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Advanced Statistical Iterative Reconstruction Method on Toshiba CT System

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Outline

- History of **S**tatistical **I**terative **R**econstruction (SIR)
- Key components of SIR
- Potential benefits and challenges of SIR
- Toshiba's SIR: FIRST
- Challenges & methods in evaluating SIR image quality
- Phantom and clinical image comparison of FIRST vs. FBP
- Quiz

Scientific field: "Statistical Iterative Reconstruction" = **Marketing world** "Model-based Iterative Reconstruction"

Disclaimer: FIRST is currently pending FDA 510(k) clearance. Availability of this software is regionally dependent. Please check with your local Toshiba representative to determine availability.

History of statistical iterative reconstruction

- Statistical recon has been routinely used in PET & SPECT
  - *Shepp LA, Vardi Y. Maximum likelihood reconstruction for emission tomography. IEEE Trans Med Imag. 1982*
- First statistical recon for mono-energy transmission tomography
  - *Lange K, Carson R. EM reconstruction algorithms for emission and transmission tomography. J Comput Assist Tomogr 1984*
- First statistical recon for x-ray CT with Bayesian estimation
  - *Sauer K, Bouman C. A local update strategy for iterative reconstruction from projections. IEEE Trans Sig Proc 1993*

- Why SIR from emission tomography is not directly transferable to CT?
  - X-ray source has wide energy spectrum instead of mono-energy
  - CT is energy integration detector instead of photon counting
  - CT has high photon flux/data sampling, FBP gives "satisfactory" result
  - CT requires complex data calibration and pre-processing
  - CT requires almost real time reconstruction speed

Key components of statistical iterative recon

- Objective function

$$\mathbf{f}^* = \underset{\mathbf{f}}{\operatorname{argmax}}\, Pr(\mathbf{f}|\mathbf{g}) = \underset{\mathbf{f}}{\operatorname{argmax}}\, [\log Pr(\mathbf{g}|\mathbf{f}) + \log Pr(\mathbf{f})].$$

Posterior probability Log-likelihood Log-prior

  - Log-likelihood/data consistency term
    - Data domain: pre-log vs post-log for CT
    - Data statistical modeling: Gaussian, Poisson, Compound Poisson for CT

    One example: post-log data domain, Gaussian distribution (Weighted-Least-Square)

  - Log-prior/regularizer term (optional)
    - Regularize the ill-posed data consistency term
    - Constrain neighborhood pixels
    - Vast forms: convex versus non-convex MRF, variational function, sparsity prior, nonlocal-mean patch, etc

    One example: smooth TV, enhance smoothness => small pixel value difference
    preserve edge => Large pixel value difference

Potential benefits of statistical iterative recon

- Be able to model geometry & physics effects into system matrix
  - Flexible to accommodate any scanner geometry
  - Can model blur due to focal spot size, detector element & shift-variant anode angle
  - Can model physical factors, such as beam-hardening & scatter
- Be able to design special statistical weight to suppress noise or artifacts
- Be able to design special regularizer to achieve uniform local impulse response function, at least in uniform regions
- Be able to adjust the global strength of the regularizer to achieve desired global image noise appearance

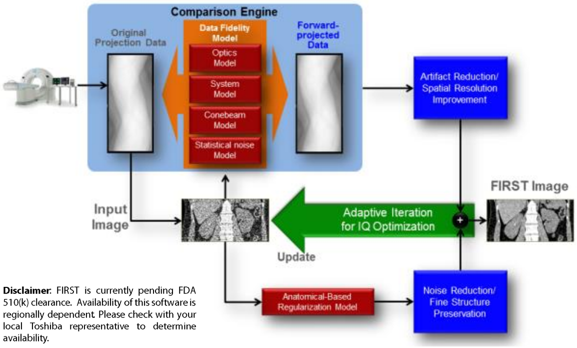
Potential challenges of statistical iterative recon

- Objective function (especially w/ regularizer) is quite complex and thus needs optimization algorithm to get to the global maximum solution.
  - PCG, ICD (Sauer & Bouman), SPS for non-quadratic prior (U. Michigan), ASD-POCS (U. Chicago), Chambolle-Pock (U. Chicago), ADMM (U. Michigan), FISTA (Beck and Teboulle), etc.

