MAYO CLINIC

Principles, strengths, and weaknesses of Three classes of noise reduction techniques for Low Dose Computed Tomography

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Outline

- Purpose
- Considerations for CT dose reduction
- Datasets
- Image-space based noise reduction
- Projection-space based noise reduction (PS-NR)
- Iterative Reconstruction methods
- + Examples
- Conclusion

Purpose

- To describe, compare and illustrate the differences in the three main approaches for noise reduction in low dose computed tomography.

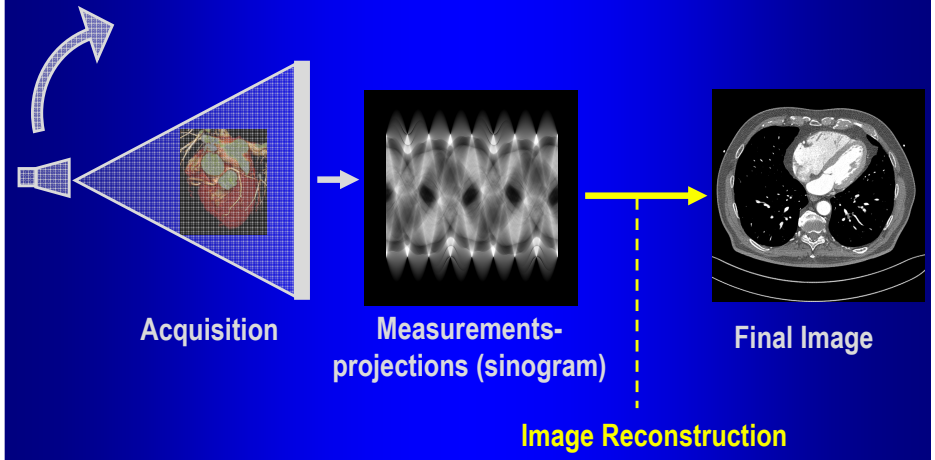
The importance of low dose CT

- Despite the fact that CT provides invaluable image information for diagnosis and treatment, there is also a potential risk of radiation-induced malignancy.
- Consequently, we should seek to comply with the ALARA principle (As Low As Reasonable Achievable).
- Special cases of concerns are pediatrics and young patients requiring serial imaging.

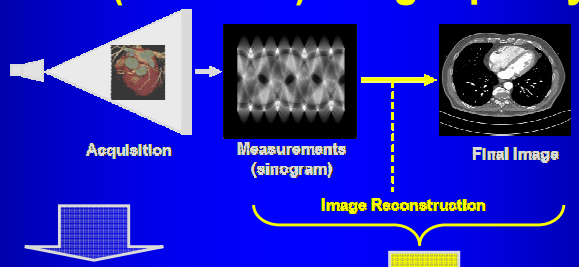
Why can't we just dial down the dose?

- Lower doses lead to:
  - Higher image noise
  - Increased likelihood of artifacts
  - Lower SNR and CNR
  - Reduced spatial resolution and low contrast detectability
- To reduce radiation dose in CT, it is critical to examine the entire acquisition and image reconstruction process.

Data acquisition and image reconstruction in CT



How can we reduce dose and keep same (or better) image quality?



•Better hardware: source(s), detectors, collimators, bowtie filter, etc.

•Automatic Exposure Control (tube current modulation)

•'Optimal' kV selection.

NOISE REDUCTION ALGORITHMS

•Image space noise reduction.

•Projection space noise reduction.

•Iterative reconstruction methods.

Dataset

- A clinical case at routine dose
- Slice thickness 3 mm
- Acquired using automatic exposure control
- Validated noise insertion to simulate 50% dose (taking into account Poisson-like noise + bowtie filter effect + tube current modulation).

