Iterative Reconstruction in CT – the Siemens Approach

Standard CT Reconstruction: Filtered Backprojection (FBP)

- CT raw data
- FBP reconstruction
- CT image

Limitations of Filtered Backprojection (FBP)

- FBP is only an approximate 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)
Iterative Reconstruction
Basic Idea: Introduction of a Correction Loop

- Simulation of a CT scan from the images
- Modeling of system features (focus, detector, ...)
- Validation of the reconstructed images w.r.t. the measured data

Artifact Reduction by IR

Iterative Reconstruction with Statistical Optimization: Statistical Weighting and Regularization

- Weight data according to their statistical quality, typically $\propto 1/\text{variance}$
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

Advantages of Non-Linear Regularization versus Linear Filtering

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
Maximum Likelihood:

\[ f = \arg \max P(p_{\text{meas}} \mid f) \]

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

Additional assumption: Data are nearly Gaussian

\[ \Rightarrow \text{Problem reduces to a minimization problem} \]

(Penalized weighted least squares):

\[
\begin{align*}
\tilde{f} &= \arg \min \left( \frac{1}{2} W^{-1} p_{\text{meas}} - Pf \right)^T + \gamma(R(f)) \\
&= \arg \min \left( \frac{1}{2} \| W^{-1} p_{\text{meas}} - Pf \|_2^2 + \gamma(R(f)) \right)
\end{align*}
\]

Iterative solution e.g. by steepest descent:

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

Now we have:

\[ f_n = f_{n-1} + \alpha \cdot \frac{Q W (p_{\text{meas}} - P f_{n-1}) - \gamma R f_{n-1}}{\| W^{-1} p_{\text{meas}} - Pf_{n-1} \|_2^2} \]

Define ...

1. ... the operator \( X_w = Q W P \)
   - 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 \( f_w = Q W p_{\text{meas}} \)

\[ f_w = \frac{Q W p_{\text{meas}}}{\| W^{-1} p_{\text{meas}} - Pf_{n-1} \|_2^2} \]

\[ f_n = f_{n-1} + \alpha \cdot \frac{Q W (p_{\text{meas}} - P f_{n-1}) - \gamma R f_{n-1}}{\| W^{-1} p_{\text{meas}} - Pf_{n-1} \|_2^2} \]

\[ X_w = Q W P \]

\[ f_w = Q W p_{\text{meas}} \]

\[ f_n = f_{n-1} + \alpha \cdot \frac{Q W (p_{\text{meas}} - P f_{n-1}) - \gamma R f_{n-1}}{\| W^{-1} p_{\text{meas}} - Pf_{n-1} \|_2^2} \]

\[ f_w = \frac{Q W p_{\text{meas}}}{\| W^{-1} p_{\text{meas}} - Pf_{n-1} \|_2^2} \]

\[ f_n = \alpha \cdot f_w + \left[ 1 - \alpha (X_w + \gamma R) \right] f_{n-1} \]

\[ X_w = Q W P \]

\[ f_w = Q W p_{\text{meas}} \]

\[ f_n = \alpha \cdot f_w + \left[ 1 - \alpha (X_w + \gamma R) \right] f_{n-1} \]

\[ f_w = \frac{Q W p_{\text{meas}}}{\| W^{-1} p_{\text{meas}} - Pf_{n-1} \|_2^2} \]

\[ f_n = f_{n-1} + \alpha \cdot \frac{Q W (p_{\text{meas}} - P f_{n-1}) - \gamma R f_{n-1}}{\| W^{-1} p_{\text{meas}} - Pf_{n-1} \|_2^2} \]

\[ f_w = \frac{Q W p_{\text{meas}}}{\| W^{-1} p_{\text{meas}} - Pf_{n-1} \|_2^2} \]

\[ f_n = \alpha \cdot f_w + \left[ 1 - \alpha (X_w + \gamma R) \right] f_{n-1} \]

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))

### 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)

---

© Siemens AG 2015 All rights reserved.

Page 14

K. Stierstorfer, Siemens Healthcare

---

Page 15

K. Stierstorfer, Siemens Healthcare

---

Page 16

K. Stierstorfer, Siemens Healthcare
Siemens Generations of IR:
SAFIRE – Sinogram Affirmed Iterative Reconstruction

FBP

Master 3D Volume
Loop B

System Modeling (FP)

Statistical Modeling (Image)

Loop A

Siemens Generations of IR:
ADMIRE – Advanced Modeling Iterative Reconstruction

Improved performance at very low signals

FBP

Master 3D Volume
Loop B

System Modeling (FP)

Statistical Modeling (Image)

Loop A

Improved performance for high-contrast images

Improved noise texture

ADMIRE – Advanced Modeling Iterative Reconstruction

Standard B4D

ADMIRE B4D
**ADIMIRE – Advanced Modeling Iterative Reconstruction**

**Extremely Low Dose**

CTDIsn: 0.04 mGy / DLP 1.64 mGy·cm / eff. Dose 0.025 mSv

**What Should Be Compared?**

- 35% less noise
- 30% less noise
- up to 55% less noise

Plain FBP

Siemens WFBP reconstruction

1st generation IR

2nd generation IR

**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

- Definition of a meaningful task
- Usage of a "Channelized Hotelling Observer" → mimics visual perception
- ROC analysis

What is a relevant imaging task?

- 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

- 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?
Thank you!