Effects of Ray-Modeling: Simulation Study

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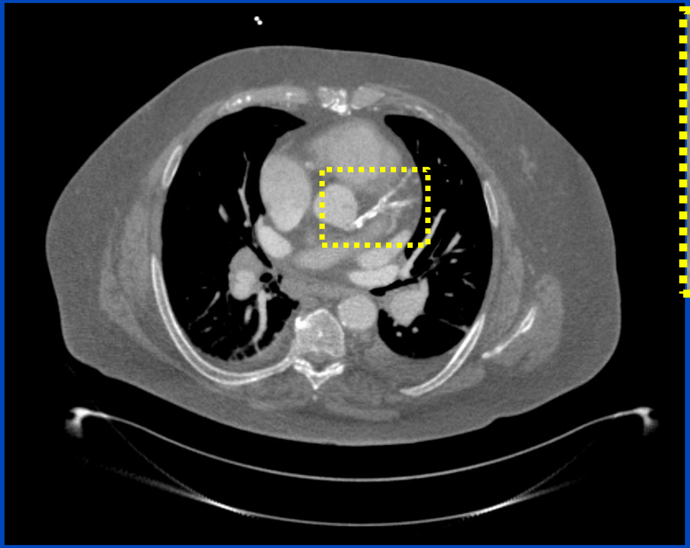
FRIEDRICH-ALEXANDER-UNIVERSITÄT ERLANGEN-NÜRNBERG

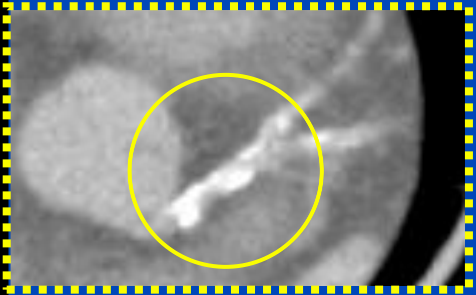
DEUTSCHES KREBSFORSCHUNGSZENTRUM IN DER HELMHOLTZ-GEMEINSCHAFT

Motivation: Blooming Artifacts in Cardiac Imaging

- **Blooming artifacts arising from calcified vessels lead to an over-estimation of the degree of luminal narrowing.**



Calcifications

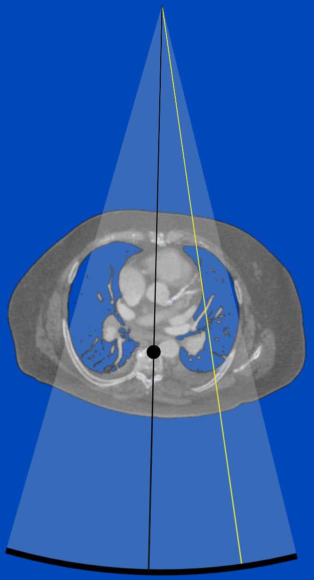


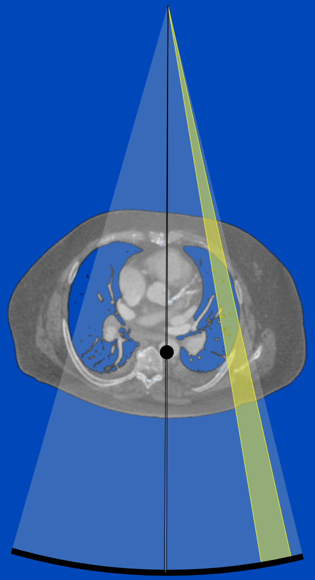
C = 0 HU
W = 1000 HU

Aim:
Is Ray-Modeling Necessary ?

- Investigate the effects of ray-modeling without incorporation of further knowledge (ray statistics, regularization,…)
- Investigate the effects of ray-modeling when further knowledge is used (regularization approach)

Needle beam





Divergent beam

Prior Art Ray-Modeling

- A. Ziegler, T. Nielsen, and M. Grass, **"Iterative reconstruction of a region of interest for transmission tomography"**, Med. Phys. 35 (4), Mar. 2008
- A. Ziegler, Th. Kohler, and R. Proksa, **"Noise and resolution in images reconstructed with FBP and OSC algorithms for CT"**, Med. Phys. 34 (2), Jan. 2007
- J. Thibault, K. D. Sauer, C. A. Bouman, J. Hsieh, **"A Three-Dimensional Statistical Approach to Improve Image Quality for Multislice Helical CT"**, Med. Phys. 34 (11), Nov. 2007
- Jiao Wang; Thibault, J.-B. Zhou Yu Sauer, K. Bouman, C. , **"System modeling studies in iterative X-ray CT reconstruction"** Signals, Systems and Computers, 2008 42nd Asilomar Conference, pp. 1072-1076, 26-29 Oct. 2008
- K. Zeng, B. De Man, J.-B. Thibault, C. Zhou Yu Bouman, K. Sauer, **"Spatial resolution enhancement in CT iterative reconstruction"**, Nuclear Science Symposium Conference Record (NSS/MIC), 2009 IEEE, pp. 3748-3751, Oct. 2009
- S. Do, S. Cho, W. Karl, M. Kalra, T. Brady, and H. Pien, **"Accurate model-based high resolution cardiac image reconstruction in dual source CT"**, Biomedical Imaging: From Nano to Macro, 2009. ISBI '09. IEEE International Symposium on, pp. 330–333, Jul. 2009

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  → Statistical reconstruction + blobs

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  → Statistical reconstruction + regularization

→ **Ray-modeling but also regularization and/or statistical reconstruction**

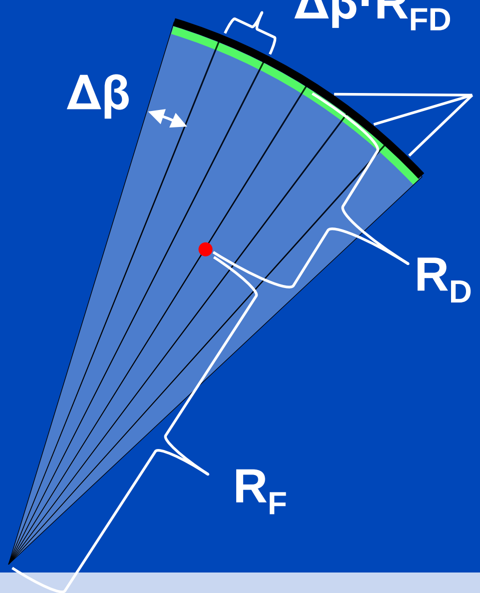
Outline

- 2D simulation approach for ray-modeling
  - Geometry
  - Ray-modeling and phantom
  - Reconstruction algorithms (FBP, OSSART,…)
- Analysis of effects of accurate ray-modeling without further knowledge
  - 2D simulation results of ray-modeling
- Analysis of effects of ray-modeling when further knowledge is used
  - Iterative scheme with bilateral filter (BF) as a regularization
  - 2D simulation results of ray-modeling with the regularization approach
- Apply regularization approach on a 3D cardiac measurement

