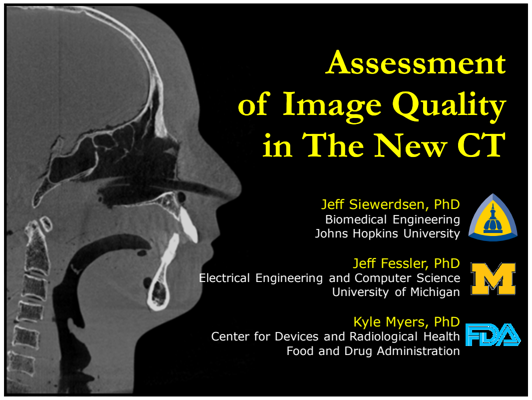
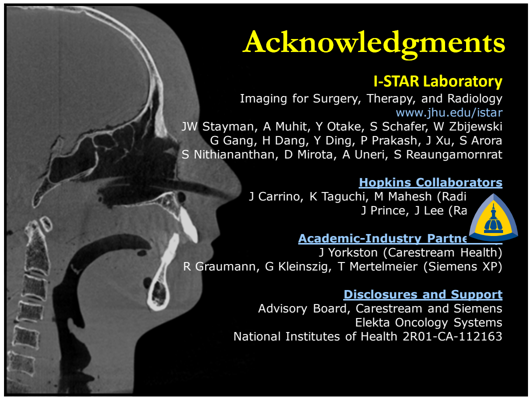

Assessment
of Image Quality
in The New CT
Jeff Siewerdsen, PhD
Biomedical Engineering
Johns Hopkins University
Jeff Fessler, PhD
Electrical Engineering and Computer Science
University of Michigan
Kyle Myers, PhD
Center for Devices and Radiological Health
Food and Drug Administration


Acknowledgments
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Imaging for Surgery, Therapy, and Radiology
www.jhu.edu/istar
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G Gang, H Dang, Y Ding, P Prakash, J Xu, S Arora
S Nithiananthan, D Mirota, A Uneri, S Reaungamornrat
Hopkins Collaborators
J Carrino, K Taguchi, M Mahesh (Radi
J Prince, J Lee (Ra
Academic-Industry Partne
J Yorkston (Carestream Health)
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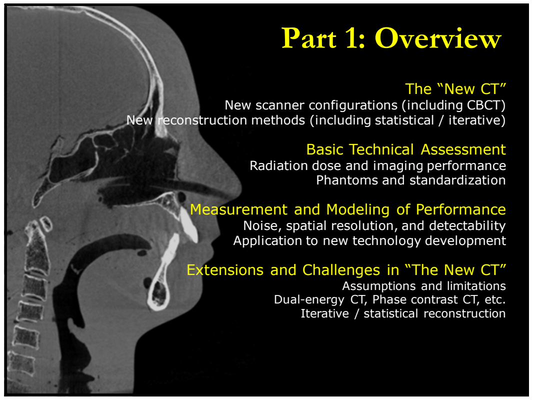
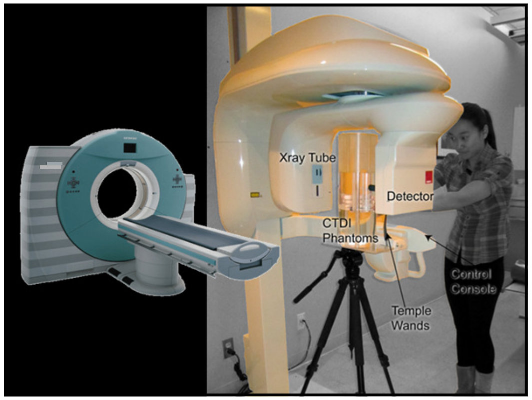
National Institutes of Health 2R01-CA-112163


Part 1: Overview
The "New CT"
New scanner configurations (including CBCT)
New reconstruction methods (including statistical / iterative)
Basic Technical Assessment
Radiation dose and imaging performance
Phantoms and standardization
Measurement and Modeling of Performance
Noise, spatial resolution, and detectability
Application to new technology development
Extensions and Challenges in "The New CT"
Assumptions and limitations
Dual-energy CT, Phase contrast CT, etc.
Iterative / statistical reconstruction



Basic Technical Assessment

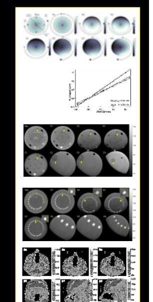
Radiation Dose
Farmer chamber + 16 cm cylinder
Short-scan protocols

Quantitative Accuracy
Electron density inserts
Comparison to MDCT

Contrast Resolution
Low-contrast tissue inserts
SDNR versus kVp, mAs

Spatial Resolution
Line-pair pattern (subjective)
Modulation transfer function (MTF)

