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Iterative Reconstruction in CT – the Siemens Approach

Answers for life.

Standard CT Reconstruction: Filtered Backprojection (FBP)

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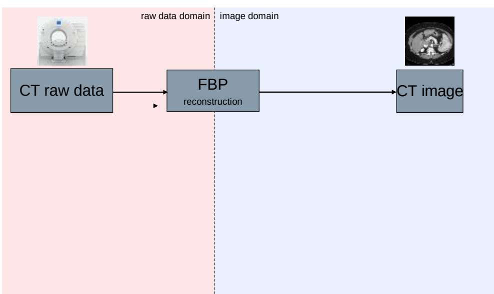

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Limitations of Filtered Backprojection (FBP)

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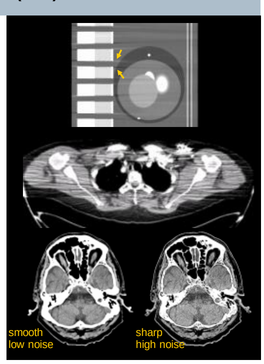
- FBP is only an <u>approximate</u> realization of the inverse Radon transformation
  → „geometric artifacts“
  (cone beam artifacts)
- FBP uses raw data with equal weight irrespectively of their statistical quality
  → streak artifacts
- Tradeoff between spatial resolution and noise (linear algorithm)



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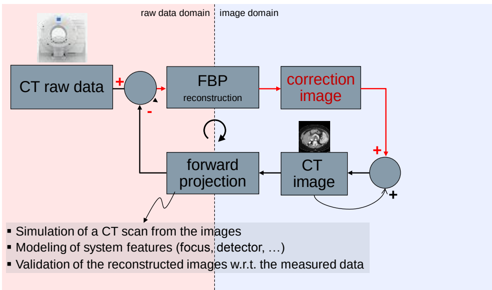
Iterative Reconstruction
Basic Idea: Introduction of a Correction Loop



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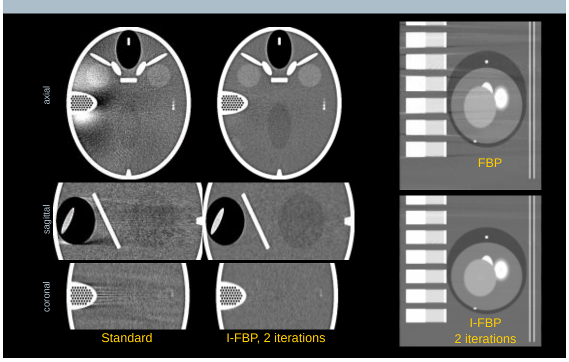
Artifact Reduction by IR



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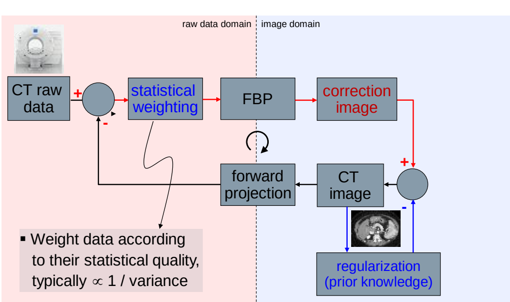
Iterative Reconstruction with Statistical Optimization:
Statistical Weighting and Regularization



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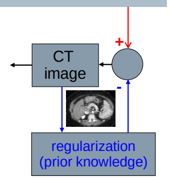
Regularization / Prior Knowledge

Regularization

- Local smoothness constraint – this is where prior knowledge is introduced
- Ensures convergence of the iterative reconstruction
- Is **the** essential mechanism for noise and dose reduction!
- Has to be non-linear to get rid of the tradeoff between resolution and noise



How it works

- Estimate/model the (local) image standard deviation
- Separate information and noise on the basis of statistical significance → intelligent high-pass filter based on local contrast-to-noise
- Subtract the detected noise