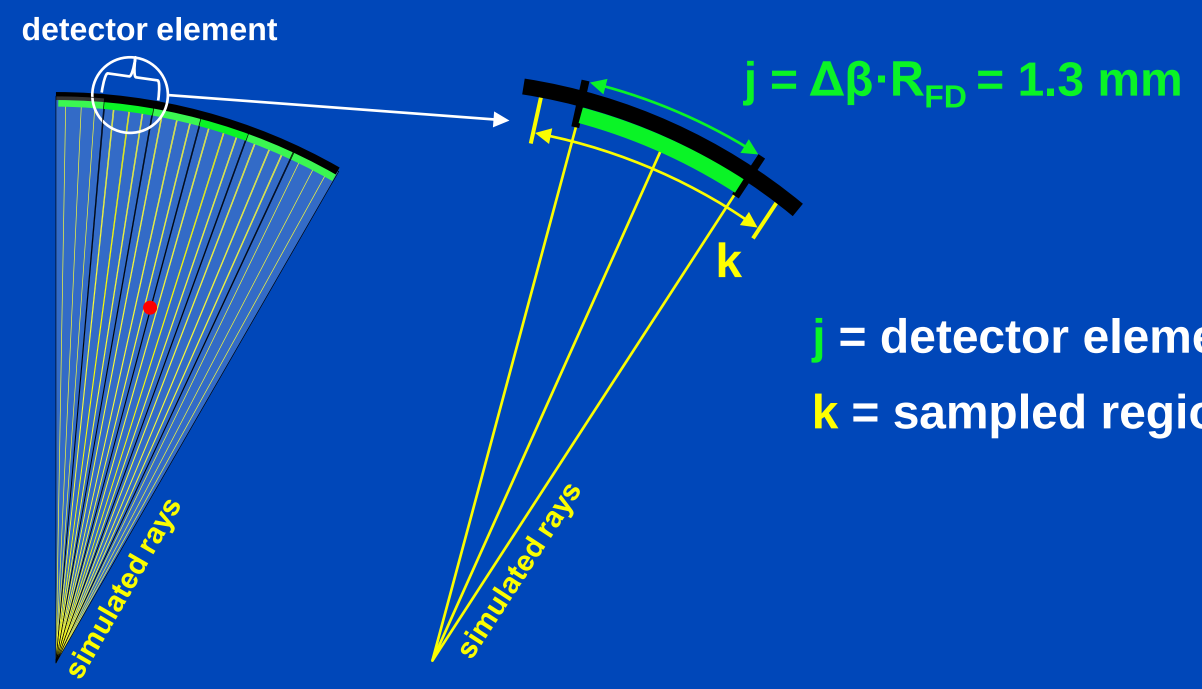
2D System Geometry: Siemens Definition Flash

- R_F = 595.0 mm
- R_D = 490.6 mm
- $R_{FD} = R_F + R_D$
- N_a = 1160
- $\Delta\alpha$ = 0.31°
- $\Delta\beta \cdot R_{FD}$ = 1.3 mm
- Columns = 736
- Rows = 1 (center row)
- Single source simulated

