Quantitative Image Quality Assessment of Model-Based Iterative Reconstruction (MBIR): Challenges and Potential Solutions

Ke Li

Assistant Professor
Department of Medical Physics and Department of Radiology
School of Medicine and Public Health, University of Wisconsin-Madison

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  - Daniel Gomez-Cardona
  - Juan Pablo Cruz-Bastida
  - Yongshuai Ge
  - Adam Budde
  - Dr. Timothy Szczykutowicz

Outline

- Quantitative image quality assessment of conventional linear CT systems
- Challenges in the quantitative image quality assessment of MBIR-based nonlinear CT systems
- Potential solutions

Quantitative Image Quality Assessment

- Measures the degradation/distortion of the acquired image (relative to an ideal image) using a quantitative figure-of-merit
- Advantages over *qualitative* image quality assessment:
  - Reduces subjectivity associated with qualitative assessments
  - Enables more meaningful comparison of CT systems across institutions and vendors
  - Usually has higher efficiency and lower cost

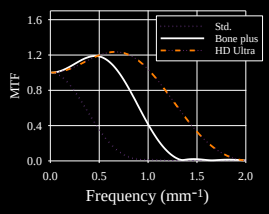
Quantitative Image Quality Metrics for CT

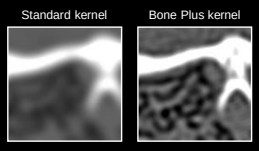
- Frequency-independent metrics
  - Noise magnitude
  - CT number uniformity
  - Contrast
  - Contrast-to-noise ratio (CNR)
  - CNR normalized by dose (CNRD)
- Frequency-dependent metrics
  - Noise power spectrum (NPS)
  - Modulation transfer function (MTF)
  - Task-based detectability index

Quantitative Image Quality Assessment for CT

- Quantitative CT image quality assessment does not include:
  - Visual determination of linear pair resolution (not quantitative)
  - X-ray beam collimation accuracy (not an assessment of image quality)
  - Measurement of dose-length product (assessment of CT dosimetry instead of image quality)

Quantitative Image Quality Assessment: Example Application I





Hi-Res mode with HD Ultra kernel

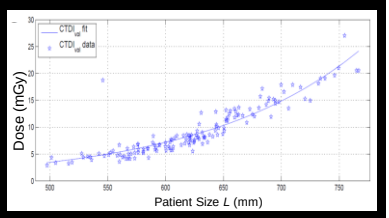
(in vivo results)

J. P. Cruz-Bastida et al. *Med. Phys.* 43, 2399 (2016)

Quantitative Image Quality Assessment: Example Application II

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

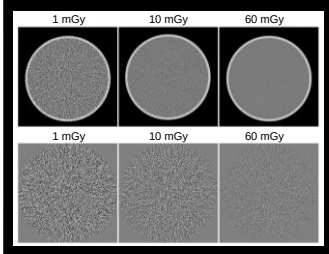
$$\text{Dose} = \frac{\alpha}{\sigma^2}\exp(uL)$$



Courtesy of Dr. Szczykutowicz

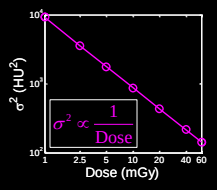
Szczykutowicz, T. P., Bour, R. K., Pozniak, M., & Ranallo, F. N. Journal of Applied Clinical Medical Physics, 16, 2 (2015)

Quantitative Image Quality Metrics: Noise Variance



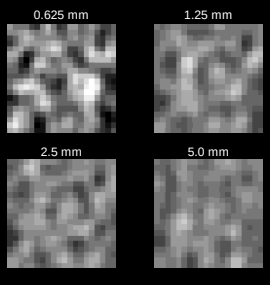
- Noise variance (σ^2) or noise standard deviation (σ)

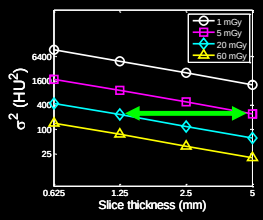
$$\sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})$$