Methods

- Image-space Denoising
  - Commercial Reconstruction Kernel that minimize noise (Siemens B26 and B46 ASA)
  - 3D-Bilateral filter (Non-linear adaptive filter).
  - Total Variation L2 norm method.
- Projection-space Denoising
  - Denoises individual CT projections, which are then re-imported back onto scanner for routine reconstruction
  - Bilateral filter, include noise model, tube current modulation and bowtie filter effect
  - Ref: 'Manduca et al. Med Physics, 2009 (In Press)'
- Iterative-reconstruction
  - Reconstruct images by optimizing a particular objective function, usually including a penalty term to achieve a better noise resolution performance.

Filtered Backprojection (FBP)

B45 kernel (medium) | B30 kernel (medium-smooth) | B10 kernel (very smooth)

Lower Noise

Higher spatial resolution

Filtered Backprojection (FBP)

- Advantages
  - Clinically used
  - 'Fast'
  - Simple and efficient
- Disadvantages
  - Inherent 'noise vs spatial resolution (image sharpness)' tradeoff
  - Image only 'exact' if data is perfect
  - Does not model the physics of the CT acquisition process (beam hardening, scattering, etc)

Image-space based noise reduction

Sinogram | CT image | Output: filtered CT image

- Requires an image dataset.
- Applies non-linear, edge-preserving spatial filtering.
- Various approaches possible.

Image-space based noise reduction

Some noise reduction possible w/o excessive blurring, keeping tissue texture.

Standard Kernels | Kernels with Image-space Denoising (ASA)

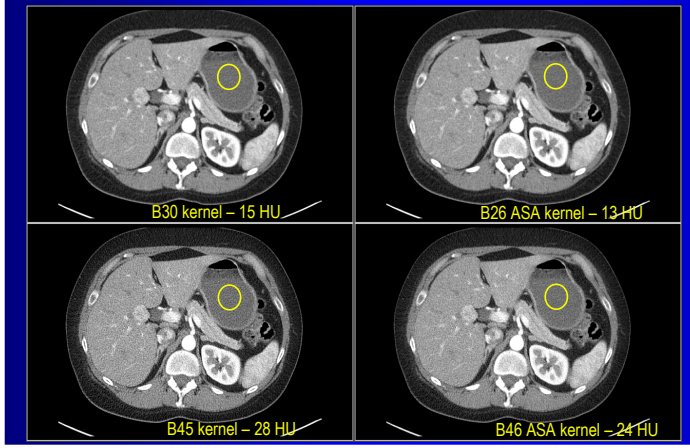


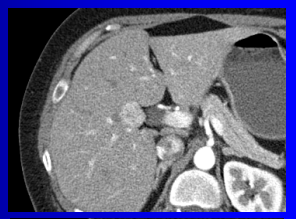
Image-space denoising may permit a noise reduction for the same sharpness (top right) or an increase in sharpness at the same noise level (bottom right).

MAYO CLINIC 1.Purpose| 2.Considerations| 3.Datasets |4.Image-space |5.Projection-space |6. IR|7.Conclusion

Image-space based noise reduction

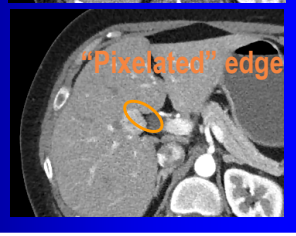
Excessive filtration lead to 'cartoon' like images, potentially leading to loss of diagnostic information.

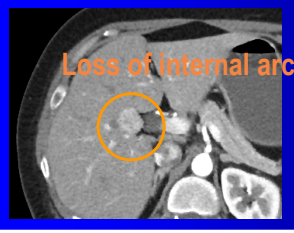
original



Filtered 1*

Filtered 2*





Filtered 3*

* 3D Bilateral Filtering

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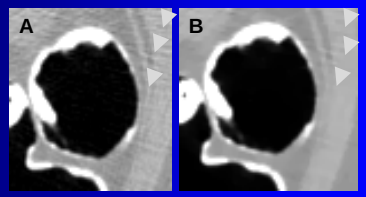
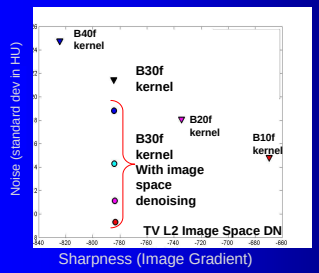
Image-space based noise reduction





