Low Dose CT: Where do we stand now?

Guang-Hong Chen PhD
Professor of Medical Physics and Radiology

Scientific foundation of radiation dose reduction;
- Low dose CT software method (1):
  Combination of denoising and the conventional filtered backprojection (FBP) reconstruction;
- Low dose CT software method (2):
  Combination of denoising and modeling of photon statistics in model based image reconstruction (MBIR);
- Challenges and opportunities in low dose CT software technologies
- Summary

Outline

Financial disclosure

Patent royalties received from GE Healthcare

Outline

Scientific foundation of radiation dose reduction;
- Low dose CT software method (1):
  Combination of denoising and the conventional filtered backprojection (FBP) reconstruction;
- Low dose CT software method (2):
  Combination of denoising and modeling of photon statistics in model based image reconstruction (MBIR);
- Challenges and opportunities in low dose CT software technologies
- Summary
Scientific foundation of radiation dose reduction;
- Low dose CT software method (1):
  Combination of denoising and the conventional filtered backprojection (FBP) reconstruction;
- Low dose CT software method (2):
  Combination of denoising and modeling of photon statistics in model based image reconstruction (MBIR);
- Challenges and opportunities in low dose CT software technologies
- Summary

**Scientific foundation of low dose CT**

ALARA\(^1,^2\) principle: reduce radiation dose as low as it is reasonably achievable such that **diagnostic performance is not compromised!**

\(^1\)ICRP, Publication 87 (2000)

**What is performance and how to quantify it?**

- **Signal quantification**
  Signal amplitude: CT Number and integration over a finite size area
  Signal blurring: Point Spread Function (PSF) and modulation transfer function (MTF)
- **Noise quantification**
  Noise amplitude: Noise variance
  Noise power: Noise Power Spectrum (NPS)
- **Overall performance quantification**
  Contrast-to-noise ratio (CNR)
  Task-based detectability index \((d')^2\)
Task-based detectability (ideal observer):
\[ (d')^2 = \int dk |T(k)MTF(k)|^2 \]

\[ \frac{NPS(k)}{|T(k)MTF(k)|^2} \]

Under the prewhitening condition, NPS is considered to be "white". This assumption helps reduce the detectability index to the more commonly used concept of CNR:
\[ \frac{S^2}{\sigma^2} = \text{CNR}^2 \]

Since signal level does not change too much with scanning parameters except the tube potential, one can cheat a bit by studying noise variance and spatial resolution separately to assess “image quality/performance”.

Cautions must be taken to avoid overly extrapolating conclusions.

Simplified cheat sheet to develop low dose CT techniques!
Spatial resolution is independent of dose and contrast.

- Noise variance ($\sigma^2$) or noise standard deviation ($\sigma$)
  
  \[ \sigma^2 = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2 \]

- Noise variance is inversely proportional to the slice thickness.

- Noise variance is inversely proportional to the cubic of $\Delta x$.
Noise amplitude: Patient size dependence (FBP)

\[ \sigma^2 = \frac{\alpha}{\text{Dose}} \exp(uL) \]

\[ \text{Dose} = \frac{\alpha}{\sigma^2} \exp(uL) \]


NPS: Scale invariance in NPS (FBP)

Dose scale invariance: The shape of the NPS is independent of radiation dose!

Performance: Radiation Dose Dependence (FBP)

\[ (d')^2 \propto \text{Dose} \]

\[ \text{CNR} \propto \sqrt{\text{Dose}} \]


CNR \( \propto \text{Dose} \)

\[ R^2 = 0.994 \]
Secret sauce in **NEW** low dose CT software technologies:

Develop software technologies to modify the functional dependence of either detectability or noise variance on the CT scanning parameters.

---

Is low dose CT software technology all about noise reduction?

Well, noise reduction plus preserving image edges for the sake of spatial resolution.

But is that all?

---

Low dose CT: **Reduction of Noise and Noise streaks**

Reference dose  
25% of Reference dose

Gomez-Cardona et al, SPIE (2017)
Outline

- Scientific foundation of radiation dose reduction;
- Low dose CT software method (1):
  Combination of denoising and the conventional filtered backprojection (FBP) reconstruction;
- Low dose CT software method (2):
  Combination of denoising and photon statistics modeling in model based image reconstruction (MBIR);
- Challenges and opportunities in low dose CT software technologies
- Summary

Low dose CT techniques: Hardware

- CT system hardware improvements
  - Quantum and geometrical detector efficiency
  - Modification of pre- and post-patient collimators
  - Development of patient-oriented beam shaping filters (e.g. bowtie filters)
  - Incorporation of angular and longitudinal tube current modulation
  - Optimization of tube potential control