K. Li, J. Tang, G.-H. Chen, *Med. Phys.* **41**, 041906 (2014)

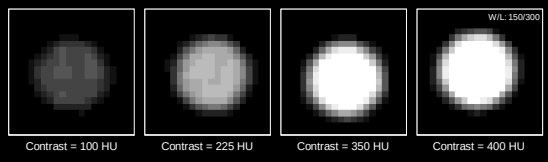
Noise Variance: Slice Thickness Dependence





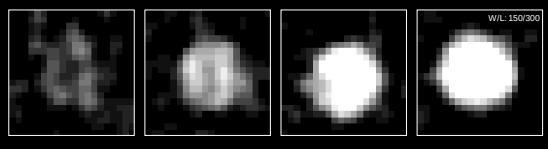
Quantitative Image Quality Metrics: Contrast

- Contrast $C = \bar{x}_{\text{feature}} - \bar{x}_{\text{background}}$

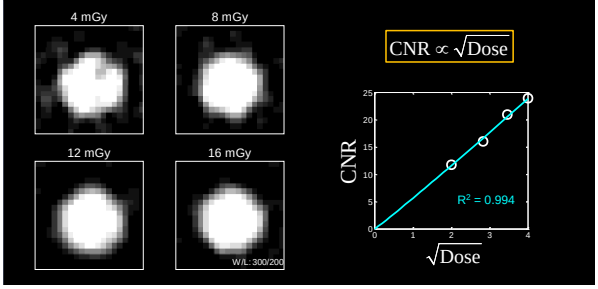


Quantitative Image Quality Metrics: Contrast-to-Noise Ratio

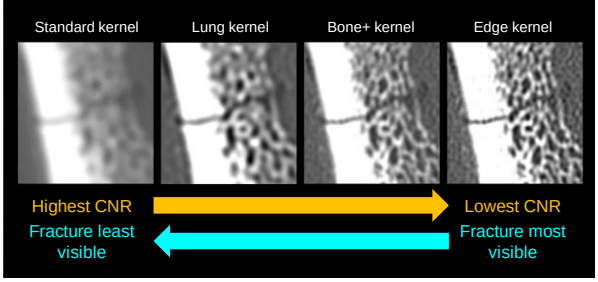
- Contrast-to-noise ratio (CNR) $\text{CNR} = \frac{C}{\sigma}$



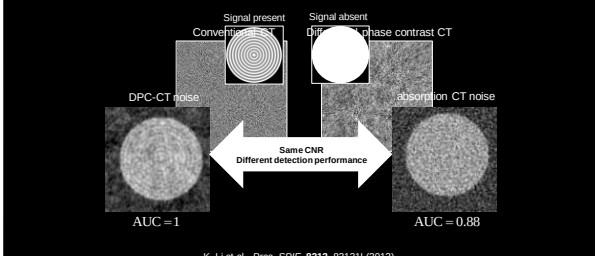
CNR: Radiation Dose Dependence



Limitations of Frequency-Independent Metrics



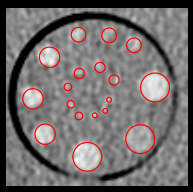
Limitations of Frequency-Independent Metrics



K. Li et al., *Proc. SPIE*, **8313**, 83131L(2012)

Limitations of Frequency-Independent Metrics

- Same CNR, different object detectability

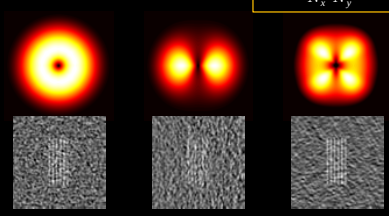


Contrast = 30 HU
W/L: 50/16
CTDIvol = 16 mGy

Quantitative Image Quality Assessment for Conventional CT: Frequency-Dependent Metrics

- Noise power spectrum (NPS)