Siemens Definition Flash Scanner



Detector Sampling



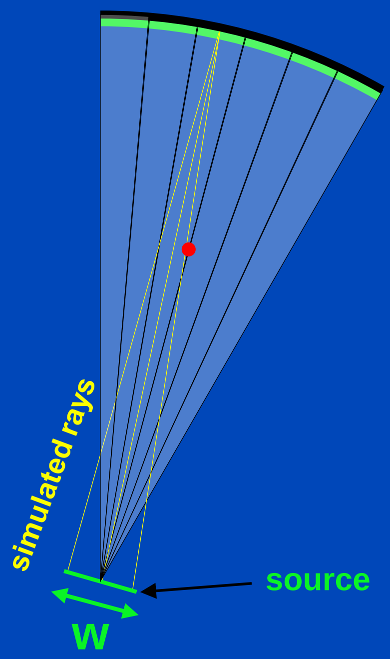
j = detector element width

k = sampled region

Example for detector sampling $N_{Detector} = 3$

Aperture = k/j = 1.5 for simulations

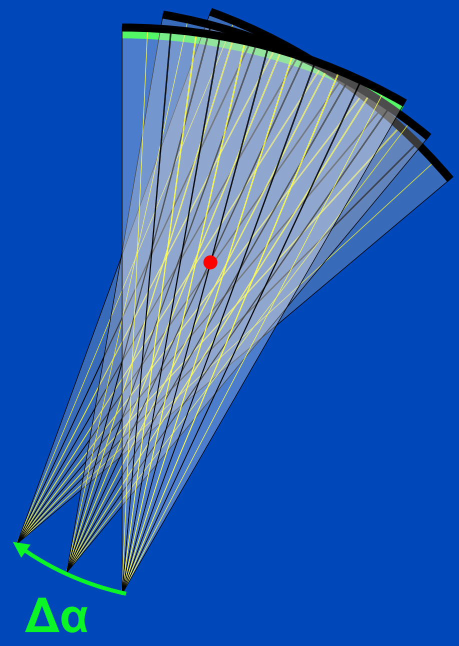
Focal Spot Sampling



Example for
source sampling
$N_{Source} = 3$

Source width w = 0.6 mm
for simulations

Angular Blurring

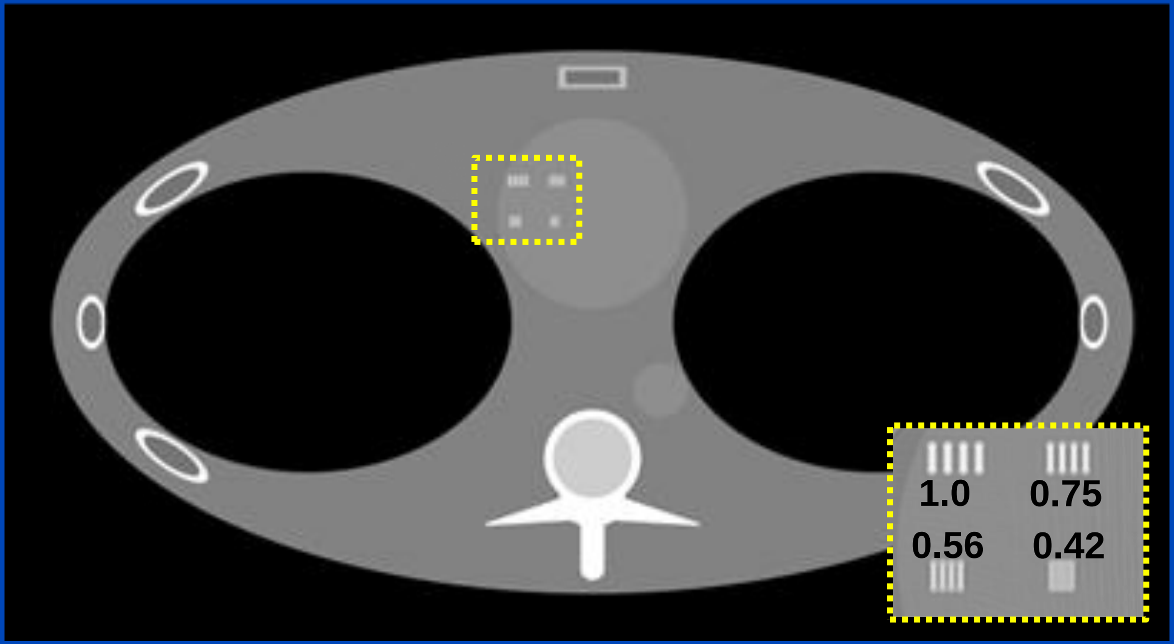


Example for angular sampling $N_{\Delta\alpha} = 3$

Angular increment $\Delta\alpha = 0.31°$ for simulations

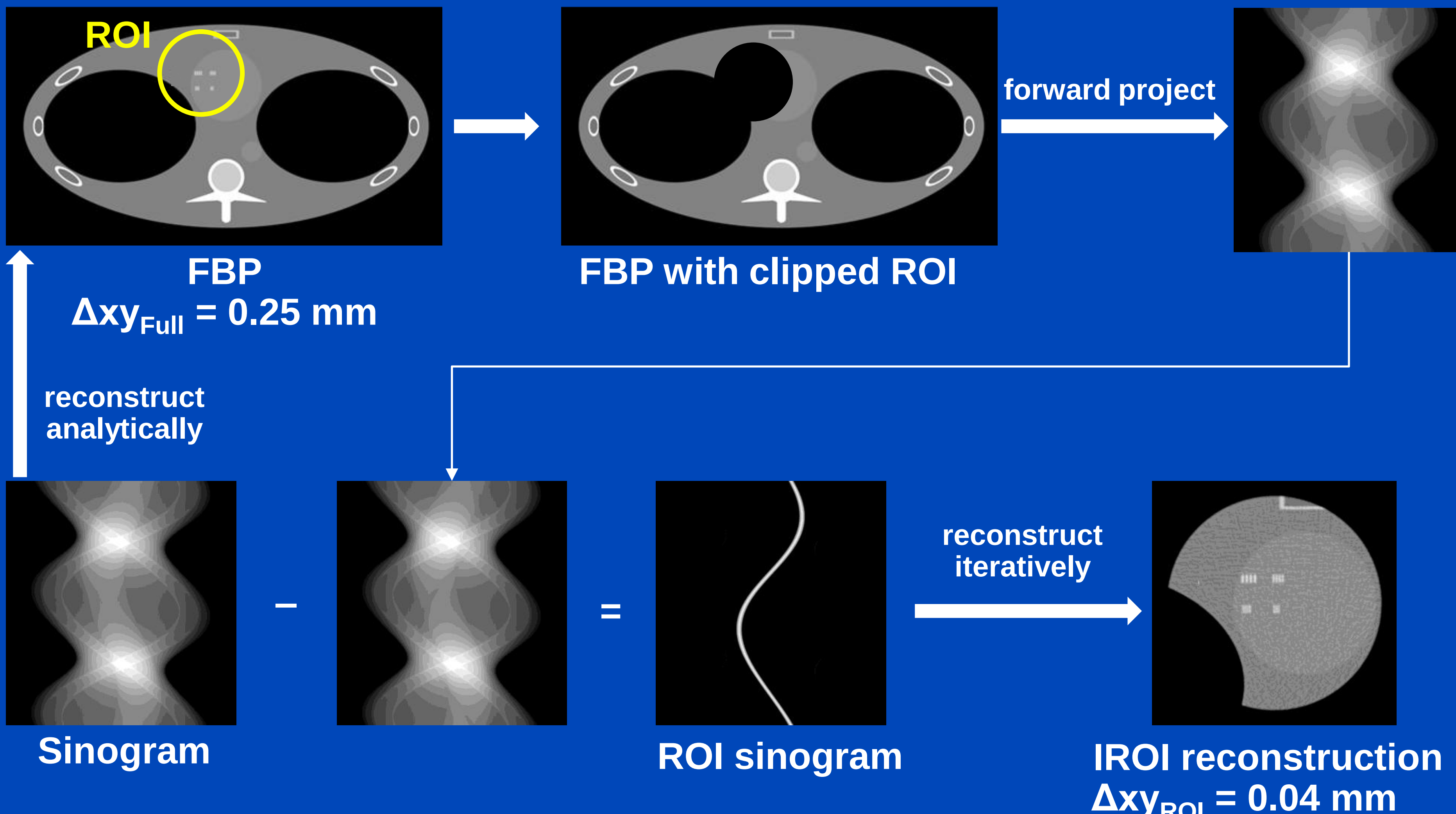
Phantom

- Forbild thorax phantom with 20 HU noise
- Line profiles with successive smaller dimensions
  → 0.75^n mm with n ϵ [0,3] (= 1.0 / 0.75 / 0.56 / 0.42 mm)
- Line profiles with 400 HU contrast



M. Kachelrieß, “The FORBILD CT–simulation phantoms”, Proc. of the 1999 Int. Meeting on Fully 3D Image Reconstruction, p. 383, Jun. 1999

Iterative Region of Interest (IROI)



Reconstruction for Simulations

- FBP with Ram-Lak kernel
- OSSART (Ordered Subsets Simultaneous Algebraic Reconstruction Technique)
- OSSART-RM (ray-modeling is considered in forward projection)
  - Sampling simulated rawdata 9-fold for each detector, source, and angular blurring (9^3 needle beams per x-ray)
  - Sampling forward projection in reconstruction 3-fold for each detector, source, and angular blurring (3^3 needle beams per x-ray)
  - Aperture = 1.5
  - Focal spot size (line) = 0.6 mm
- Diameter ROI = 50.0 mm
- Δxy_{ROI} = 0.04 mm, Δxy_{Full} = 0.25 mm

OSSART

(Ordered Subsets Simultaneous Algebraic Reconstruction Technique)

Update equation:

$$\boldsymbol{f}^{(n+1)} = \boldsymbol{f}^{(n)} + \frac{1}{\hat{\boldsymbol{X}}_\nu^T 1} \hat{\boldsymbol{X}}_\nu^T \frac{(\boldsymbol{p}^{(\nu)} - \boldsymbol{X}_\nu \boldsymbol{f}^{(n)})}{\boldsymbol{X}_\nu 1}$$

$\boldsymbol{f}^{(n)}$ = image after update n

$\boldsymbol{X}_\nu$ = forward projection of the ν–th subset

$\hat{\boldsymbol{X}}_\nu^T$ = backprojection operation

$\boldsymbol{p}^{(\nu)}$ = projection data of subset ν

$\mathrm{N}_{\mathrm{Iter}}$ = Number of iterations

Analysis of the 2D Simulations of the Ray-Modeling

Analytical reconstruction:

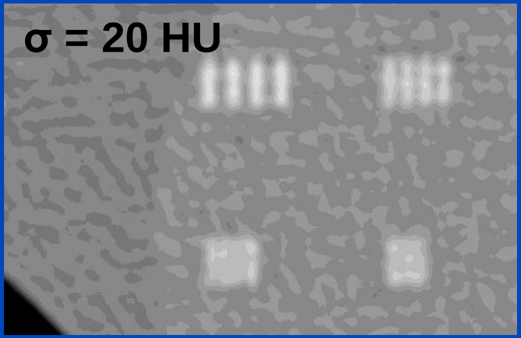
- FBP with 20 HU noise

Iterative reconstruction:

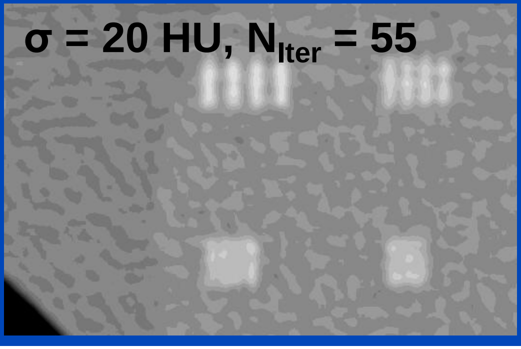
- OSSART / OSSART-RM
- Stopping criteria:
  - Matched noise (20 HU)
  - Constant N_{Iter}
  - Iterate until “convergence” is reached
    - » update falls below a defined threshold

