Medical CT: Algorithms, Designs and Potential Benefits for Non-Destructive Testing

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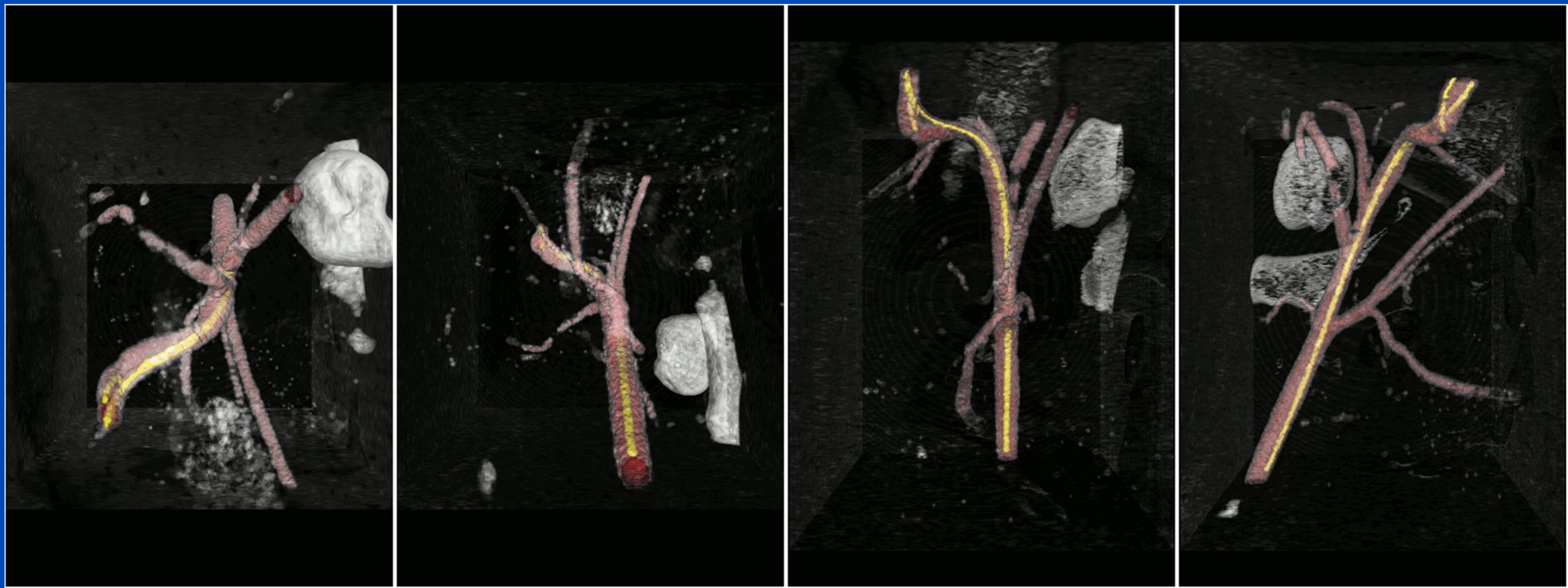
DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

CT from Just 10 Projections: 3D+T Fluoroscopy at 2D+T Dose

Guide wire in pig carotis with angiographic roadmap overly



J. Kuntz, B. Flach, R. Kueres, W. Semmler, M. Kachelrieß, and S. Bartling, "Constrained reconstructions for 4D intervention guidance", PMB 58:3283-3300, 2013.

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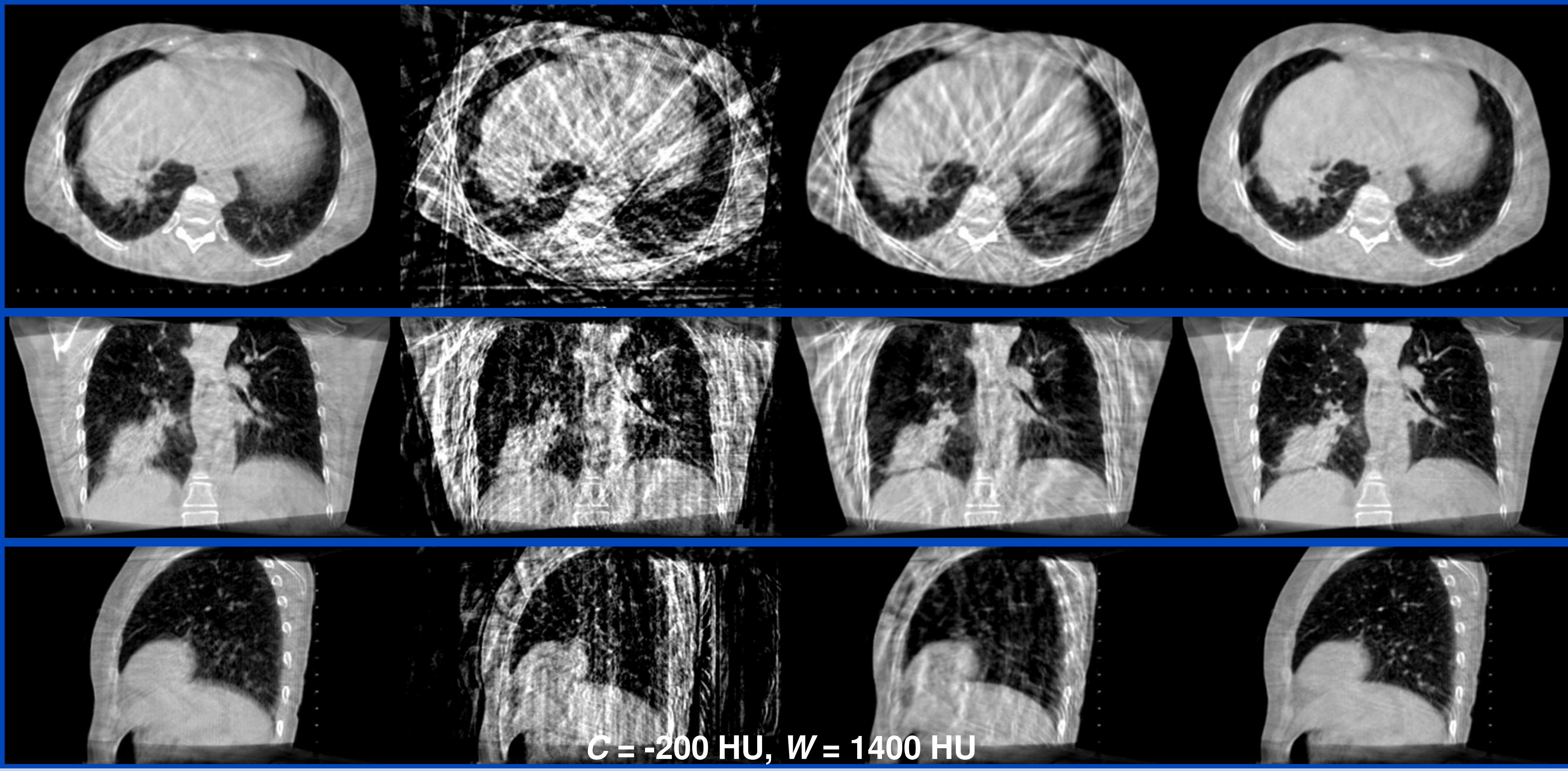
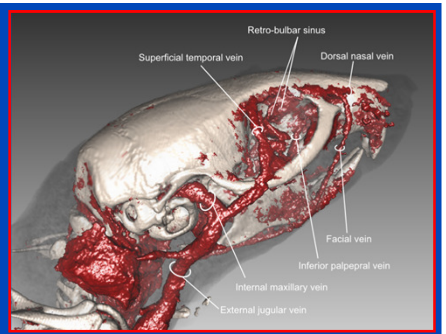
Motion-Compensated Reconstruction

3D CBCT	Gated 4D CBCT	sMoCo	aMoCo
Standard	Conventional Phase-Correlated	Standard Motion Compensation	Artifact Model-Based Motion Compensation



M. Brehm, P. Paysan, M. Oelhafen, P. Kunz, and M. Kachelrieß, “Self-adapting cyclic registration for motion-compensated cone-beam CT in image-guided radiation therapy”, MedPhys 39(12):7603-7618, December 2012.

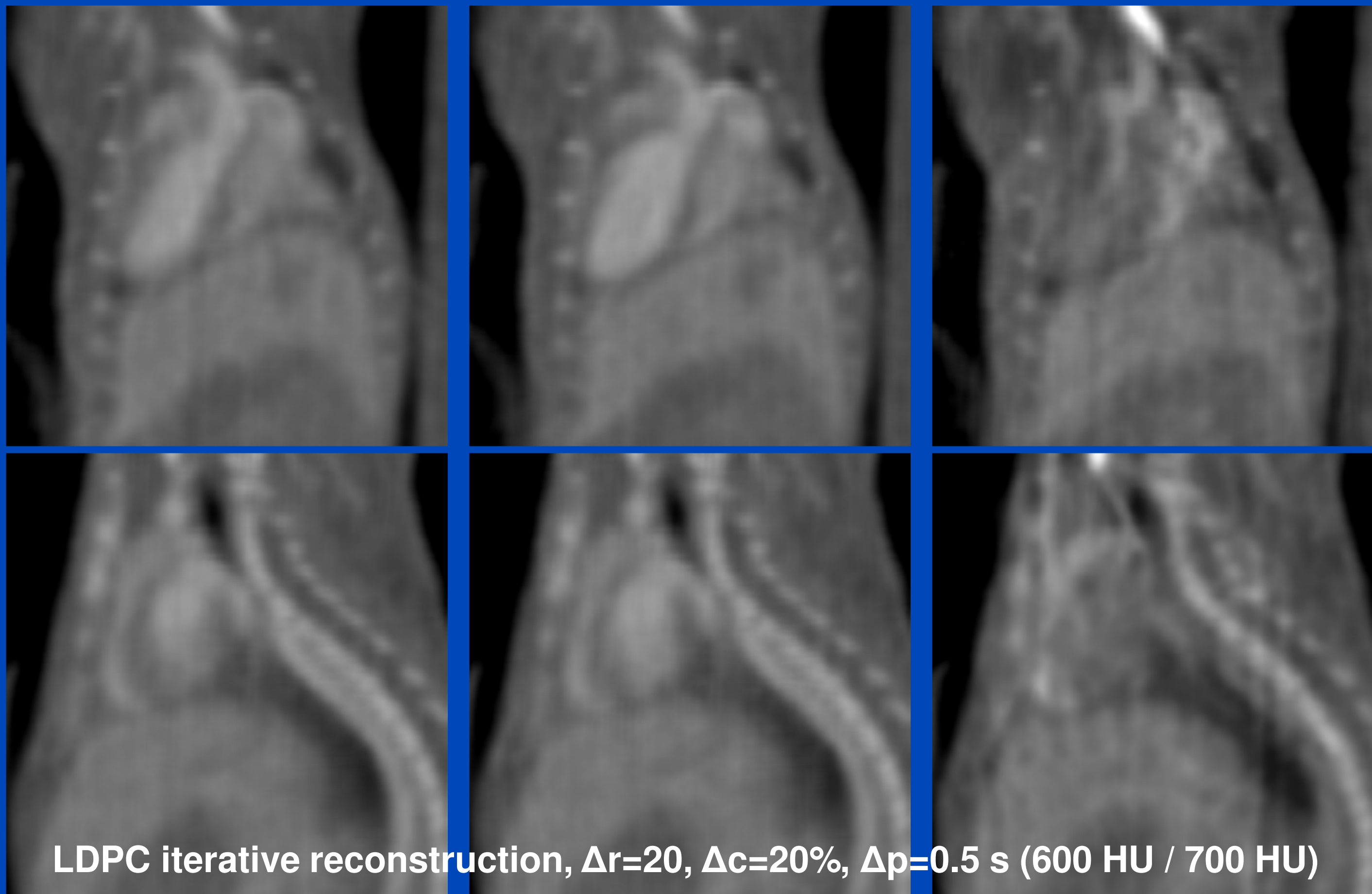
Fully 6D Imaging at Lowest Dose



Respiration | Cardiac Motion | Perfusion

Coronal

Sagittal



S. Sawall, and M. Kachelrieß, “Imaging of cardiac perfusion of free-breathing small animals using dynamic phase-correlated micro-CT”, MedPhys 39(12):7499-7506, December 2012.