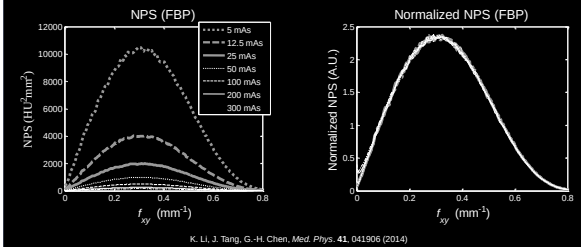
$$\mathrm{NPS} = \frac{\Delta x}{N_x}\frac{\Delta y}{N_y}\left|\mathrm{DFT}(\mathrm{ROI}-\overline{\mathrm{ROI}})\right|^2$$



D. Gomez-Cardona et al., *Med. Phys.* **43**, 4495 (2016)

Important Assumption behind NPS Assessment

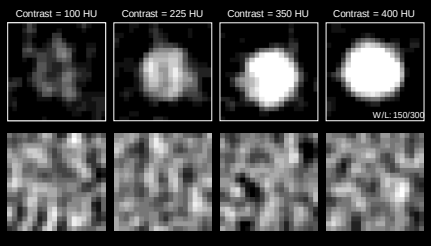
The shape of the NPS is independent on radiation dose



K. Li, J. Tang, G.-H. Chen, *Med. Phys.* **41**, 041906 (2014)

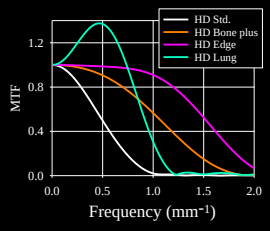
Important Assumption behind NPS Assessment

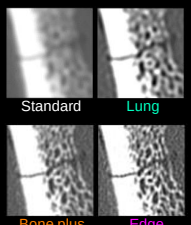
NPS magnitude is independent on contrast level



Quantitative Image Quality Assessment for Conventional CT: Frequency-Dependent Metrics

- Point spread function (PSF) or modulation transfer function (MTF)





J. P. Cruz-Bastida et al. *Med. Phys.* 43, 2399 (2016)

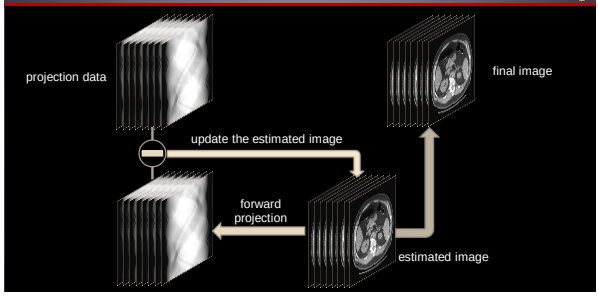
Important Assumption behind Spatial Resolution Assessment

Spatial resolution is independent on dose and contrast

Question: Are these assumptions still valid in MBIR?

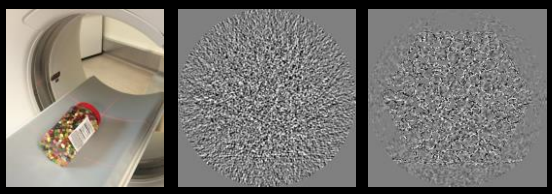
Li, Garrett, Ge, Chen, *Med. Phys.* 41, 071911 (2014)

Model-Based Iterative Reconstruction (MBIR)



Quantitative Assessment of Noise Performance of MBIR: Challenge A

~~Noise magnitude is independent on contrast level~~

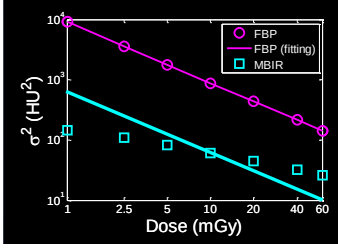


MBIR noise-only image

Li et al., *RSNA 2014 Annual Meeting*
Solomon and Samei, *Proc SPIE* **8668**, 86684M (2013)
Solomon and Samei, Med. Phys. **41**, 091908 (2014)

