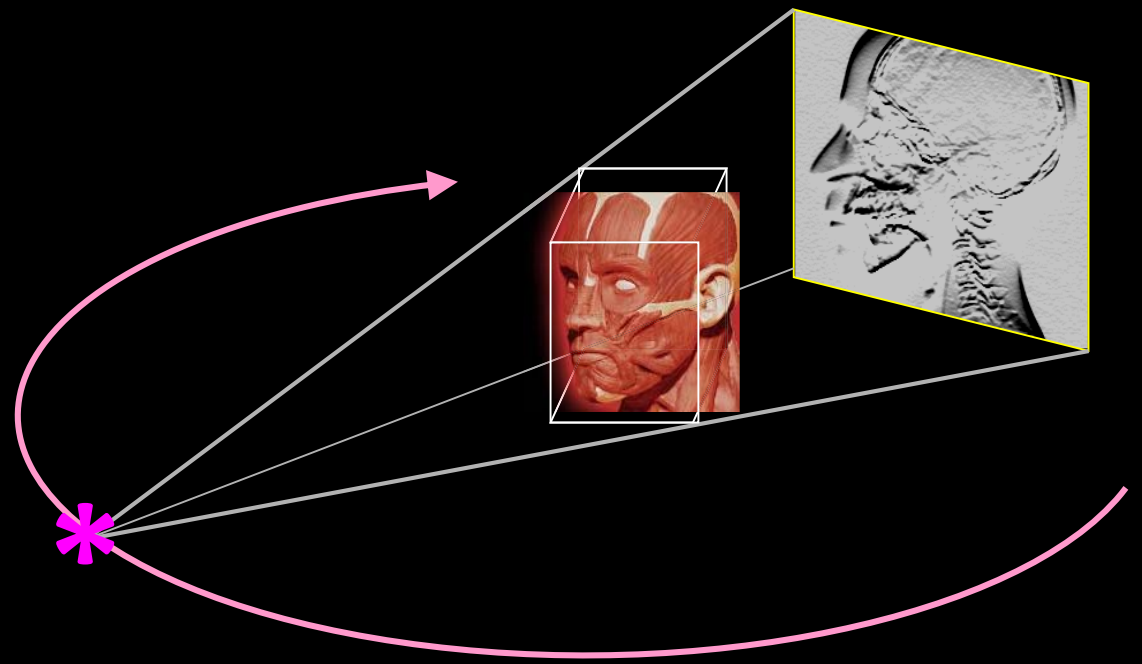
# Physical Configuration



## Multi-Detector CT




## Open Gantry / Cone-Beam CT

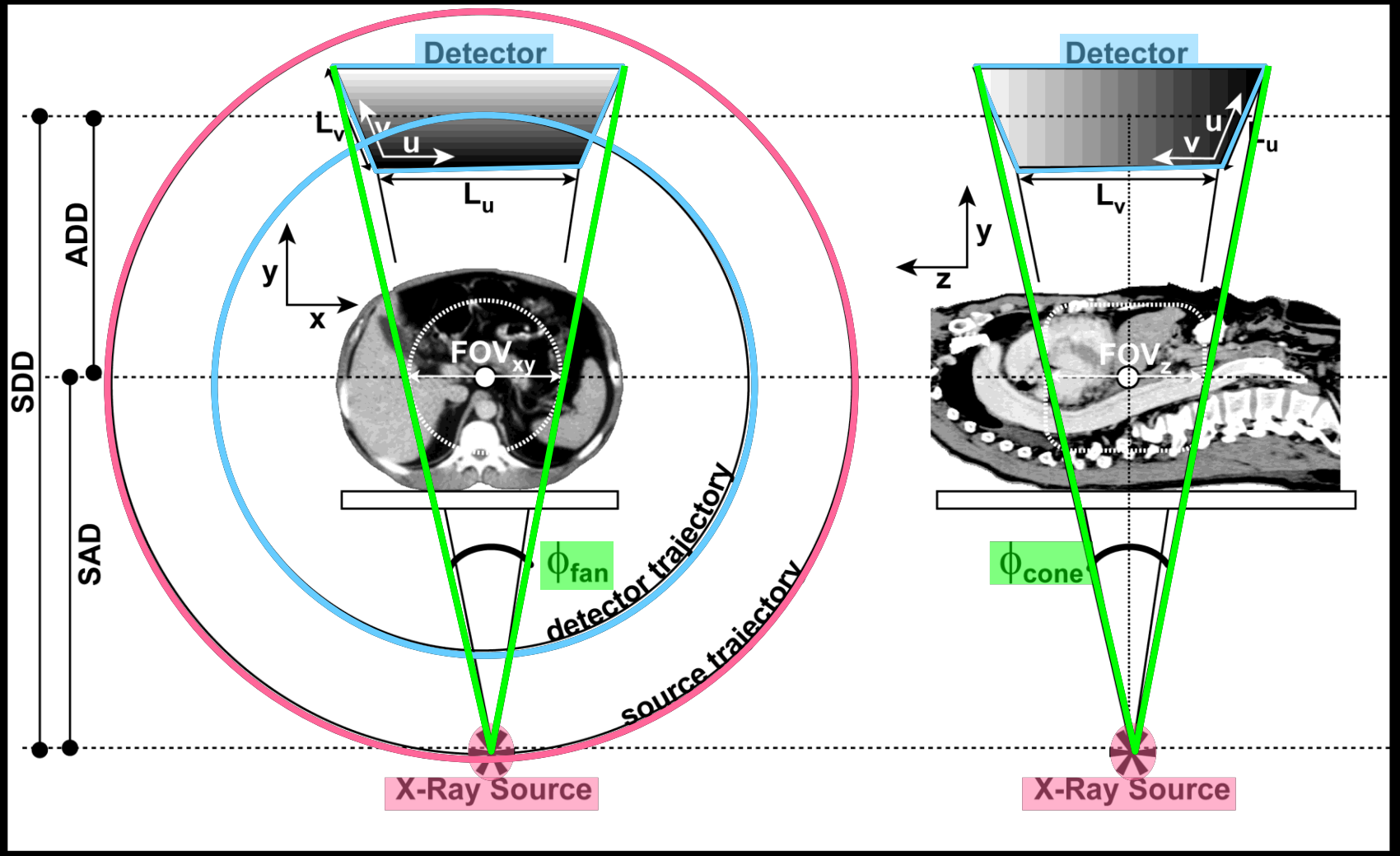


Large-area detector (typically 25-43 cm)
2D projections (typically hundreds, circular orbit)
3-D Volume (from a single rotation)
Many, varied configurations / applications

| ~*Typical* Characteristics | | |
|---|---|---|
| | **Multi-Detector CT**  | **Open Gantry / Cone-Beam CT**   …  |
| **X-ray Source** | High Power (100-240 kW)<br>Continuous mA | Lower Power (3-100 kW)<br>Pulsed mA |
| **Detector** | 1-64 rows (up to 256-320 rows)<br>~few cm Z coverage (up to 16 cm) | >1024 – 2048 rows<br>>20 cm Z coverage |
| **Acquisition Speed and Orbit** | Fast<br>Circular / Helical<br>~3-5 rotations / sec<br>Fast table feed (>10-50 cm / sec)<br>(1000s of projections / rotation) | Slow<br>Circular (semi-circular) or Non-Circular<br>~1 rotation / 5-60 sec<br>No table motion<br>(100s of projections / rotation) |
| **Image Quality** | Good<br>(bone + soft tissues)<br>(CE-enhanced scans; DE protocols) | Moderate<br>(CNR challenged by scatter)<br>(isotropic sub-mm spatial resolution)<br>(artifacts) |
| **Applications** | Diagnostic Radiology<br>(some interventional) | Image-Guided Procedures<br>(specialty diagnostic applications) |

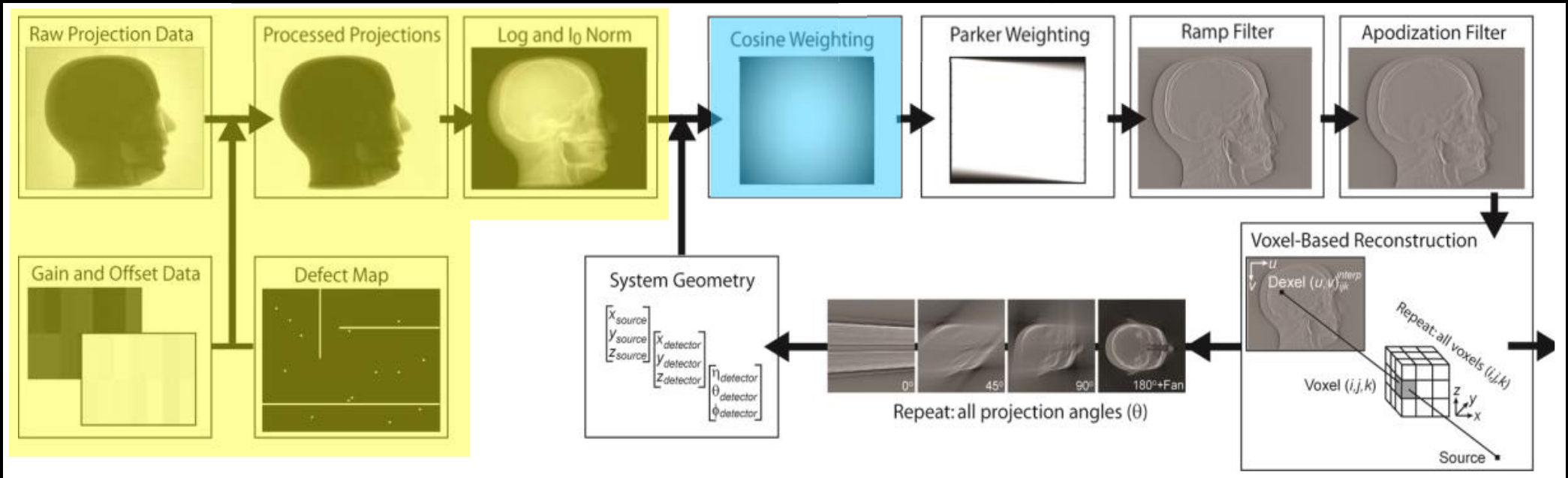
# Cone-Beam System Geometry





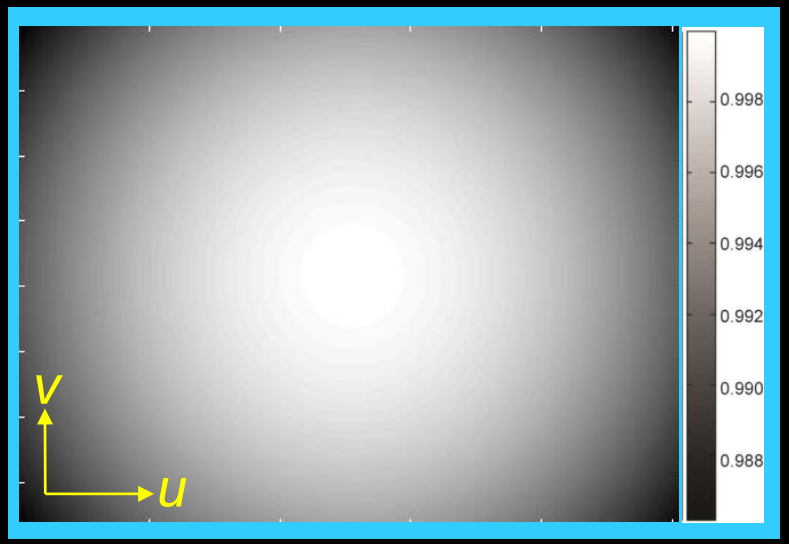
# 3D Filtered Back-Projection






## Cosine Weighting (Feldkamp Weights)

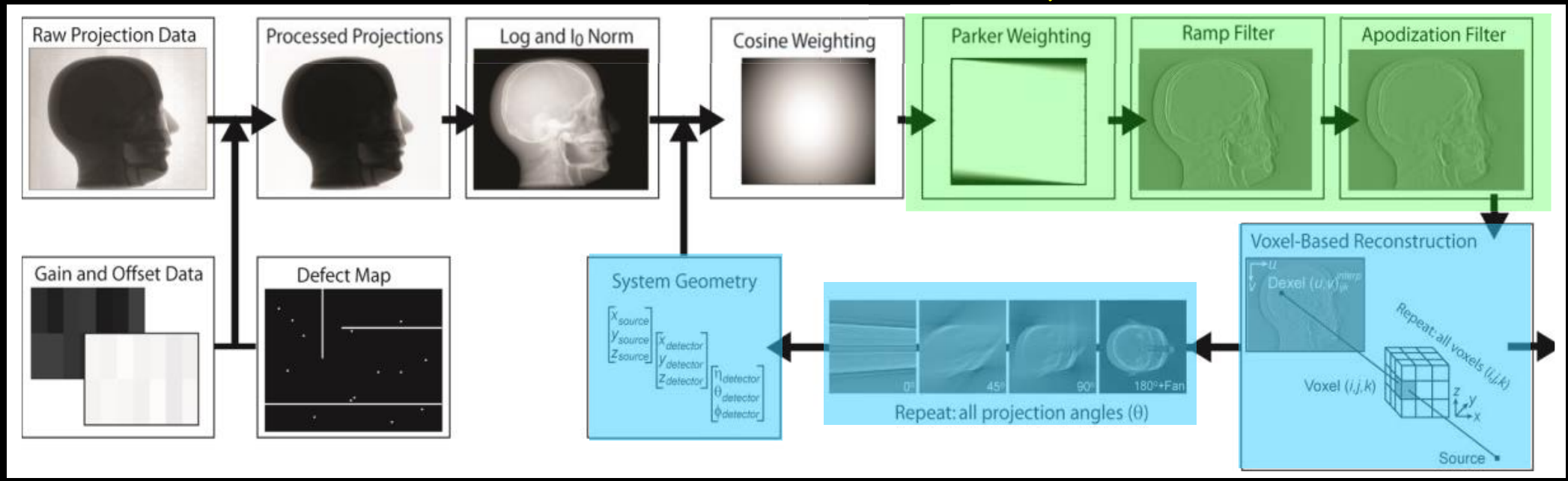
$$p_2(u,v;\theta) = p_1(u,v;\theta)\left[\frac{SDD}{\sqrt{SDD^2+u^2+v^2}}\right]$$