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Contents

- Metal artifact reduction (MAR)
- Beam hardening correction (BHC)
- Scatter reduction
- ROI tomography

Metal Artifact Reduction

Metal implants:

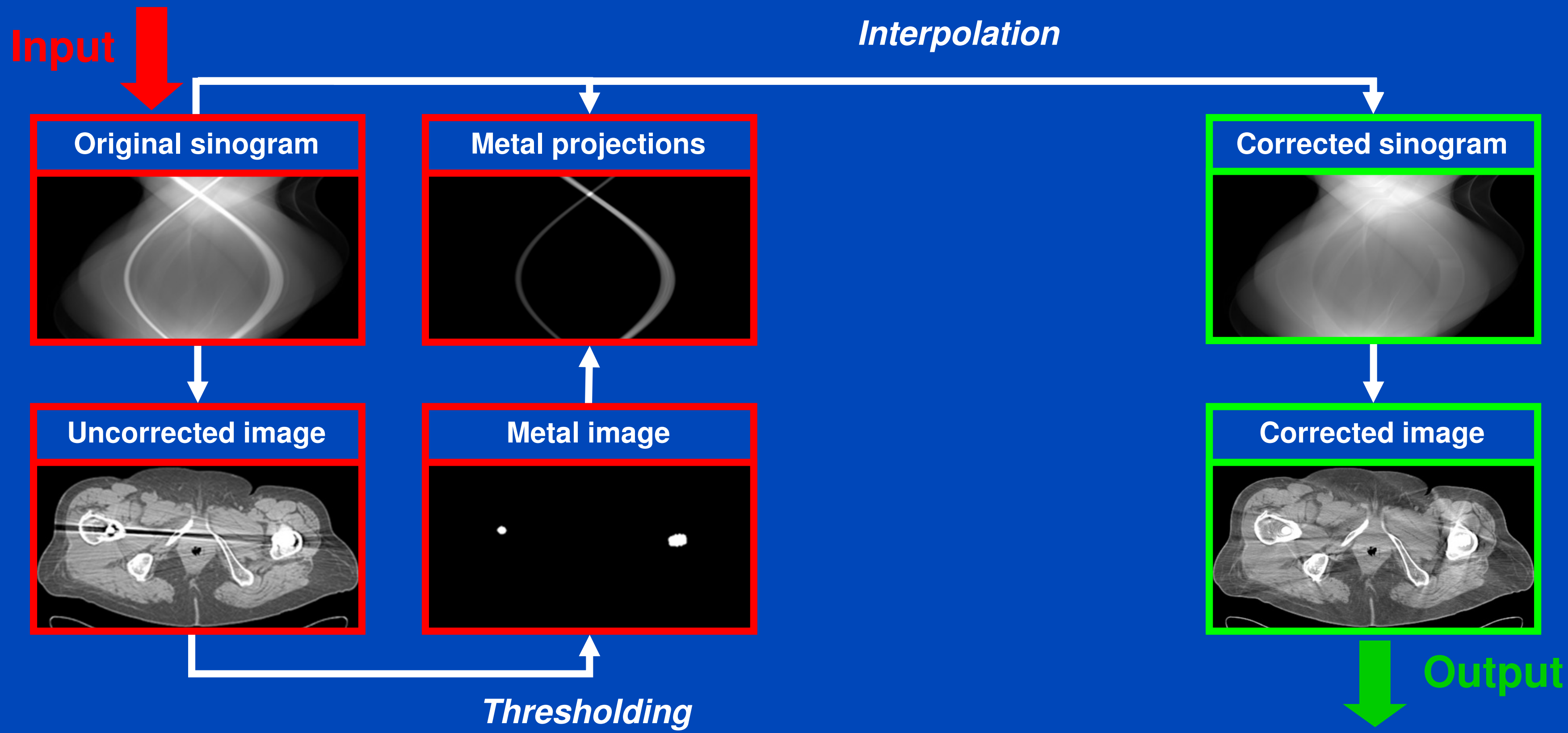
- Hip, knee, and shoulder prostheses
- Coils, clips, cables, needles
- Spine fixations
- Dental hardware
- …

They vary in:

- Material
- Size
- Shape
- Number
- …

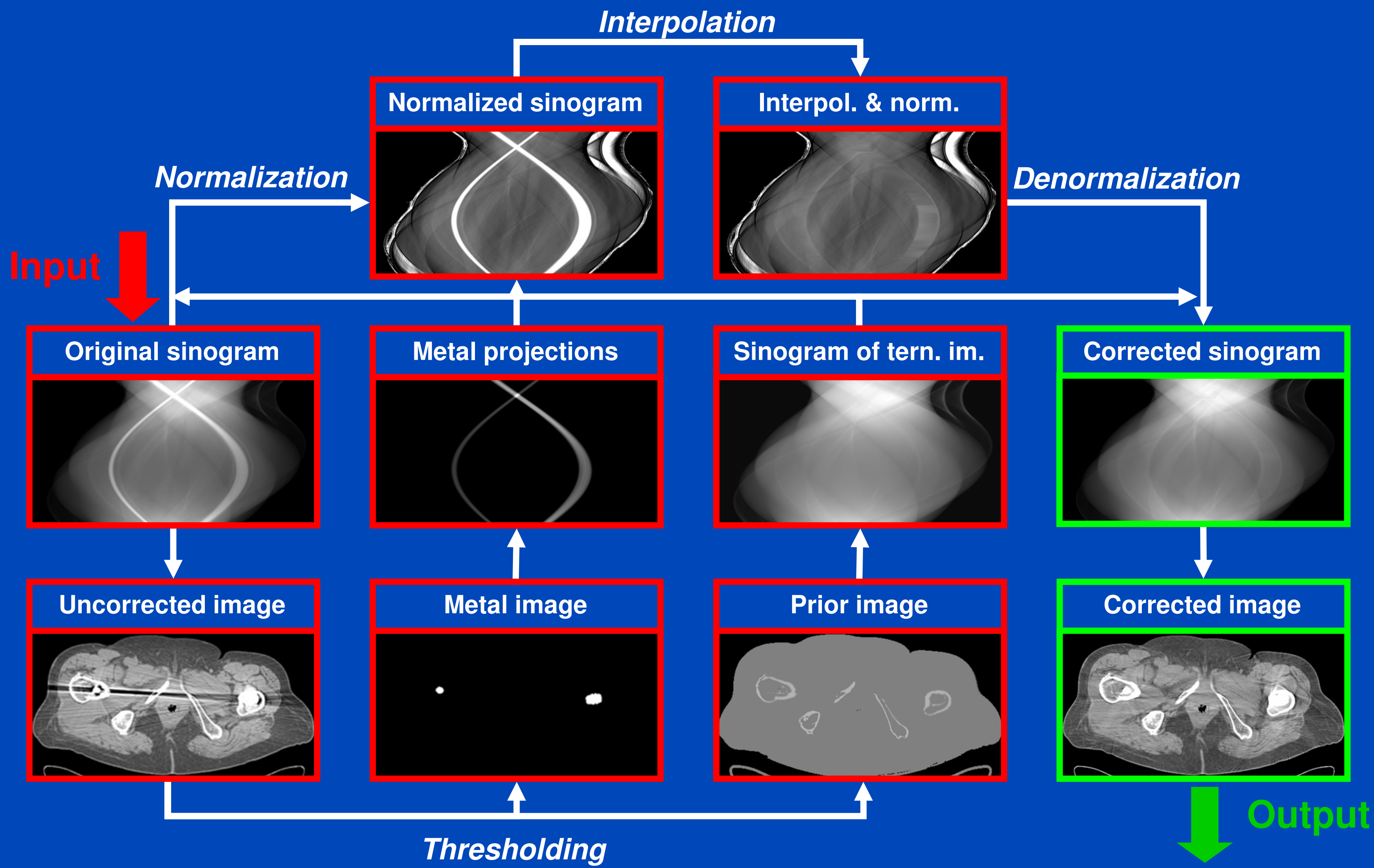
Bilateral hip prosthesis | Coil | Spine fixation | Dental fillings

MAR1



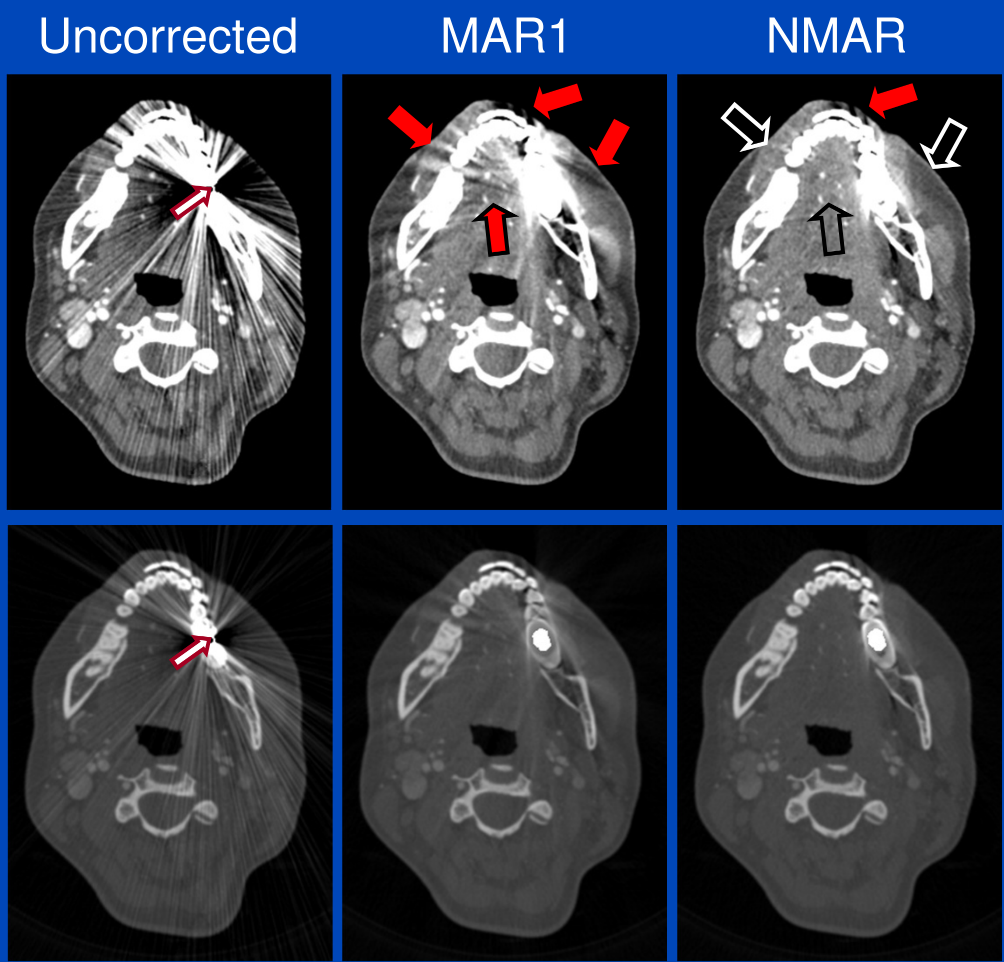
W. A. Kalender, R. Hebel and J. Ebersberger, "Reduction of CT artifacts caused by metallic implants", *Radiology,* 164(2):576-577, August 1987.

Normalized MAR (NMAR)



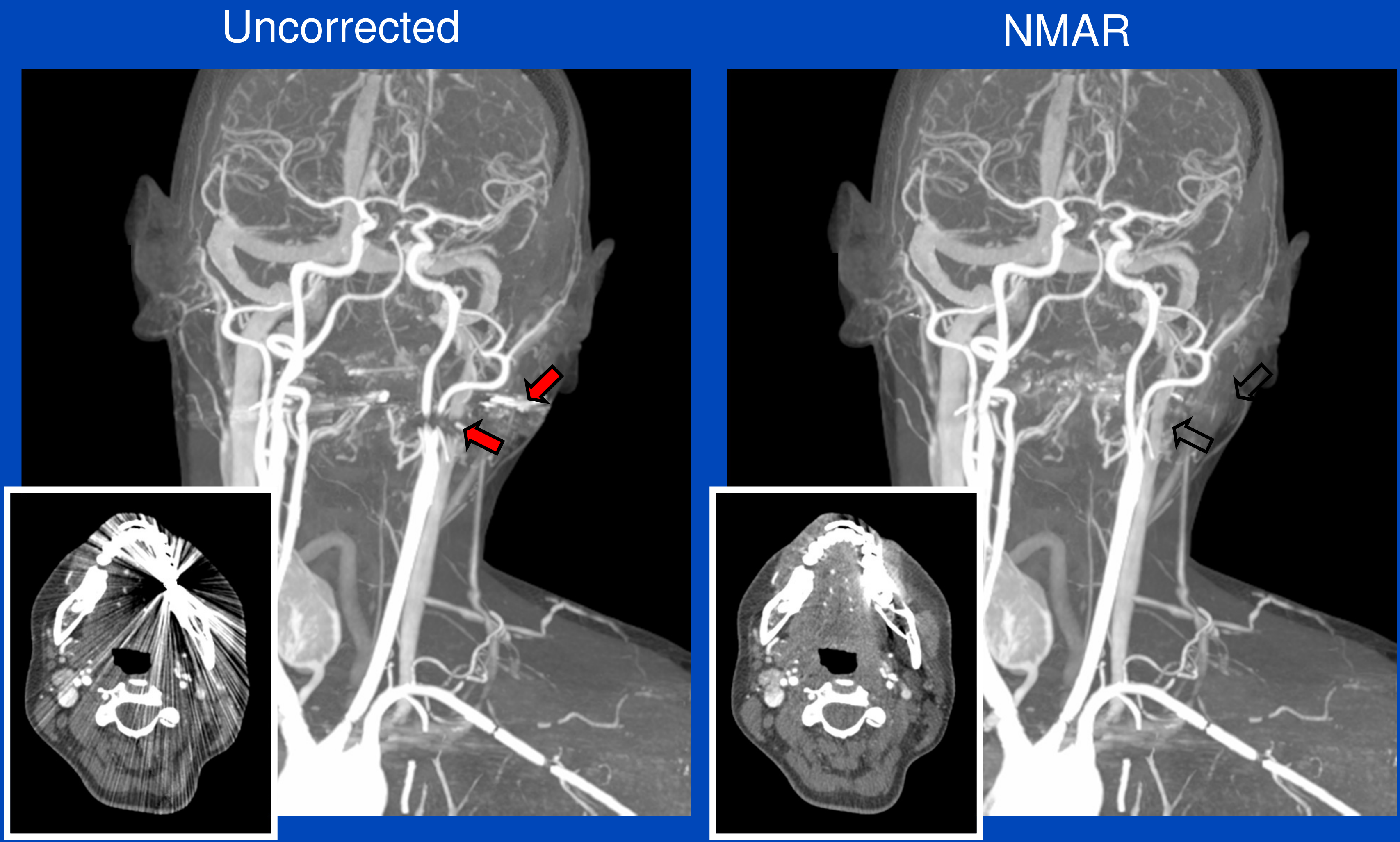
E. Meyer, R. Raupach, M. Lell, B. Schmidt, and M. Kachelrieß, "Normalized metal artifact reduction (NMAR) in computed tomography", Med. Phys., 37(10):5482-5493, October 2010.