- Due to the complexity of CT system matrix modeling, algorithm takes longer iterations to converge. To get to the right solution quickly, need
  - Algorithm acceleration
  - GPU/CPU acceleration

Toshiba's statistical iterative recon:

FIRST ›rward-projected Model-based **I**terative **R**econstruction **S**olu**T**ion



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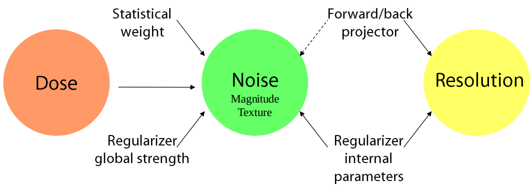
Factors affecting statistical recon image quality



Challenges & methods in evaluating SIR (1)

- **Image noise** is controlled by
  - Dose
  - Statistical weight design
  - Regularizer design and its internal parameter(s)
  - Regularizer global strength
- Image noise may also vary with pixel's
  - Spatial location
  - Contrast level
- Image noise may even affect noise texture
  - NPS
  - Modified Q-matrix (ref: Zhang M. et. Al., Blocky artifacts assessment in PET images, MIC 2015)

Challenges & methods in evaluating SIR (2)

- Image noise definitions
  - σ^2 in a VOI (e.g., N pixels) in one noisy sample

$$\sigma^2 = \frac{1}{N}\sum_{(x,y,z)}\left(I(x,y,z)-\bar{I}\right)^2$$

  - $\sigma^2(x, y, z)$ in noisy ensembles (e.g., M samples)

$$\sigma^2(x,y,z) = \frac{1}{M}\sum_{m=1}^{M}\left(I_m(x,y,z)-\bar{I}(x,y,z)\right)^2$$

  - Noise power spectrum (NPS)

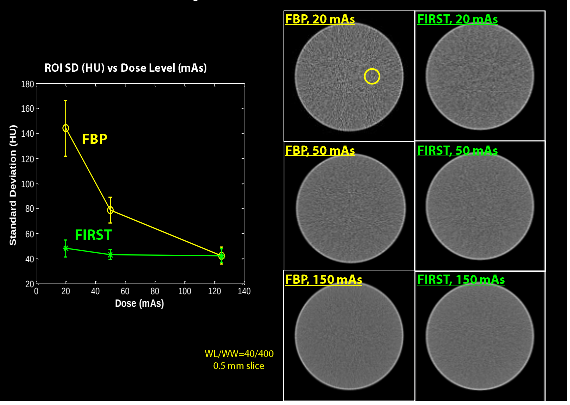
$$NPS(f_x, f_y, f_z) = \frac{\Delta x \Delta y \Delta z}{N_x N_y N_z}\frac{1}{M}\sum_{m=1}^{M}\left(DFT_{3D}\left[I_m(x,y,z)-\bar{I}(x,y,z)\right]\right)^2$$

- Reference:
  - *Li K, Tang J, Chen GH, Statistical model based iterative reconstruction (MBIR) in clinical CT systems: experimental assessment of noise performance, Medical Physics, 2014*

Challenges & methods in evaluating SIR (3)

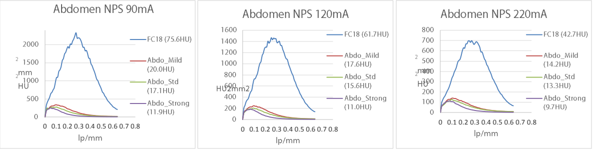
- **Image resolution** is controlled by
  - Data sampling
  - Forward/back projector
  - Regularizer design and its internal parameter(s)
- Image resolution may depend on contrast level, pixel location & photon counts
  - Contrast level: use Catphan or ACR phantom's disk inserts to evaluate ESF -> MTF in different materials
  - Pixel location: use large size phantom, or shift phantom so that disk insert has different distance to scanner's ISO center
  - Photon counts: different mAs
- Reference:
  - *Li K, Garrett J, Ge YS, Chen GH, Statistical model based iterative reconstruction (MBIR) in clinical CT systems, Part II. Experimental assessment of spatial resolution performance, Medical Physics, 2014*

FIRST's noise depends less on dose



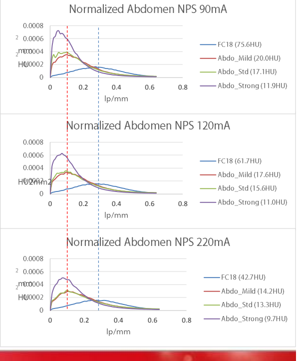
FIRST has lower NPS than FBP

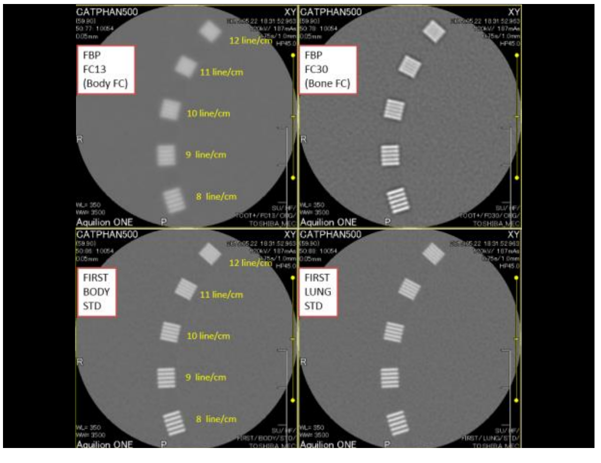
- FIRST's NPS is lower than FBP at all dose levels
- At the same dose, when regularizer strength increases, FIRST's NPS gets lower and its peak frequency shifts towards the low-frequency.