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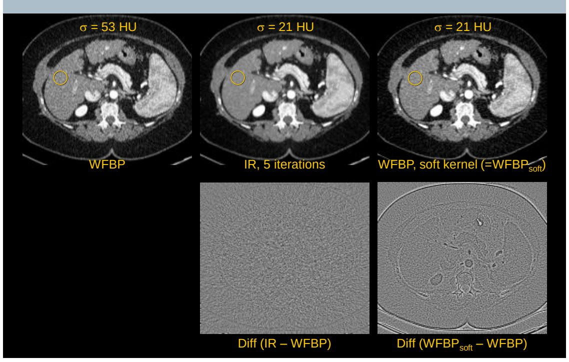
Advantages of Non-Linear Regularization versus Linear Filtering



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General Approach

For the different objectives of iterative reconstruction, choose the domain most efficient to accomplish them:

Need low signal data enhancement?
→ work in the raw data domain; apply statistical modeling

Need (cone beam) artifact reduction?
→ need a full raw data/image loop including a forward projection of images

Need noise reduction?
→ best apply iterative regularization in image domain

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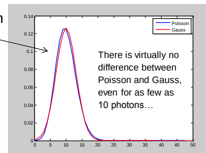
Iteration Scheme

Maximum Likelihood: best image, data, image

$$\bar{f} = \arg\max_f P(p_{meas} \mid f)$$

"The best image is the most likely image based on the data"

Additional assumption: Data are nearly Gaussian



→ Problem reduces to a minimization problem (Penalized weighted least squares):

best image, data weight, proj. operator, regularizer

$$\bar{f} = \arg\min_f \left(\frac{1}{2} \left\| W \cdot (p_{\text{meas}} - Pf) \right\|^2 + \gamma R(f) \right)$$

Iterative solution e.g. by steepest descent:

reconstruction (backprojection)

$$f_n = f_{n-1} + \alpha \cdot \left[QW\left(p_{\text{meas}} - Pf_{n-1}\right) - \gamma \nabla R(f_{n-1}) \right]$$

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Iteration Scheme

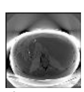
Now we have:

$$f_n = f_{n-1} + \alpha \cdot \left[QW\left(p_{\text{meas}} - Pf_{n-1}\right) - \gamma \nabla R f_{n-1} \right]$$

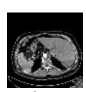
correction image regularization

Define …

1. … the operator $X_W = QWP$
   - Performs forward projection, then weighting, followed by reconstruction, i.e. takes an image and returns an image
   - X_W depends on the raw data via W, but can be pre-calculated
2. … a „weighted" image $f_W = QWp_{\text{meas}}$



$f_W = QWp_{\text{meas}}$



Qp_{meas}

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Iteration Scheme

$$f_n = f_{n-1} + \alpha \cdot \left[QW\left(p_{\text{meas}} - Pf_{n-1}\right) - \nabla R f_{n-1} \right]$$

correction image regularization

$$X_W = QWP$$
$$f_W = QWp_{\text{meas}}$$

⇕

$$f_n = \alpha \cdot f_W + \left[1 - \alpha\left(X_W + \nabla R \right) \right] f_{n-1}$$

- No access to measured raw data necessary in the loop!

→ **Iterative image manipulation can be equivalent to a noise weighted raw data loop**

General Approach

Is **system modeling** essential for **noise reduction**?
→ No – noise reduction is achieved exclusively through the regularization term

Does **system modeling** improve the **resolution**?
→ No – for a stable reconstruction, the resolution is still limited by the focus size, the detector aperture and the data sampling

Is a **raw data loop** essential for noise reduction?
→ No – cf. previous slides

(For a similar – and mathematically rigorous – approach, see also:
G. L. Zeng, *Noise-weighted spatial domain FBP algorithm*, Med. Phys. 41, 051906 (2014))

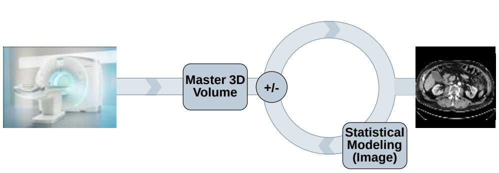
General Approach

Relevant questions for choosing an IR algorithm are:

- How can the IR approach be implemented **efficiently** with clinically valuable results and acceptable computational performance?
- How can a **natural noise texture** be realized? (Radiologists reject “plastic-like” de-noised images)
- What is the benefit with routine reconstruction parameters (e.g. thick slices)?
- How can we **predict/assess** the achievable **dose reduction** in a meaningful way?