NMAR: Results



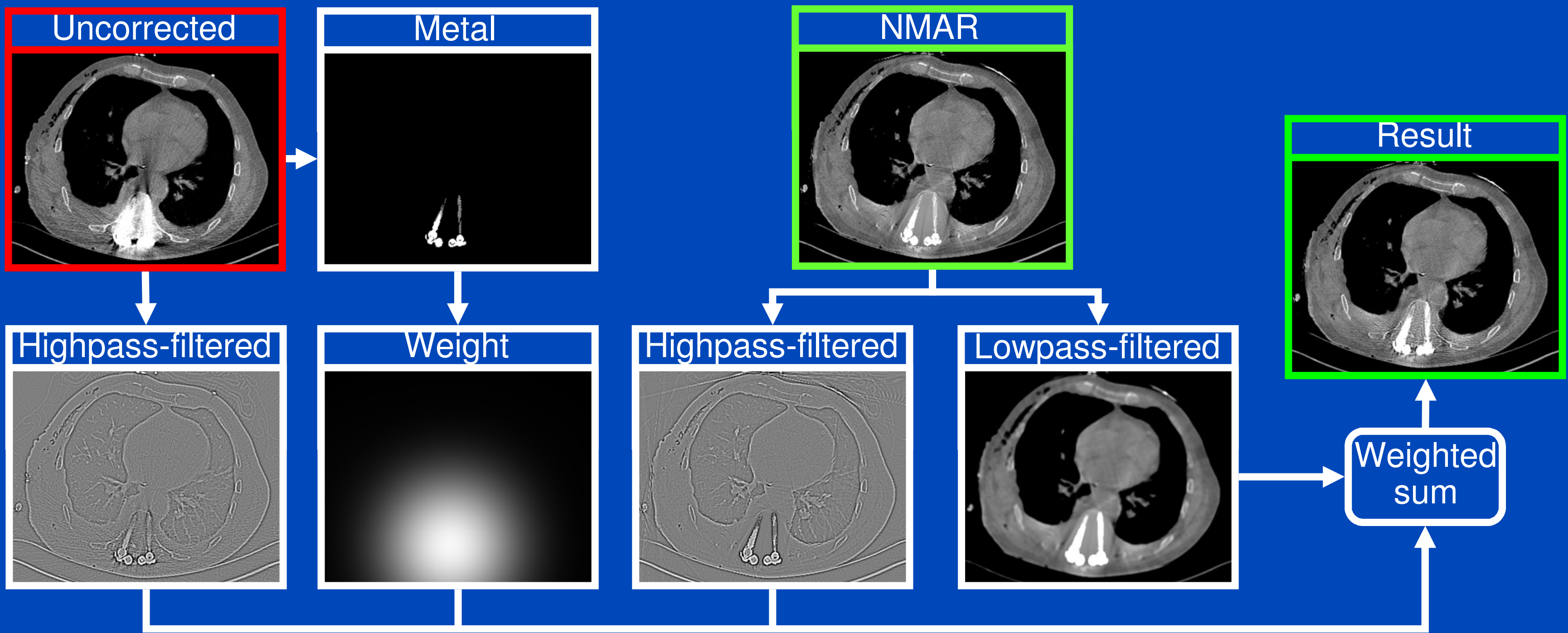
Patient dental fillings, Somatom Definition Flash, pitch 0.9. Top and middle row: (C=100/W=750). Bottom row: (C=1000/W=4000).

NMAR: Results



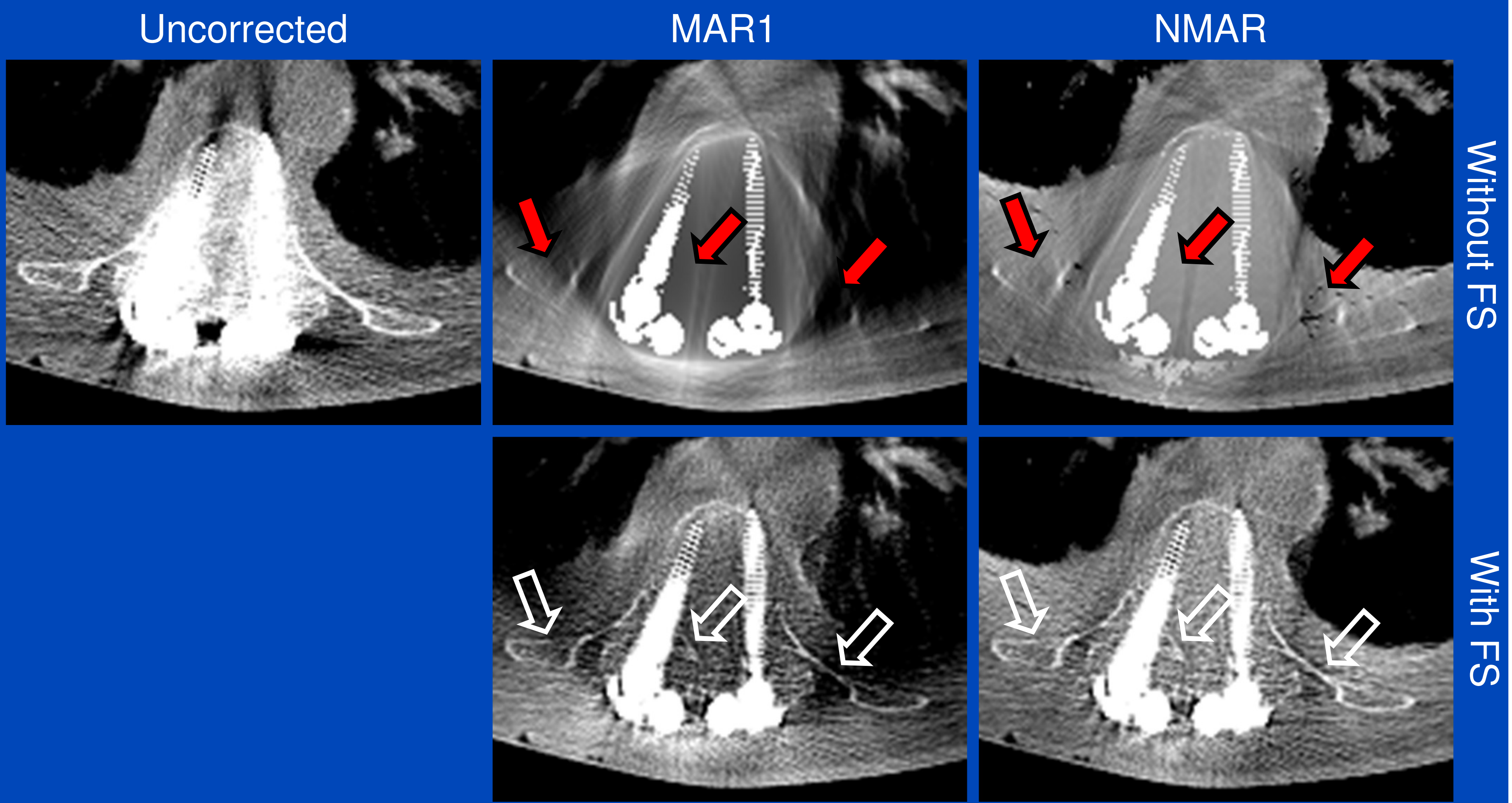
Bone removal (with scanner software), (C=40/W=500).

FSMAR: Scheme



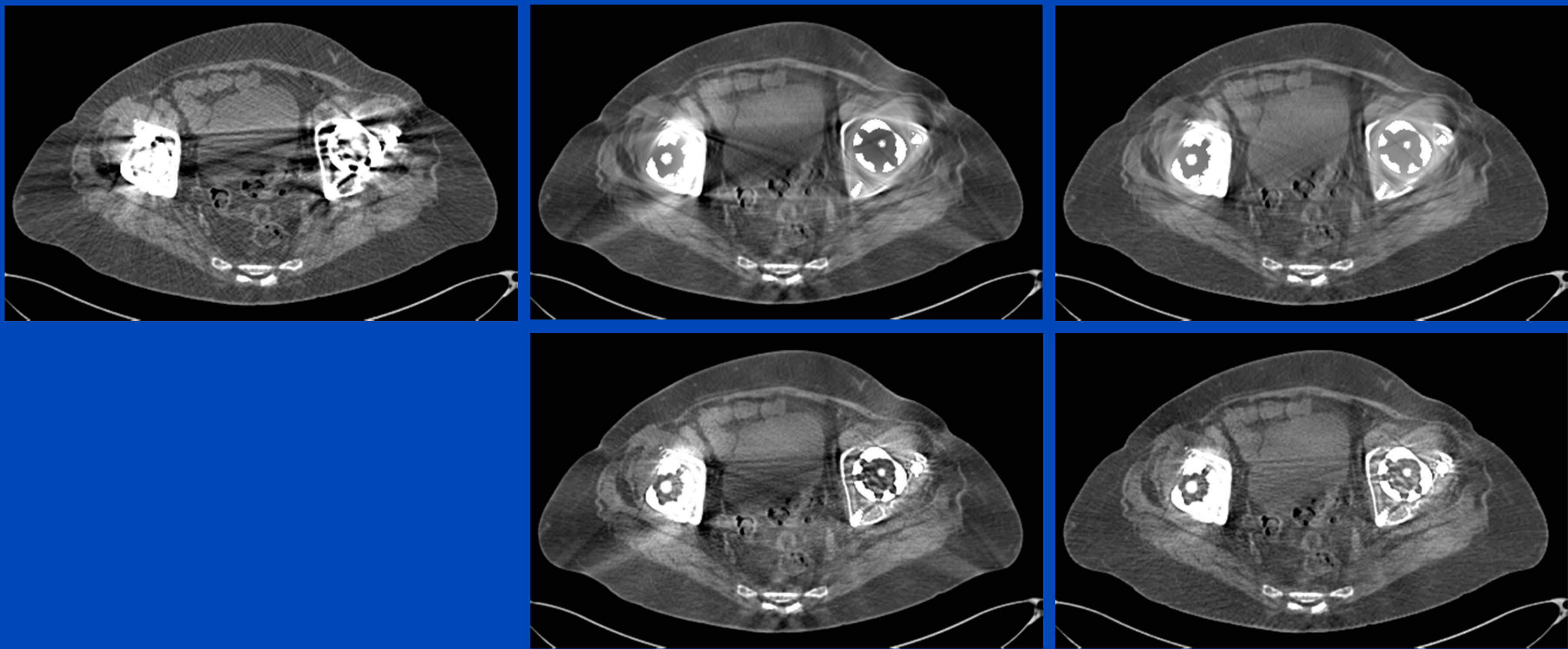
E. Meyer, R. Raupach, M. Lell, B. Schmidt, M. Kachelrieß, "Frequency split metal artifact reduction (FSMAR) in computed tomography", Med.Phys. 39(4):1904-1916, April 2012.

FSMAR: Results



Patient with spine fixation, Somatom Definition, (C=100/W=1000).

FSMAR: Results

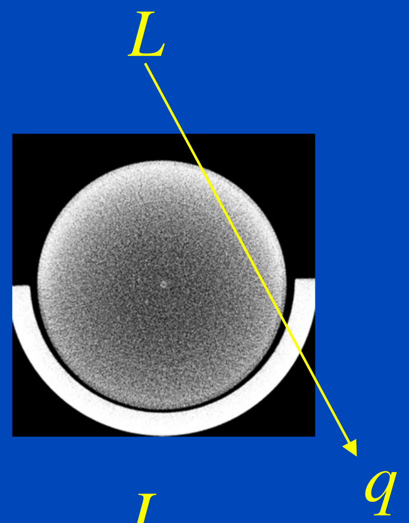


Patient with bilateral hip prosthesis, Somatom Definition Flash, (C=40/W=500).

Conclusions on FSNMAR

- NMAR as a robust MAR basis method for different types of metal implants
- FSMAR for more details close to the implants

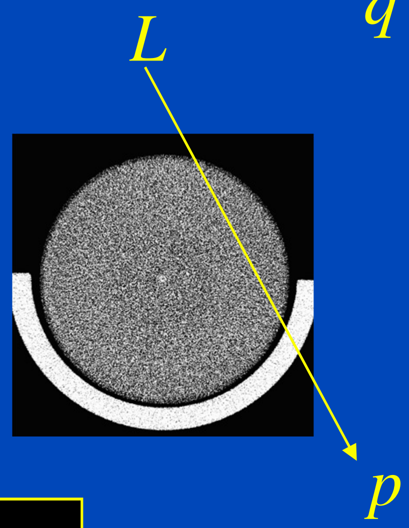
First Order Beam Hardening Correction (Water Precorrection)



- **Measured projection value q**
  - Detected spectrum w(L, E)

$$q(L) = -\ln \int dE\, w(L,E)\, e^{-\int dL\, \mu(\boldsymbol{r},E)}$$

  - Scatter
  - Normalization



- **Ideal monochromatic projection value p**

$$p(L) = \int dL\, \mu(\boldsymbol{r}, E_0)$$

Determine a function *P* such that *p*=*P*(*L*, *q*) corrects for the cupping.