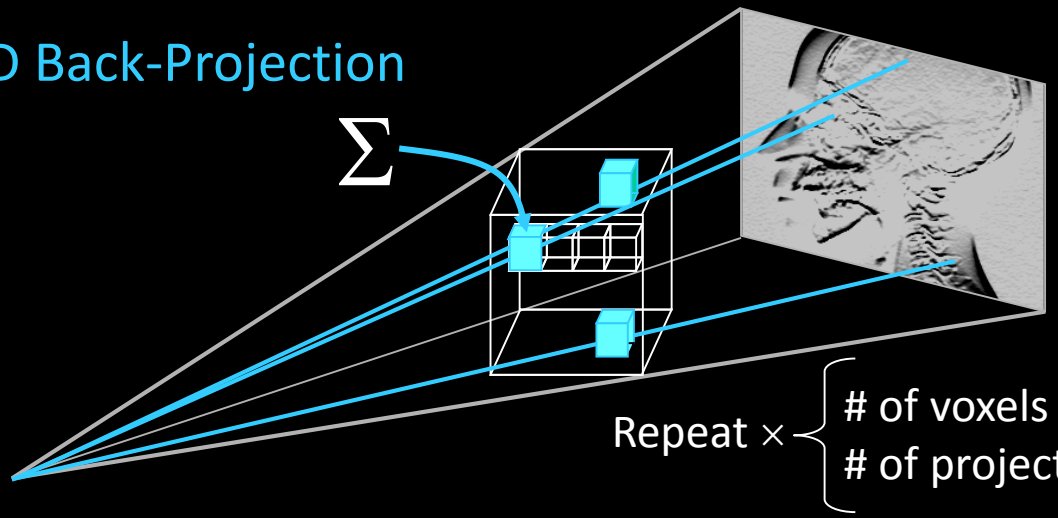

Siewerdsen, Stayman, and Noo (Chapter 13 in *Image Processing in Radiation Therapy,* K. K. Brock, Ed, CRC Press 2013)

# 3D Filtered Back-Projection






## 3D Back-Projection




Siewerdsen, Stayman, and Noo (Chapter 13 in *Image Processing in Radiation Therapy,* K. K. Brock, Ed, CRC Press 2013)

# System Configurations and Applications


Basic Principles

CBCT Systems

Imaging Performance

Future Directions


















IGRT

Image-Guided Surgery

ENT

Breast

MSK

# System Configurations and Applications

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

## Image-Guided Radiation Therapy (IGRT)

CBCT on a linear accelerator

- Elekta Synergy
- Varian OBI

New systems for proton / heavy ion Tx

## IG Surgery / Interventional Radiology

FIXED-ROOM:

- Siemens Artis (Pheno, Zeego, Zee, …), Philips Allura, Toshiba Infinix

MOBILE:

- Medtronic O-arm, Siemens Cios Spin, Ziehm Vario, Xoran Xcat

## Diagnostic Specialties

Breast CT:

- Koning (Ning), UC-Davis (Boone)

ENT / Maxillofacial:

- Carestream CS9300, Xoran MiniCAT, TeraRecon PreXion, …

Musculoskeletal (MSK) / Orthopaedics:

- PlanMed Verity
- CurveBeam pedCAT
- Carestream OnSight

*Errors and omissions are responsibility of the author.

# System Configurations and Applications

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

## Image-Guided Radiation Therapy (IGRT)

CBCT on a linear accelerator
- Elekta Synergy
- Varian OBI

New systems for proton / heavy ion Tx

## IG Surgery / Interventional Radiology

FIXED-ROOM:
- Siemens Artis (Pheno, Zeego, Zee, …), Philips Allura, Toshiba Inf

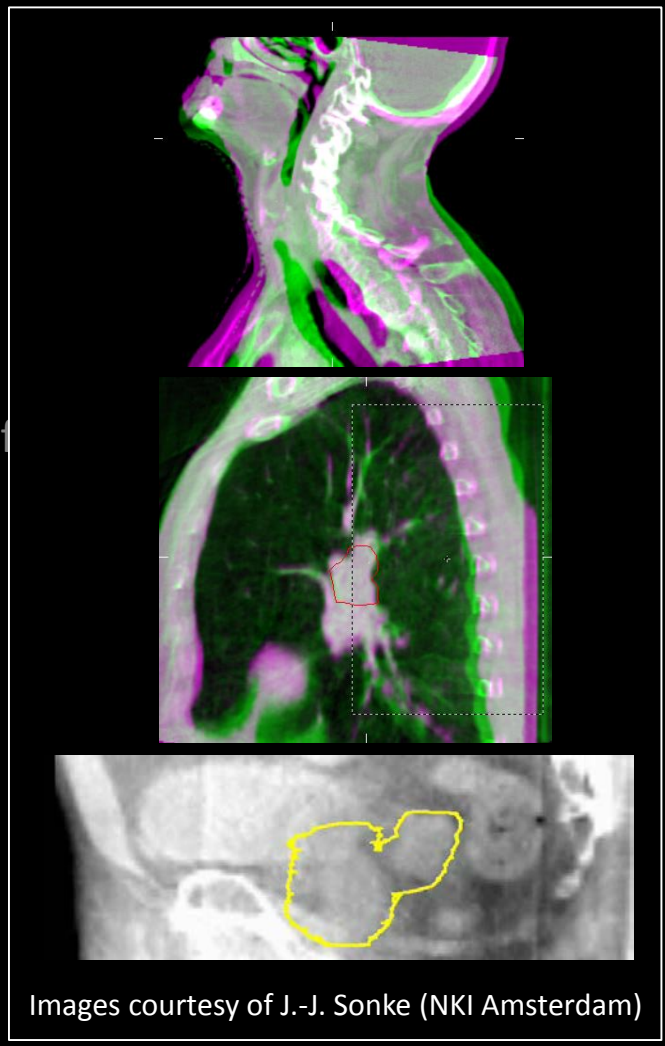
MOBILE:
- Medtronic O-arm, Siemens Cios Spin, Ziehm Vario, Xoran Xcat

## Diagnostic Specialties

Breast CT:
- Koning (Ning), UC-Davis (Boone)

ENT / Maxillofacial:
- Carestream CS9300, Xoran MiniCAT, TeraRecon PreXion, …

Musculoskeletal (MSK) / Orthopaedics:
- PlanMed Verity
- CurveBeam pedCAT
- Carestream OnSight



Images courtesy of J.-J. Sonke (NKI Amsterdam)

*Errors and omissions are responsibility of the author.

# System Configurations and Applications

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

## Image-Guided Radiation Therapy (IGRT)

CBCT on a linear accelerator

- Elekta Synergy
- Varian OBI

New systems for proton / heavy ion Tx

## IG Surgery / Interventional Radiology

FIXED-ROOM:

- Siemens Artis (Pheno, Zeego, Zee, …), Philips Allura, Toshiba Infinix

MOBILE:

- Medtronic O-arm, Siemens Cios Spin, Ziehm Vario, Xoran Xcat

## Diagnostic Specialties

Breast CT:

- Koning (Ning), UC-Davis (Boone)

ENT / Maxillofacial:

- Carestream CS9300, Xoran MiniCAT, TeraRecon PreXion, …

Musculoskeletal (MSK) / Orthopaedics:

- PlanMed Verity
- CurveBeam pedCAT
- Carestream OnSight

*Errors and omissions are responsibility of the author.

# System Configurations and Applications

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

## Image-Guided Radiation Therapy (IGRT)

CBCT on a linear accelerator

- Elekta Synergy
- Varian OBI

New systems for proton / heavy ion Tx

## IG Surgery / Interventional Radiology

FIXED-ROOM:

- Siemens Artis (Pheno, Zeego, Zee, …), Philips Allura, Toshiba Infinix

MOBILE:

- Medtronic O-arm, Siemens Cios Spin, Ziehm Vario, Xoran Xcat

## Diagnostic Specialties

Breast CT:

- Koning (Ning), UC-Davis (Boone)

ENT / Maxillofacial:

- Carestream CS9300, Xoran MiniCAT, TeraRecon PreXion, …

Musculoskeletal (MSK) / Orthopaedics:

- PlanMed Verity
- CurveBeam pedCAT
- Carestream OnSight


Tognolini et al.
Acad Radiol 2011

Batra et al.,
Int For All Rhin 2011

Image courtesy of
Boulder Neurosurg.
Spine Assoc.

Wang et al.
Phys Med Biol 2014

*Errors and omissions are responsibility of the author.

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

# System Configurations and Applications

## Image-Guided Radiation Therapy (IGRT)

CBCT on a linear accelerator

- Elekta Synergy
- Varian OBI

New systems for proton / heavy ion Tx

## IG Surgery / Interventional Radiology

FIXED-ROOM:

- Siemens Artis (Pheno, Zeego, Zee, …), Philips Allura, Toshiba Infinix

MOBILE:

- Medtronic O-arm, Siemens Cios Spin, Ziehm Vario, Xoran Xcat

## Diagnostic Specialties

Breast CT:

- Koning (Ning), UC-Davis (Boone)

ENT / Maxillofacial:

- Carestream CS9300, Xoran MiniCAT, TeraRecon PreXion, …

Musculoskeletal (MSK) / Orthopaedics:

- PlanMed Verity
- CurveBeam pedCAT
- Carestream OnSight

*Errors and omissions are responsibility of the author.

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

# System Configurations and Applications

## Image-Guided Radiation Therapy (IGRT)

CBCT on a linear accelerator

- Elekta Synergy
- Varian OBI

New systems for proton / heavy ion Tx

## IG Surgery / Interventional Radiology

FIXED-ROOM:

- Siemens Artis (Pheno, Zeego, Zee, …), Philips Allura, Toshiba Infi

MOBILE:

- Medtronic O-arm, Siemens Cios Spin, Ziehm Vario, Xoran Xcat

## Diagnostic Specialties

Breast CT:

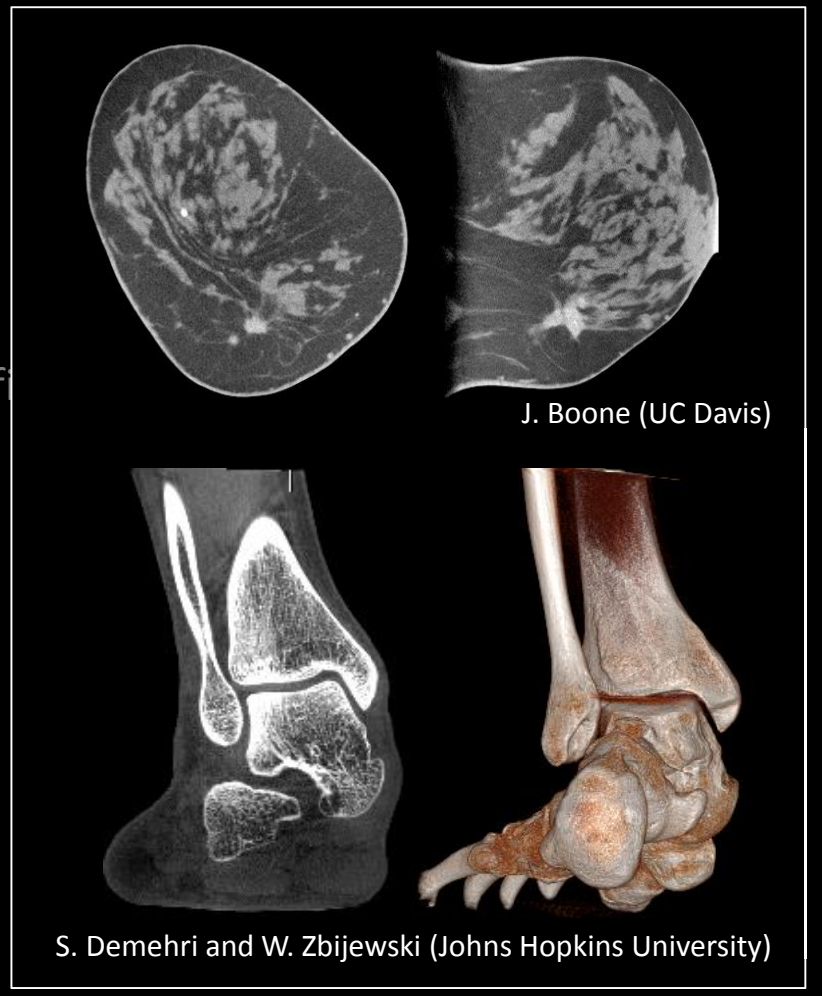
- Koning (Ning), UC-Davis (Boone)

ENT / Maxillofacial:

- Carestream CS9300, Xoran MiniCAT, TeraRecon PreXion, …

Musculoskeletal (MSK) / Orthopaedics:

- PlanMed Verity
- CurveBeam pedCAT
- Carestream OnSight



J. Boone (UC Davis)

S. Demehri and W. Zbijewski (Johns Hopkins University)

*Errors and omissions are responsibility of the author.

# The AAPM Task Group 238

## 3D C-Arms with Volumetric Imaging Capability

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

Charge: Assessment of 3D C-Arm Cone Beam CT (CBCT) technology for applications in image-guided interventions. … … characteristics of 3D C-arm systems, quantitative metrics, sources of uncertainty, and quality assurance measures, including dose and image quality.