Transverse CT colonography images before (A) and after (B) **image space denoising**. Note the marked reduction in the noise throughout the image after denoising (B), and with respect to the linear beam hardening artifacts, in particular (B, arrows).(C) Standard deviation of noise in air ROI vs. largest gradient in profile for different reconstruction kernels (triangles) and different levels of image space denoising followed by standard B30f reconstruction (circles). **Similar to projection space denoising, image space denoising can reduce noise with much less effect on resolution**.

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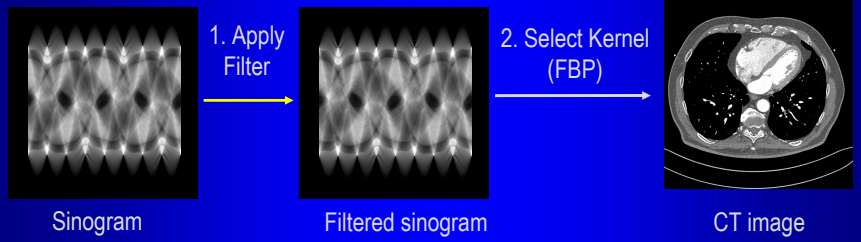
Image-space based noise reduction

- Advantages
  - Low computational cost
  - Simple to implement (only require image data)
  - Dose reduction possible, especially for high contrast diagnostic tasks
- Disadvantages
  - It is hard to incorporate a statistical model in image domain
  - No correction for artifacts
  - Excessive denoising may change CT image appearance, degrading diagnostic quality

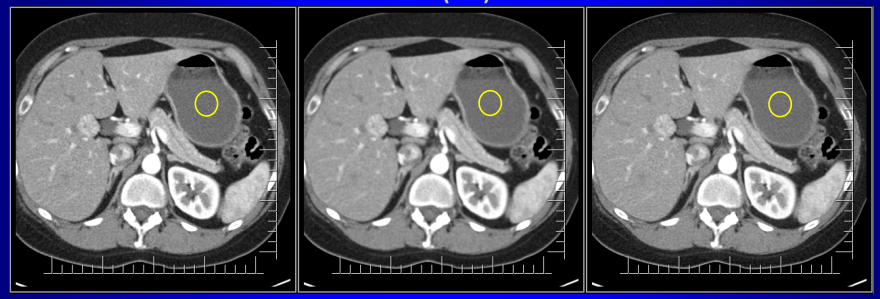
Projection-space based noise reduction



- Requires access to raw projection data (sinogram).
- Various approaches possible.