Analytical Cupping Correction

- **Know the detected spectrum**

detector material's attenuation × thickness

primary intensity

$$w(L,E) \propto E\, I(L,E)\,(1-e^{-\mu_D(E)d_D(L)})$$

energy weighting detectors

- **Assume the object to be decomposed as**

$$\mu(\boldsymbol{r},E) = f(\boldsymbol{r})\psi(E)$$

- **such that**

$$q(L) = -\ln \int dE\, w(L,E)\, e^{-p\psi(E)}$$

$$p(L) = \int dL\, f(\mathbf{r})$$

- **Invert to get p**

$$p = P(L,q)$$

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Empirical Cupping Correction (ECC)

- Series expansion of the precorrection function

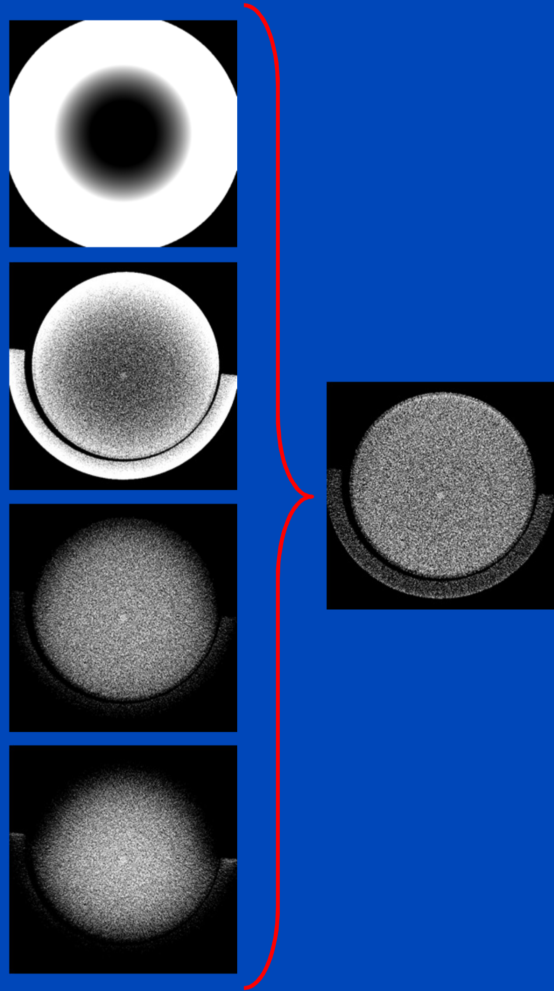
$$p = P(q) = \sum_{n=0}^{N} c_n P_n(q) = \sum_{n=0}^{N} c_n q^n$$

- Go to image domain by reconstructing q^n

$$f_n(\boldsymbol{r}) = \mathsf{R}^{-1} P_n(q) = \mathsf{R}^{-1} q^n.$$

- Find coefficients from

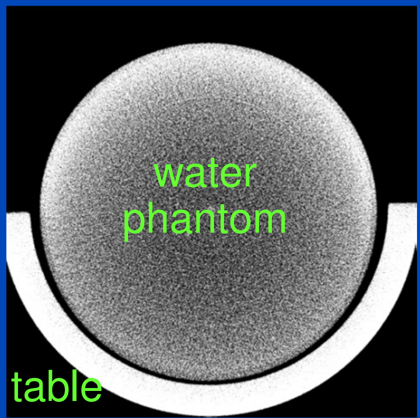
$$f(\boldsymbol{r}) = \mathsf{R}^{-1} p = \mathsf{R}^{-1} P(q) = \sum_{n=0}^{N} c_n f_n(r)$$



M. Kachelrieß et al., "Empirical cupping correction: A first-order raw data precorrection for cone-beam computed tomography", Med. Phys. 33(5):1269-1274, May 2006.

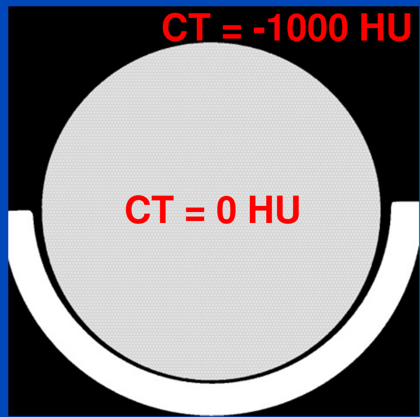
ECC Template Image

$$\int d^2 r\, w(\boldsymbol{r})\,(f(\boldsymbol{r}) - t(\boldsymbol{r}))^2 = \min \quad \textbf{with} \quad f(\boldsymbol{r}) = \sum_{n=0}^{N} c_n f_n(r)$$

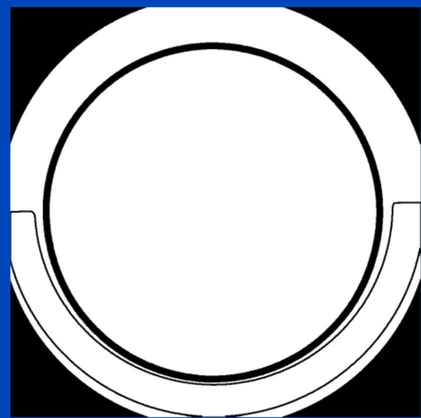


Original image
$f_1(\boldsymbol{r})$

segment and
specify CT-values



Template image
$t(\boldsymbol{r})$

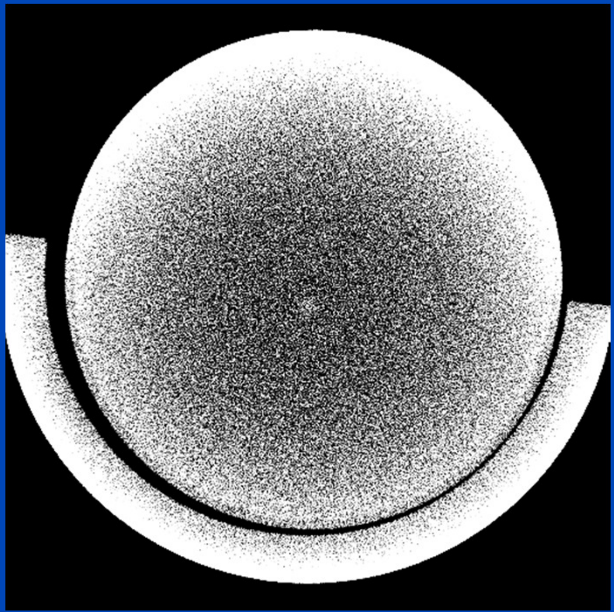


Weight image
$w(\boldsymbol{r})$

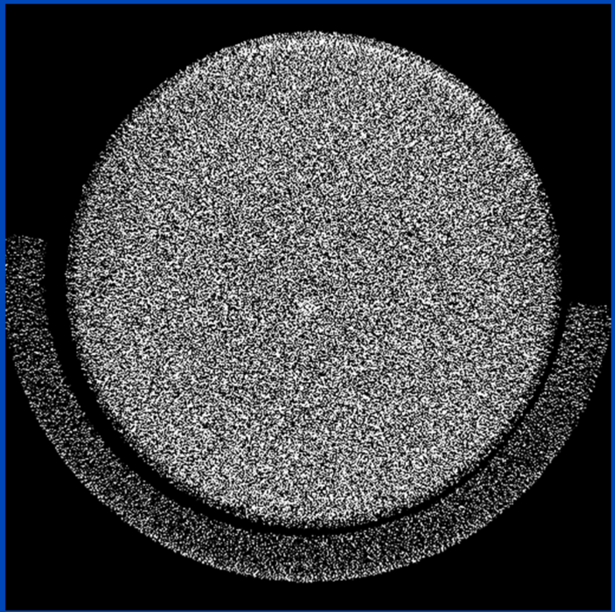
M. Kachelrieß et al., "Empirical cupping correction: A first-order raw data precorrection for cone-beam computed tomography", Med. Phys. 33(5):1269-1274, May 2006.

Results: Water Phantom

Orig (Mean±4Sigma)



ECC (Mean±4Sigma)



M. Kachelrieß et al., “Empirical cupping correction: A first-order raw data precorrection for cone-beam computed tomography", Med. Phys. 33(5):1269-1274, May 2006.

Results: Mouse Scan

No correction (Mean±4Sigma)

ECC (Mean±4Sigma)

M. Kachelrieß et al., "Empirical cupping correction: A first-order raw data precorrection for cone-beam computed tomography", Med. Phys. 33(5):1269-1274, May 2006.

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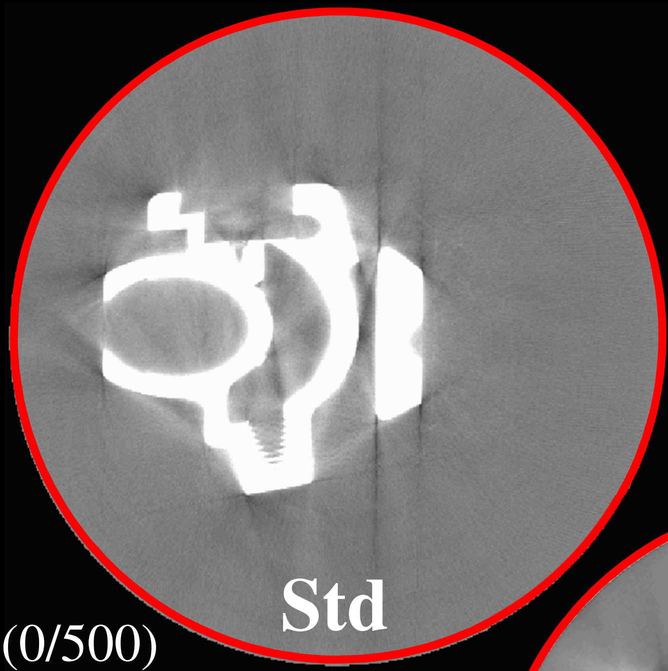
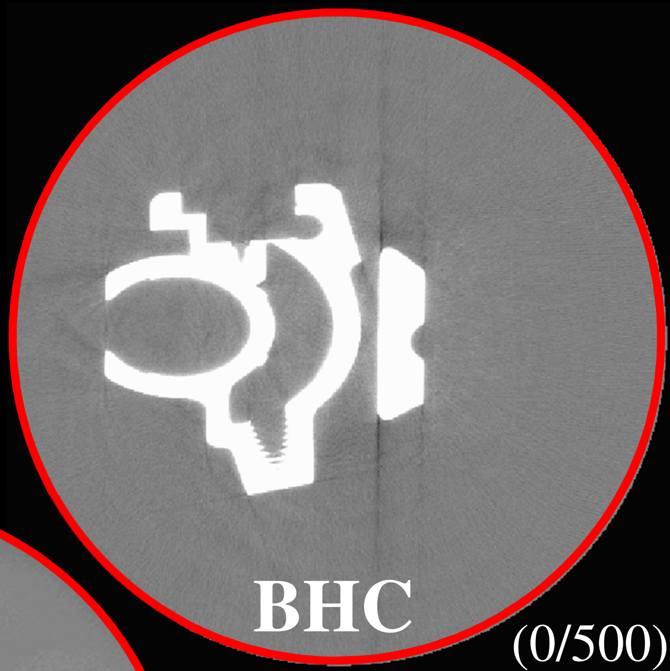
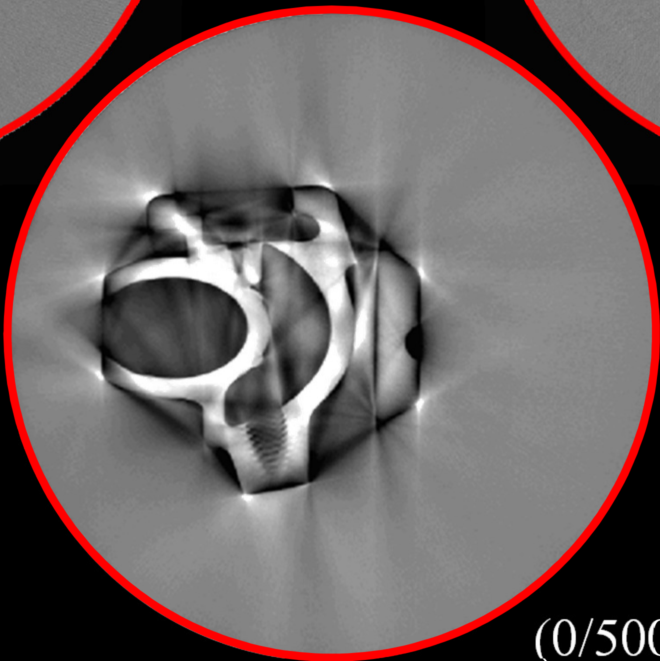


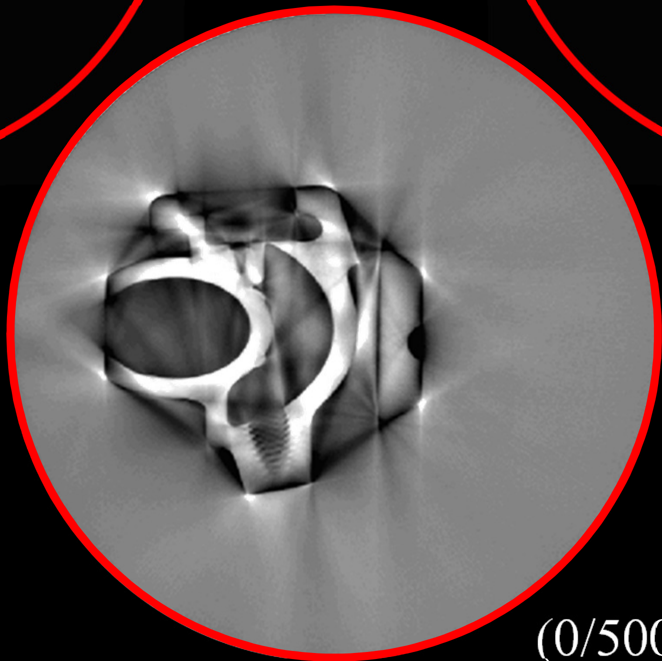




CT Metrology

(1000/200)

(1000/200)