"Clinical" Image Quality
Anthropomorphic phantoms
Expert readers



J Xu et al. Med. Phys. (in press - August)

Basic Technical Assessment

Radiation Dose
Farmer chamber + 16 cm cylinder
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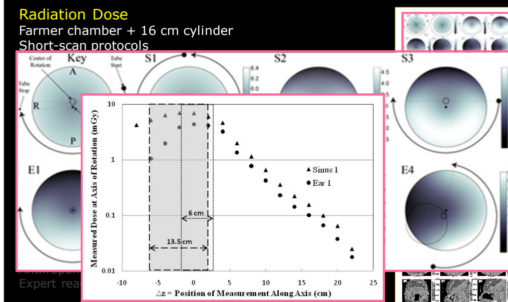
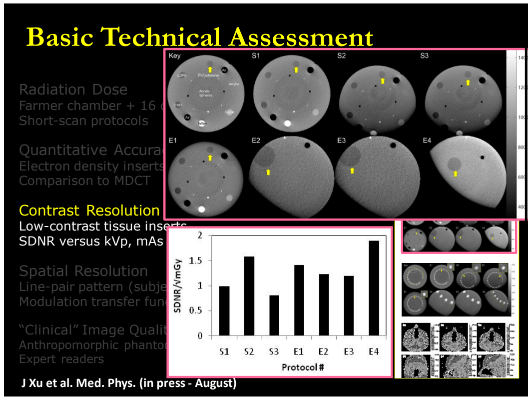


Expert rea

J Xu et al. Med. Phys. (in press - August)


Basic Technical Assessment
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Farmer chamber + 16
Short-scan protocols
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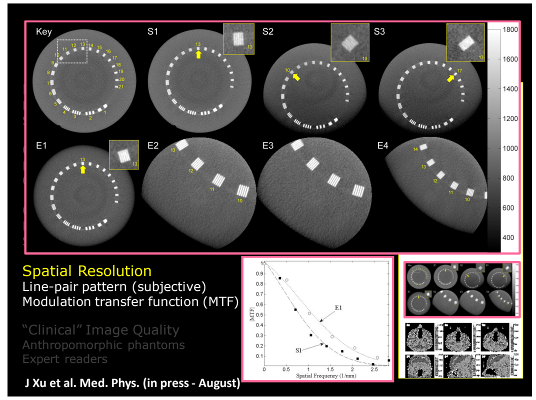
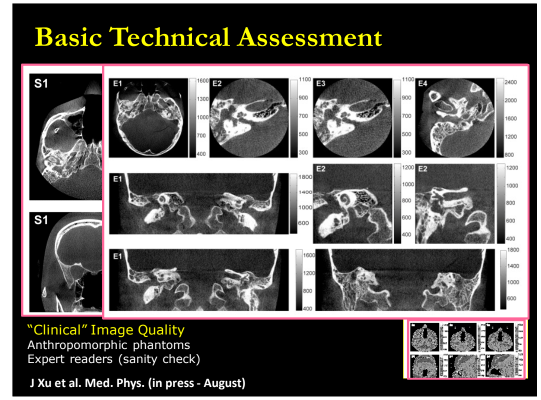
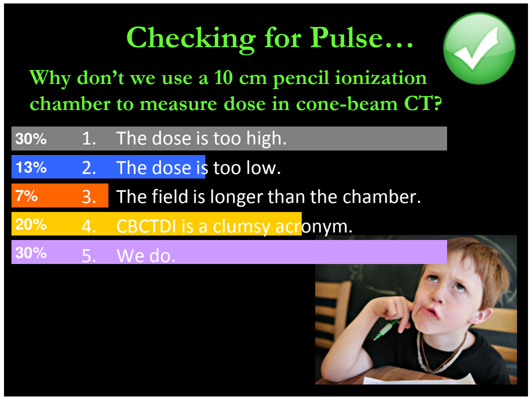
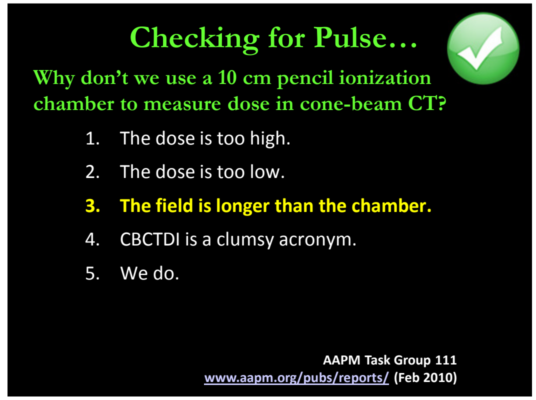
Comparison to MDCT
Contrast Resolution
Low-contrast tissue
SDNR versus kVp, mAs
Spatial Resolution
Line-pair pattern
Modulation transfer
"Clinical" Image
Anthropomorphic
Expert readers
SDNR/√mGy
S1 S2 S3 E1 E2 E3 E4
Protocol #
J Xu et al. Med. Phys. (in press - August)


