Assessment of Image Quality in The New CT

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Acknowledgments

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J Prince, J Lee (RadOnc)

Academic-Industry Partners
J Yorkston (Carestream Health)
R Graumann, G Kleinszig, T Mertelmeier (Siemens XP)

Disclosures and Support
Advisory Board, Carestream and Siemens
Elekta Oncology Systems
National Institutes of Health R01-CA-112163

presented at the 54th Annual Meeting of the AAPM (Charlotte NC)
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

Basic Technical Assessment

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Checking for Pulse…

Why don’t we use a 10 cm pencil ionization chamber to measure dose in cone-beam CT?

0% 1. The dose is too high.
0% 2. The dose is too low.
0% 3. The field is longer than the chamber.
0% 4. CBCTDI is a clumsy acronym.
0% 5. We do.
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AAPM Task Group 111
www.aapm.org/pubs/reports/ (Feb 2010)
Measuring the Noise

*Noise-Power Spectrum*

\[ NPS(f_x, f_y, f_z) = \frac{a_x}{L_x} \frac{a_y}{L_y} \frac{a_z}{L_z} \langle |DFT\{\Delta I(x, y, z)\}|^2 \rangle \]

\[ \sigma^2 = \iiint NPS(f_x, f_y, f_z) df_x df_y df_z \]

\[ \sigma \propto \sqrt{\frac{1}{D_0}} \frac{k_E}{\eta} \frac{1}{a_{xy}^3} \frac{K_{xy}}{a_z} \]

Barrett, Gordon, and Hershel (1976)
**Measuring the Noise**

**Noise-Power Spectrum**

**Axial Plane (x,y)**

\[ NPS(f_x, f_y, f_z) = \frac{a_x a_y a_z}{L_x L_y L_z} \langle |DFT(\Delta I(x,y,z))|^2 \rangle \]

**Sagittal Plane (x,z)**

\[ NPS(f_x, f_y, f_z) = \frac{a_x a_y a_z}{L_x L_y L_z} \langle |DFT(\Delta I(x,y,z))|^2 \rangle \]
Measuring the Noise

Noise-Power Spectrum

Axial domain \((f_x, f_y)\)
“Filtered-ramp”
Mid-Pass

Longitudinal domain \((f_z)\)
“Band-limited”
Low-Pass

Low-frequency NPS
\[ \text{NPS}(f_x, f_y) \propto f \]
\[ (\alpha \text{NPS} / df) \propto \text{NEQ}(0) \]
\[ \text{NPS}(0,0,0) \neq 0 \text{ (aliasing)} \]

Units

\([\text{signal}^2] [\text{Hz}^{\text{domain}}] \]
\[ [\mu]^2 [x] [y] [z] \rightarrow (\text{HU}^2)(\text{mm}^3) \]
\[ \rightarrow (/\text{mm}^2)(\text{mm}^3) \]

1. Hanson, Med Phys 1979
2. Kijewski and Judy, Phys Med Biol 1987

Sanity Check

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

0% 1. The magnitude is wrong.
0% 2. The units are wrong.
0% 3. Ignores correlation in the z direction.
0% 4. Would overestimate the NEQ.
0% 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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Modeling the Noise

2D PROJECTION DATA

- Incident Quanta $q_0(E)$
- Scintillator
- Detection
- Gain, Blur
- Flat-Panel Detector
- Conversion
- Aperture
- Electronics
- Sampling
- Noise

Cunningham et al. (1994)
Siewerdsen et al. (1997)
Zhao et al. (1997)
and others

$S_{proj}(f_x, f_z)$

presented at the 54th Annual Meeting of the AAPM (Charlotte NC)
Modeling the Noise

\[ d^2 = \iiint \frac{MTF^2(f) W_{\text{task}}(f)}{NPS_Q(f)} + S_B(f) \, df \]

Generalized NEQ
- Quantum Noise
- Background Noise
- Focal Spot, Scatter
A Dedicated Musculoskeletal Extremity Scanner

Detectability Index (d')

1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0

High-Frequency Task (Edge Detection)

Low-Frequency Task (Muscle-Fat)

Example

Pixel Size (mm)

Magnification

0.1
0.2
0.3
0.4

0.1
0.2
0.3
0.4

Zbijewski et al. Med Phys 2011
Prakash et al. Med Phys 2011

A Dedicated Musculoskeletal Extremity Scanner

0.194 mm pixels
0.388 mm pixels

1x1 Readout
2x2 Binning

8/6/2012

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Assumptions and Limitations

For Example: Stationarity

Axial $\mu(x,y)$

Noise (stdev) $\sigma_{\mu}(x,y)$

Angel Pineda et al.
Modeling Noise Stationarity

Example
CSA model for NPS
H$_2$O cylinder (16 cm)
No bowtie filter
Polyenergetic beam
90 kVp
1 mGy
360 views
360° orbit
FBP

Extensions of the Models

Non-Linear Reconstruction Algorithms

For example: Penalized Likelihood

Forward model:

For example: Penalized Likelihood

Forward model:

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

Discretized Object Volume

Number of photons

Log-Likelihood

Measurments

Objective Function

Projection Operator

Regularization Term

Log-likelihood estimator:

\[ \hat{\mu} = \text{argmax} \Phi(\mu; y) = \text{argmax} [\log L(\mu; y) - \beta R(\mu)] \]

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

\[ \text{Cov}[\hat{\mu}] \approx [F(\hat{\mu}) + R]^{-1} A^T \text{Cov}[y] A [F(\hat{\mu}) + R]^{-1} \]

J Web Stayman et al. AAPM (2010)
Example
Estimator model for NPS
H₂O ellipse (32x16 cm)
No bowtie filter
Mono-energetic beam
H₂O ~0.018 mm⁻¹
1 mGy
360 views
360° orbit
PL reconstruction
Quadratic penalty
I₀ = 5x10⁵
β = 5x10⁻⁷

Modeling Noise Stationarity

Example
Estimator model for NPS
H₂O ellipse (32x16 cm)
No bowtie filter
Mono-energetic beam
Extensions of the Models
2D, 3D, Dual-Energy, Phase Contrast, …

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Waiter, Check Please…

CT image noise is non-stationary:

0% 1. due to variation in $N_{\text{photons}}$ at the detector.
0% 2. due to a finite number of projections.
0% 3. due to the cone-beam effect.
0% 4. but we can still model the local NPS.
0% 5. All of the above.

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Extensions of the Models

- DE Radiography
- Tomosynthesis
- Cone-Beam CT
- DE CBCT
- Phase Contrast

Richard et al.
Ducote et al.
Zhao et al.
Glick et al.
Tward, Gang et al.
Fredenberg et al.
Tang et al, Chen et al.

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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