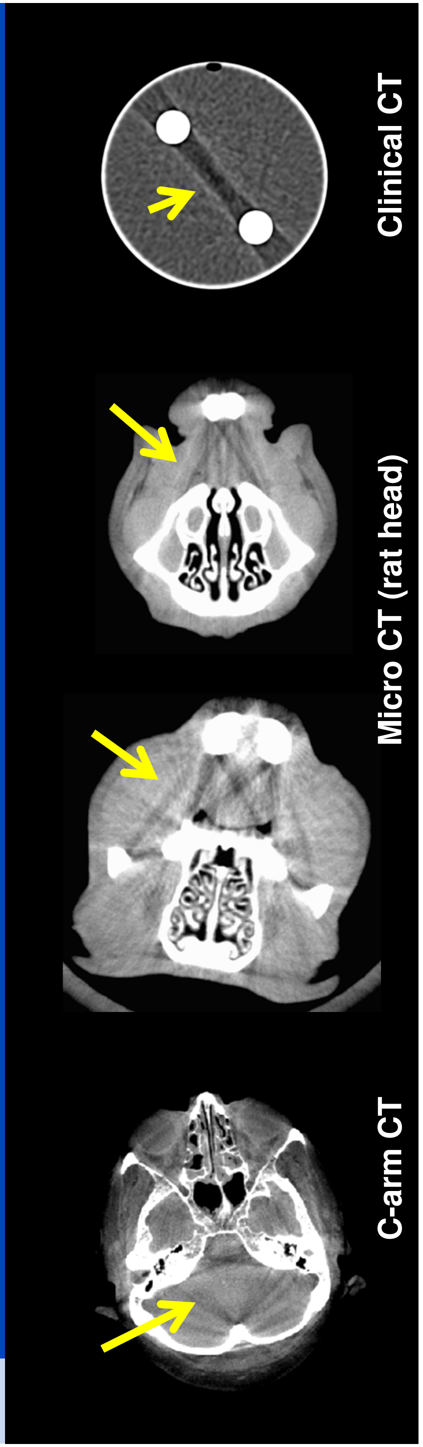
(0/500)

CT Metrology

Higher Order
Beam Hardening Correction

Empirical Beam Hardening Correction (EBHC)

- **Requirements/Objectives**
  - Empirical correction of <u>higher order</u> beam hardening effects
  - No assumptions on attenuation coefficients, spectra, detector responses or other properties of the scanner
  - Image-based and system-independent method
- **Overview of correction steps**
  - Forward project segmented bone volume to obtain artificial rawdata
  - Pass the artificial rawdata through basis functions
  - Reconstruct the basis functions
  - Linearly combine the correction volumes and the original volume using flatness maximization



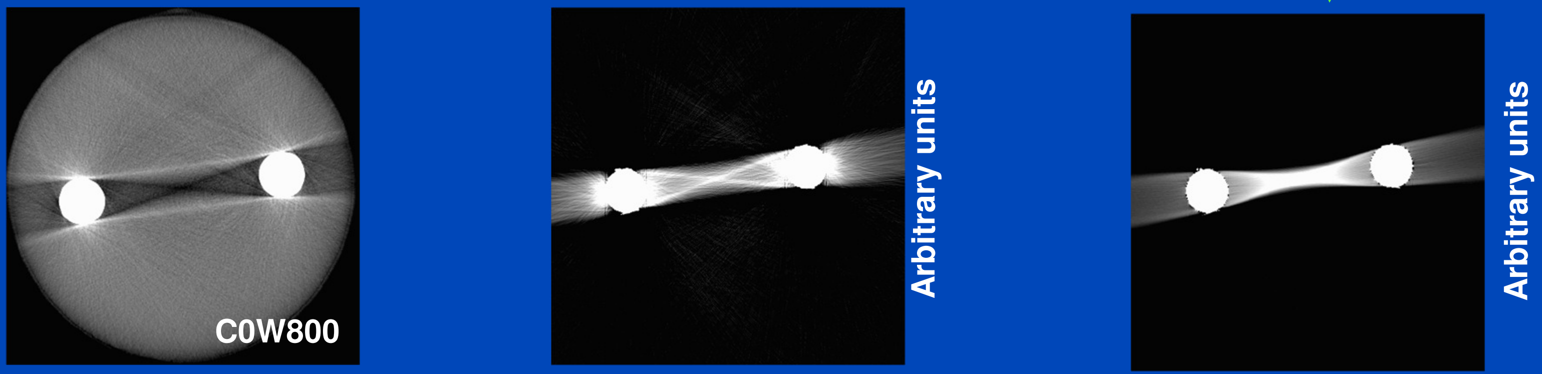
Y. Kyriakou, E. Meyer, D. Prell, and M. Kachelrieß, "Empirical beam hardening correction (EBHC) for CT", Med. Phys. 37(10):5179-5187, October 2010.

EBHC Details

- We solve for $\hat{p}_1(r)$ using a series expansion

$$\hat{p}_1(p_0, p_2) = \sum_{ij} c_{ij} p_0^i p_2^j = p_0 + c_{01} p_2 + c_{11} p_0 p_2 + c_{02} p_2^2 + \ldots$$

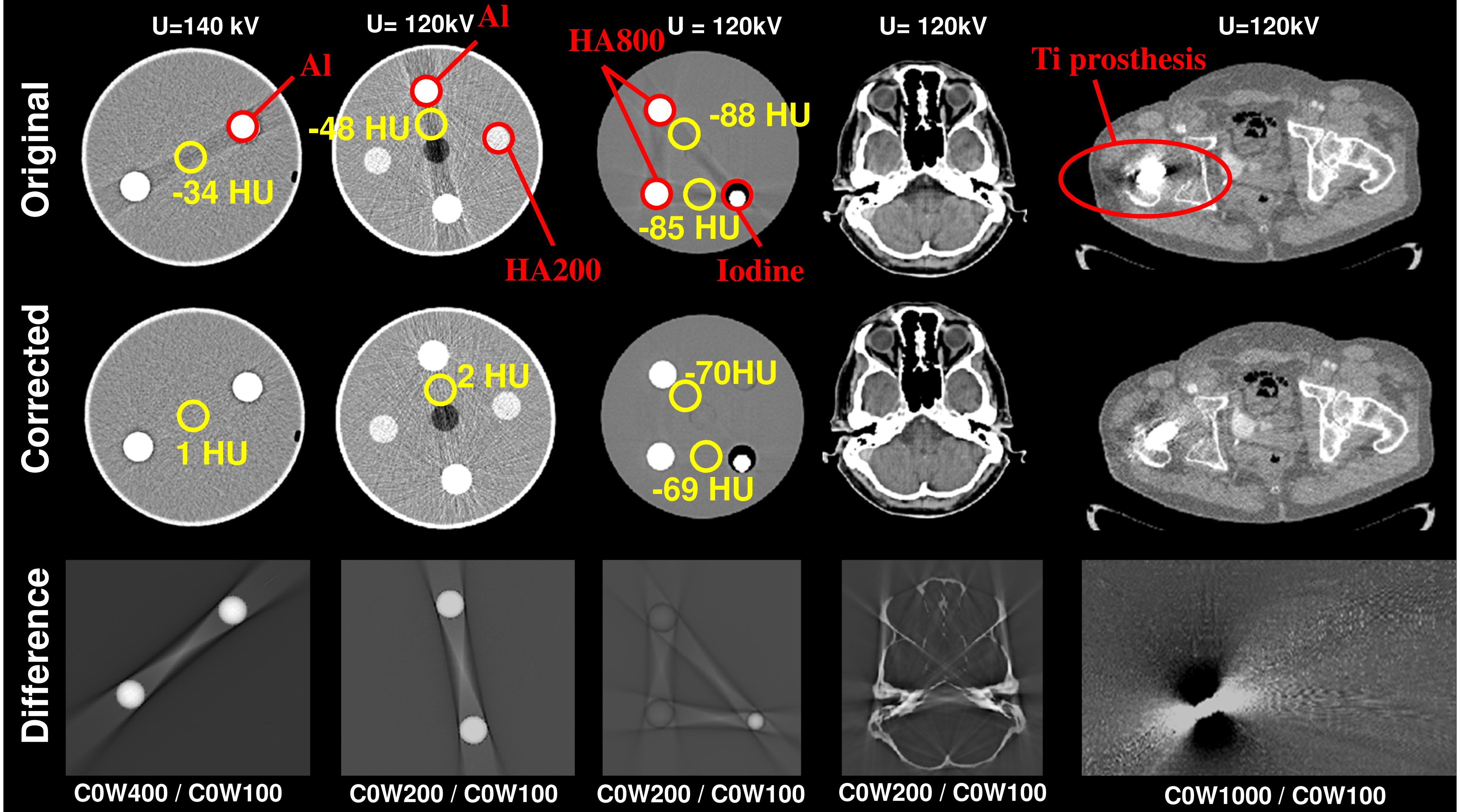
$\mathbf{R}^{-1}$ $\mathbf{R}^{-1}$ $\mathbf{R}^{-1}$



- Empirically find c_{11} and c_{02} to correct initial image by flatness maximization

Y. Kyriakou, E. Meyer, D. Prell, and M. Kachelrieß, "Empirical beam hardening correction (EBHC) for CT", Med. Phys. 37(10):5179-5187, October 2010.

EBHC for Clinical CT



Y. Kyriakou, E. Meyer, D. Prell, and M. Kachelrieß, "Empirical beam hardening correction (EBHC) for CT", Med. Phys. 37(10):5179-5187, October 2010.

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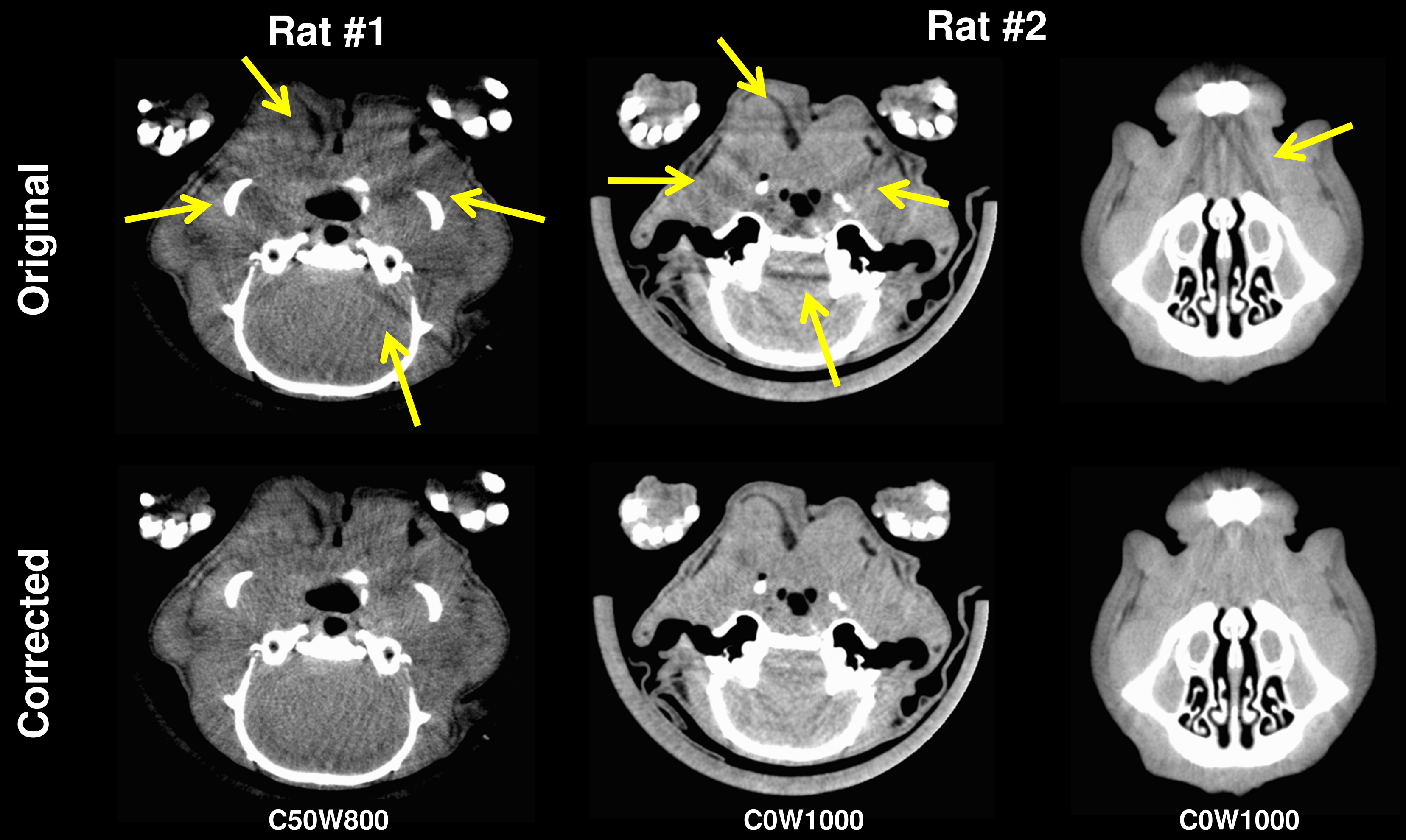
EBHC for Micro CT



Y. Kyriakou, E. Meyer, D. Prell, and M. Kachelrieß, “Empirical beam hardening correction (EBHC) for CT", Med. Phys. 37(10):5179-5187, October 2010.

dkfz.

Conclusions on Empirical Cupping and Beam Hardening Corrections

- X-ray spectra need not necessarily be known
- Scatter is implicitly accounted for as well
- ECC and EBHC are robust methods that work well in clinical CT and that also have been applied to some industrial situations.

Scatter Correction

- **Remove or prevent scattered radiation (anti scatter grid, slit scan, large detector distance, …)**
- **Compute scatter to subtract it (convolution-based, Monte Carlo-based, …)**
- **Measure scatter distribution and subtract it (collimator shadow, beam blockers, primary modulators, …)**

- **Literature:**

- E.-P. Rührnschopf and K. Klingenbeck, *"A general framework and review of scatter correction methods in x–ray cone–beam computerized tomography. Part 1: Scatter compensation approaches,"* Med. Phys., vol. 38, pp. 4296–4311, July 2011.
- E.-P. Rührnschopf and K. Klingenbeck, *"A general framework and review of scatter correction methods in x–ray cone beam CT. Part 2: Scatter estimation approaches,"* Med. Phys., vol. 38, pp. 5186–5199, Sept. 2011.