M. Supanich

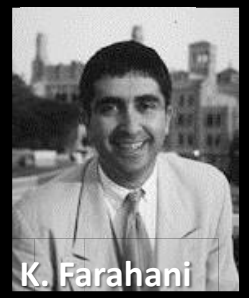

R. Fahrig


A. K. Jones


J. Zhang


S. Schafer


C. Riddell


K. Farahani


A. Kuhls-Gilchrist


M. Lin


B. Schueler


J. Siewerdsen

Also:
G. J. Gang
P. A. Helm
L. Ritschl
M. D. Silver
J. Timmer
Y. Trousset

Applications
Nomenclature
System Calibration
3D Image Reconstruction
Image Quality
Dosimetry
Training Issues for Medical Physicists

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

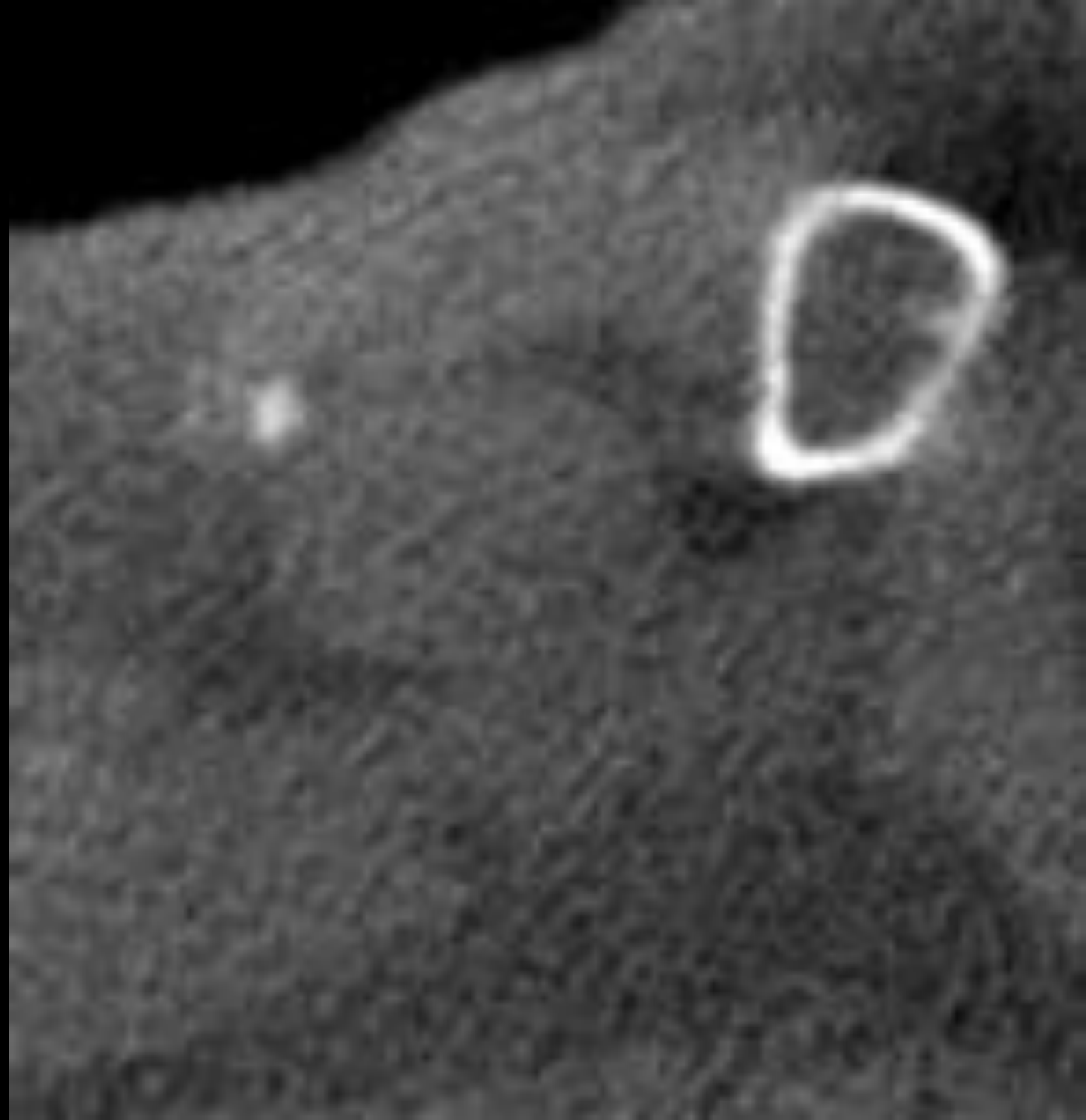
## Spatial Resolution

## Contrast Resolution

## Temporal Resolution

## Task-Based Performance

## Artifacts



Basic Principles

CBCT Systems

Imaging Performance

Future Directions

# Spatial Resolution

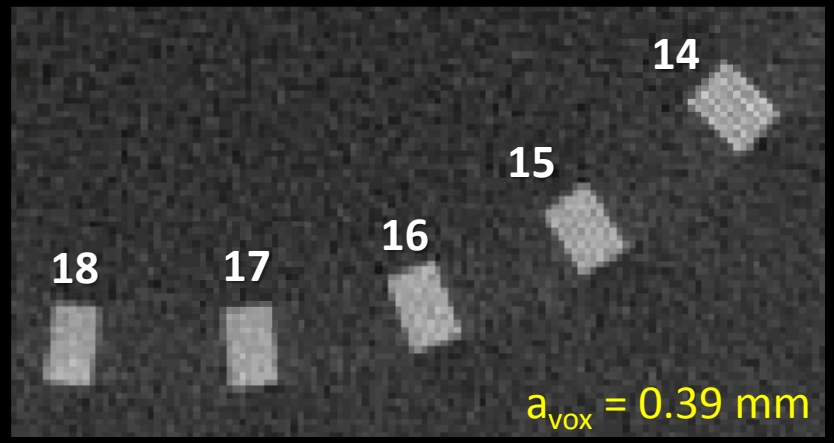
Smallest discernible feature size
(in the absence of noise)

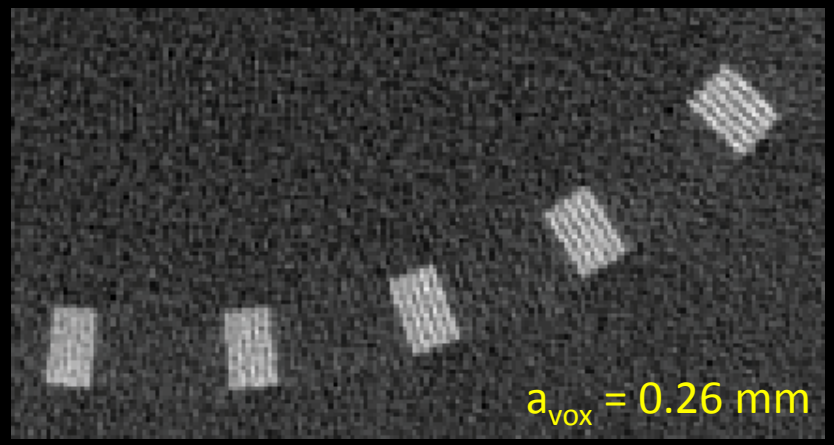
Governed by:

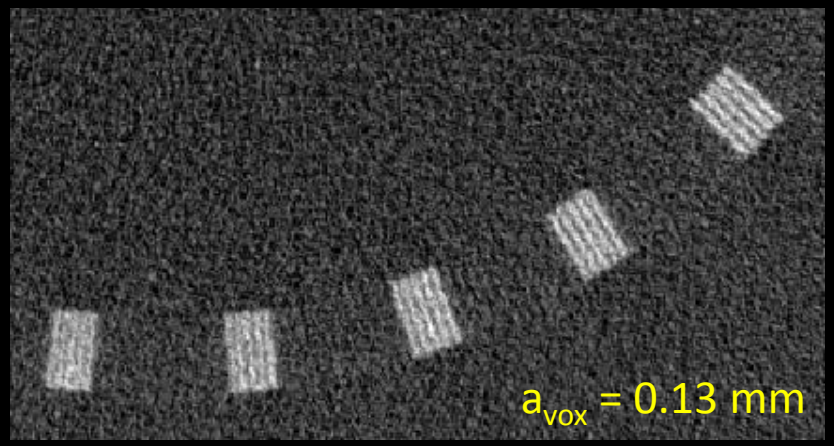
- Geometric calibration
- Focal spot size
- Scintillator
- Detector pixel size
- Reconstruction (smoothing filters)

Metrics:

- Qualitative (line-pair patterns)
- Spread function width (PSF, ESF)
- Modulation Transfer Function (MTF)
- *Note:* shift variance / stationarity
  - → *local* approximations
- *Caveat:* nonlinear reconstruction / processing algorithms
  - → *contrast-dependent*




Siewerdsen, Zbijewski, and Xu (Chapter 4 in *Cone Beam Computed Tomography,* C. Shaw, Ed, CRC Press 2014)

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

# Spatial Resolution

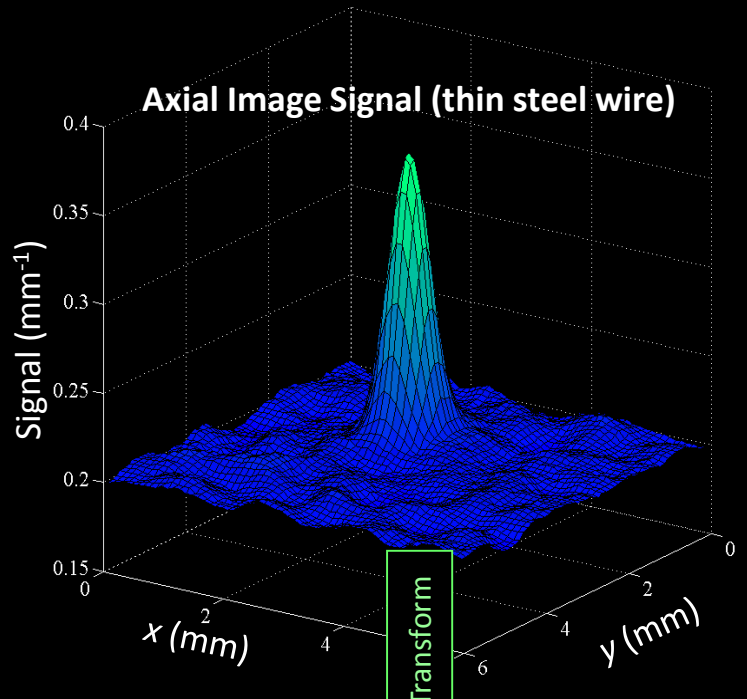
Smallest discernible feature size
(in the absence of noise)

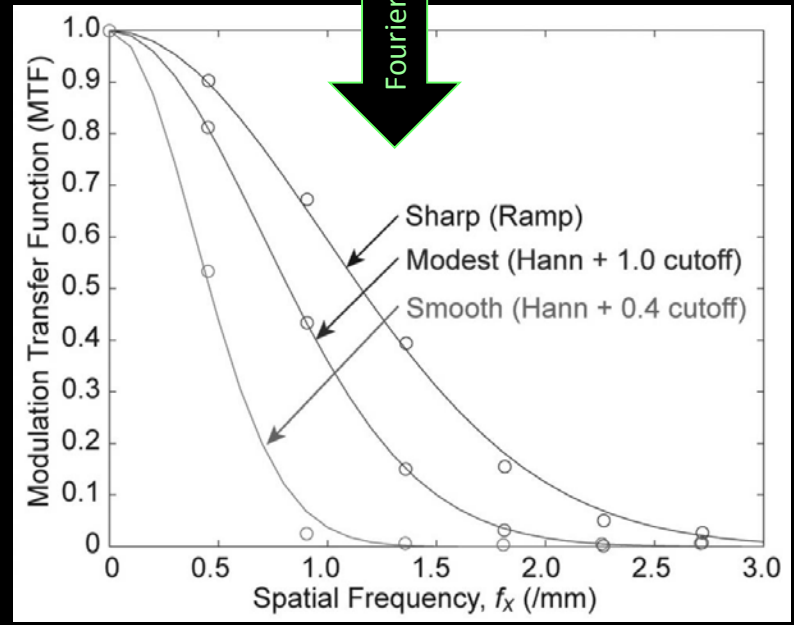
Governed by:

- Geometric calibration
- Focal spot size
- Scintillator
- Detector pixel size
- Reconstruction (smoothing filters)

Metrics:

- Qualitative (line-pair patterns)
- Spread function width (PSF, ESF)
- Modulation Transfer Function (MTF)
- *Note:* shift variance / stationarity
  - → *local* approximations
- *Caveat:* nonlinear reconstruction / processing algorithms
  - → *contrast-dependent*




Siewerdsen, Zbijewski, and Xu (Chapter 4 in *Cone Beam Computed Tomography,* C. Shaw, Ed, CRC Press 2014)