Key S1 S2 S3
E1 E2 E3 E4
Spatial Resolution
Line-pair pattern (subjective)
Modulation transfer function (MTF)
"Clinical" Image Quality
Anthropomorphic phantoms
Expert readers
J Xu et al. Med. Phys. (in press - August)


Basic Technical Assessment
S1
E1 E2 E3 E4
"Clinical" Image Quality
Anthropomorphic phantoms
Expert readers (sanity check)
J Xu et al. Med. Phys. (in press - August)


Checking for Pulse…
Why don't we use a 10 cm pencil ionization chamber to measure dose in cone-beam CT?
30% 1. The dose is too high.
13% 2. The dose is too low.
7% 3. The field is longer than the chamber.
20% 4. CBCTDI is a clumsy acronym.
30% 5. We do.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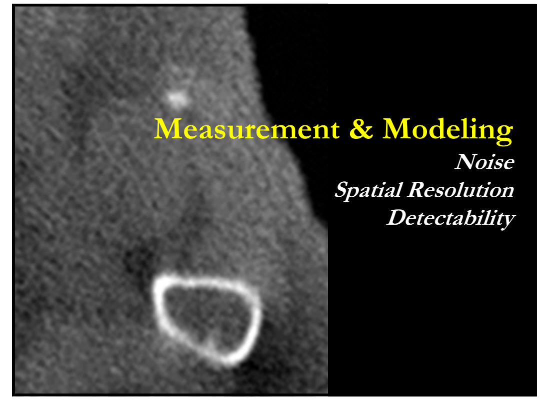
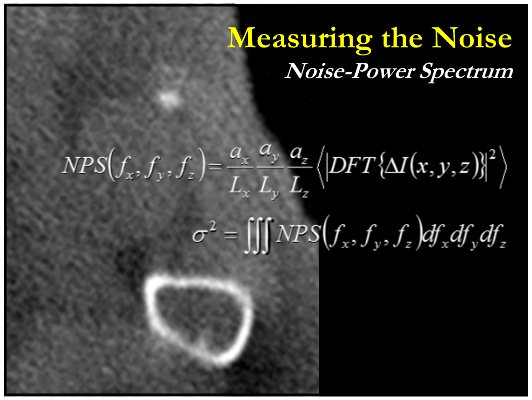
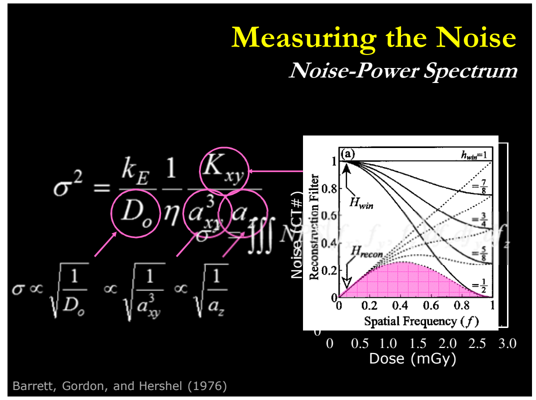
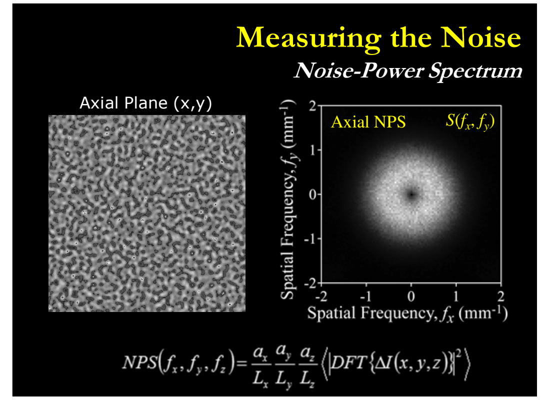
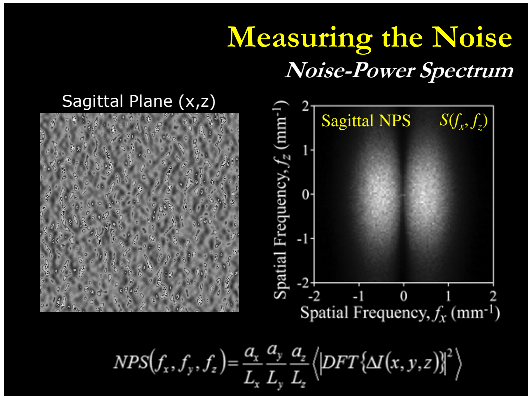
AAPM Task Group 111
www.aapm.org/pubs/reports/ (Feb 2010)