Siemens Generations of IR:
IRIS – Iterative Reconstruction in Image Space

- No reduction of geometric (cone beam) artifacts
- Limited potential for anisotropic noise distribution (e.g. shoulder)



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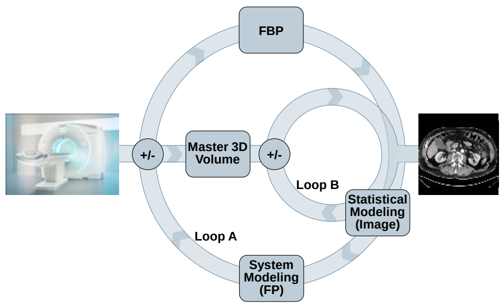
Siemens Generations of IR:
SAFIRE – Sinogram Affirmed Iterative Reconstruction



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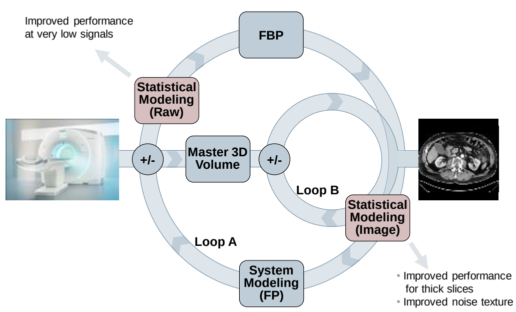
Siemens Generations of IR:
ADMIRE – Advanced Modeling Iterative Reconstruction



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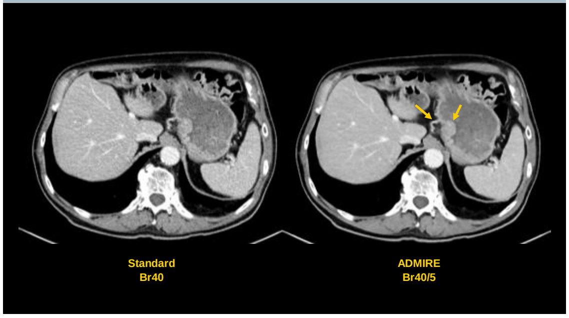
ADMIRE – Advanced Modeling Iterative Reconstruction



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ADMIRE – Advanced Modeling Iterative Reconstruction

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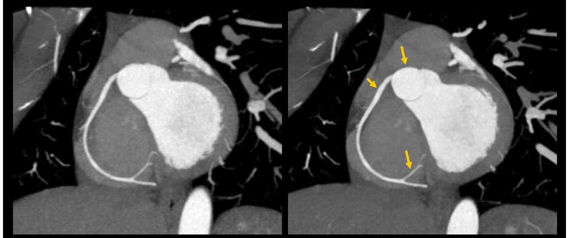

Standard
Bv40

ADMIRE
Bv40/5

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ADMIRE – Advanced Modeling Iterative Reconstruction

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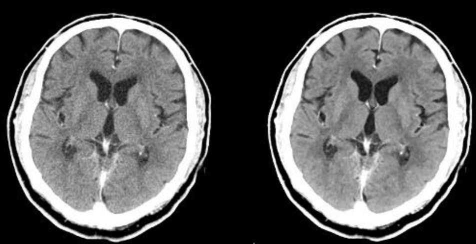

Standard
Hc44

ADMIRE
Hc44/5

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ADMIRE – Advanced Modeling Iterative Reconstruction