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

# Contrast Resolution

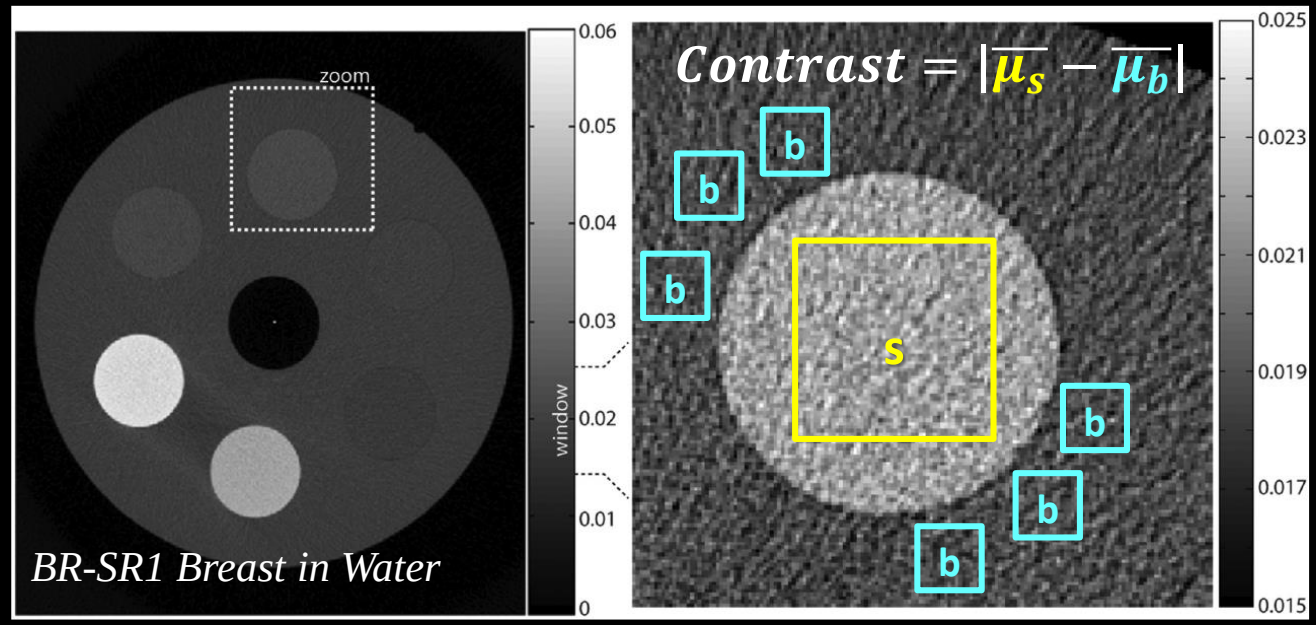
Smallest discernible signal difference (large stimulus)

Governed by:

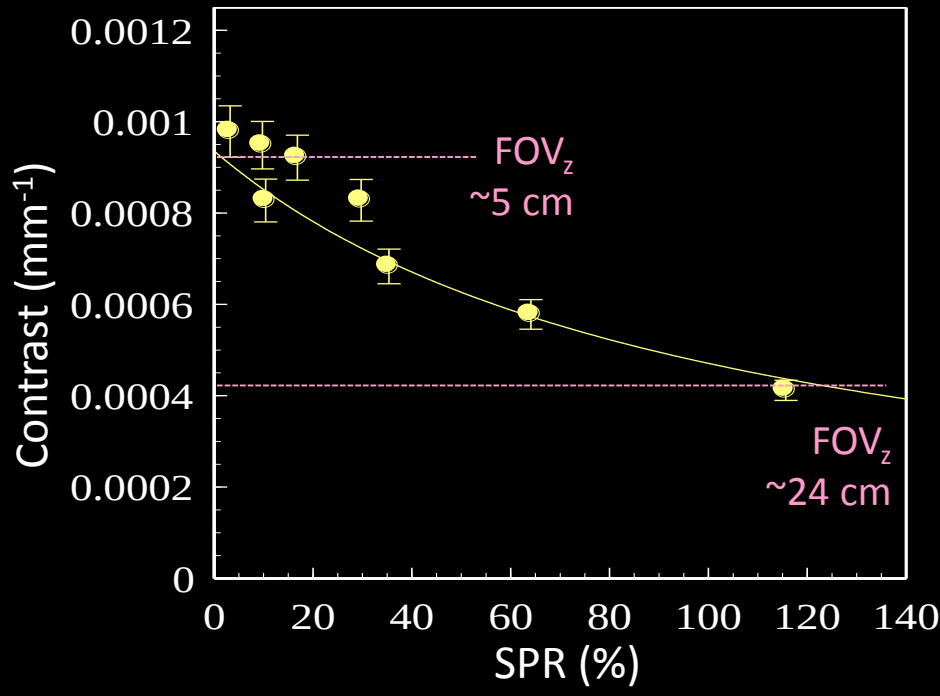
- Dose
- Electronic noise
- X-ray scatter

Metrics:

- Contrast
- Noise, Noise-Power Spectrum
- *Note:* shift variance / stationarity
  → *local* approximations




$$\Delta\mu' = \Delta\mu - \frac{1}{\alpha d}\ln\left(\frac{1+\mathrm{SPR}}{1+\mathrm{SPR}\,e^{-\Delta\mu\alpha d}}\right)$$




Siewerdsen, Zbijewski, and Xu (Chapter 4 in *Cone Beam Computed Tomography,* C. Shaw, Ed, CRC Press 2014)

# Contrast Resolution

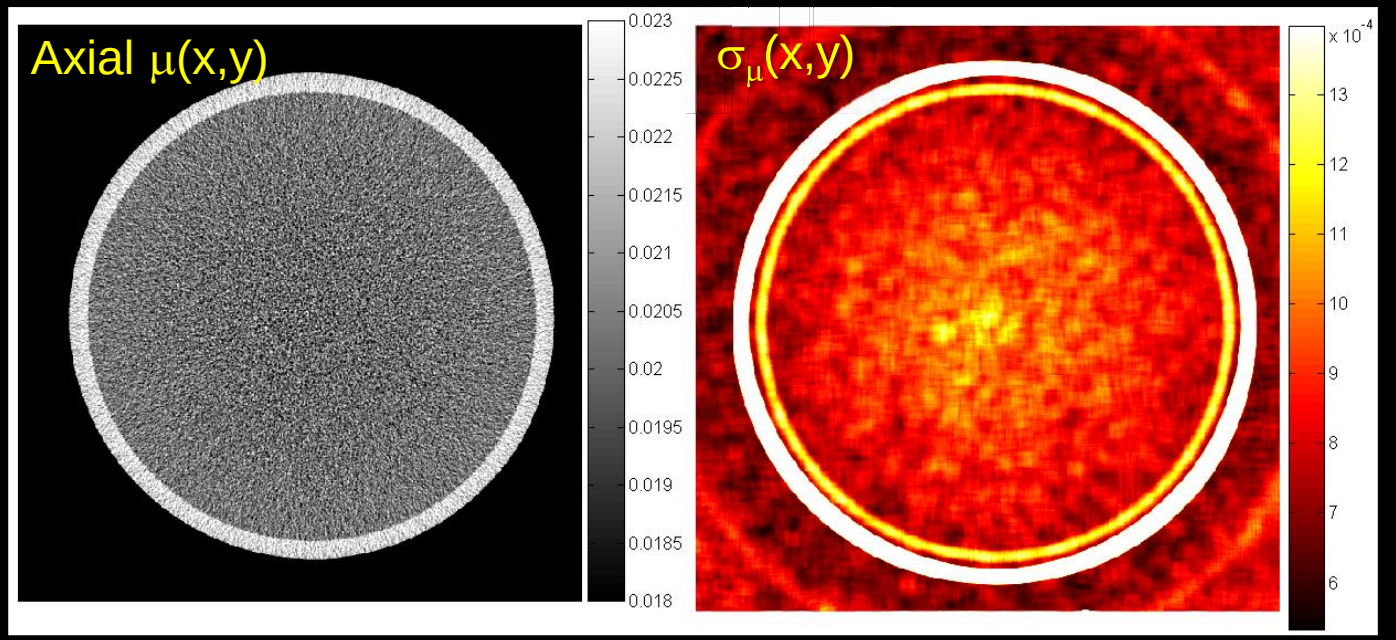
Smallest discernible signal difference (large stimulus)

Governed by:

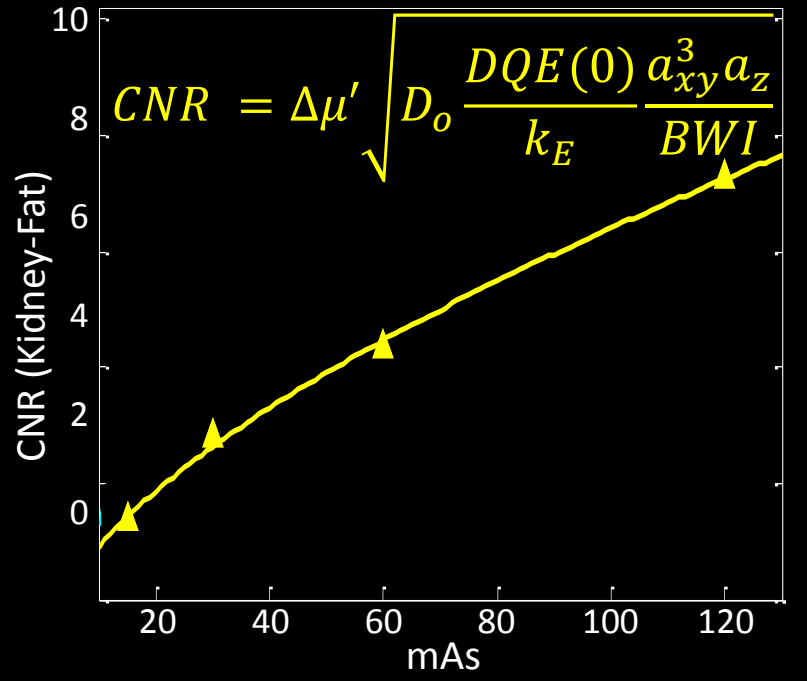
- Dose
- Electronic noise
- X-ray scatter

Metrics:

- Contrast
- Noise, Noise-Power Spectrum
- *Note:* shift variance / stationarity
  → *local* approximations







## Contrast Resolution

Smallest discernible signal difference (large stimulus)

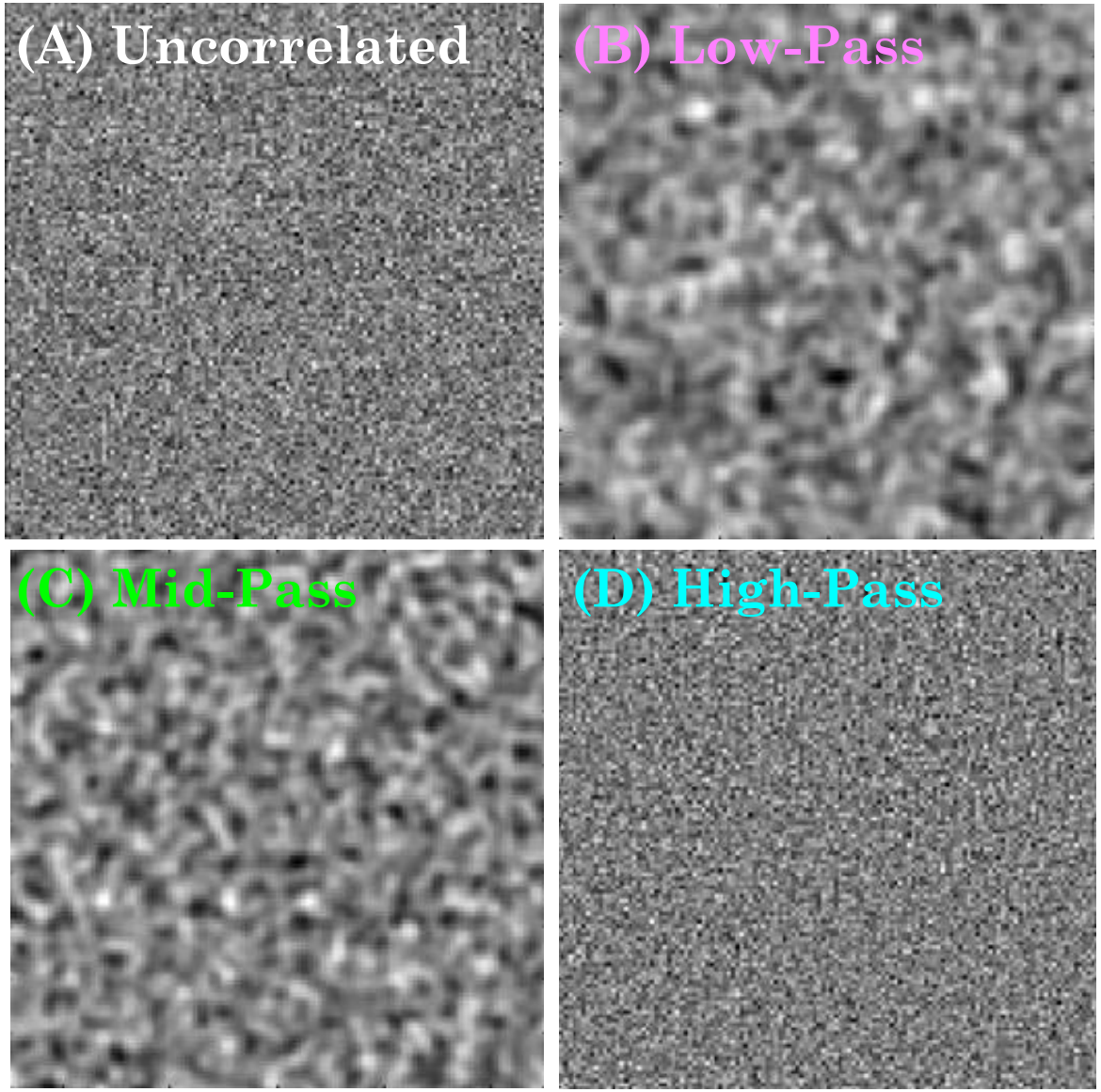
Governed by:

- Dose
- Electronic noise
- X-ray scatter

Metrics:

- Contrast
- Noise, Noise-Power Spectrum
- *Note:* shift variance / stationarity
  → *local* approximations

Noise-Power Spectrum



Basic Principles

CBCT Systems

Imaging Performance

Future Directions

## Contrast Resolution

Smallest discernible signal difference (large stimulus)