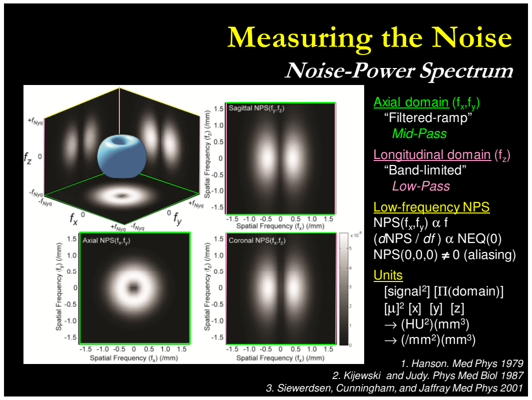

Measurement & Modeling
Noise
Spatial Resolution
Detectability

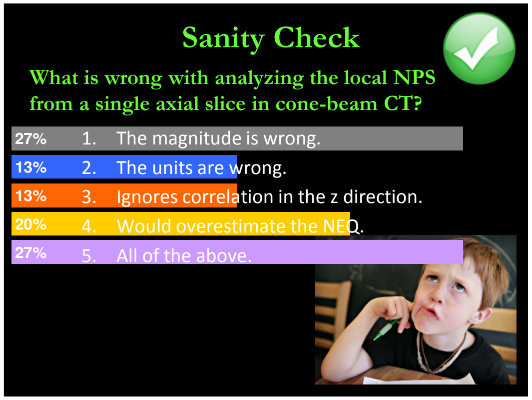

Measuring the Noise
Noise-Power Spectrum
NPS(f_x, f_y, f_z) = (a_x/L_x)(a_y/L_y)(a_z/L_z) ⟨|DFT{ΔI(x,y,z)}|^2⟩
σ^2 = ∭ NPS(f_x, f_y, f_z) df_x df_y df_z


Measuring the Noise
Noise-Power Spectrum
σ^2 = (k_E/D_o)(1/η)(K_xy/(a_xy^3 a_z))
σ ∝ √(1/D_o) ∝ √(1/a_xy^3) ∝ √(1/a_z)
Reconstruction Filter
Spatial Frequency (f)
Dose (mGy)
Barrett, Gordon, and Hershel (1976)


Measuring the Noise
Noise-Power Spectrum
Axial Plane (x,y)
Axial NPS
S(f_x, f_y)
Spatial Frequency, f_y (mm^-1)
Spatial Frequency, f_x (mm^-1)
NPS(f_x, f_y, f_z) = (a_x/L_x)(a_y/L_y)(a_z/L_z) ⟨|DFT{ΔI(x,y,z)}|^2⟩


Measuring the Noise
Noise-Power Spectrum
Sagittal Plane (x,z)
Sagittal NPS
$S(f_x, f_z)$
Spatial Frequency, f_z (mm^{-1})
Spatial Frequency, f_x (mm^{-1})
$NPS(f_x,f_y,f_z)=\frac{a_x}{L_x}\frac{a_y}{L_y}\frac{a_z}{L_z}\left\langle \left|DFT\{\Delta I(x,y,z)\}\right|^2\right\rangle$


Measuring the Noise
Noise-Power Spectrum
Sagittal NPS(f_y,f_z)
Axial NPS(f_x,f_y)
Coronal NPS(f_x,f_z)
Axial domain (f_x,f_y)
"Filtered-ramp"
Mid-Pass
Longitudinal domain (f_z)
"Band-limited"
Low-Pass
Low-frequency NPS
NPS(f_x,f_y) α f
(dNPS / df) α NEQ(0)
NPS(0,0,0) ≠ 0 (aliasing)
Units
[signal^2] [Π(domain)]
[μ]^2 [x] [y] [z]
→ (HU^2)(mm^3)
→ (/mm^2)(mm^3)
1. Hanson. Med Phys 1979
2. Kijewski and Judy. Phys Med Biol 1987
3. Siewerdsen, Cunningham, and Jaffray Med Phys 2001


Sanity Check
What is wrong with analyzing the local NPS from a single axial slice in cone-beam CT?
27% 1. The magnitude is wrong.
13% 2. The units are wrong.
13% 3. Ignores correlation in the z direction.
20% 4. Would overestimate the NEQ.
27% 5. All of the above.

Sanity Check

What is wrong with analyzing the local NPS from a single axial slice in cone-beam CT?