Analysis of Line Profile: Matched Noise

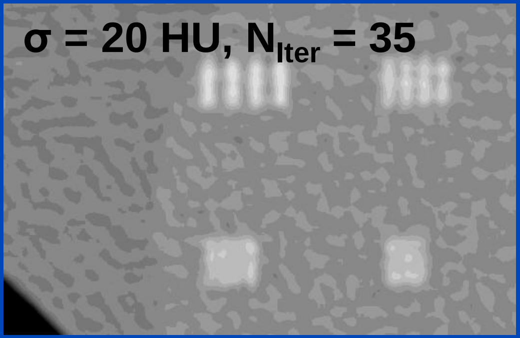
FBP

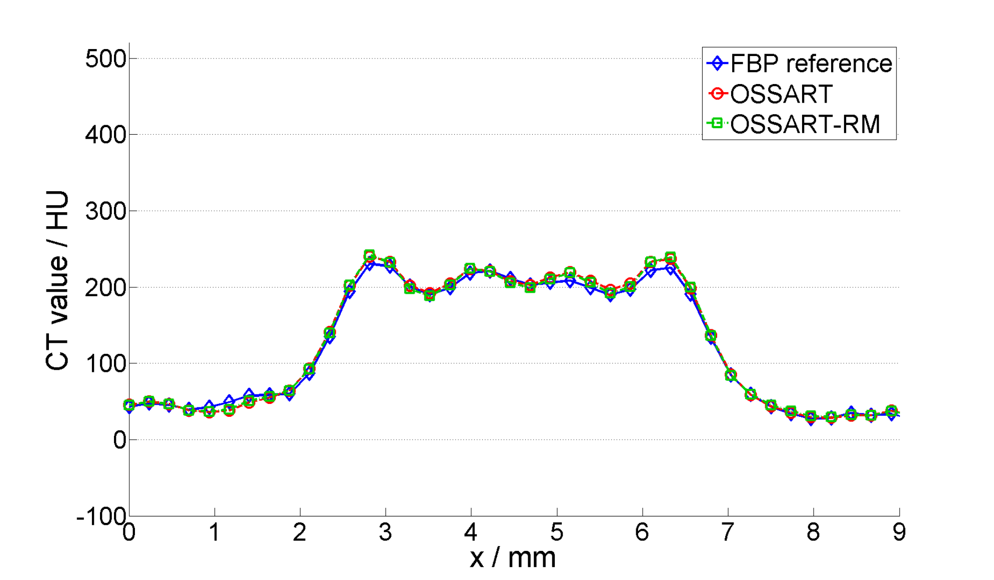


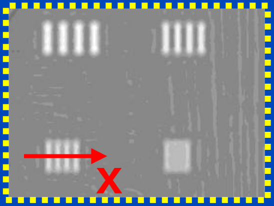
OSSART



OSSART-RM



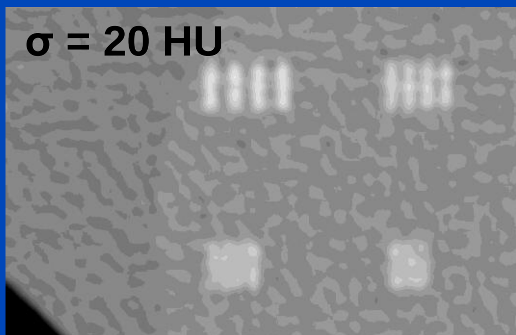




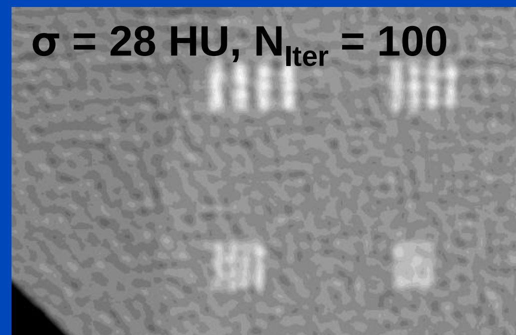
C = 0 HU
W = 1000 HU

Analysis of Line Profile: Constant N_{Iter}

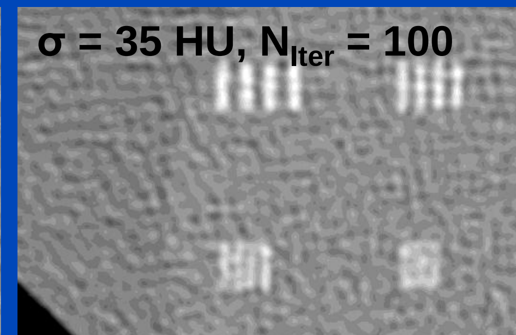
FBP

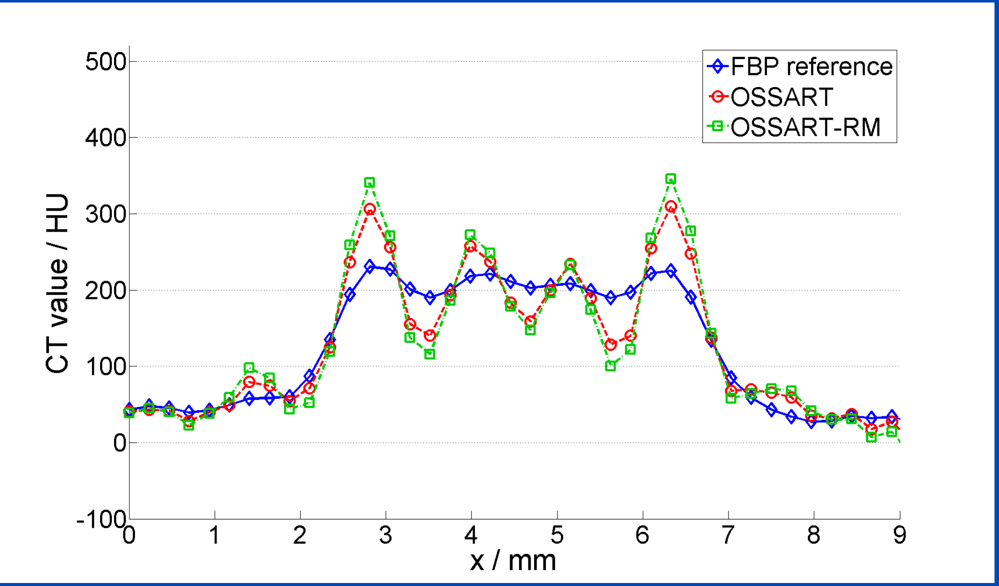


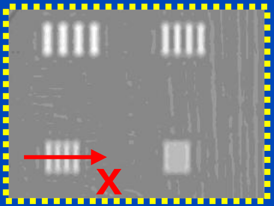
OSSART



OSSART-RM





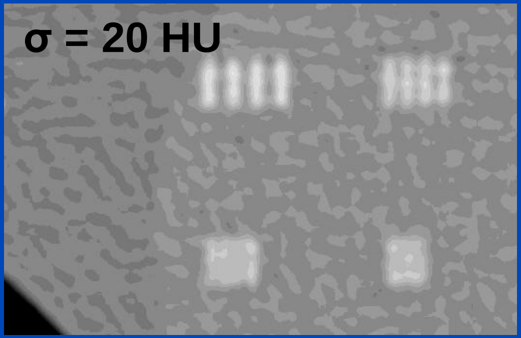


C = 0 HU
W = 1000 HU

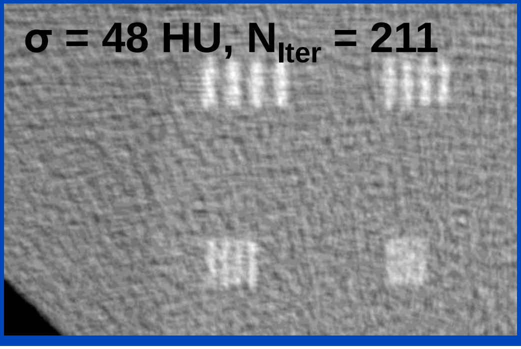
FAU dkfz.