Projection-space based noise reduction

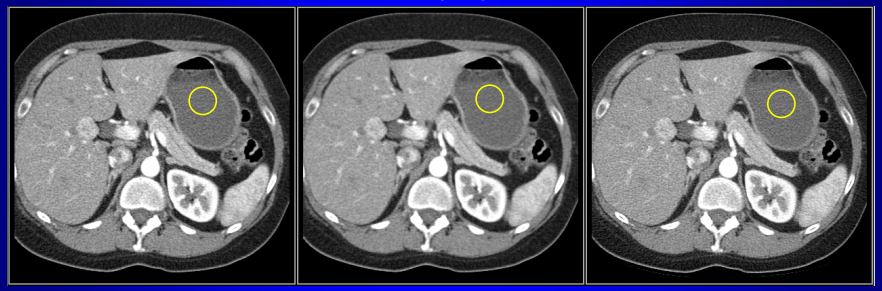
Full dose (FD) dataset



	FD	FD + Excessive PS-NR	FD + PS-NR (optimized)
Noise @ ROI	13 HU	8 HU	11 HU

Projection-space based noise reduction

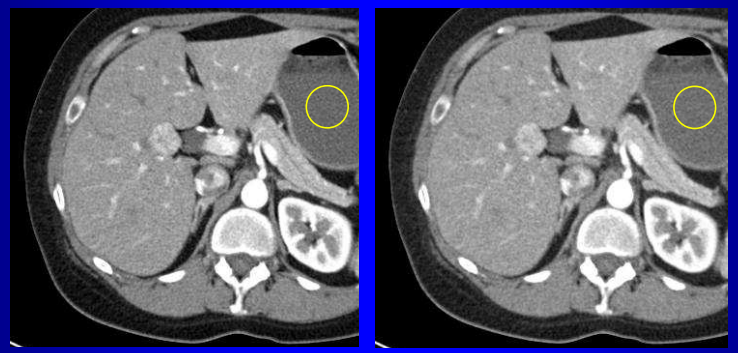
Half dose (HD) dataset



	HD	HD + PS-NR (same kernel)	HD + PS denoising (sharper kernel)
Noise @ ROI	18 HU	12 HU	19 HU

Projection-space based noise reduction

Potential for Dose Reduction



	Full Dose	Half Dose + PS-NR
Noise @ ROI	13 HU	12 HU

Projection-space based noise reduction

Potential for Dose Reduction

Full Dose | Half Dose | Half Dose + PS-NR

Intrinsic organ-specific properties such as intrinsic contrast differences, noise and heterogeneity affect the potential for noise (and dose) reduction.

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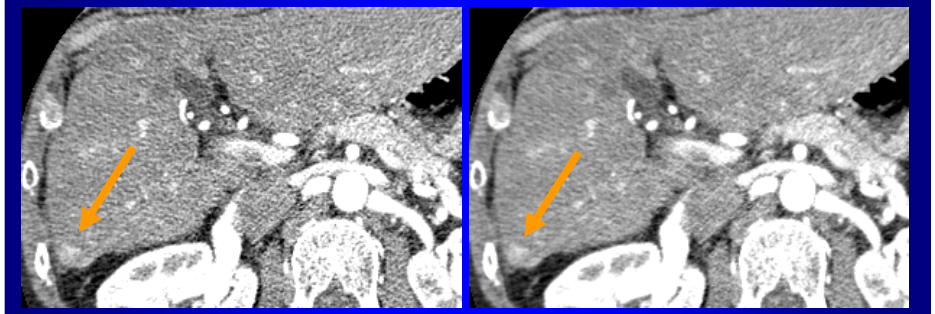
Projection-space based noise reduction

Potential for Dose Reduction



A denoising example from a dual-energy biphase liver exam. The above image is the output of the 80 kV tube in the arterial phase, demonstrating a hypervascular liver lesion (arrow). The left image was reconstructed using the commercial kernel B40f. Note the dramatic noise reduction in the liver and pancreatic parenchyma, without loss of anatomic detail (e.g., when looking at the vessels or liver lesion).

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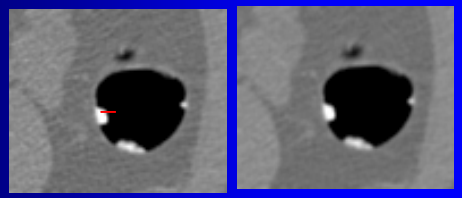
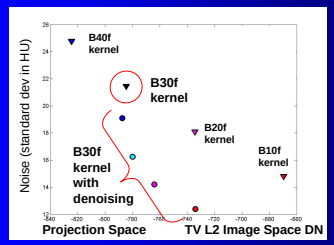
Projection-space based noise reduction





(A) Image of the colon containing labeled stool with standard B30f reconstruction kernel and line profile across stool-air interface. (B) Image with projection space denoising. (C) Standard deviation of noise in air ROI vs. largest gradient in profile in 7A for different reconstruction kernels (triangles) and different levels of projection space denoising followed by standard B30f reconstruction (circles). **While different kernels alone trade off resolution vs. noise level, projection space denoising can reduce noise with much less effect on resolution**.