Quantitative Assessment of Noise Performance of MBIR: Challenge B

~~Noise variance is inversely proportional to radiation dose~~

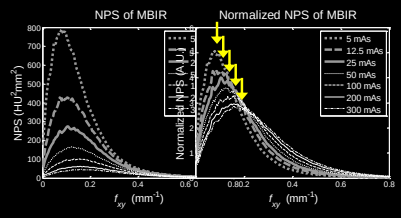


FBP: $\sigma^2 \propto \frac{1}{\text{Dose}}$

MBIR: σ^2 ? Dose

Quantitative Assessment of Noise Performance of MBIR: Challenge C

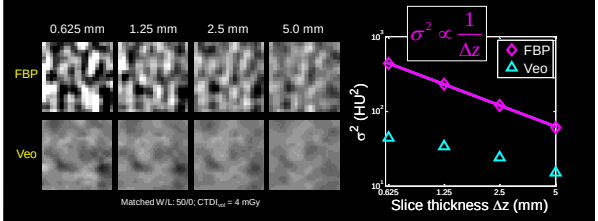
The shape of the NPS independent on radiation dose



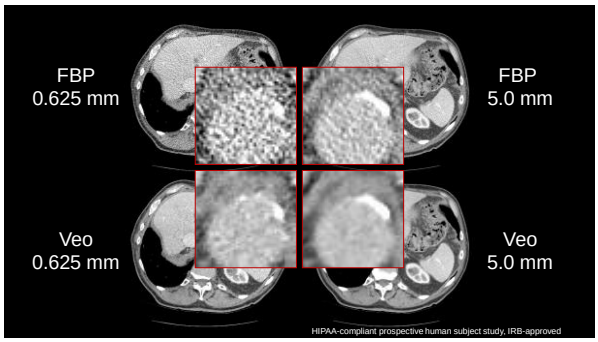
K. Li, J. Tang, G.-H. Chen, *Med. Phys.* **41**, 041906 (2014)

Quantitative Assessment of Noise Performance of MBIR: Challenge D

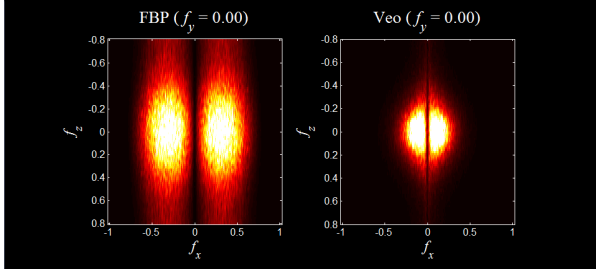
Noise variance is inversely proportional to slice thickness



K. Li, J. Tang, G.-H. Chen, *Med. Phys.* **41**, 041906 (2014)



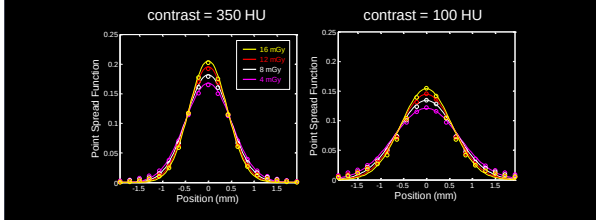
Comparison of 3D NPS between FBP and MBIR



K. Li, J. Tang, G.-H. Chen, *Med. Phys.* **41**, 041906 (2014)

Quantitative Assessment of Spatial Resolution Performance of MBIR: Challenges

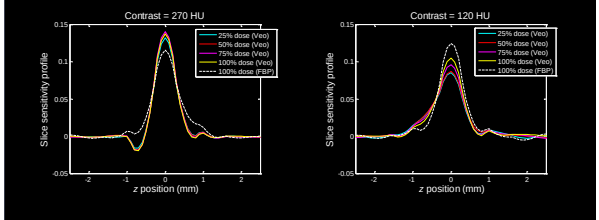
~~Spatial resolution is independent on dose and contrast~~



Li, Garrett, Ge, Chen, *Med. Phys.* **41**, 071911 (2014)

Quantitative Assessment of Spatial Resolution Performance of MBIR: Challenges

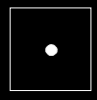
~~The Z resolution is independent on dose and contrast~~