Basis Images EBHC + ESC

Beam hardening basis images[1]

p : beam hardening-corrected projections

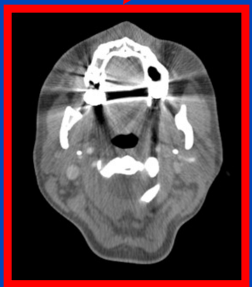
p_0 : water-precorrected projections of tissue

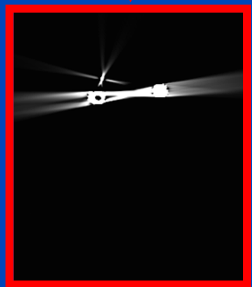
p_m : projections of metal

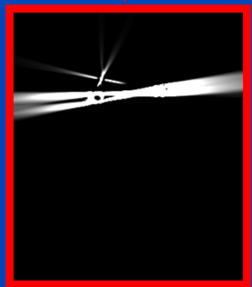
$$p(p_0, p_m) = \sum_{ij} c_n p_0^i p_m^j =$$

$$= p_0 + c_1 p_m + c_2 p_0 p_m + c_3 p_m^2 + \ \ldots$$

R^{-1} R^{-1} R^{-1}







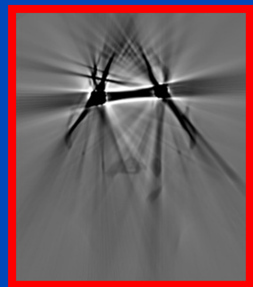
Scatter basis images[2]

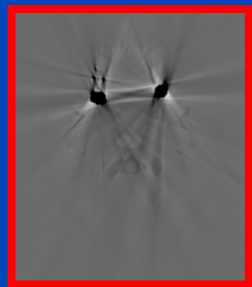
I_S : scatter intensity

I_F : forward scatter intensity

K : scatter kernel

$$I_S(a,b,c) = I_F(a) * K(b,c)$$

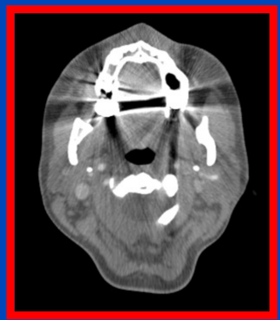
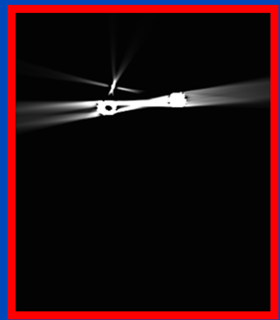
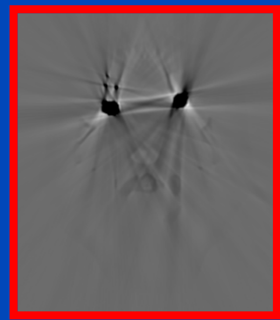
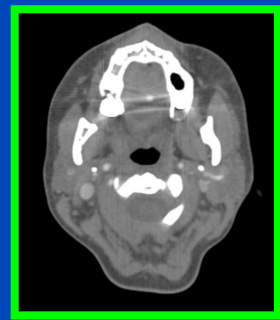




[1] Y. Kyriakou, E. Meyer, D. Prell, and M. Kachelrieß, “Empirical beam hardening correction for CT”, MedPhys 37: 5179-5187, 2010.

[2] B. Ohnesorge et al., “Efficient object scatter correction algorithm for third and fourth generation CT scanners”, EuRad 9:563-569, 1999.

EBHSC: Scheme

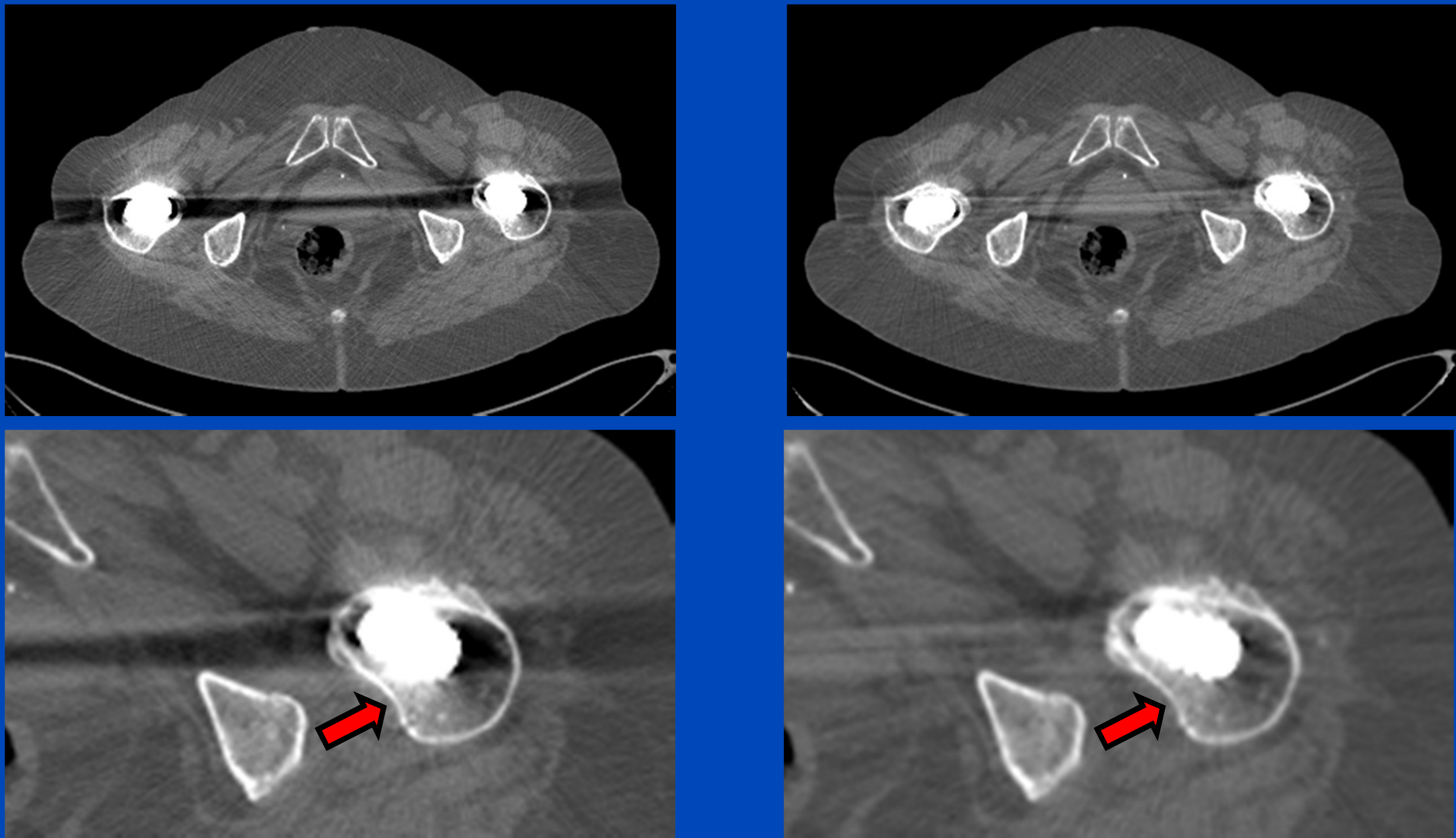
 $+c_1\cdot$  $+\ldots+c_N\cdot$  $=$ 

$$c_1 \ldots c_N = \arg\min_{c_1 \ldots c_N} \mathrm{f}_{\mathrm{cost}}\left(U - \sum_{i=1}^{N} c_i B_i\right)$$

E. Meyer, C. Maaß, M. Baer, R. Raupach, B. Schmidt, and M. Kachelrieß, "Empirical Scatter Correction (ESC) ", IEEE Medical Imaging Conference Record 2010:2036-2041, November 2010.

EBHSC: Results

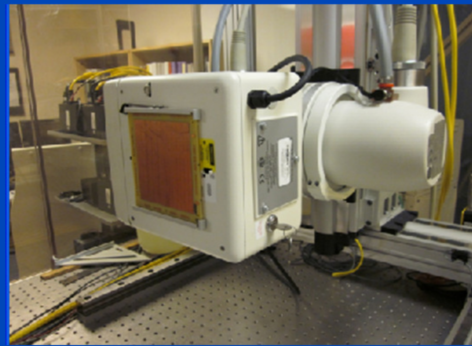
Uncorrected image | EBHSC image



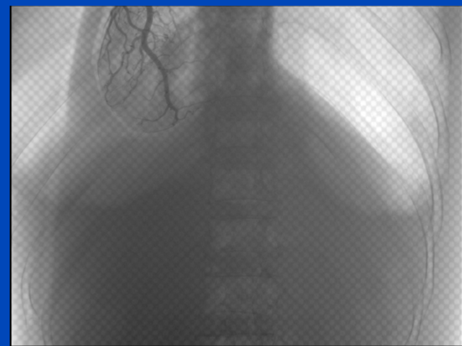
Patient with bilateral hip prosthesis, Siemens Somatom Definition (C=100/W=1000).

Primary Modulation-based Scatter Estimation (PMSE)

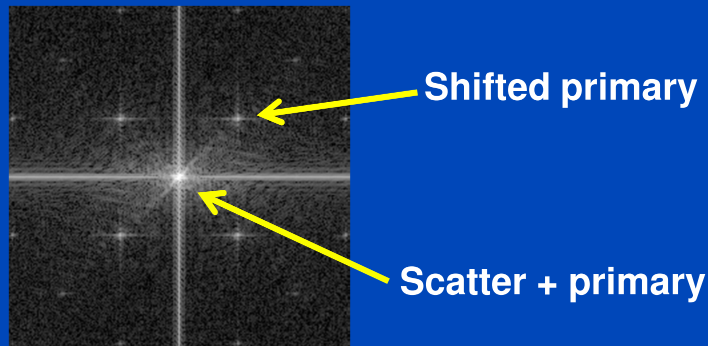
- **Idea: Insert a high frequency modulation pattern between the source and the object scanned**



- **Rationale: The primary intensity is modulated. The scatter is created in the object and only consists of low frequency components.**



- **Method: Estimate low frequency primary without scatter by Fourier filtering techniques**



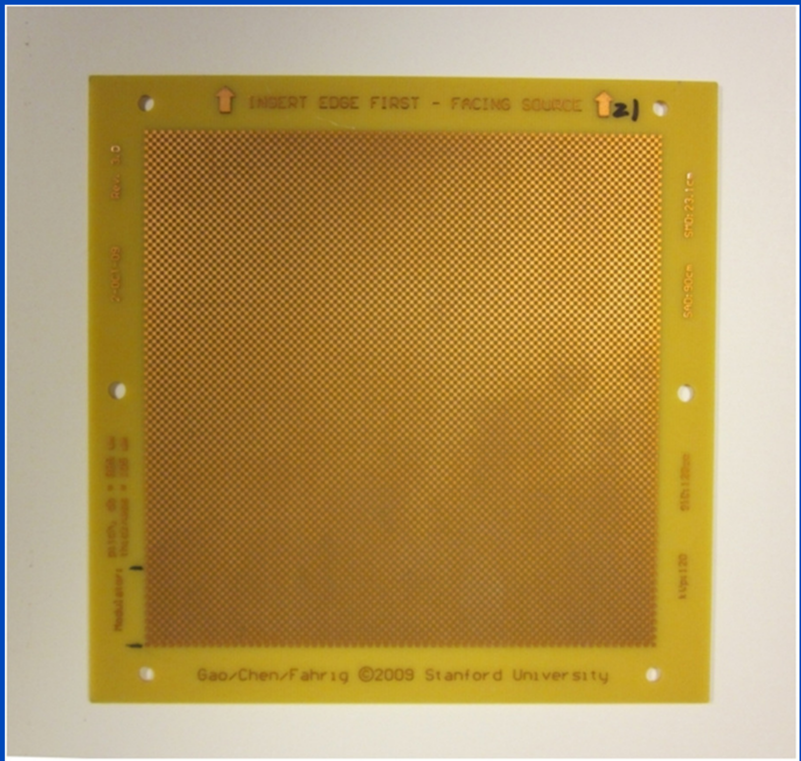
L. Zhu, R. N. Bennett, and R. Fahrig, "Scatter correction method for x–ray CT using primary modulation: Theory and preliminary results," IEEE Transactions on Medical Imaging, vol. 25, pp. 1573–1587, Dec. 2006.

Primary Modulation-based Scatter Estimation (PMSE[1])

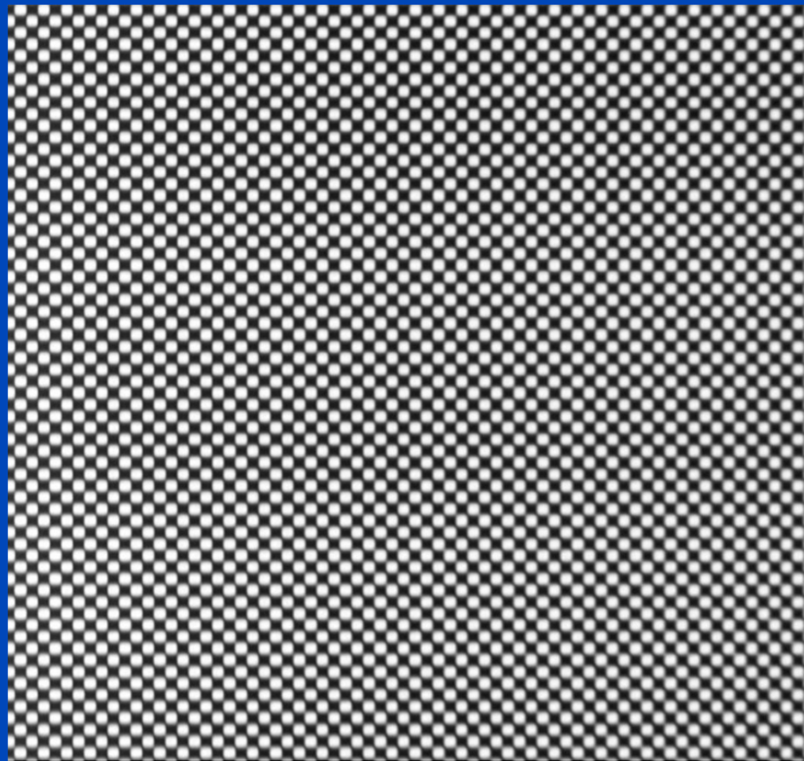
- **Advantages:**
  - Non-destructive measurement of the scatter distribution
  - Works with high accuracy on laboratory setups
  - Corrected projection data can be used for projective imaging (fluoroscopy) or for tomographic reconstruction
- **Drawbacks:**
  - Sensitive to non-linearities due to polychromaticity of x-rays. Ring artifacts are introduced[1]. Can be resolved using ECCP[2].
  - Requires exact rectangular pattern on the detector. Very sensitive to non-idealities of the projected modulation pattern (blurring, distortion, manufacturing errors of the modulator). Can be resolved using iPMSE[3].