Analysis of Line Profile: Until Convergence

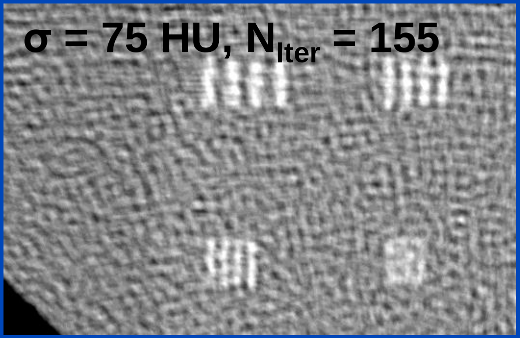
FBP

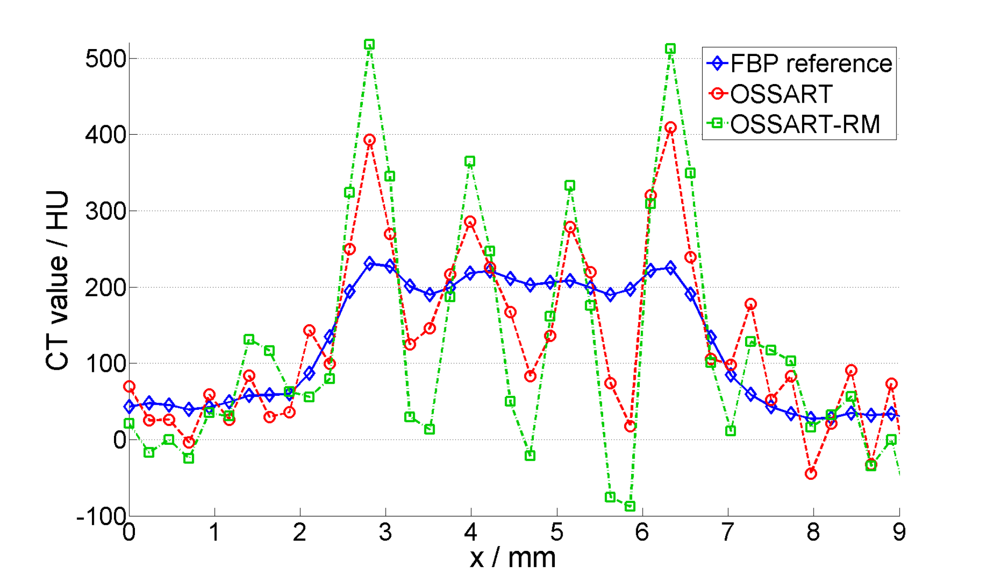


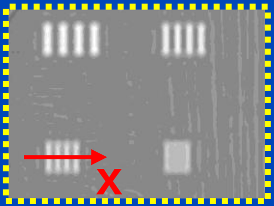
OSSART



OSSART-RM







C = 0 HU
W = 1000 HU

Conclusion of 2D Simulations

- Ray-modeling on its own does not improve the signal-to-noise ratio significantly in the simulated geometry and with the approach we used.
- Ray-modeling has effects on the behavior of the OSSART such as convergence speed in terms of number of iterations.
- Ray-modeling has effects on the result at convergence (higher resolution with the downside of higher noise).

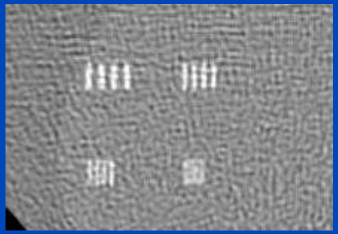
→What about a regularization approach combined with ray-modeling to bring out effects of ray-modeling?

Bilateral Filter
(Edge Preserving Filter In Image Domain)

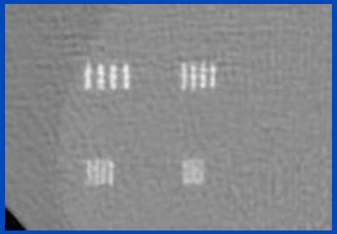
Definition:

$$\mathrm{B}f(x) = \frac{\int dt D(x,t) R(x,t) f(t)}{\int dt D(x,t) R(x,t)}$$

$f(x)$



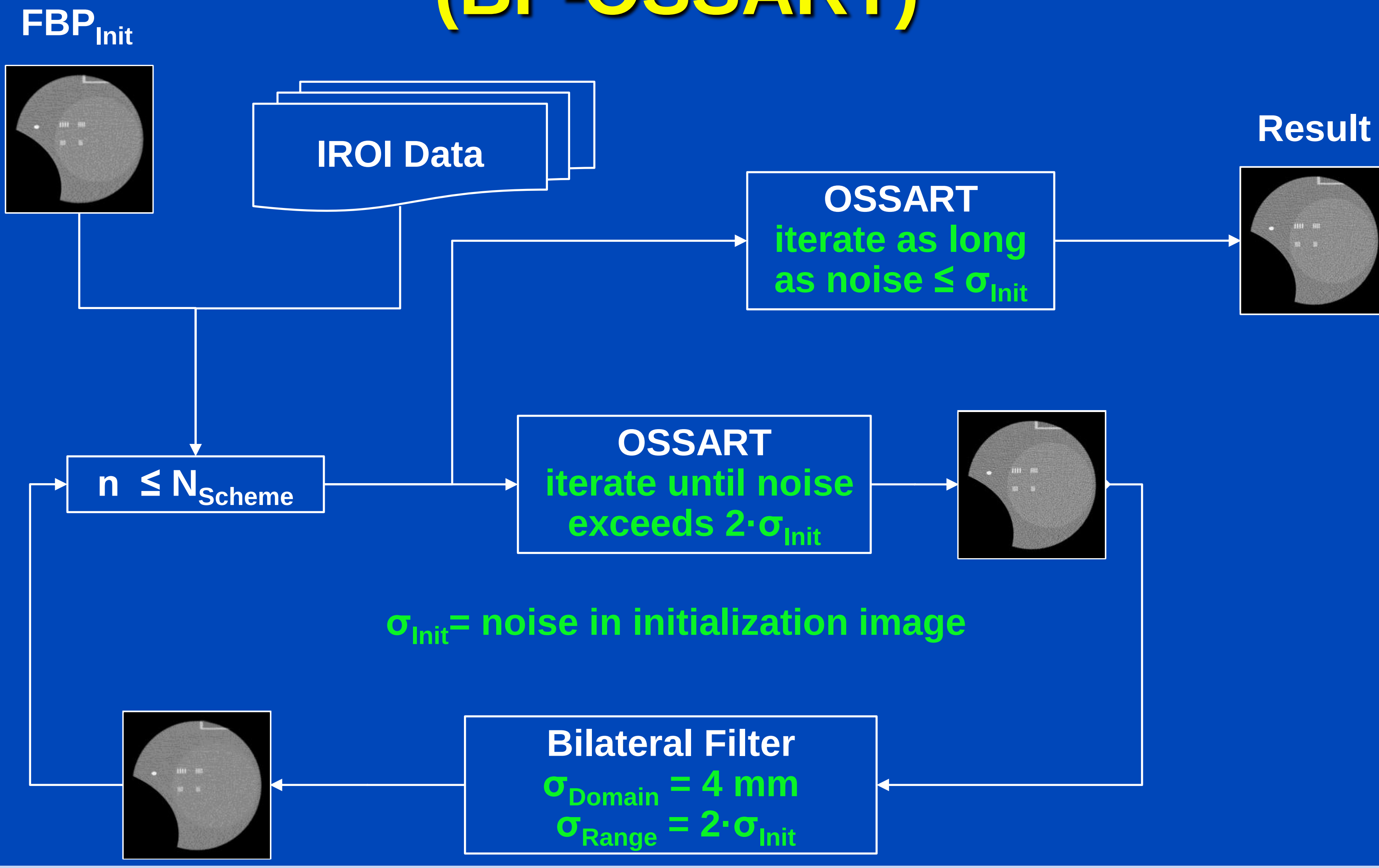
$\mathrm{B}f(x)$



Domain: $D(x,t) = e^{-\left(\frac{x-t}{\sigma_x}\right)^2} \rightarrow$ smoothing