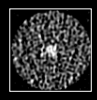
Li, Garrett, Ge, Chen, *Med. Phys.* **41**, 071911 (2014)

Summary of Technical Challenges

- Noise assessments
  - Contrast dependence
  - Modified dose dependence
    - Magnitude
    - NPS shape
  - Modified slice thickness dependence
    - Magnitude
    - NPS shape
- Spatial resolution assessments
  - Contrast dependence
  - Dose dependence
  - Spatial resolution assessments at low-contrast and low dose conditions are extremely challenging

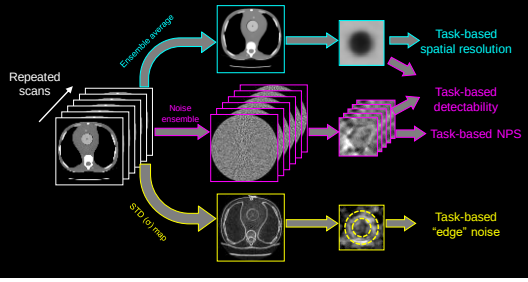


High contrast, high dose

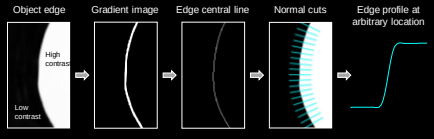


Low contrast, low dose

Potential Solutions: Repeated Acquisitions and Task-Based Image Quality Assessments

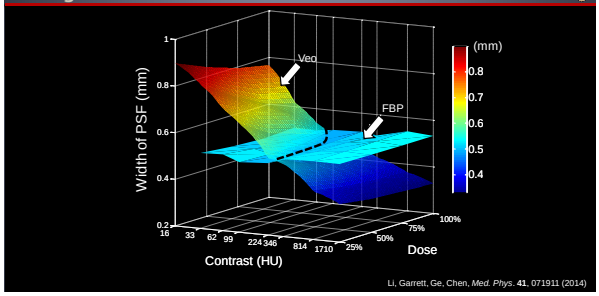


A Paradigm Shift in Spatial Resolution Assessment



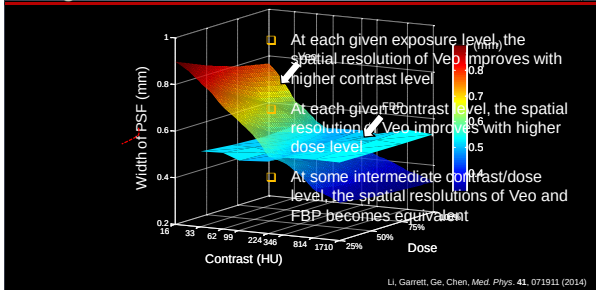
- Richard *et al.*, "Towards task-based assessment of CT performance: System and objective MTF across different reconstruction algorithm." *Med. Phys.* **39**, 4115 (2012)
- Li *et al.*, "Statistical Model Based Iterative Reconstruction (MBIR) in clinical CT systems: Part II. Experimental assessment of spatial resolution performance." *Med. Phys.* **41**, 071911(2014)
- Yu *et al.*, "Technical Note: Measuring contrast-and noise-dependent spatial resolution of an iterative reconstruction method in CT using ensemble averaging." Med. Phys. **42**, 2261 (2015)

Spatial Resolution of MBIR: Joint Dependence on Image Contrast and Radiation Dose



Li, Garrett, Ge, Chen, *Med. Phys.* **41**, 071911 (2014)

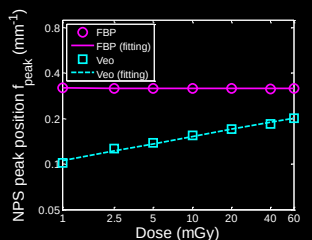
Spatial Resolution of MBIR: Joint Dependence on Image Contrast and Radiation Dose



- At each given exposure level, the spatial resolution of Veo improves with higher contrast level
- At each given contrast level, the spatial resolution of Veo improves with higher dose level
- At some intermediate contrast/dose level, the spatial resolutions of Veo and FBP becomes equivalent