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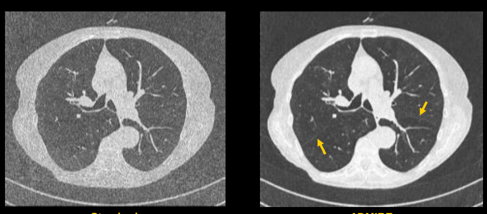
Low Dose
CTDIvol 0.23 mGy / DLP 8.3 mGy·cm / eff. Dose 0.12 mSv



Standard
BI64

ADMIRE
BI64/5

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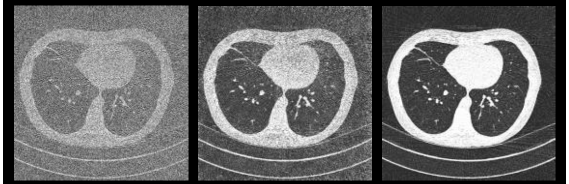
ADMIRE – Advanced Modeling Iterative Reconstruction

Extremely Low Dose
$CTDI_{vol}$: 0.04 mGy / DLP 1.64 mGy·cm / eff. Dose 0.025 mSv



Standard Bl64	SAFIRE Bl64/5	ADMIRE Bl64/5

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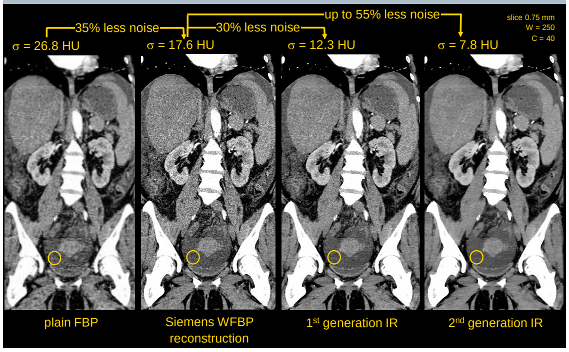
What Should Be Compared?



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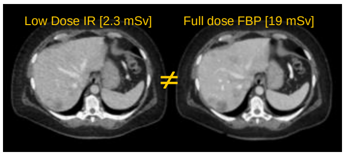
Iterative Reconstruction
Evaluation with Model or Human Observers

How low can you go?

- IR leads to a **noise level** comparable with higher radiation dose, even at about 90% dose reduction
- But: diagnostic equivalence not necessarily given - some details may be lost.
- Technical metrics (noise, contrast, …) are not sufficient (cf. previous talk)
- More sophisticated objective tests are required



Iterative Reconstruction
Evaluation with Model Observers

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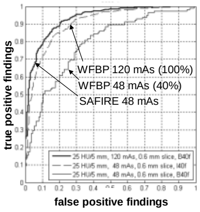
- Definition of a meaningful task
- Usage of a „Channelized Hotelling Observer“
  → mimics visual perception

Task: lesion present or not?

- ROC analysis



What is a relevant imaging task?

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- Currently, all claims of dose reduction are based on studies with **low contrast detection** tasks („Is there a lesion or not?“), possibly with localization („Where is the lesion?“).
- But: *Is this the most relevant task in CT?*
  There are other tasks like **distinction of different shapes** („Lesion round or hexagon?“, „Lesion fuzzy or sharply delineated?“) which might be closer to typical clinical applications of CT. However, they are less easy to standardize – and it may be more difficult to build phantoms!

Conclusion

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- Iterative reconstruction is a meaningful way to improve various aspects of CT image quality.
- Various flavors of iterative reconstruction are available: data domain, image domain or data+image domain. They should be combined in a meaningful way to achieve the desired objectives efficiently.
- With respect to noise, IR is equivalent to a complex local, non-isotropic adaptive filter realizing a spatial resolution depending on the local contrast/noise ratio.
- Important questions from a clinical perspective:
  - Image quality aspects: Natural noise texture? Edge appearance? Good also for thicker slice widths?
  - What is the dose reduction potential for various tasks?
  - Is it capable of routine usage?
- Dose reduction claims should be taken with a grain of salt: What is the point of comparison in a relative claim? Is the task clinically relevant?

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Thank you!