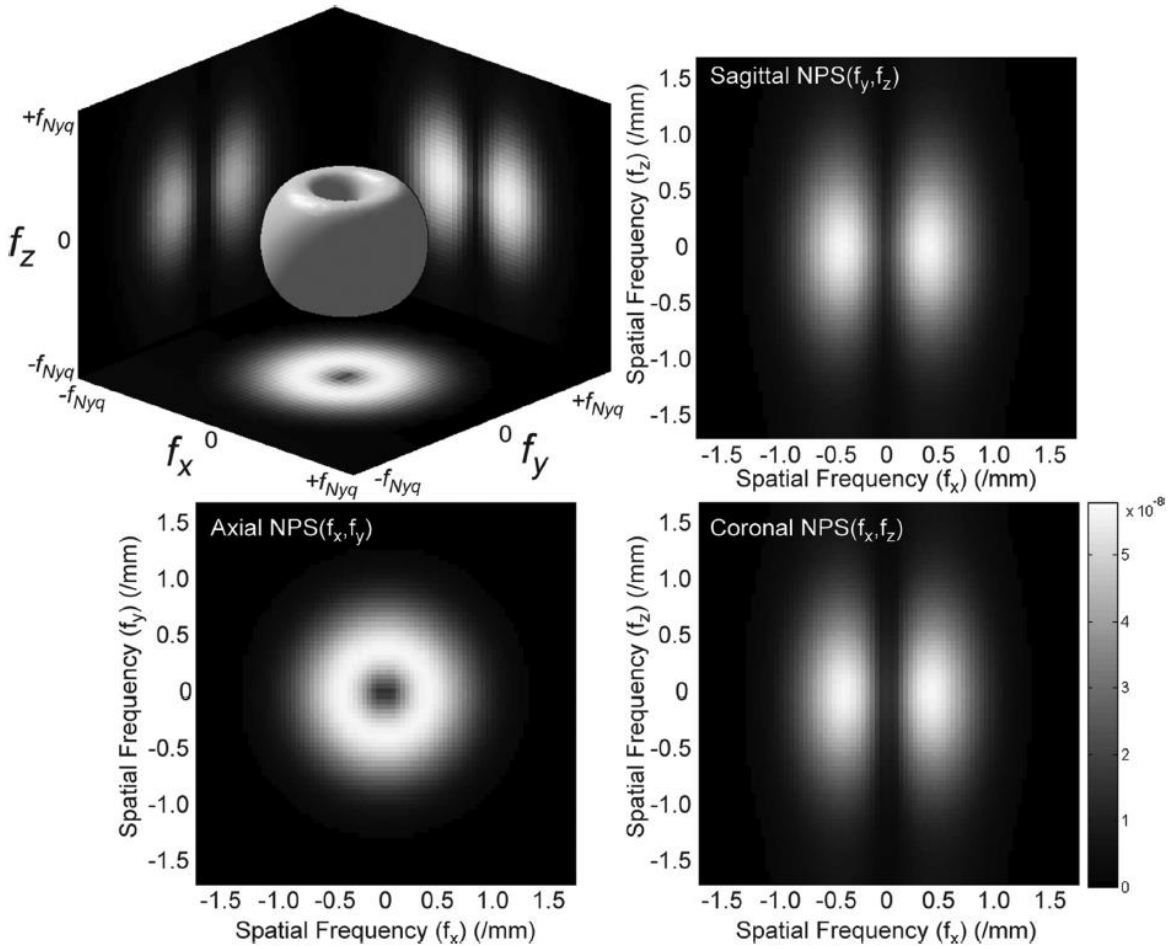
Governed by:

- Dose
- Electronic noise
- X-ray scatter

Metrics:

- Contrast
- Noise, Noise-Power Spectrum
- *Note:* shift variance / stationarity
  → *local* approximations

Noise-Power Spectrum




$$NPS(f_x, f_y, f_z) = \frac{a_x a_y a_z}{N_x N_y N_z} \langle |FT[\Delta(x, y, z)]|^2 \rangle$$

# Task-Based Imaging Performance

Considers:
- Fidelity of signal transfer (MTF)
- Correlation of noise (NPS)
- Spatial frequencies of interest ($W_{task}$)

Variations in Observer Model:
- Prewhitening (PW / Hotelling)
- PW with eye filter (PWEi)
- Non-prewhitening (NPW)
- Channelized Hoteling (CHO)

$$d'^2 = \iiint \frac{MTF^2(f)}{NPS(f)} W_{task}^2(f)\, df_x df_y df_z$$

Useful for:
- Observer-independent performance
- System design, optimization
- Low-dose performance limits

*Note:* linearity, shift variance / stationarity
→ *local* approximations

P. Prakash et al. Med Phys 2011

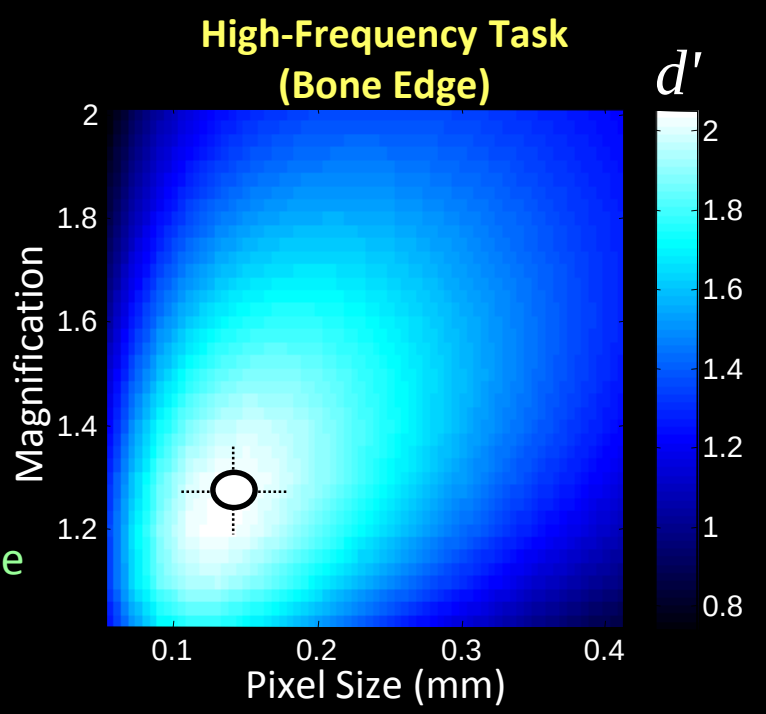
# Task-Based Imaging Performance

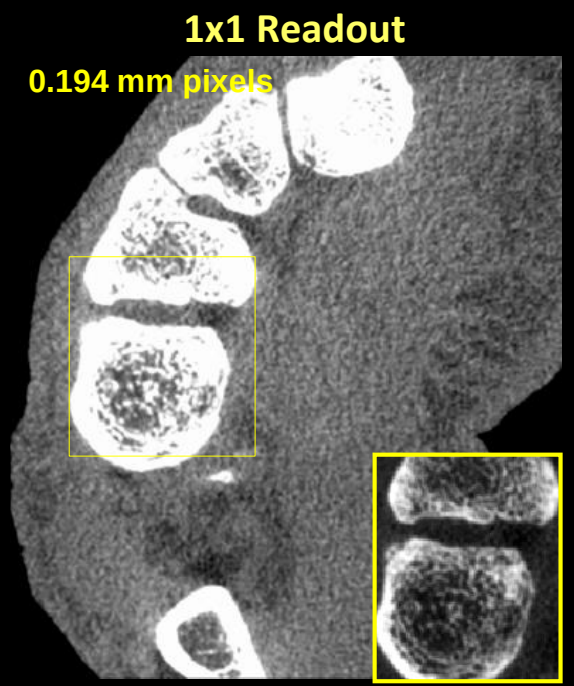
Considers:
- Fidelity of signal transfer (MTF)
- Correlation of noise (NPS)
- Spatial frequencies of interest ($W_{task}$)

Variations in Observer Model:
- Prewhitening (PW / Hotelling)
- PW with eye filter (PWEi)
- Non-prewhitening (NPW)
- Channelized Hoteling (CHO)

Useful for:
- Observer-independent performance
- System design, optimization
- Low-dose performance limits

*Note:* linearity, shift variance / stationarity
→ *local* approximations




P. Prakash et al. Med Phys 2011

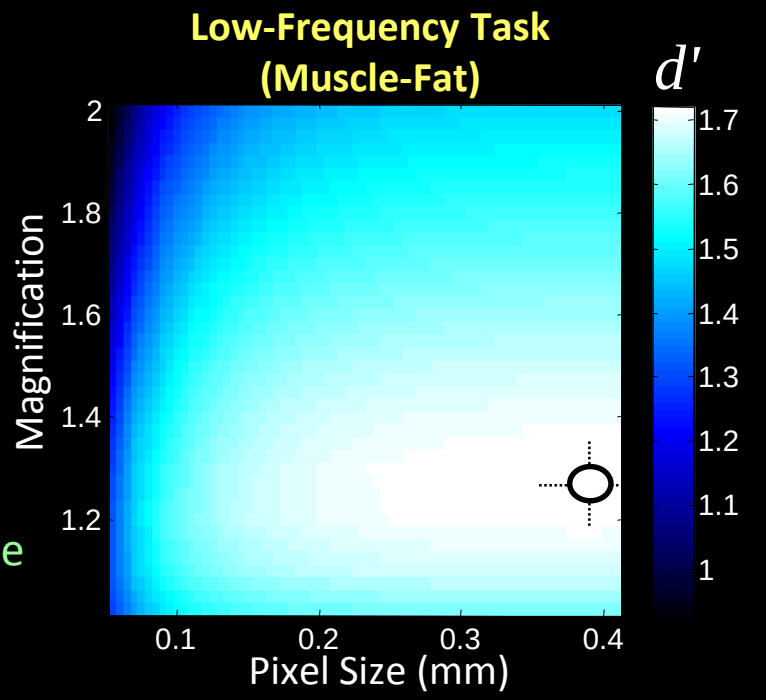
# Task-Based Imaging Performance

Considers:
- Fidelity of signal transfer (MTF)
- Correlation of noise (NPS)
- Spatial frequencies of interest ($W_{task}$)

Variations in Observer Model:
- Prewhitening (PW / Hotelling)
- PW with eye filter (PWEi)
- Non-prewhitening (NPW)
- Channelized Hoteling (CHO)

Useful for:
- Observer-independent performance
- System design, optimization
- Low-dose performance limits

*Note:* linearity, shift variance / stationarity
→ *local* approximations





P. Prakash et al. Med Phys 2011

Basic Principles

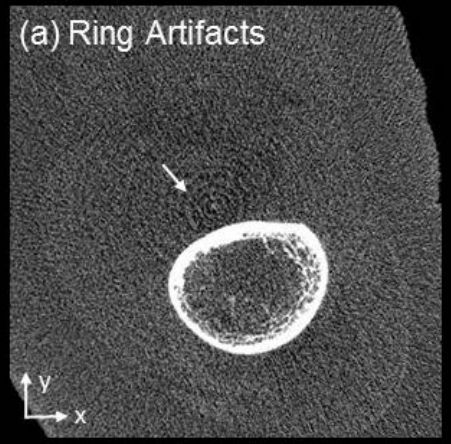
CBCT Systems

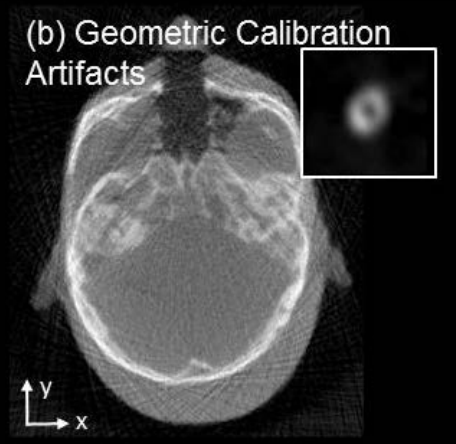
Imaging Performance

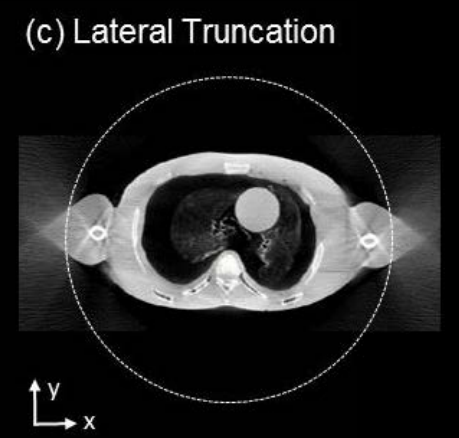
Future Directions

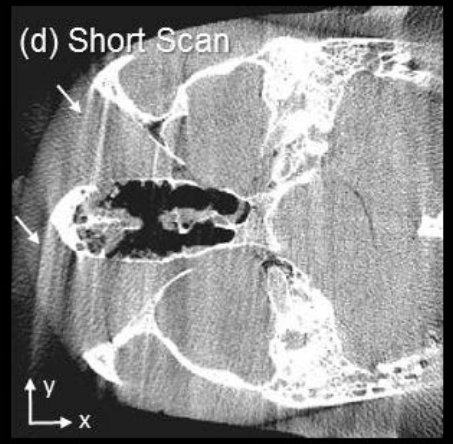
# Artifacts

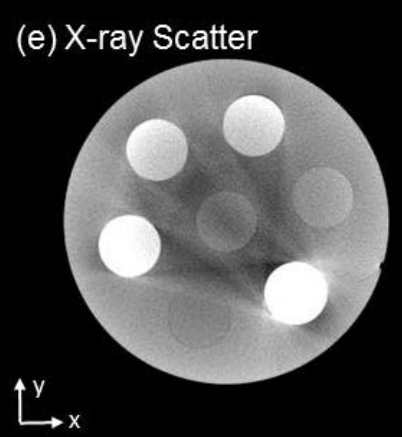
- Ring Artifacts
  - Defective pixel elements
- Geometric Calibration
  - Irreproducible orbit
- Lateral Truncation
  - Limited detector FOV
- Short Scan (<180°+fan)
  - Insufficient data, Parker weights
- X-ray Scatter
  - Large volumetric FOV
- Beam Hardening
  - (as with MDCT)
- Image Lag
  - Residual signal from previous frames
- Cone-Beam Artifact
  - Circular orbit, divergent beam
- Patient Motion
  - Slow scan time