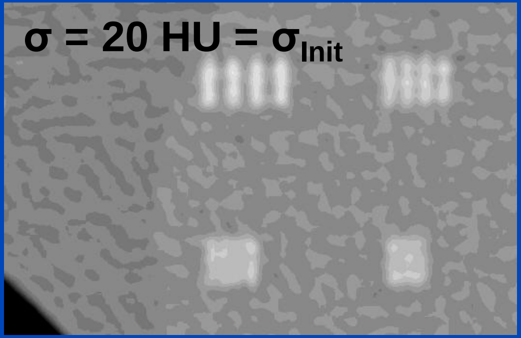
Range: $R(x,t) = e^{-\left(\frac{f(x)-f(t)}{\sigma_f}\right)^2} \rightarrow$ edge preservation

Iterative Bilateral Filter Scheme (BF-OSSART)

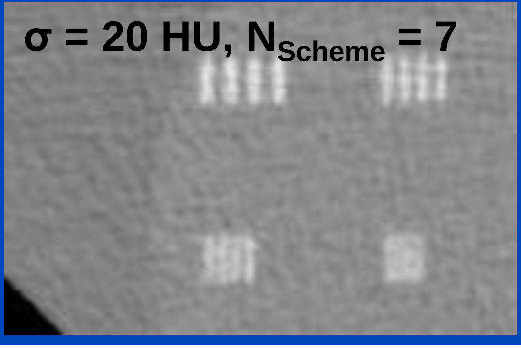


Iterative Bilateral Filter Scheme: Simulation Results

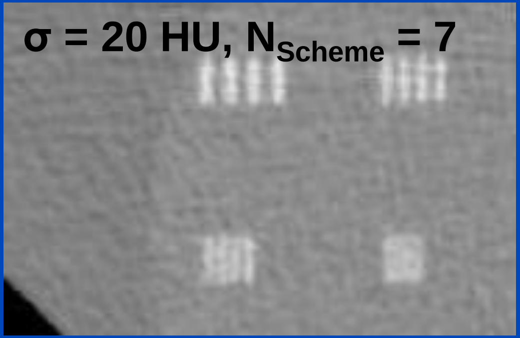
FBP

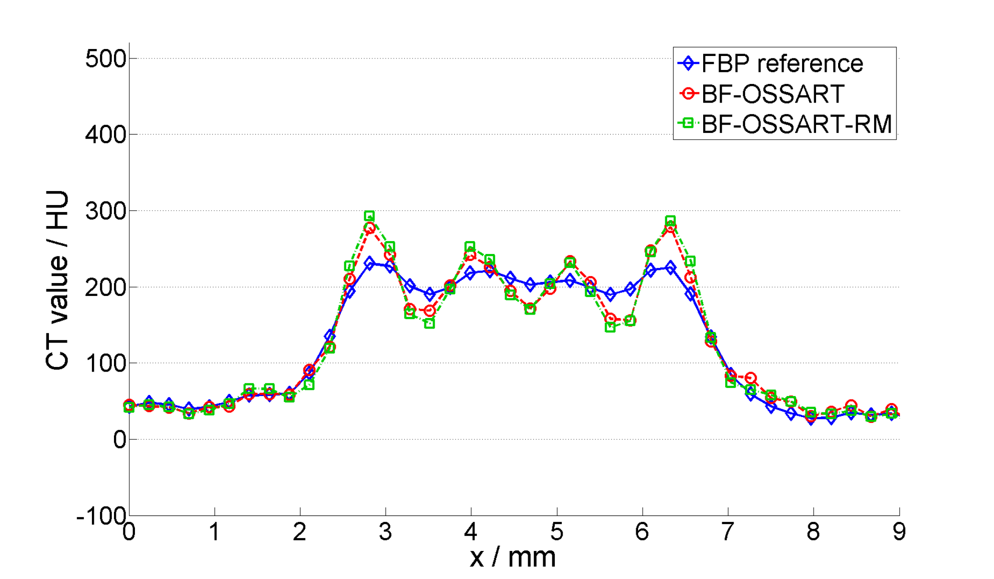


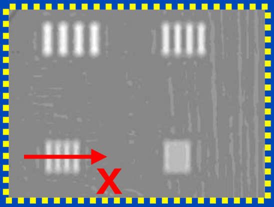
BF-OSSART



BF-OSSART-RM







C = 0 HU
W = 1000 HU

FAU dkfz.

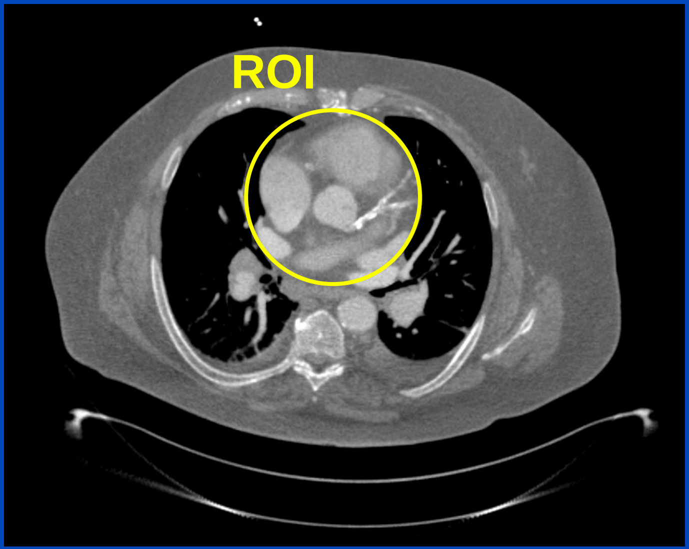
Overall Conclusion of 2D Simulations

- The regularization approach improves the signal-to-noise ratio.
- Minor differences between the results of the bilateral filter scheme with and without ray-modeling
- Improvements mainly due to regularization approach not to ray-modeling

→ Try bilateral filter scheme on 3D cardiac measurement (without ray-modeling)

Reconstruction for Cardiac Data

- EPBP for dual source spiral cardiac data
- BF-OSSART
- Diameter ROI = 80.0 mm
- Δxy_{ROI} = 0.3 mm, Δxy_{Full} = 0.6 mm
- N_{Scheme} = 7
- σ_{Init} = 35 HU