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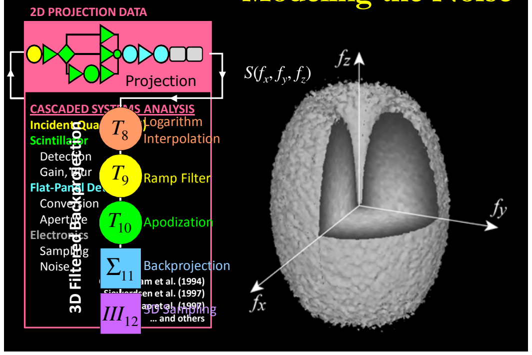
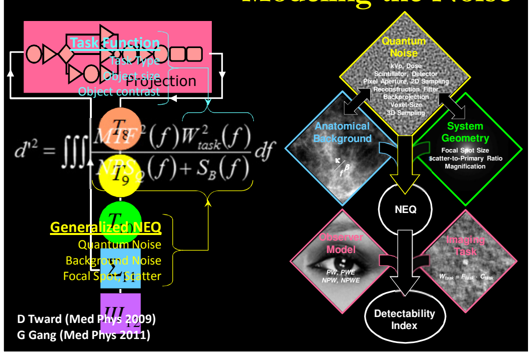
4. Would overestimate the NEQ.
5. **All of the above.**

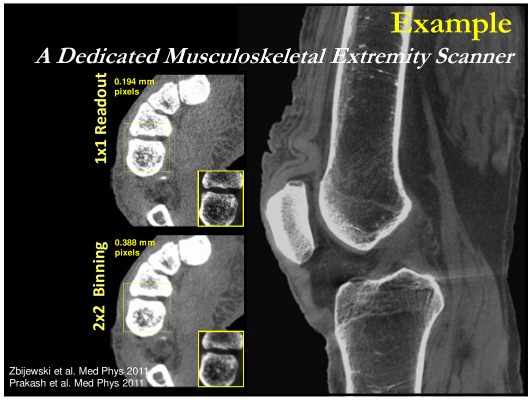
Siewerdsen, Jaffray, and Cunningham
Med Phys 29(11) (2002)

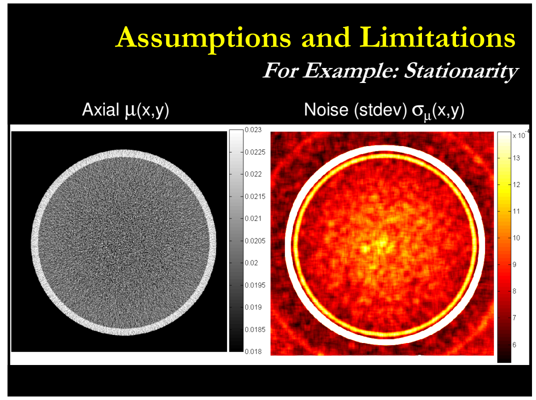
Modeling the Noise

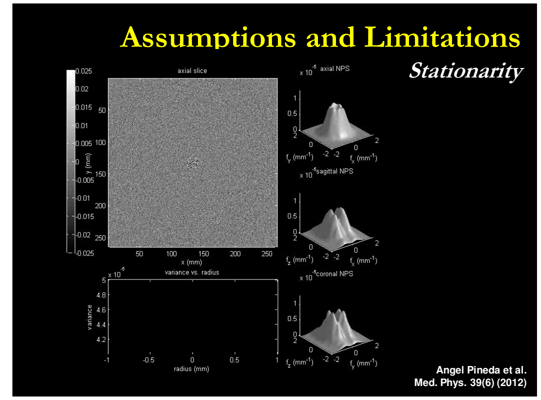


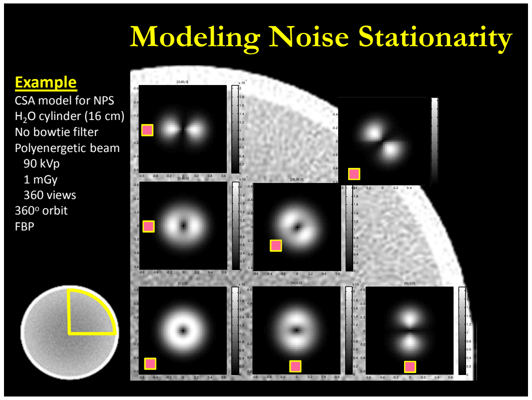
Modeling the Noise




Example
A Dedicated Musculoskeletal Extremity Scanner
1x1 Readout
0.194 mm pixels
2x2 Binning
0.388 mm pixels
Zbijewski et al. Med Phys 2011
Prakash et al. Med Phys 2011


Assumptions and Limitations
For Example: Stationarity
Axial μ(x,y)
Noise (stdev) σμ(x,y)


Assumptions and Limitations
Stationarity
axial slice
axial NPS
sagittal NPS
coronal NPS
variance vs. radius
Angel Pineda et al.
Med. Phys. 39(6) (2012)