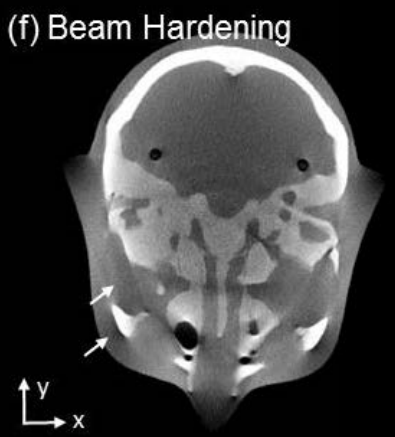


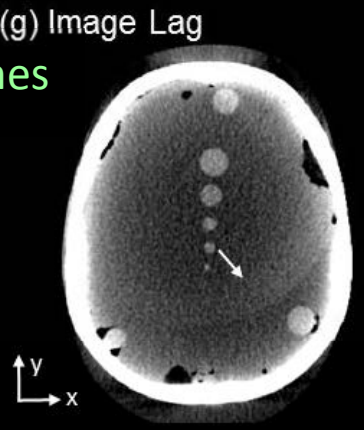



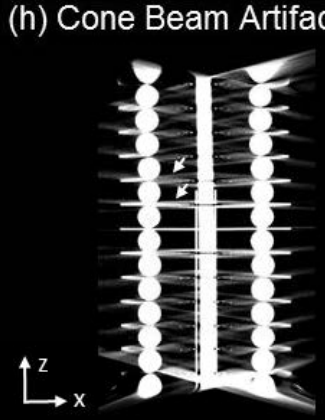



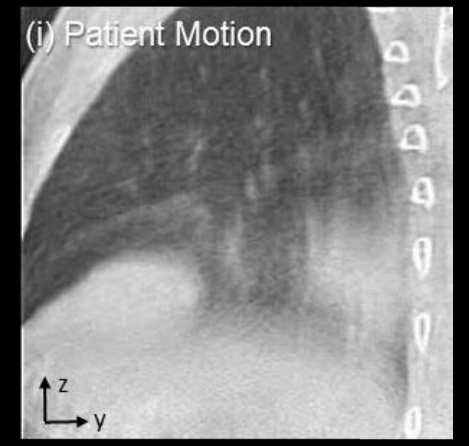



Basic Principles

CBCT Systems

Imaging Performance

Future Directions

# Dosimetry

See also:

- AAPM Task Group 111 (Dixon et al.)
- AAPM Task Group 200 (Bakalyar et al.)

Extended CTDI Phantoms

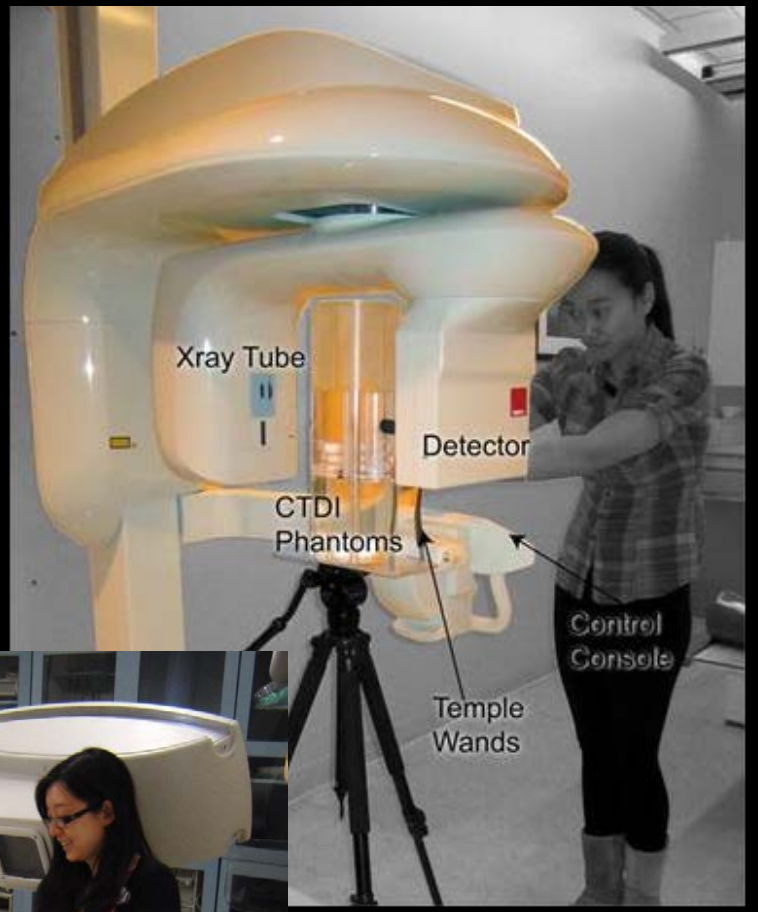
- Longitudinal stack (3 cylinders ~45 cm)
- Long x-ray scatter tails

Point Dose Measurements

- Farmer chamber (0.6 $cm^3$ air volume)
- Central dose ($D_o$)
- Peripheral dose ($D_p$)

Short scans and object truncation

- Nonuniform dose distributions




Basic Principles

CBCT Systems

Imaging Performance

Future Directions

# Dosimetry

See also:

- AAPM Task Group 111 (Dixon et al.)
- AAPM Task Group 200 (Bakalyar et al.)

Extended CTDI Phantoms

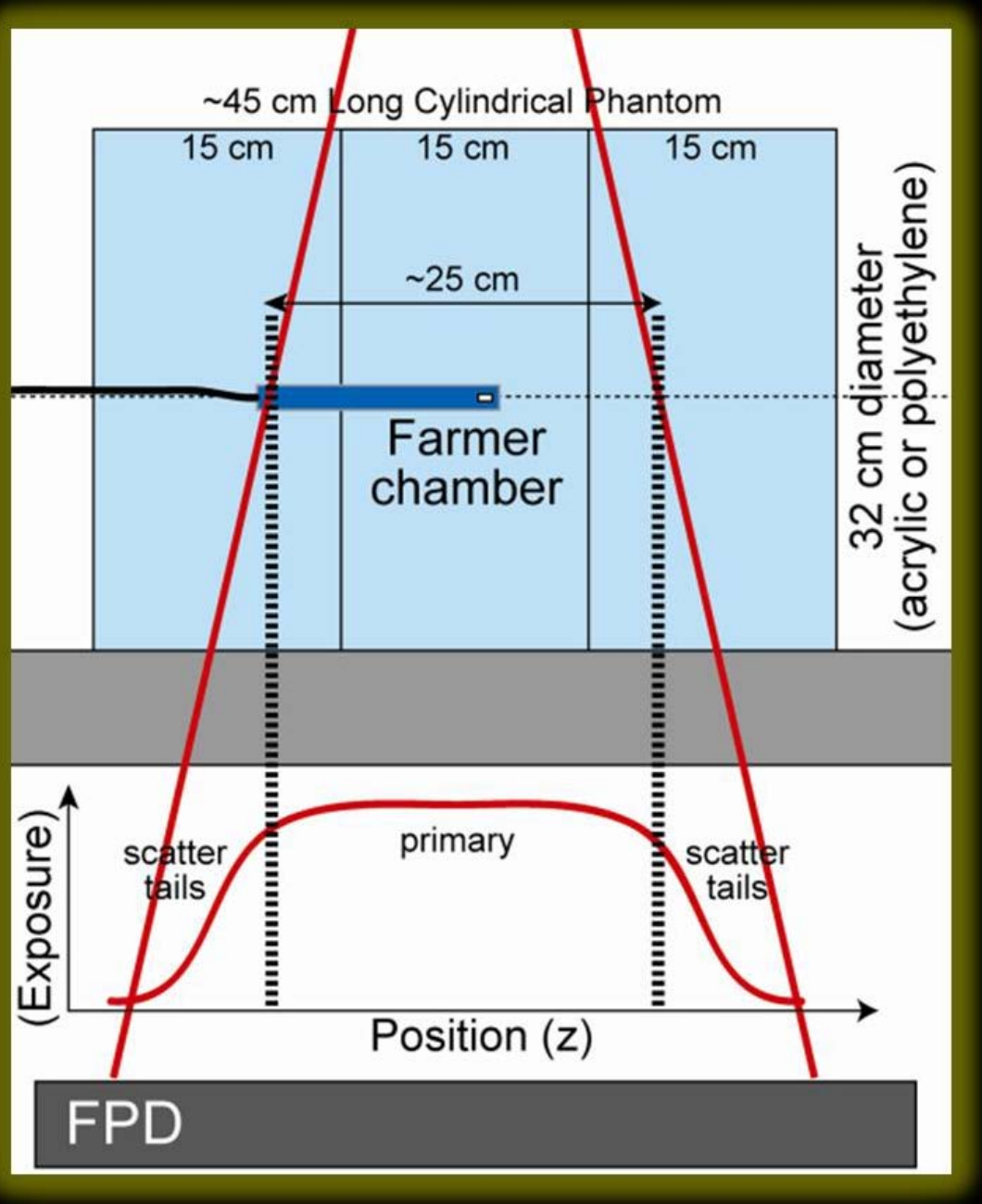
- Longitudinal stack (3 cylinders ~45 cm)
- Long x-ray scatter tails

Point Dose Measurements

- Farmer chamber (0.6 $cm^3$ air volume)
- Central dose ($D_o$)
- Peripheral dose ($D_p$)

Short scans and object truncation

- Nonuniform dose distributions



# Dosimetry

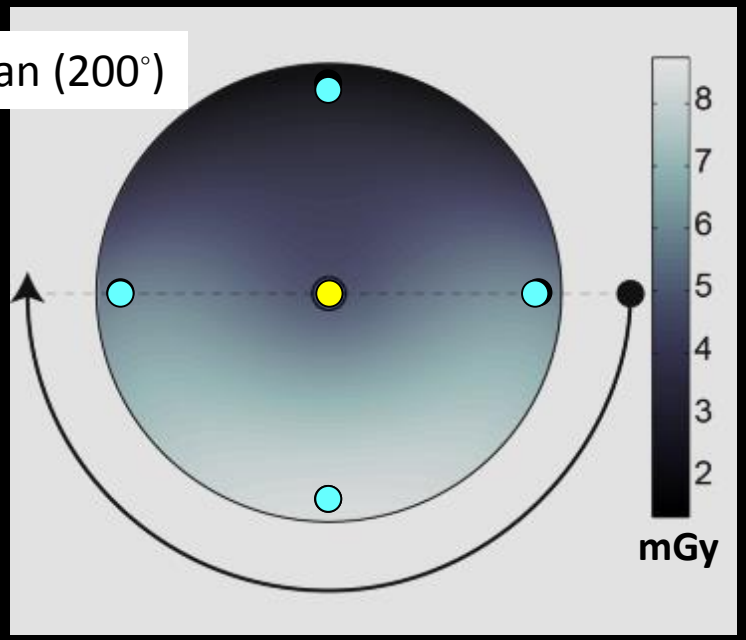
$$D_w = \frac{1}{3} D_0 + \frac{2}{3} \overline{D_P}$$

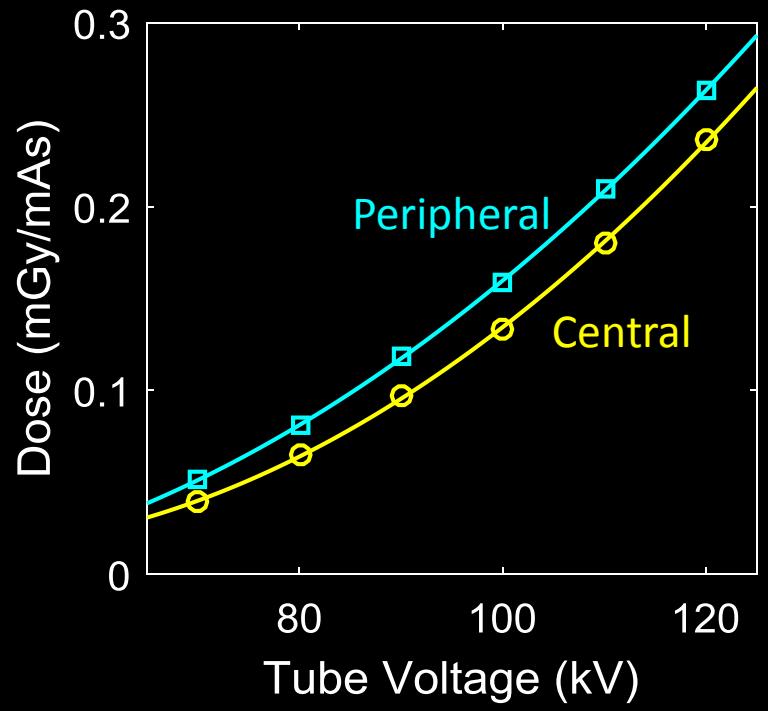
See also:
- AAPM Task Group 111 (Dixon et al.)
- AAPM Task Group 200 (Bakalyar et al.)