[1]H. Gao, L. Zhu, and R. Fahrig. *Modulator design for x-ray scatter correction using primary modulation: Material selection.* Med. Phys. 37:4029–4037, 2010.
[2]R. Grimmer, R. Fahrig, W. Hinshaw, H. Gao, and M. Kachelrieß. *Empirical cupping correction for CT scanners with primary modulation (ECCP)*. Med. Phys. 39:825-831, 2012.
[3]L. Ritschl, R. Fahrig, and M. Kachelrieß, Robust primary modulation-based scatter estimation for cone-beam CT. IEEE NSS/MIC proceedings, 2012.

Modulator



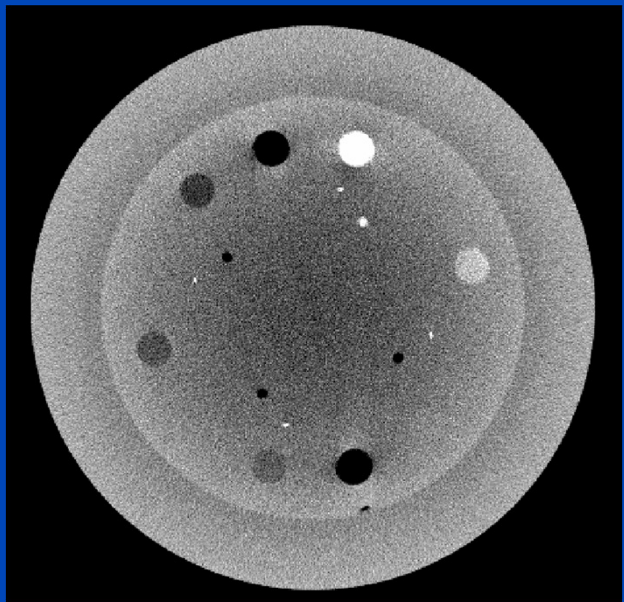
Photograph of the copper modulator



Projection image of the modulator

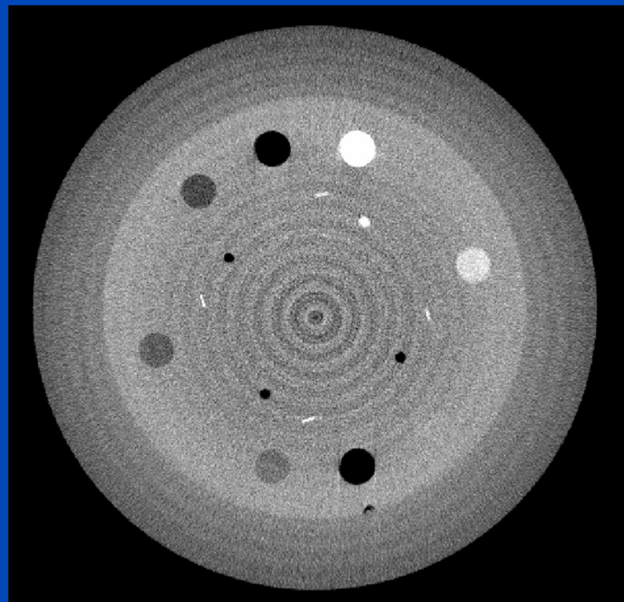
Primary Modulator Introduces Beam Hardening

- The primary modulator introduces high frequency variations of the incident x-ray spectrum.
- These variations show up as ring artifacts in the reconstructed images[1,2,3].



Scan without modulator, no scatter correction

(0 HU, 500 HU)



Scan with modulator, after PMSE correction

[1]Gao et al. MedPhys 37(2):934-946, 2010. [2]Gao et al. Proc. SPIE 7622, 2010. [3]Gao et al. MedPhys 37(8):4029-4037, 2010.

ECCP Idea

- **Perform a scan of a homogenous test phantom and obtain:**

$$p(\alpha,u,v)=\sum_{ij} c_{ij} M^i(\alpha,u,v) q^j(\alpha,u,v)$$

- **The unkown coefficients are then determined by minimizing**

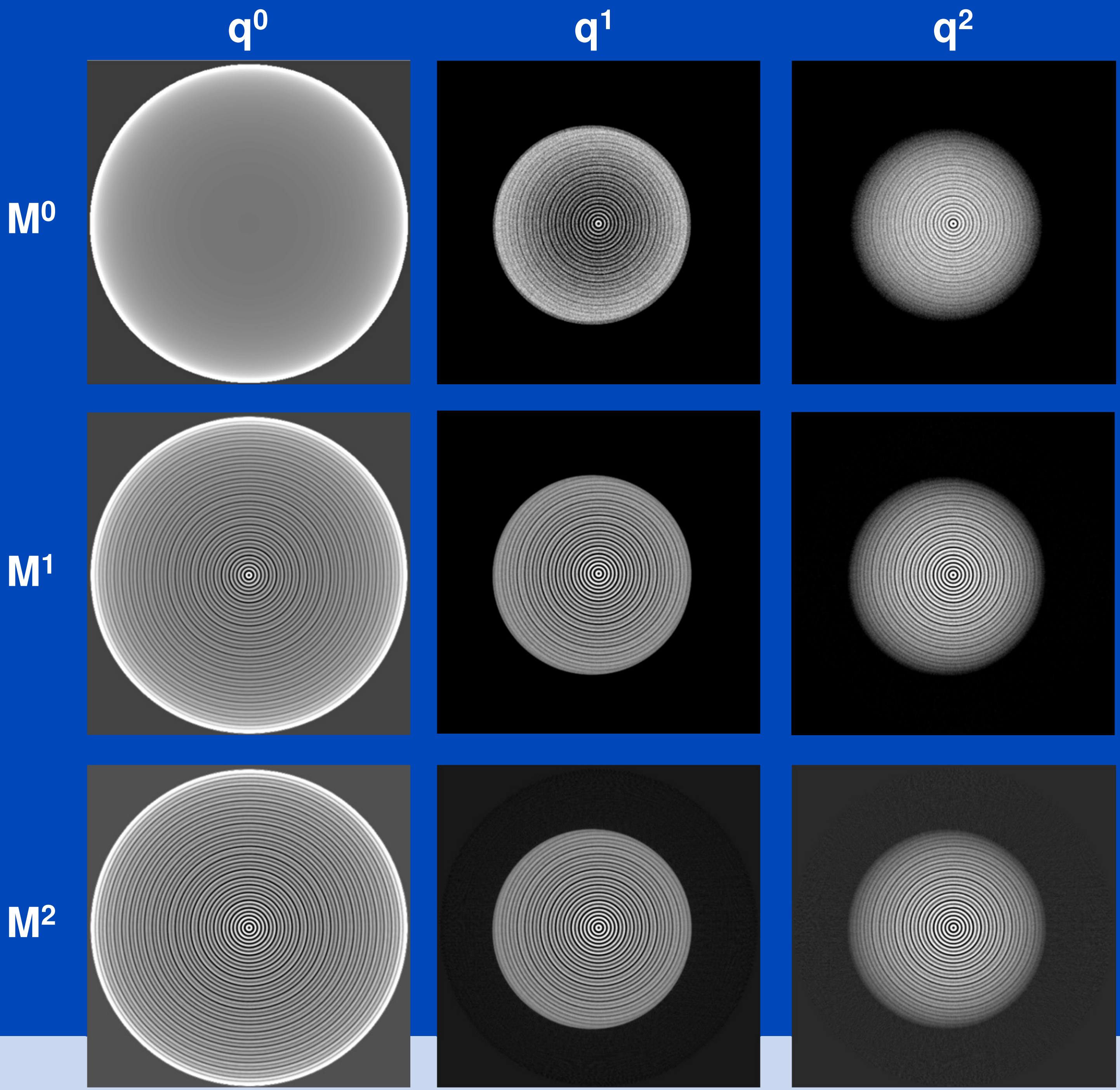
$$\int d^3 w(\mathbf{r})\big(f(\mathbf{r})-t(\mathbf{r})\big)^2$$

with

$$f(\mathbf{r})=\sum_{ij} c_{ij} f_{ij}(\mathbf{r})$$

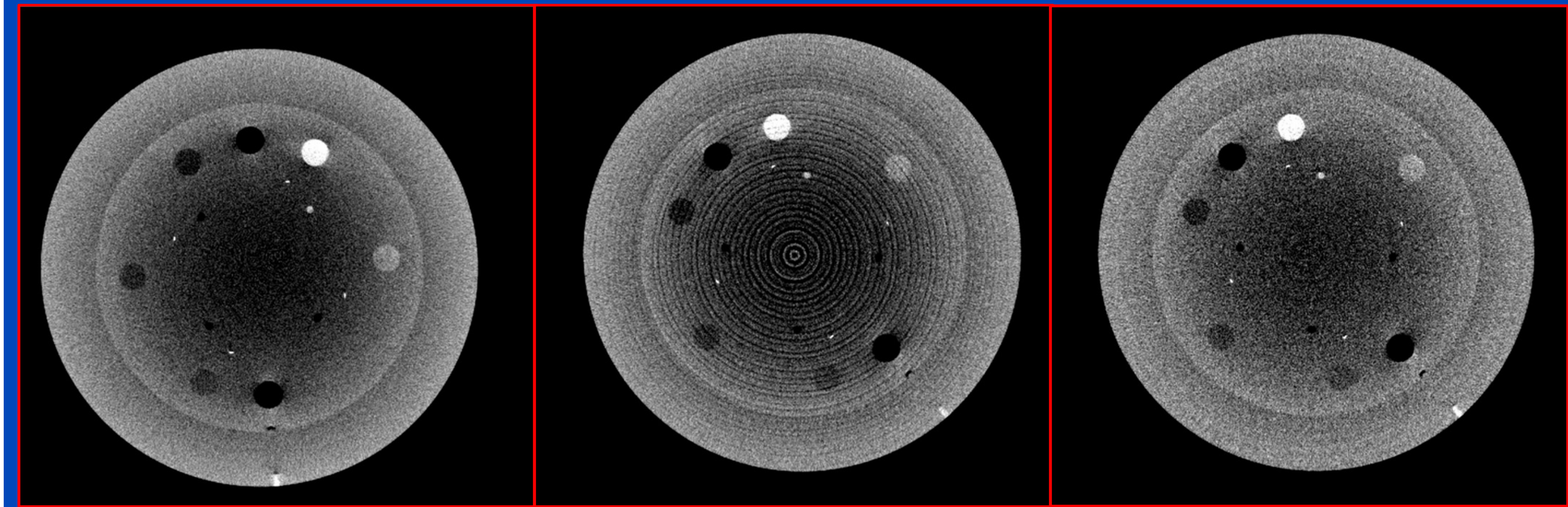
where the basis volumes are defined as

$$f_{ij}(\mathbf{r})=R^{-1}\big(M^i(\alpha,u,v)q^j(\alpha,u,v)\big)$$


q0
q1
q2
M0
M1
M2

Catphan Phantom

Measurement without Modulator | Measurement with Modulator | ECCP–corrected

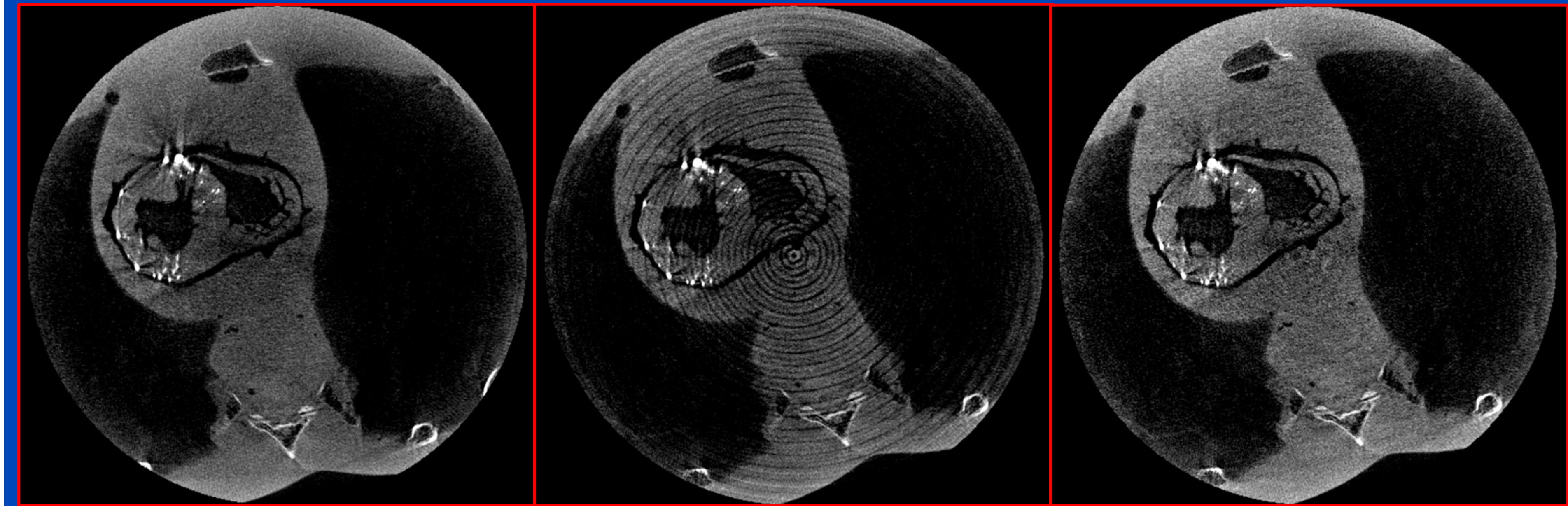


C = 0 HU, W = 500 HU

ECCP coefficients obtained from the water phantom calibration scan.

dkfz.