Iterative Bilateral Filter Scheme: Patient Data Overview

EPBP

BF-OSSART

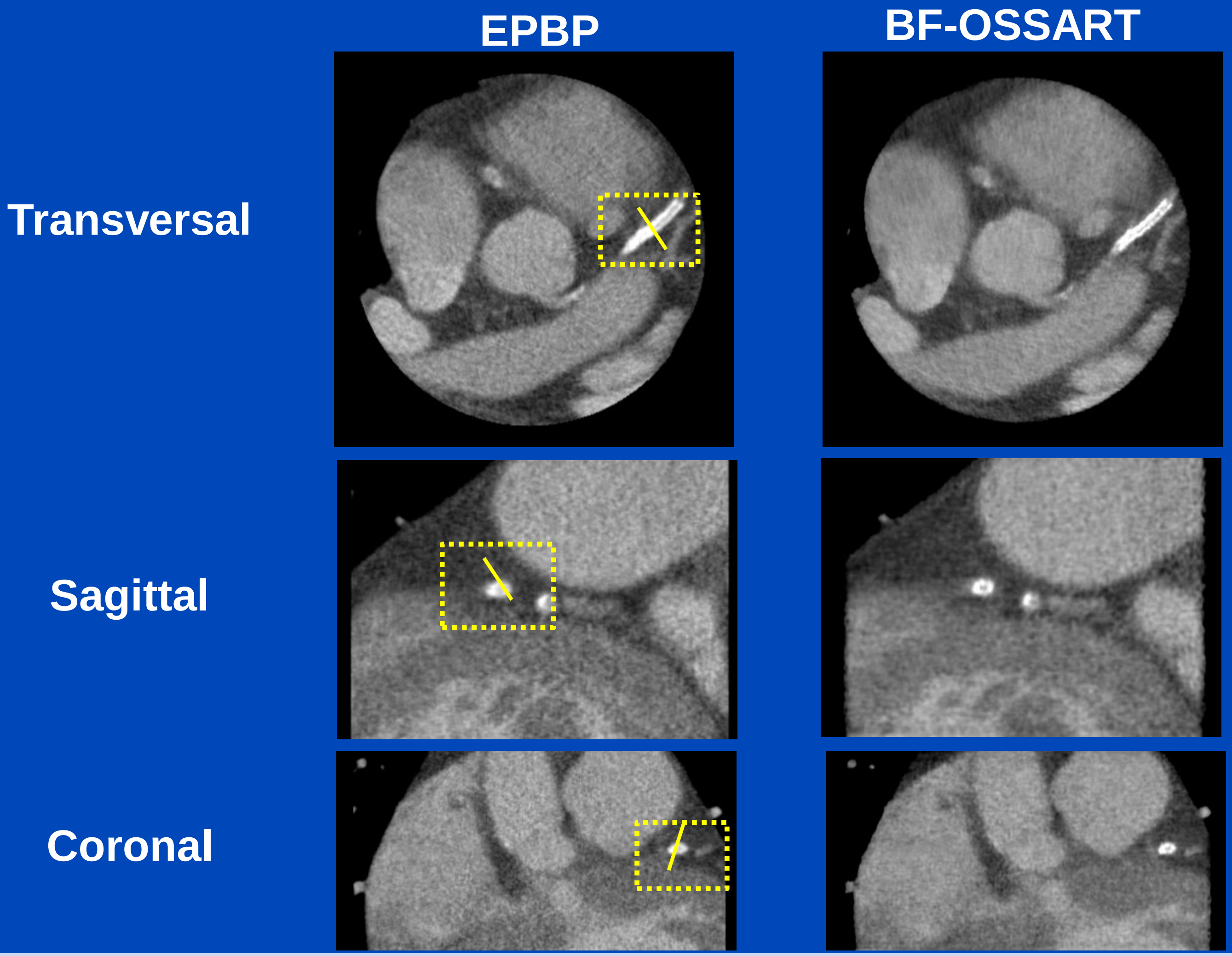
Transversal

Sagittal

Coronal

C = 150 HU
W = 800 HU

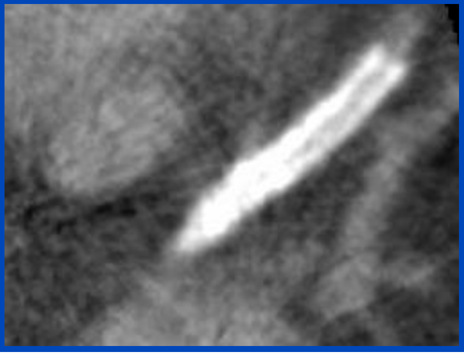
Iterative Bilateral Filter Scheme: Patient Data Overview