FIRST NPS's peak-freq vs dose

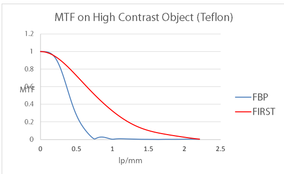
- FBP's NPS curve shape (peak-freq) remains the same for all dose levels
- FIRST's curve shape (peak-freq) has negligible shift with reducing dose if its regularizer strength is the same.



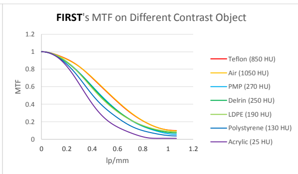


Advantage of FIRST: improved MTF

- FBP's MTF does not depend on dose or contrast
- FIRST's MTF depends more on contrast less on dose

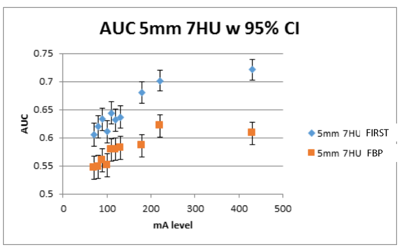


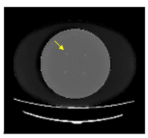
50 mm FOV



240 mm FOV

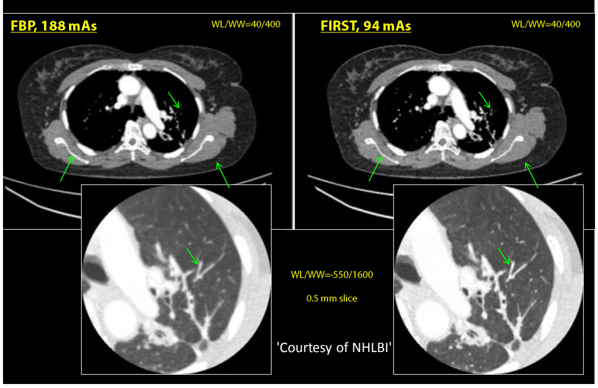
Advantage of FIRST: LCD w/ model observer



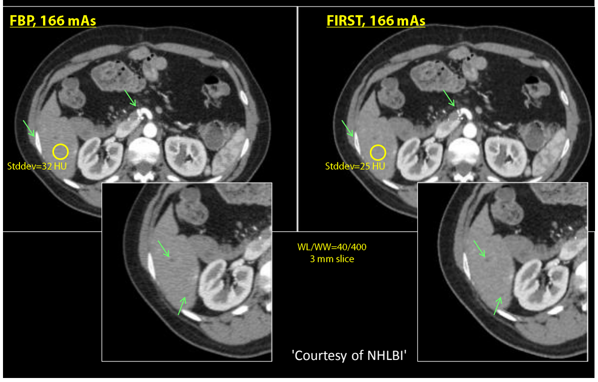


SKE/BKE
NPWE observer
2AFC experiment

FIRST: lung with dose reduction



FIRST: abdomen with better resolution & noise



Summary and conclusion

- FIRST is a fully statistical reconstruction algorithm, with system matrix modeling cone-beam geometry and x-ray optics, edge-preserving regularizer reducing noise but preserving fine anatomical structure.
- FIRST can reduce dose but preserve image quality as FBP at normal dose.
- At the same dose, FIRST has higher image resolution/contrast and lower noise than FBP.

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Quiz (1)

- The key difference between statistical reconstruction and analytical reconstruction is
  A. Statistical recon is iterative
  B. Statistical recon assumes data follows a certain statistical model
  C. Statistical recon reduces dose
  D. All of above

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Correct Answer: B

Quiz (2)

- In statistical reconstruction, which factor does not impact image resolution:
  A. Data sampling
  B. Statistical weight
  C. Forward & back projector
  D. Regularizer

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Quiz (3)

- In statistical reconstruction, which factor(s) impact image noise:
  A. Statistical weight
  B. Forward & back projector
  C. Regularizer
  D. A and B
  E. A and C
  F. B and C

Quiz (3)

- In statistical reconstruction, which factor(s) impact image noise:
  A. Statistical weight
  B. Forward & back projector
  C. Regularizer
  D. A and B
  E. A and C
  F. B and C

Correct Answer: E

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