Extended CTDI Phantoms
- Longitudinal stack (3 cylinders ~45 cm)
- Long x-ray scatter tails

Point Dose Measurements
- Farmer chamber (0.6 $cm^3$ air volume)
- Central dose ($D_o$)
- Peripheral dose ($D_p$)

Short scans and object truncation
- Nonuniform dose distributions



# Dosimetry

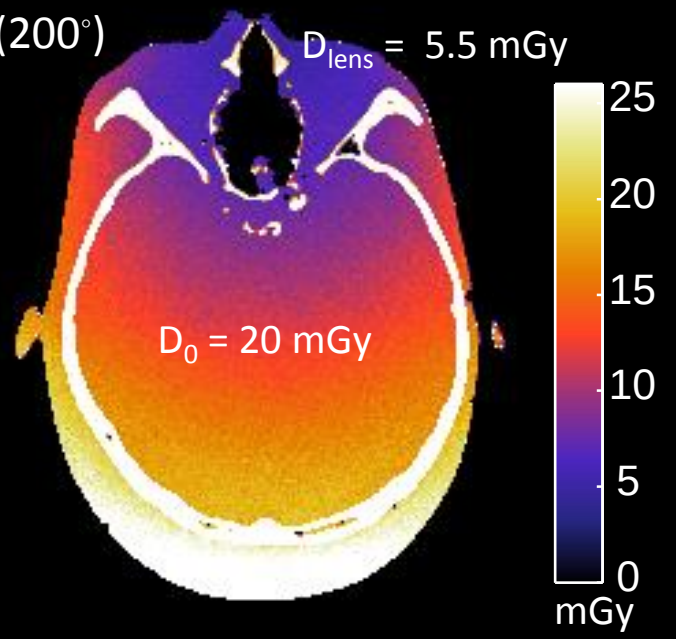
$$D_w = \frac{1}{3} D_0 + \frac{2}{3} \overline{D_P}$$

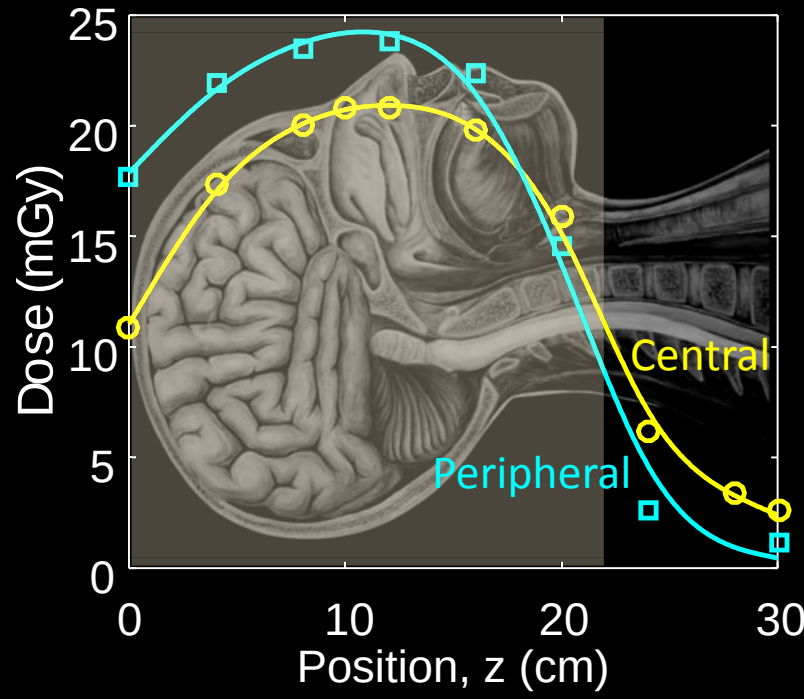
See also:
- AAPM Task Group 111 (Dixon et al.)
- AAPM Task Group 200 (Bakalyar et al.)

Extended CTDI Phantoms
- Longitudinal stack (3 cylinders ~45 cm)
- Long x-ray scatter tails

Point Dose Measurements
- Farmer chamber (0.6 $cm^3$ air volume)
- Central dose ($D_o$)
- Peripheral dose ($D_p$)

Short scans and object truncation
- Nonuniform dose distributions



Basic Principles

CBCT Systems

Imaging Performance

Future Directions

## New Systems and Acquisition Techniques

- Robotic gantry
- Noncircular orbits
- Specialty systems (point-of-care)

## New Detectors

- CMOS, Variable gain modes
- Higher resolution
- Lower electronic noise

## Improved Artifact Corrections

- Lag + Glare
- Scatter + Beam-Hardening
- Patient Motion

## New Reconstruction Methods

- Model-based image reconstruction (MBIR)
- Prior information (patient and devices)
- Accelerated reconstruction

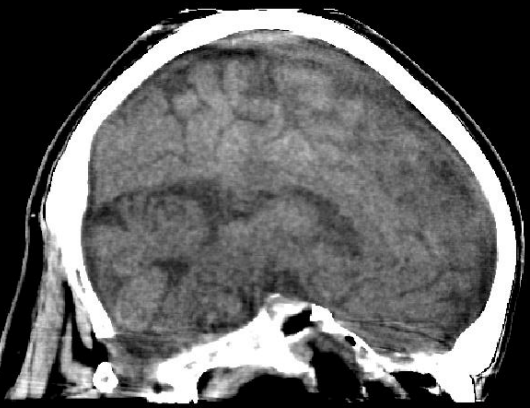

Pheno Robotic C-arm (Siemens)


Imaging Ring (medPhoton)


Multitom RAX (Siemens)


InReach (CurveBeam)


Head Scanner (Prototype)


J. Xu et al. Med Phys 2016

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

## New Systems and Acquisition Techniques

- Robotic gantry
- Noncircular orbits
- Specialty systems (point-of-care)

## New Detectors

- CMOS, Variable gain modes
- Higher resolution
- Lower electronic noise

## Improved Artifact Corrections

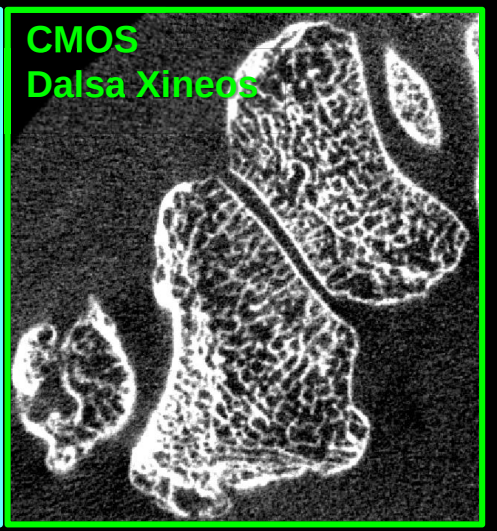
- Lag + Glare
- Scatter + Beam-Hardening
- Patient Motion

## New Reconstruction Methods

- Model-based image reconstruction (MBIR)
- Prior information (patient and devices)
- Accelerated reconstruction


$a_{pix}$ = 0. 138 mm
$\sigma_{add}$ = 5968 electrons
FOV = 43 x 43 $cm^2$


$a_{pix}$ = 0. 099 mm
$\sigma_{add}$ = 304 electrons
FOV = 29.5 x 29.5 $cm^2$


Extremity CT (Hi-Res pQCT Prototype)
W. Zbijewski, Johns Hopkins University

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

## New Systems and Acquisition Techniques

- Robotic gantry
- Noncircular orbits
- Specialty systems (point-of-care)

## New Detectors

- CMOS, Variable gain modes
- Higher resolution
- Lower electronic noise

## Improved Artifact Corrections

- Lag + Glare
- Scatter + Beam-Hardening
- Patient Motion

## New Reconstruction Methods

- Model-based image reconstruction (MBIR)
- Prior information (patient and devices)
- Accelerated reconstruction

### Detector Lag Deconvolution

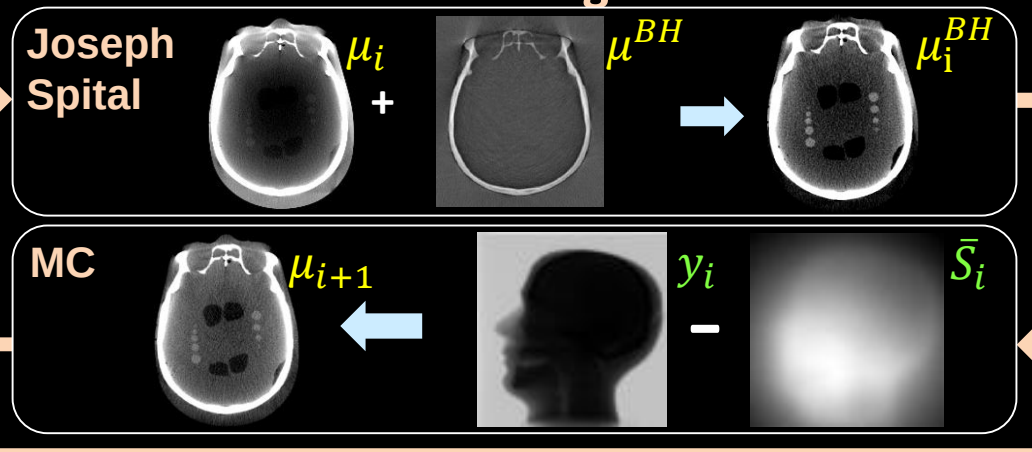
$$*^{-1} \sum_{n=1}^{N} b_n \cdot e^{-a_n k} u(k)$$

### Veiling Glare Deconvolution

$$*^{-1}\left[(1 - c_1 \exp\left(\frac{-x^2}{2c_2^2}\right)) + \frac{c_1}{\pi c_3}\left(\frac{1}{1 + x^2/c_3^2}\right)\right]$$

Short range PSF — Glare PSF

### MC Scatter + Beam Hardening




Sisniega et al., Phys Med Biol 2015

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

## New Systems and Acquisition Techniques

- Robotic gantry
- Noncircular orbits
- Specialty systems (point-of-care)

## New Detectors

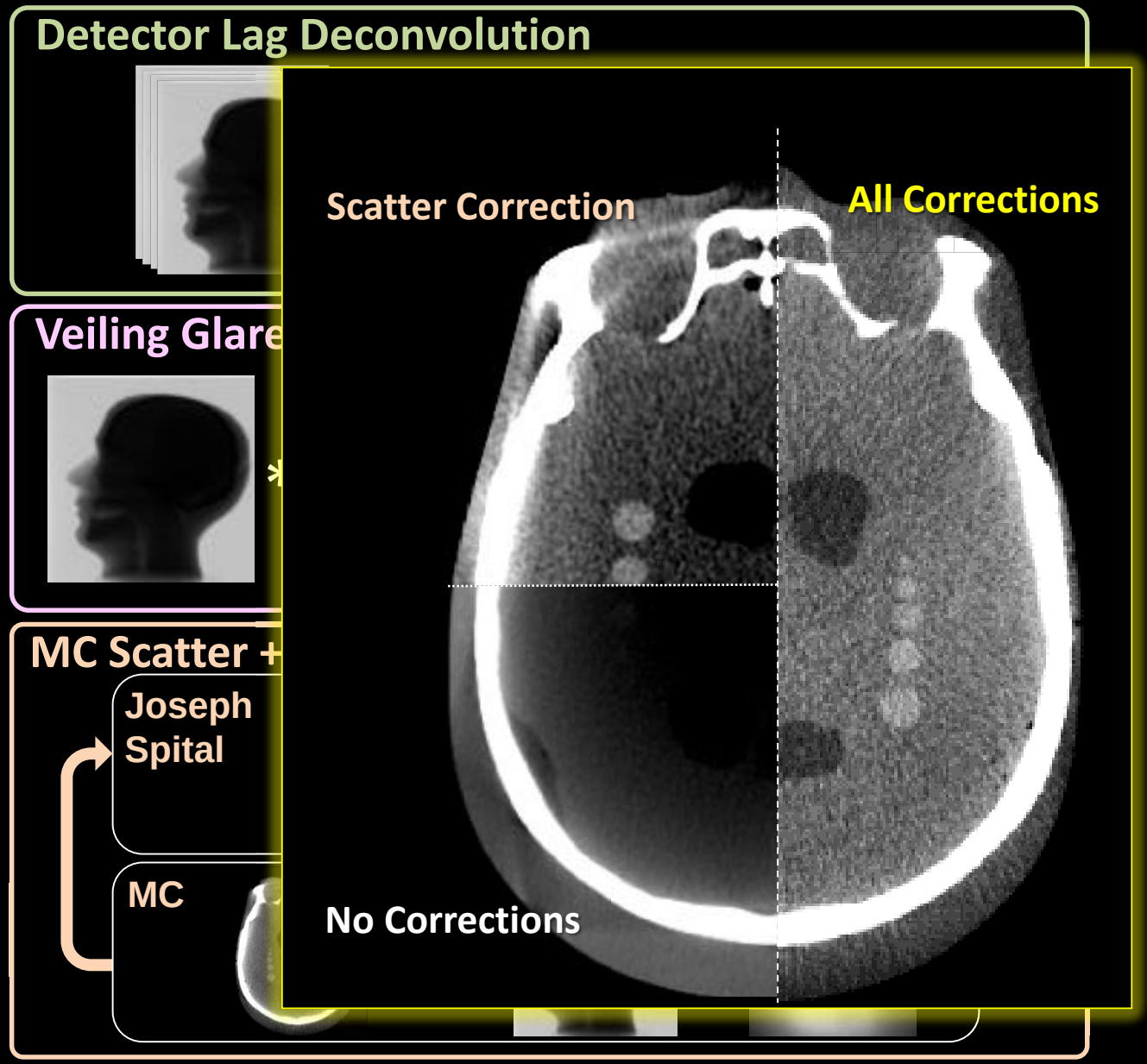
- CMOS, Variable gain modes
- Higher resolution
- Lower electronic noise

## Improved Artifact Corrections

- Lag + Glare
- Scatter + Beam-Hardening
- Patient Motion

## New Reconstruction Methods

- Model-based image reconstruction (MBIR)
- Prior information (patient and devices)
- Accelerated reconstruction




Sisniega et al., Phys Med Biol 2015

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

## New Systems and Acquisition Techniques

- Robotic gantry
- Noncircular orbits
- Specialty systems (point-of-care)