Software advances need to be in synergy with hardware advances to achieve improved imaging performance at low dose levels

L. Yu, et. al., Radiographics (2011)
Y. J. Suh, et. al., Radiology (2013)

Low dose CT techniques: Software

- There is a wide spectrum of software approaches that aim to enable low dose CT, some of them are:
  - Analytical reconstruction methods + denoising
  - FBP + Image domain post-processing
  - Log-transform domain denoising + FBP
  - Raw data domain denoising + FBP
  - Model based Iterative reconstruction (MBIR) methods
  - Statistical model
  - Noise suppression regularizer model (denoising process)
Image domain denoising can be challenging when severe noise streaks are present and anatomical structures are already highly distorted.


Despite the success of some techniques, it is still challenging to mitigate noise streaks due to amplified variability after performing log-transform.


Working directly with the measured raw data facilitates correction of photon-starved measurements.

Gomez Cardona et al., SPIE (2017)
Some examples of methods reported in the literature:

- Adaptive trimmed mean filter
- Multi-dimensional adaptive filtering
- Spline-based penalized-likelihood sinogram
- Adaptive noise model-based bilateral filtering for streaking and noise reduction in multi-slice CT
- Multi-dimensional tensor-based adaptive filter
- Anisotropic diffusion has been shown to reduce noise while accurately localizing and preserving edge structural information

---

Two categories of filters: Trimmed mean filter

Exactly two parameters control this filter:
- Window width, W
- Trimming proportion, \( \alpha \)

---

Two types of filters: spatial filter (diffusion example)

Two features make diffusion as a denoising process possible:

- The polarity of the 2nd-order partial derivative is opposite that of the noise
- The modulation of this term is non-expansive
\[
\frac{\partial I}{\partial t} = \nabla \cdot (D(x,t) \nabla I) = D \cdot \nabla^2 I
\]

\[
I(x,t + \Delta t) \approx I(x,t) + \nabla \cdot (I \nabla I) + D \nabla^2 I
\]

Noisy raw counts \(I(x,t) = 0\)

\[W = [50, 550]\]

\[W = [0, 1700]\]

\[W = [-3, 3]\]

\[W = [-3, 3]\]

1. Perona and Malik, IEEE (1990)


### Remarks on diffusion denoising filter

- The dot product term generates the desired polarity for noise cancellation already, there is no need for the Laplacian term for denoising purpose! That is perhaps one of the reasons that this term was dropped in the numerical implementation in the original paper by Perona and Malik.¹

- Numerically, the computation of higher order derivatives involves the average over more neighboring pixels and thus smooth image edges more than the computation of only first order derivatives.

- More often used bi-lateral filters can be considered as a special case of the diffusion filter when the diffusion coefficient function, \(D(x,t)\), is selected to be a Gaussian-like function.²

¹ Perona and Malik, IEEE (1990)

² Barash, IEEE (2002)

### Outline

- Scientific foundation of radiation dose reduction;
- Low dose CT software method (1):
  - Combination of denoising and the conventional filtered backprojection (FBP) reconstruction;
- Low dose CT software method (2):
  - Combination of denoising and photon statistics modeling in model based image reconstruction (MBIR);
- Challenges and opportunities in low dose CT software technologies
- Summary
Given a single sample of stochastic measurement of x-ray photons, the best we know is the probability of the occurrence, that is given by the Poisson statistics model:

\[ P(I_i) = e^{-\frac{T_i}{I_i}} \]

Joint probability of a data set:

\[ P(I_i | \mu) = \prod_{i=1}^{\mu} e^{-\frac{T_i}{I_i}} \]

What is the probability of estimating the attenuation distribution of an image object given the measured data set in your hand?

Bayesian rule

\[ P(\{N\} | \mu) \rightarrow P(\mu | \{N\}) = \frac{P(\{N\} | \mu) P(\mu)}{P(\{N\})} \]

Image Reconstruction problem statement:

Seek for an estimation to maximize the probability!