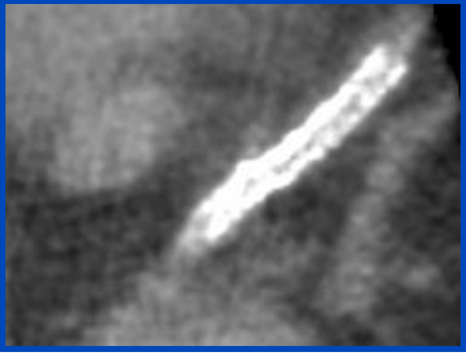


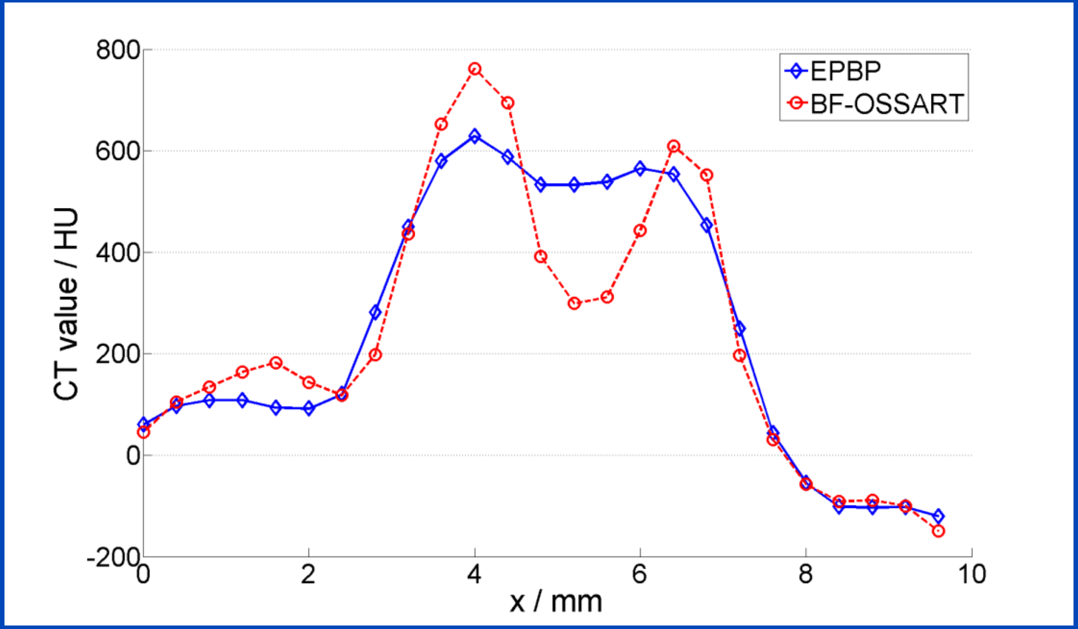
C = 150 HU
W = 800 HU

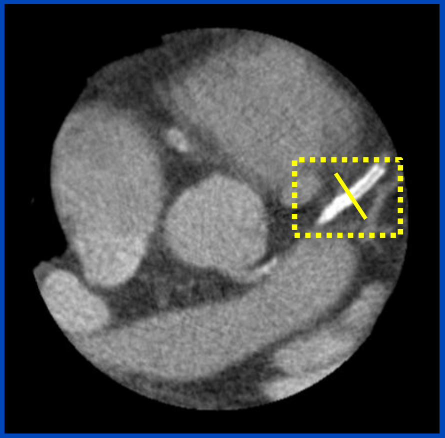
Coronary Stent: Transversal Slice

EPBP **BF-OSSART**





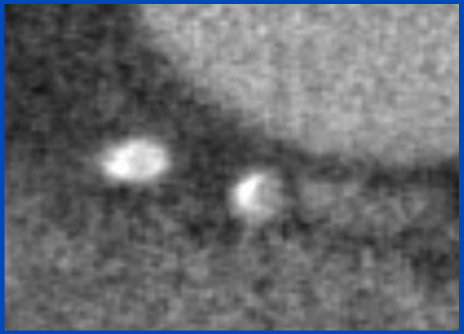




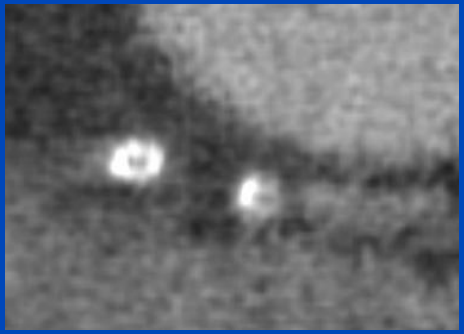
C = 150 HU
W = 800 HU

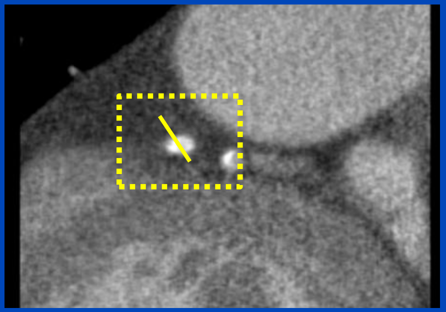
Coronary Stent: Sagittal Slice

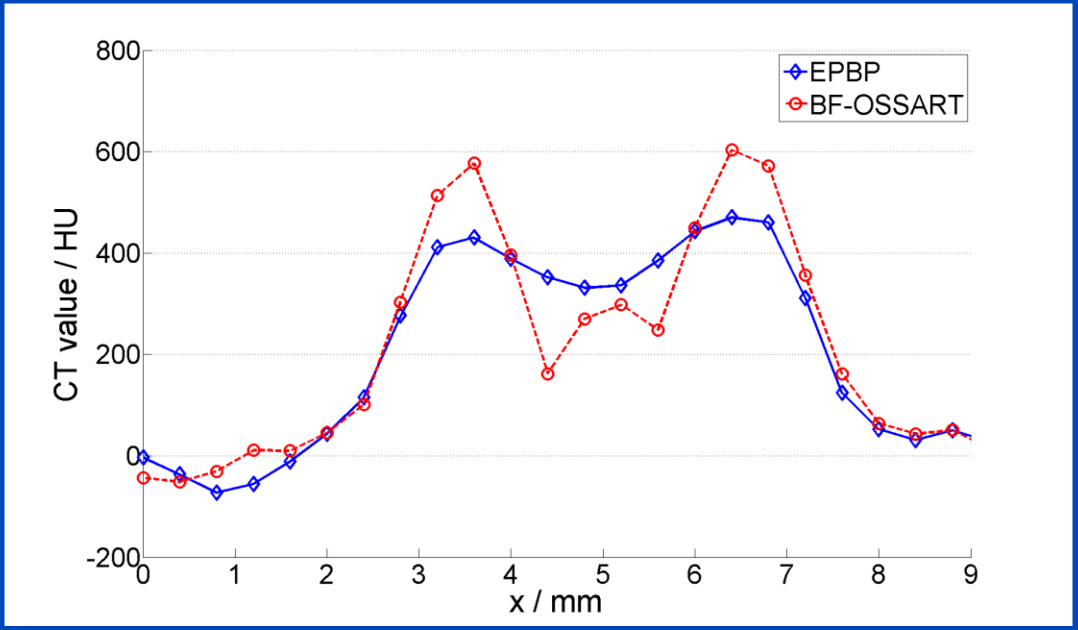
EPBP



BF-OSSART



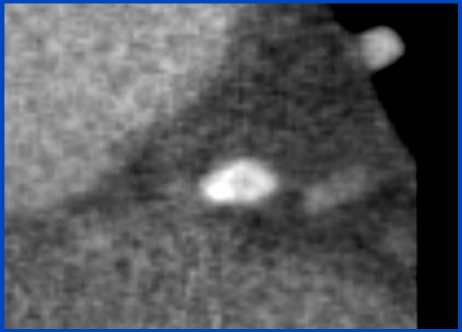




C = 150 HU
W = 800 HU

Coronary Stent: Coronal Slice

EPBP



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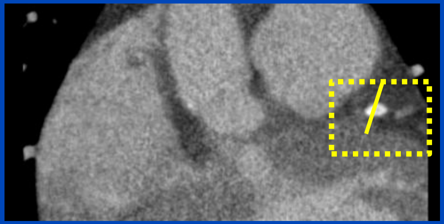

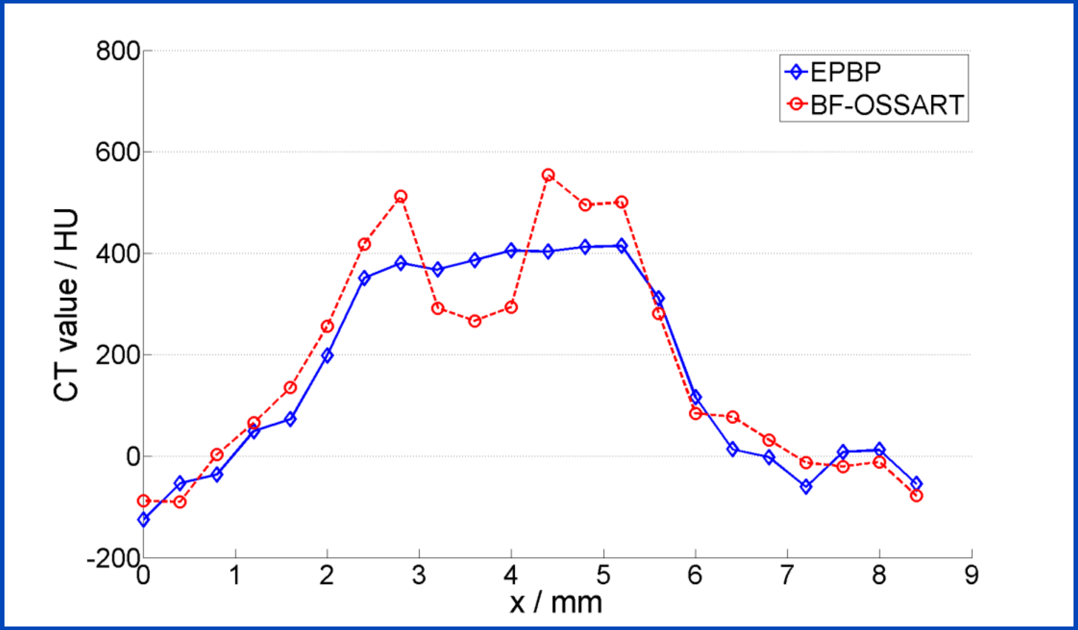

C = 150 HU
W = 800 HU

Conclusion of the Bilateral Filter Scheme on Cardiac Data

- **Iterative scheme is applicable on real cardiac data.**

- **Only preliminary results but potential to improve image quality**

Summary and Conclusion

- Effects of regularization outweigh the effects of ray-modeling.

→ Ray-modeling is not mandatory to significantly improve image quality

Thank You!

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