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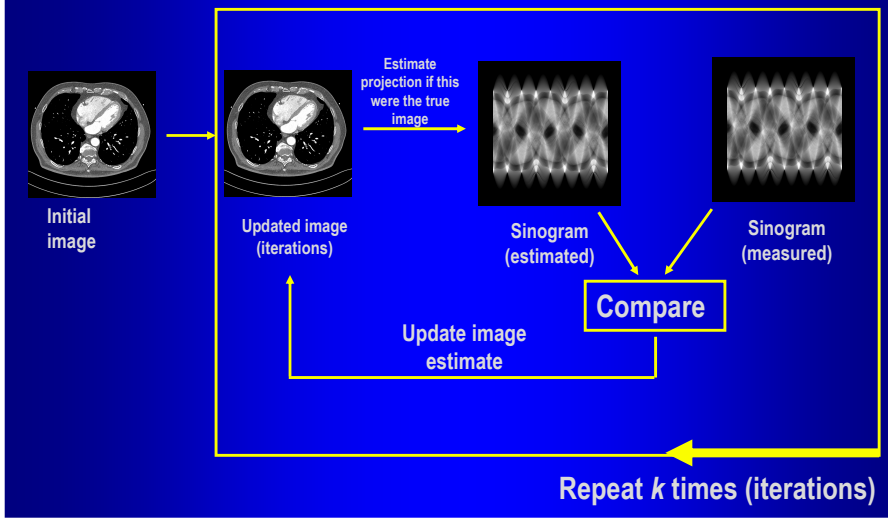
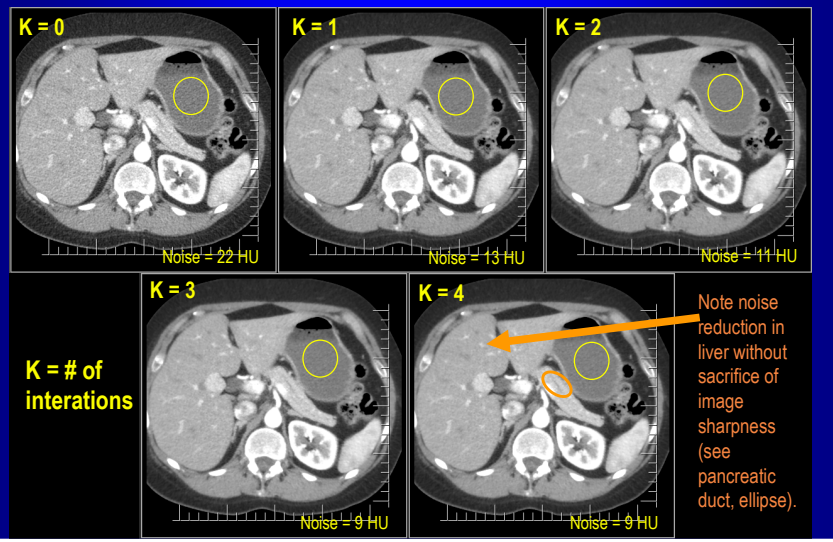
Projection-space based noise reduction

- Advantages
  - Can incorporate a statistical model that characterizes the CT system, including bowtie filter, x-ray source, detectors, etc.
  - Realistic CT noise appearance
  - A better noise-resolution tradeoff
  - Low to moderate computational cost (depends on approach)
- Disadvantages
  - Slight smoothing (i.e., increase in blur), which can be partially compensated for by using a sharper kernel.
  - If excessive, degrades diagnostic quality