Extensions of the Models

Non-Linear Reconstruction Algorithms

For example: Penalized Likelihood

Forward model:

$$\bar{y}(\mu) = I_0 \exp(-A\mu)$$

(Measurements; Number of photons; Projection Operator; Discretized Object Volume)

Log-likelihood estimator:

$$\hat{\mu} = \arg\max \Phi(\mu; y) = \arg\max \left[\log L(\mu; y) - \beta R(\mu)\right]$$

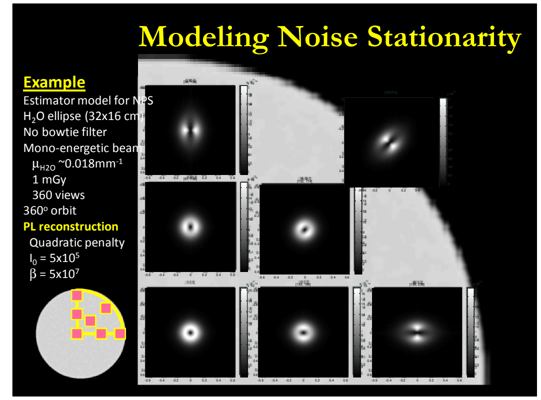
(Objective Function; Log-Likelihood; Regularization Term)

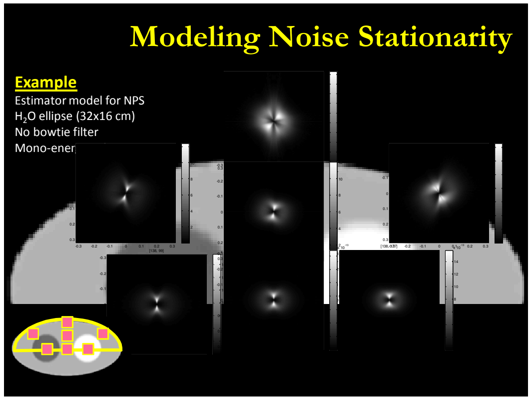
Noise and spatial resolution are ***object-dependent*** and ***spatially variant***
However, ***local covariance properties*** can still be estimated:

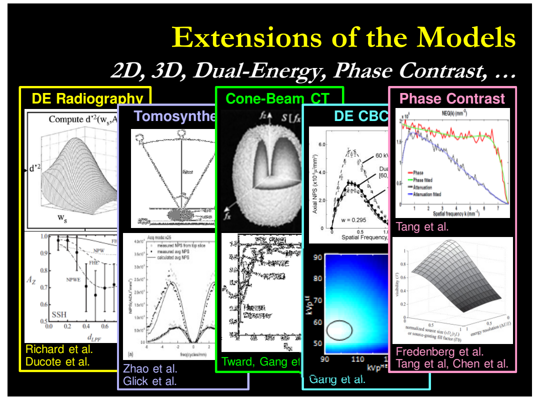
$$[\mathrm{Cov}\{\hat{\mu}\}]_{j,} \approx [F(\hat{\mu}) + R]^{-1} A^T \mathrm{Cov}\{y\} A \, [F(\hat{\mu}) + R]^{-1} e_j$$

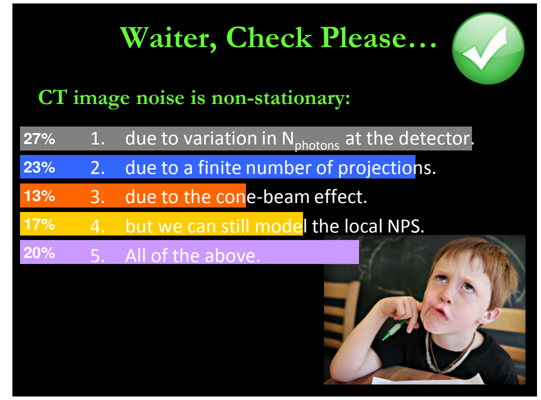
(Measurement Covariance; Regularization Operator; Weighted Projection-Backprojection Operator; j^{th} Unit Vector (at voxel j))

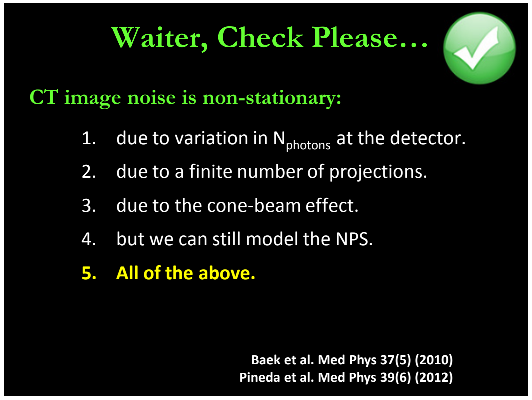
Fessler et al. IEEE-TIP (1996)
J Web Stayman et al. AAPM (2010)




Modeling Noise Stationarity
Example
Estimator model for NPS
H_2O ellipse (32x16 cm)
No bowtie filter
Mono-ener


Extensions of the Models
2D, 3D, Dual-Energy, Phase Contrast, …
DE Radiography
Tomosynthe
Cone-Beam CT
DE CBC
Phase Contrast
Tang et al.
Richard et al.
Ducote et al.
Zhao et al.
Glick et al.
Tward, Gang et
Gang et al.
Fredenberg et al.
Tang et al, Chen et al.