Maximizing the Log-likelihood function:

\[ \hat{\mu} = \arg \max_{\mu} \left[ \ln P(\mu | x, E) \{N_i\} \right] \]

\[ = \arg \max_{\mu} \left[ \sum_{i=1}^{\mu} \left( -N_i + \ln N_i - \ln \mu + \ln P(\mu) \right) \right] \]

Under the following quadratic approximation:

\[ \hat{\mu} := \arg \min_{\mu} \left[ \frac{1}{2} (\tilde{y} - A\tilde{\mu})^T D(\tilde{y} - A\tilde{\mu}) + \lambda R(\tilde{\mu}) \right] \]

\[ D = \text{diag} \{N_1, N_2, \ldots, N_M\} \]
Data consistency driven image update:

\[ \tilde{V}_{k+1} = \tilde{\mu}_k + PA^T D(y - A\tilde{\mu}_k) \]

Denoising:

\[ \tilde{\mu}_{k+1} = \arg \min_{\mu} \left\{ \frac{1}{2} \| \mu - \tilde{v}_{k+1} \|_2^2 + \lambda R(\mu) \right\} \]

\[
S(x_j) = \arg \min_x \left( \frac{1}{2} \| x - x_j \|_2^2 + \lambda |x| \right)
S(x_j) = \begin{cases} 
    x_j - \lambda & x_j \geq \lambda \\
    0 & -\lambda < x_j < \lambda \\
    x_j + \lambda & x_j \leq -\lambda
\end{cases}
\]
Benefits of MBIR

Reduce streaks caused by low photon count (high noise) projection data and reduced noise level

FBP recon

MBIR

Benefit of MBIR: Clinical Case

This Abdomen/Perine CT scan covers ~40 cm in the z direction with a 0.7 mSv effective dose. The BMI of this patient is 19.4.

Future software technique: Deep learning?

RED-CNN

Scientific foundation of radiation dose reduction;
- Low dose CT software method (1): Combination of denoising and the conventional filtered backprojection (FBP) reconstruction;
- Low dose CT software method (2): Combination of denoising and photon statistics modeling in model based image reconstruction (MBIR);
- Challenges and opportunities in low dose CT software technologies
- Summary

Question: How would our cheat sheet change when a nonlinear model based iterative reconstruction or other nonlinear denoising technique is used?
Noise Amplitude of MBIR: Dose dependence

Noise variance is inversely proportional to radiation dose

\[ \sigma^2 \propto \frac{1}{\text{Dose}} \]

MBIR: \[ \sigma^2 \propto \frac{1}{\text{Dose}} \]

Noise Amplitude of MBIR: Dose dependence

\[ \sigma^2 \propto \frac{1}{\text{Dose}} \]

MBIR: \[ \sigma^2 \propto \frac{1}{\text{Dose}} \]

Noise Amplitude of MBIR: Slice thickness dependence

Noise variance is inversely proportional to slice thickness

\[ \sigma^2 \propto \frac{1}{\Delta z} \]

\[ \sigma^2 \propto \frac{1}{\Delta z} \]
Noise Amplitude of MBIR: Slice thickness dependence

\[ \sigma^2 \propto \frac{1}{\Delta z} \]

MBIR: \[ \sigma^2 \propto \frac{1}{\sqrt{\Delta z}} \]

NPS: From FBP to MBIR

The shape of the NPS independent on radiation dose

The shape of the NPS independent on radiation dose

Noise Performance of MBIR: Dose scale variance
**Noise Performance of MBIR: Dose scale variant**

**FBP:** $f_{\text{peak}} = \text{const.}$

**MBIR:** $f_{\text{peak}} \propto (\text{dose})^{0.5}$

---

**Spatial Resolution: Joint Dependence on Image Contrast and Radiation Dose**

---

**Another challenge in low dose CT: CT number bias**

- Catphan® 600 phantom
- Acquisition parameters:
  - 50 repeated scans
  - Axial acquisition
  - Detector coverage: 20 mm x 0.625 mm
  - Head bowtie
  - Three kV levels: 80, 100, 120
  - 10 reduced mAs levels: 4-104
  - Ground truth mAs: 1400
- Reconstruction parameters
  - FBP and MBIR reconstruction methods
  - Slice thickness: 0.625 mm
  - DFOV: 22 cm

---
Scientific foundation of radiation dose reduction;
- Low dose CT software method (1):
  Combination of denoising and the conventional filtered backprojection (FBP) reconstruction;
- Low dose CT software method (2):
  Combination of denoising and photon statistics modeling in model based image reconstruction (MBIR);
- Challenges and opportunities in low dose CT software technologies

Summary

Low dose CT Software Technologies: Summary
- Low dose CT can be achieved by combining denoising techniques in the raw detector counts domain to reduce noise while suppressing photon starvation noise streaks;
- Low dose CT can also be iteratively achieved by incorporating noise streak suppression in the reconstruction process followed by a denoising filtration process;
- The conventional functional dependence of imaging performance on scanning parameters demonstrates non-linear behavior in image quality assessment;
- Low dose CT also increases CT number bias.