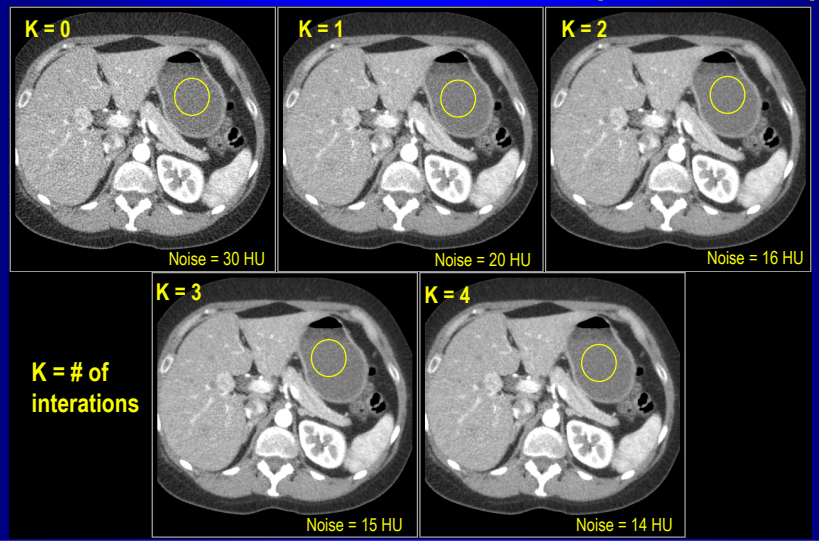
Iterative Reconstruction



Iterative Reconstruction (full dose)

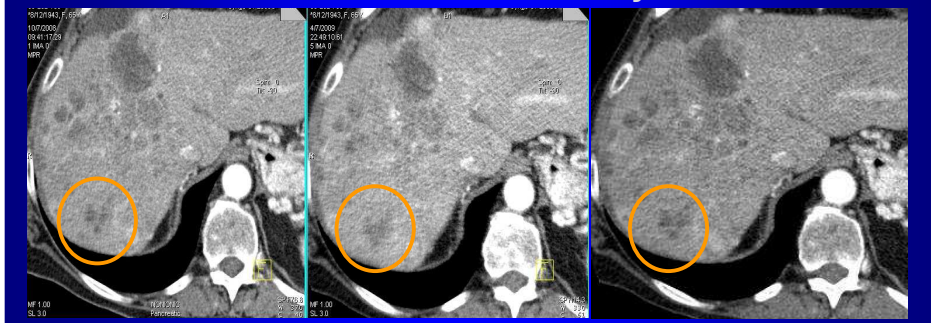


Iterative Reconstruction (half dose)



Iterative Reconstruction

Low Contrast Visibility



Full dose

Full dose with Unoptimized IR
Note loss of boundary defining circled metastases

Full dose Optimized IR (different kernel)
Note reappearance of boundary defining circled metastases

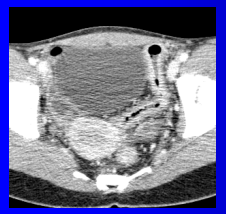
Iterative Reconstruction

- Advantages
  - Can incorporate a statistical model that characterizes the CT system, including x-ray source, detectors, etc.
  - Has the potential to improve spatial resolution and reduce noise.
  - Artifact reduction
- Disadvantages
  - Very high computational cost
  - If excessive, degrades diagnostic quality, and can result in a "pixelated" look or loss of low contrast objects

Potential Synergy of Noise-reduction Methods

From half-dose CT Enterography exam

IR alone (k=3)
- Good noise reduction
- Note artifact reduction from decreasing beam hardening
- Pixelated appearance at boundary of colon and peri-enteric fat



PS-NR alone
- Good but less noise reduction
- "Realistic" noise and anatomic boundaries
- Computationally faster (over 100 times)

IR (k=1) + PS-NR
- Computationally faster than multiple iterations
- Better noise reduction that PS-NR
- "Realistic: noise and anatomic boundaries

See RSNA # SSG07-03

Conclusion

- Noise reduction techniques can significantly contribute to save radiation dose and/or improve diagnostic quality.
- To exploit the full potential of noise reduction methods, careful clinical evaluation is needed to guarantee adequate parameter selection. Poor selection of parameters might lead to excessive blurriness, pixelated appearance, and loose of diagnostic quality.