## New Detectors

- CMOS, Variable gain modes
- Higher resolution
- Lower electronic noise

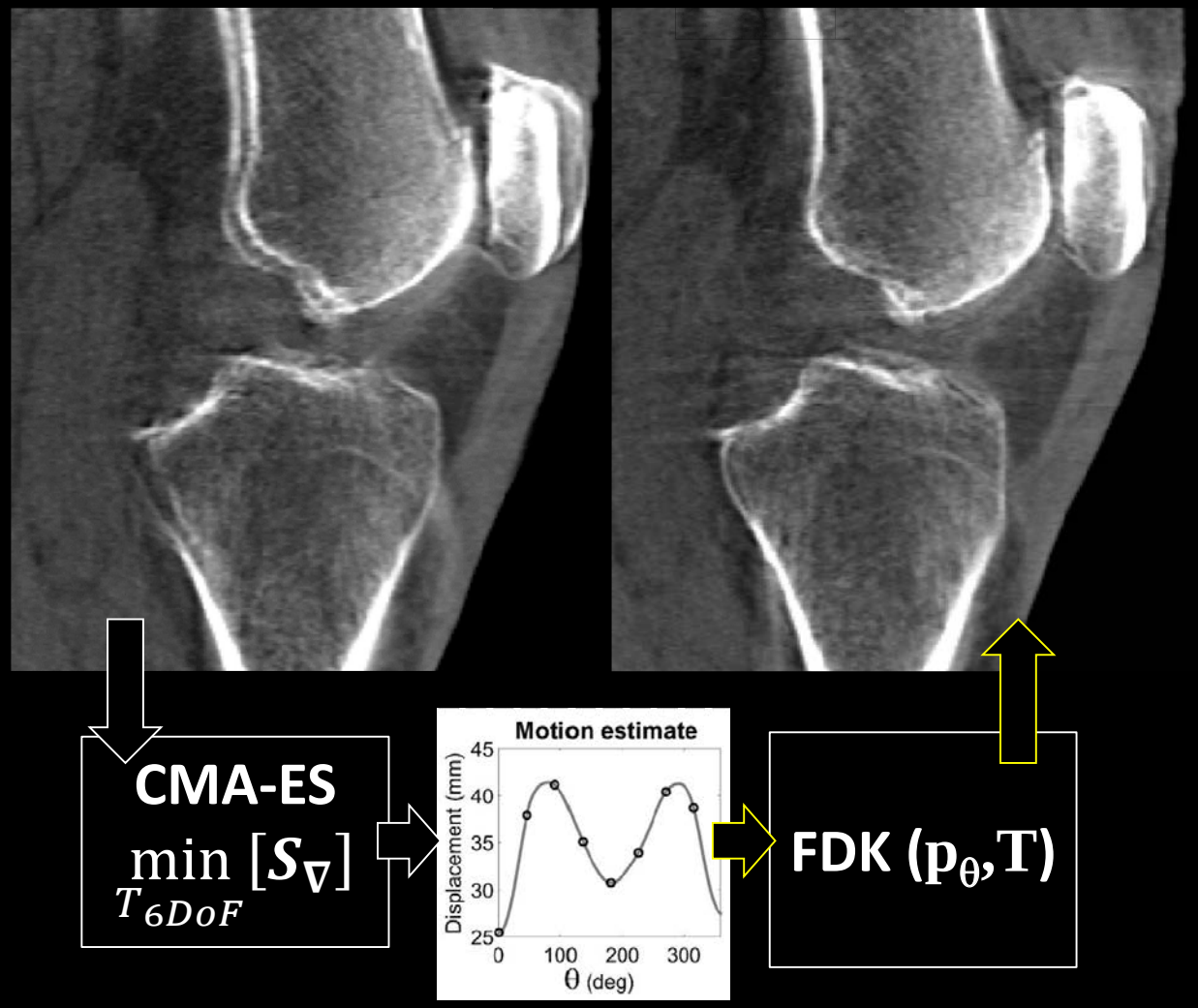
## Improved Artifact Corrections

- Lag + Glare
- Scatter + Beam-Hardening
- Patient Motion

## New Reconstruction Methods

- Model-based image reconstruction (MBIR)
- Prior information (patient and devices)
- Accelerated reconstruction

### ‘Auto-Focus’ Image Domain Motion Compensation




Sisniega et al., Phys Med Biol 2016

Sisniega et al., Phys Med Biol 2015

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

## New Systems and Acquisition Techniques

- Robotic gantry
- Noncircular orbits
- Specialty systems (point-of-care)

## New Detectors

- CMOS, Variable gain modes
- Higher resolution
- Lower electronic noise

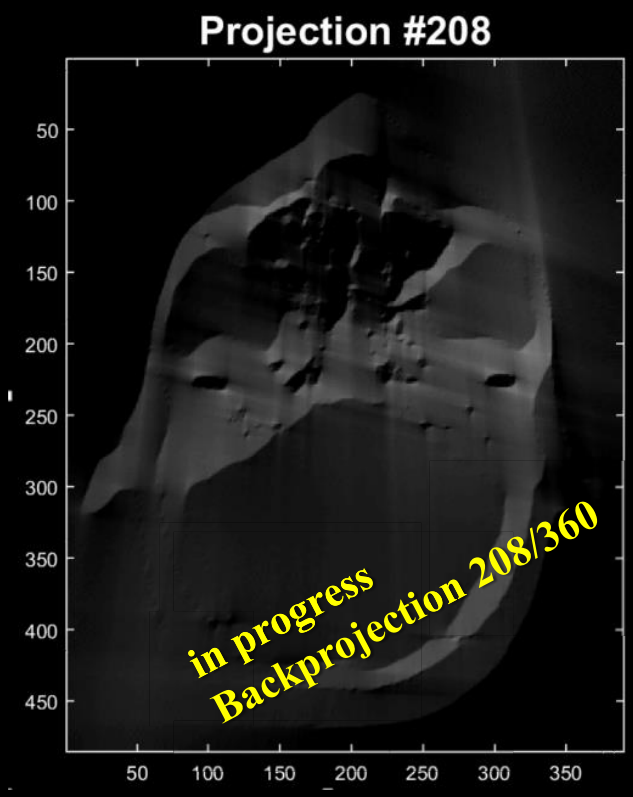
## Improved Artifact Corrections

- Lag + Glare
- Scatter + Beam-Hardening
- Patient Motion

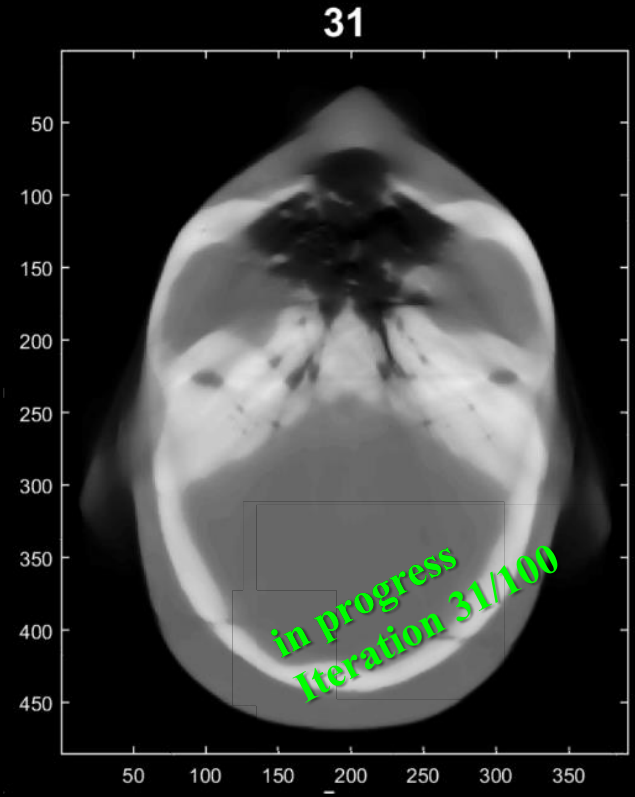
## New Reconstruction Methods

- Model-based image reconstruction (MBIR)
- Prior information (patient and devices)
- Accelerated reconstruction

**Conventional**




**MBIR**




Filtered Backprojection

$$\bar{\mu} = \int_0^{2\pi} \frac{R^2}{U^2(x,y,\theta)} p'(\xi,\theta) * k_{ramp}(\xi) d\theta$$

Penalized Likelihood

Log-Likelihood

$$\hat{\bar{\mu}} = \arg\max L(\vec{g},\vec{\mu}) - \beta R(\vec{\mu})$$

Penalty

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

## New Systems and Acquisition Techniques

- Robotic gantry
- Noncircular orbits
- Specialty systems (point-of-care)

## New Detectors

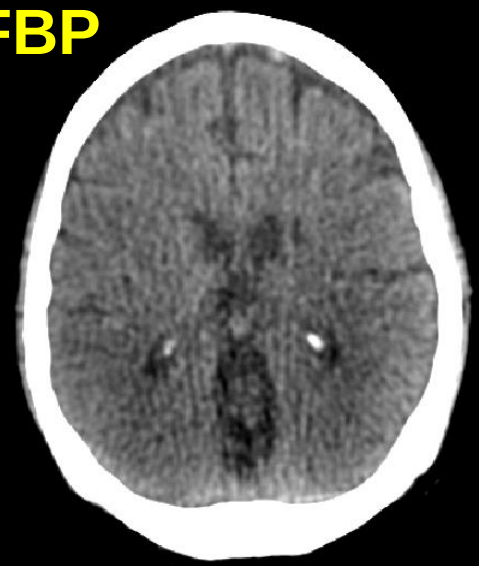
- CMOS, Variable gain modes
- Higher resolution
- Lower electronic noise

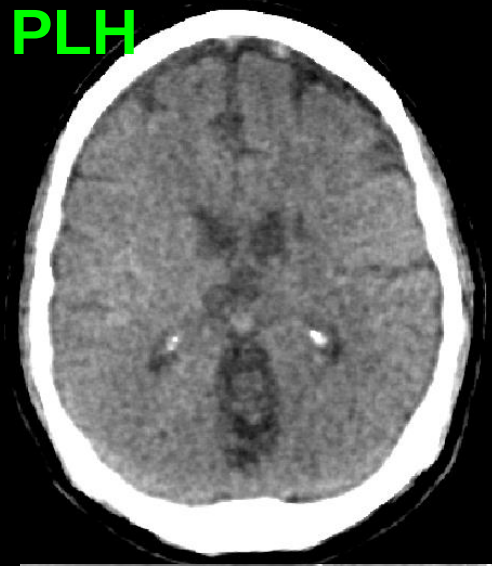
## Improved Artifact Corrections

- Lag + Glare
- Scatter + Beam-Hardening
- Patient Motion

## New Reconstruction Methods

- Model-based image reconstruction (MBIR)
- Prior information (patient and devices)
- Accelerated reconstruction

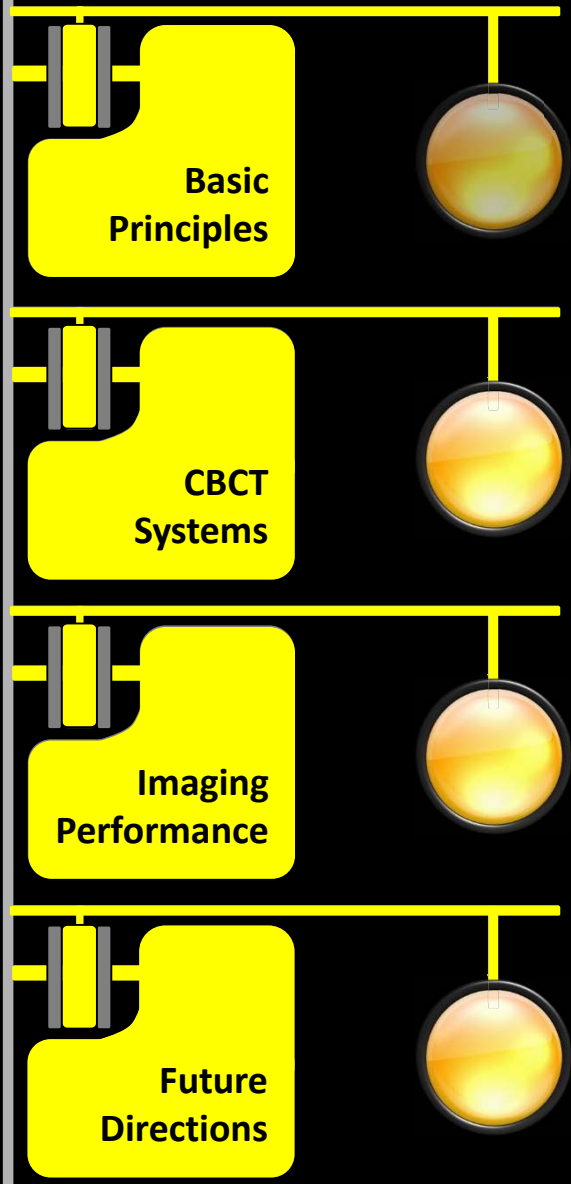



| | FBP | PLH |
|---|---|---|
| Dose | 6.6 mGy | 3.3 mGy |
| Spatial Res. (ESF) | 1.0 mm | 1.0 mm |
| CNR | 2.1 | 2.7 |
| Recon Time | 13 s | 4 hr → 19 s |

Wang et al. Med Phys (2015)

# In Summary




Large-area detector
Circular (or non-circular) orbit → Volumetric FOV

Rich diversity of system configurations
IGRT → IR → IG surgery → Specialty diagnostics (breast, MSK, …)

Good (nearly isotropic) spatial resolution
Modest soft-tissue contrast resolution
Artifacts

New systems, detectors, and acquisition techniques
Model-based image reconstruction

Handouts for this presentation available after RSNA at:
http://istar.jhu.edu/talks


# Acknowledgments


**Biomedical Engineering**

The I-STAR Lab

The Carnegie Center for Surgical Innovation

**Radiology**

N Aygun, C Weiss, K Hong, S Demehri, J Carrino

**Neuroscience**

R Stevens, V Koliatsos

**Neurosurgery**

JP Wolinsky, N Theodore, D Sciubba, T Witham

A Cohen, M Luciano, G Gallia, X Ye, H Brem

**Orthopaedic Surgery**

G Osgood, B Shafiq, J Ficke

J Khanna, L Riley

**Computer Science and ECE**

R Taylor, G Hager, P Kazanzides

J Prince


istar.jhu.edu

carnegie.jhu.edu