Li, Garrett, Ge, Chen, *Med. Phys.* **41**, 071911 (2014)

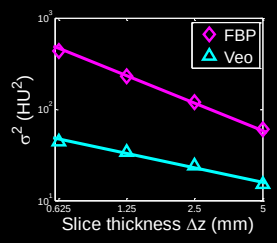
Dependence of NPS Shape on Radiation Dose



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

MBIR: $f_{peak} \propto (\text{dose})^{\frac{1}{5}}$

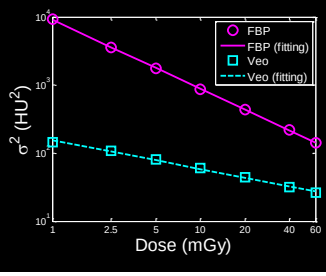
Dependence of NPS Magnitude on Slice Thickness



FBP: $\sigma^2 \propto \frac{1}{\Delta z}$

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

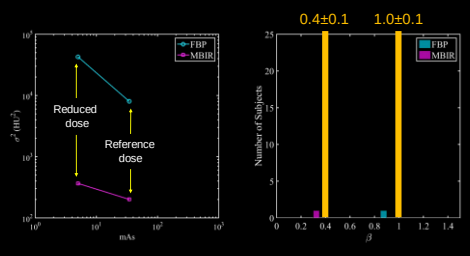
Dependence of NPS Magnitude on Radiation Dose



FBP: $\sigma^2 \propto \frac{1}{\text{Dose}}$

MBIR: $\sigma^2 \propto \frac{1}{\text{Dose}^{0.4}}$

In Vivo Validation in 110 Human Subject Cases

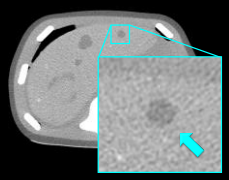


HIPAA-compliant and IRB-approved

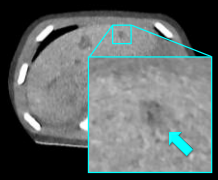
D. Gomez-Cardona et al., 2015 AAPM Annual Meeting

Consequences of Using Noise Variance Alone to Determine Dose Reduction Factor for MBIR

Noise = 15 HU
(FBP, 65 mGy)



Noise = 15 HU
(MBIR, 0.6 mGy)

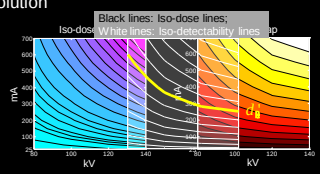


Example Application of Task-Based Model Observer Detectability Index (d') in MBIR

- Problem formulation

$$\arg\min_{kV,mA} \text{Dose}(kV,mA) \quad \text{s.t.} \quad d'(kV,mA) = d'_s$$

- Practical solution



Li et al., *Med. Phys.* **42**, 5209 (2015)

Prospective Human Subject Study

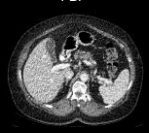
Routine dose scan

120kV 650 mA
19.4 mGy
FBP

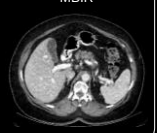
Reduced dose scan

80 kV 275 mA
2.4 mGy

FBP



MBIR



HIPAA-compliant and IRB-approved

Li et al., *Med. Phys.* **42**, 5209 (2015)

Take Home Messages

- Major challenges in quantitative image quality assessment of MBIR
  - Violation of several basic assumptions and relationships in CT image quality assessment
  - Nonlinearity of the reconstruction method determines that there is no theoretical basis in deriving the modified relationships
    - For example, how does the shape of the NPS quantitatively vary with radiation dose

Take Home Messages

- Potential solutions in address these challenges
  - Empirical relationships between image quality and CT system parameters have been found
  - Try to use frequency-dependent metrics (e.g NPS) rather than zero-frequency metrics (e.g. CNR)
  - Be task-specific rather than task-generic
  - Perform repeated acquisitions rather than shifting an ROI
  - Use model observer detectability to combine noise and spatial resolution metrics with task function

Thank You

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