Waiter, Check Please…
CT image noise is non-stationary:
27% 1. due to variation in $N_{photons}$ at the detector.
23% 2. due to a finite number of projections.
13% 3. due to the cone-beam effect.
17% 4. but we can still model the local NPS.
20% 5. All of the above.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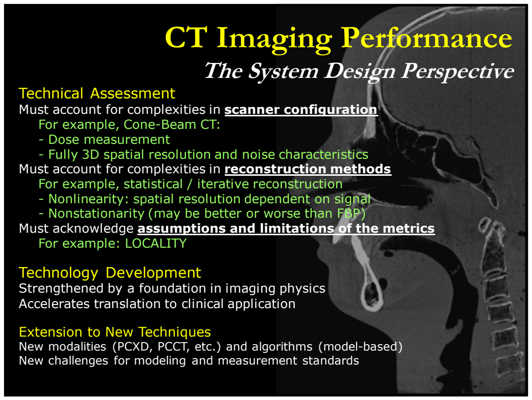
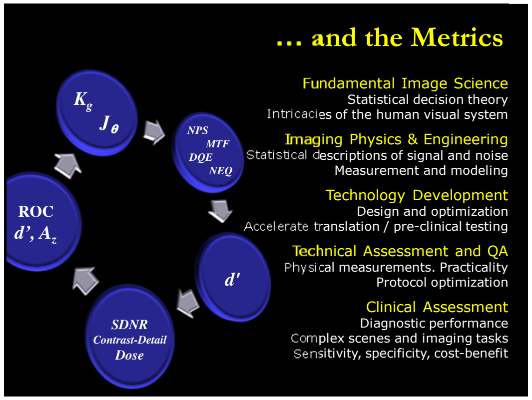
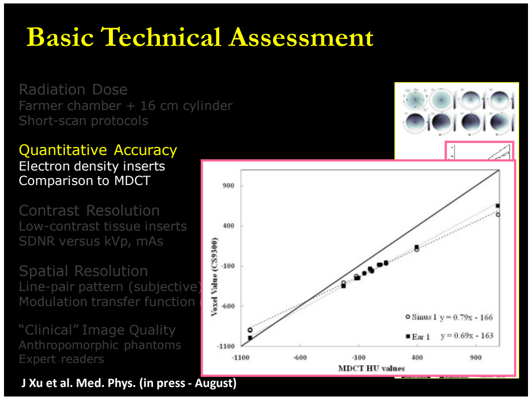
3. due to the cone-beam effect.
4. but we can still model the NPS.
5. All of the above.
Baek et al. Med Phys 37(5) (2010)
Pineda et al. Med Phys 39(6) (2012)


CT Imaging Performance
The System Design Perspective
Technical Assessment
Must account for complexities in scanner configuration
For example, Cone-Beam CT:
- Dose measurement
- Fully 3D spatial resolution and noise characteristics
Must account for complexities in reconstruction methods
For example, statistical / iterative reconstruction
- Nonlinearity: spatial resolution dependent on signal
- Nonstationarity (may be better or worse than FBP)
Must acknowledge assumptions and limitations of the metrics
For example: LOCALITY
Technology Development
Strengthened by a foundation in imaging physics
Accelerates translation to clinical application
Extension to New Techniques
New modalities (PCXD, PCCT, etc.) and algorithms (model-based)
New challenges for modeling and measurement standards