Acknowledgement

Special thanks to Dr. Ke Li, John Garrett, Yinsheng Li, Daniel Gomez-Cardona, and Juan Pablo Cruz-Bastida for help in preparing the slides.

Email Contact: gchen7@wisc.edu
“Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful.”


Where do we stand from when?

Report from the Summit on Management of Radiation Dose in CT

“This report offers a strategic roadmap for the CT user and research and manufacturer communities toward routinely achieving effective doses of less than 1 mSv, which is well below the average annual dose from naturally occurring sources of radiation.”


Where do we stand: NIBIB Low Dose U01 projects

1. UNIVERSITY OF MINNESOTA CRITICAL RESOURCES TO EVALUATE CT SCAN TECHNIQUES AND DOSE REDUCTION APPROACHES
   McCulloch, Cynthia H. Mayo Clinic Rochester
2. University of Virginia SPARSE ORDER-OF-MAGNITUDE DOSE REDUCTION WITH INTERRUPTED-BEAM ACQUISITION
   Otazo, Ricardo et al. New York University School of Medicine
3. University of Wisconsin ACCELERATED STATISTICAL IMAGE RECONSTRUCTION METHODS FOR X-RAY CT
   Fessler, Jeffrey A. University of Wisconsin
4. University of Wisconsin TASK-DRIVER DYNAMIC BEAM MODULATION FOR HIGH-PERFORMANCE LOW-DOSE CT
   Stamm, Joseph Webster Johns Hopkins University
5. University of Wisconsin HIGH DOSE EFFICIENCY CT SYSTEM
   Pelc, Norbert J. et al. Stanford University 2017
6. University of Wisconsin SOFTWARE TOOL FOR ROUTINE, RAPID, PATIENT-SPECIFIC CT ORGAN DOSE ESTIMATION
   Schmidt, Tayl Glat et al. Marquette University
<table>
<thead>
<tr>
<th>Project ID</th>
<th>Project Title</th>
<th>Principal Investigators</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>R01CA169331</td>
<td>ULTRA-LOW RADIATION DOSE BODY CT IMAGING</td>
<td>CHEN, GUANG-HONG et al.</td>
<td>UNIVERSITY OF WISCONSIN-MADISON</td>
</tr>
<tr>
<td>R01CA181156</td>
<td>QUANTITATIVE CT IMAGING FOR RESPONSE ASSESSMENT WHEN USING DOSE REDUCTION METHOD</td>
<td>MCMITT-GRAY, MICHAEL F et al.</td>
<td>UNIVERSITY OF CALIFORNIA-LOS ANGELES</td>
</tr>
<tr>
<td>R01HL109327</td>
<td>LOW DOSE MYOCARDIAL PERFUSION IMAGING BY CT</td>
<td>ALESSIO, ADAM M</td>
<td>UNIVERSITY OF WASHINGTON</td>
</tr>
<tr>
<td>R01EB016966</td>
<td>PHOTON-COUNTING SPECTRAL CT TO REDUCE DOSE AND DETECT EARLY VASCULAR DISEASE</td>
<td>MCCOLLOUGH, CYNTHIA M et al.</td>
<td>MAYO CLINIC ROCHESTER</td>
</tr>
<tr>
<td>R01CA160253-05</td>
<td>ENABLING ULTRA LOW DOSE PET/CT IMAGING</td>
<td>KINAHAN, PAUL E</td>
<td>UNIVERSITY OF WASHINGTON</td>
</tr>
<tr>
<td>R01CA154747</td>
<td>LOW DOSE CONE BEAM CT FOR IMAGE GUIDED ADAPTIVE RADIOThERAPY</td>
<td>JIANG, STEVE BIN</td>
<td>UT SOUTHEASTERN MEDICAL CENTER</td>
</tr>
<tr>
<td>R01CA219608</td>
<td>PRIOR IMAGE-BASED CT RECONSTRUCTION FOR LOW-DOSE LUNG CANCER SCREENING</td>
<td>STAYMAN, JOSEPH WEBSTER</td>
<td>JOHNS HOPKINS UNIVERSITY</td>
</tr>
<tr>
<td>R01CA199044</td>
<td>HIGH-RESOLUTION LOWER DOSE DEDICATED BREAST CT</td>
<td>VEDANTHAM, SRINIVASAN et al.</td>
<td>UNIVERSITY OF ARIZONA</td>
</tr>
</tbody>
</table>