… and the Metrics
Fundamental Image Science
Statistical decision theory
Intricacies of the human visual system
Imaging Physics & Engineering
Statistical descriptions of signal and noise
Measurement and modeling
Technology Development
Design and optimization
Accelerate translation / pre-clinical testing
Technical Assessment and QA
Physical measurements. Practicality
Protocol optimization
Clinical Assessment
Diagnostic performance
Complex scenes and imaging tasks
Sensitivity, specificity, cost-benefit
K_g J_θ
NPS MTF DQE NEQ
d'
SDNR Contrast-Detail Dose
ROC d', A_z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Farmer chamber + 16 cm cylinder
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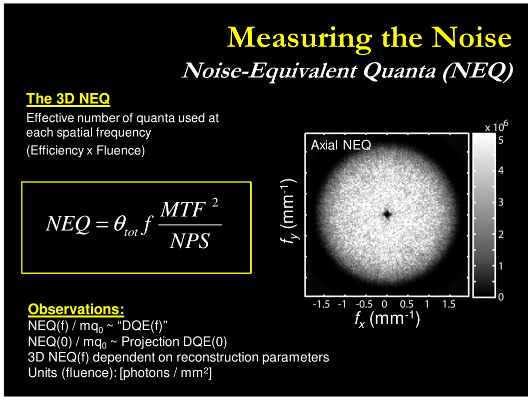
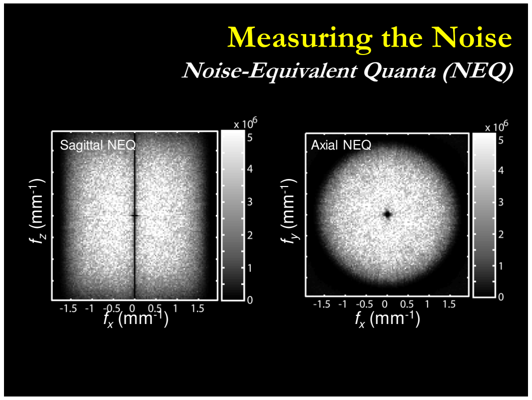
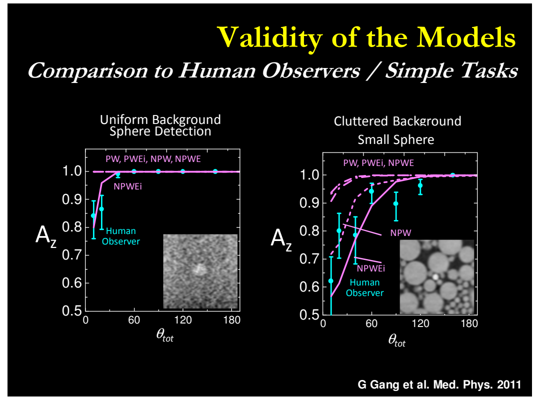
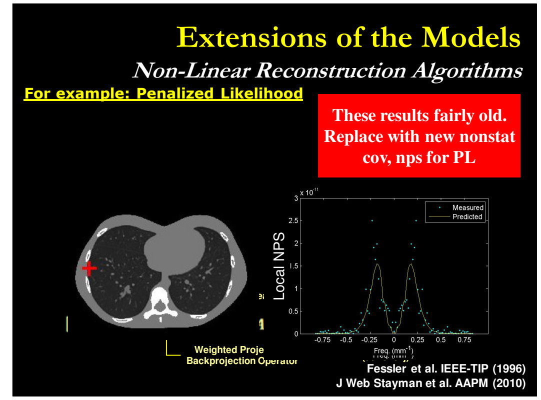
SDNR versus kVp, mAs
Spatial Resolution
Line-pair pattern (subjective)
Modulation transfer function
"Clinical" Image Quality
Anthropomorphic phantoms
Expert readers
Voxel Value (CS9300)
MDCT HU values
Sinus 1 y = 0.79x - 166
Ear 1 y = 0.69x - 163
J Xu et al. Med. Phys. (in press - August)


Measuring the Noise
Noise-Equivalent Quanta (NEQ)
The 3D NEQ
Effective number of quanta used at each spatial frequency
(Efficiency x Fluence)
$NEQ = \theta_{tot} f \frac{MTF^2}{NPS}$
Axial NEQ
f_y (mm^{-1})
f_x (mm^{-1})
x 10^6
Observations:
NEQ(f) / mq$_0$ ~ "DQE(f)"
NEQ(0) / mq$_0$ ~ Projection DQE(0)
3D NEQ(f) dependent on reconstruction parameters
Units (fluence): [photons / mm^2]


Measuring the Noise
Noise-Equivalent Quanta (NEQ)
Sagittal NEQ
Axial NEQ
x 10^6
f_z (mm^{-1})
f_y (mm^{-1})
f_x (mm^{-1})


Validity of the Models
Comparison to Human Observers / Simple Tasks
Uniform Background
Sphere Detection
Cluttered Background
Small Sphere
PW, PWEi, NPW, NPWE
PW, PWEi, NPWE
NPWEi
NPW
Human Observer
A_z
θ_{tot}
G Gang et al. Med. Phys. 2011


Extensions of the Models
Non-Linear Reconstruction Algorithms
For example: Penalized Likelihood
These results fairly old.
Replace with new nonstat
cov, nps for PL
Local NPS
Measured
Predicted
Weighted Proje
Backprojection Operator
Fessler et al. IEEE-TIP (1996)
J Web Stayman et al. AAPM (2010)