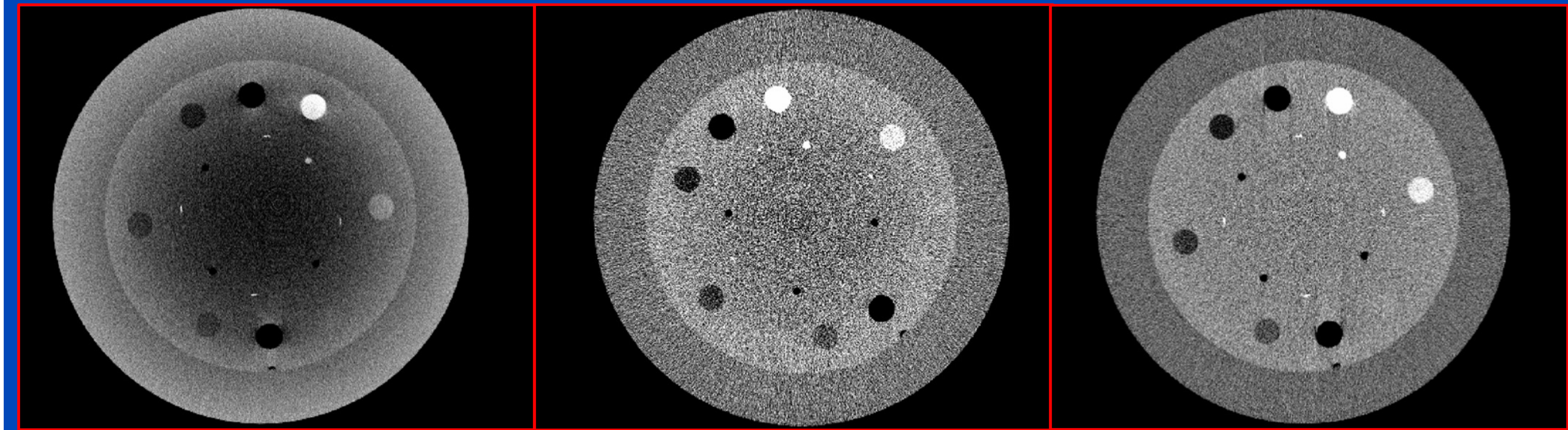
Thorax Phantom



C = 0 HU, W = 1000 HU

Combined correction with PMSE and ECCP

Measurement without Modulator	PMSE+ECCP–corrected	Slitscan without modulator



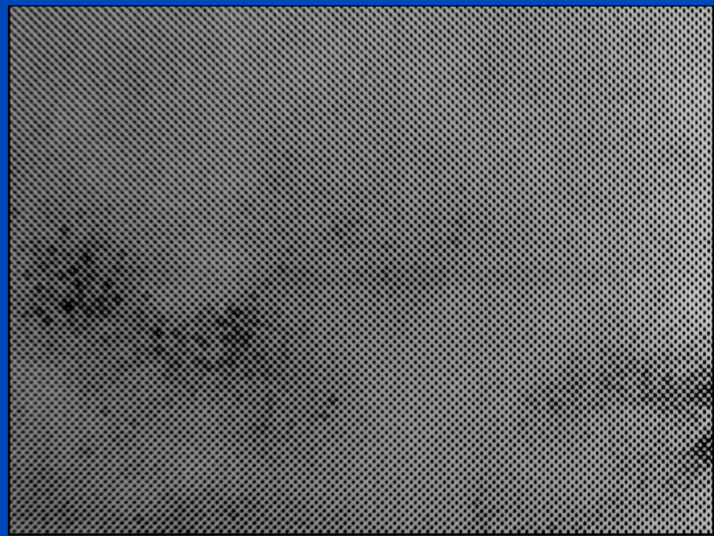
C = 0 HU, W = 500 HU

ECCP coefficients obtained from the PMSE-corrected water phantom calibration scan.

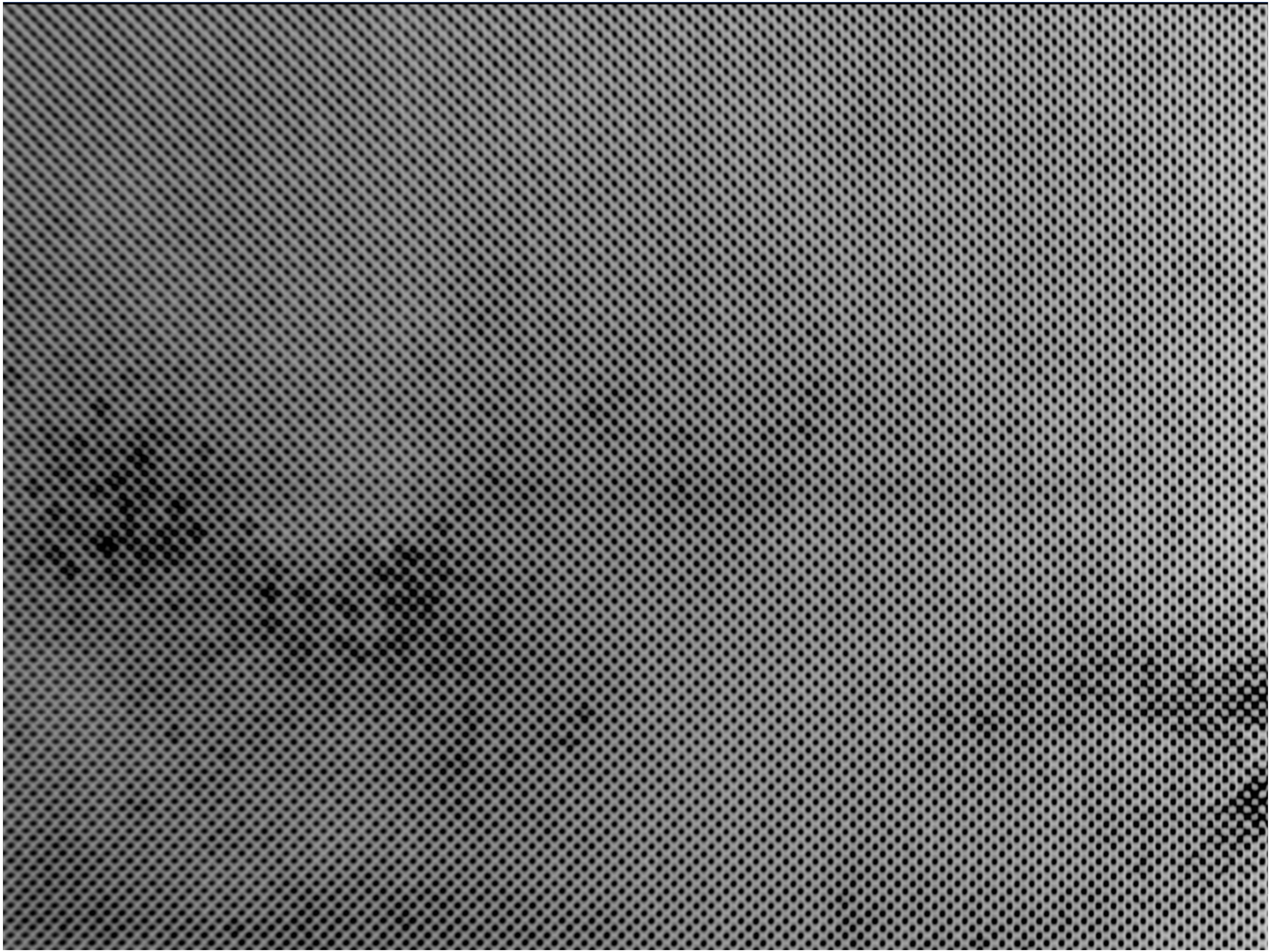
Aim of iPMSE

Create a robust scatter estimation method which is able to estimate the scatter distribution with high accuracy using a modulator with an arbitrary high frequency pattern.

"Ideal" modulator (projection image of a copper modulator)



Non-ideal modulator (projection image of the erbium modulator)



iPSME Idea

- **Subject to $H \cdot \boldsymbol{c}_\mathrm{s} = 0$ solve:**

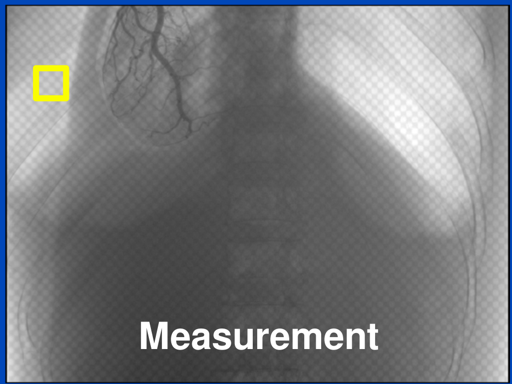
$$C(\boldsymbol{c}_\mathrm{s}) = \|\nabla \cdot M^{-1}(\boldsymbol{c}_\mathrm{m} - \boldsymbol{c}_\mathrm{s})\|_1$$

- **Assumption:**
  In a sufficiently small and sufficiently large sub image the constraint can be satisfied by assuming c_s = const.

- **Solution:**
  Solve cost function for each possible sub image separately.

- **Finally do:**

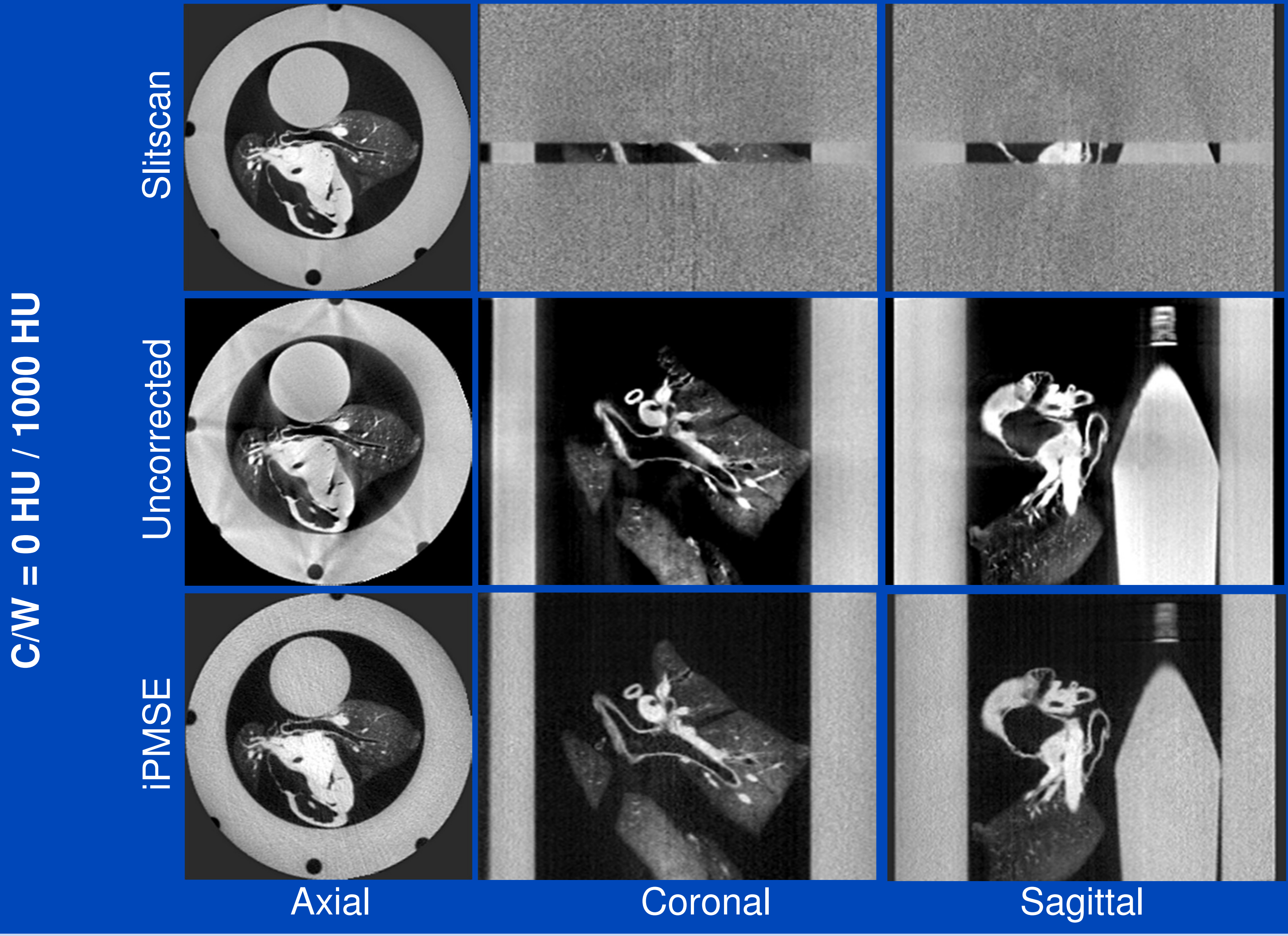
$$\boldsymbol{c}_\mathrm{p} = M^{-1}(\boldsymbol{c}_\mathrm{m} - \boldsymbol{c}_\mathrm{s})$$



Measured Intensity

iPMSE Estimation

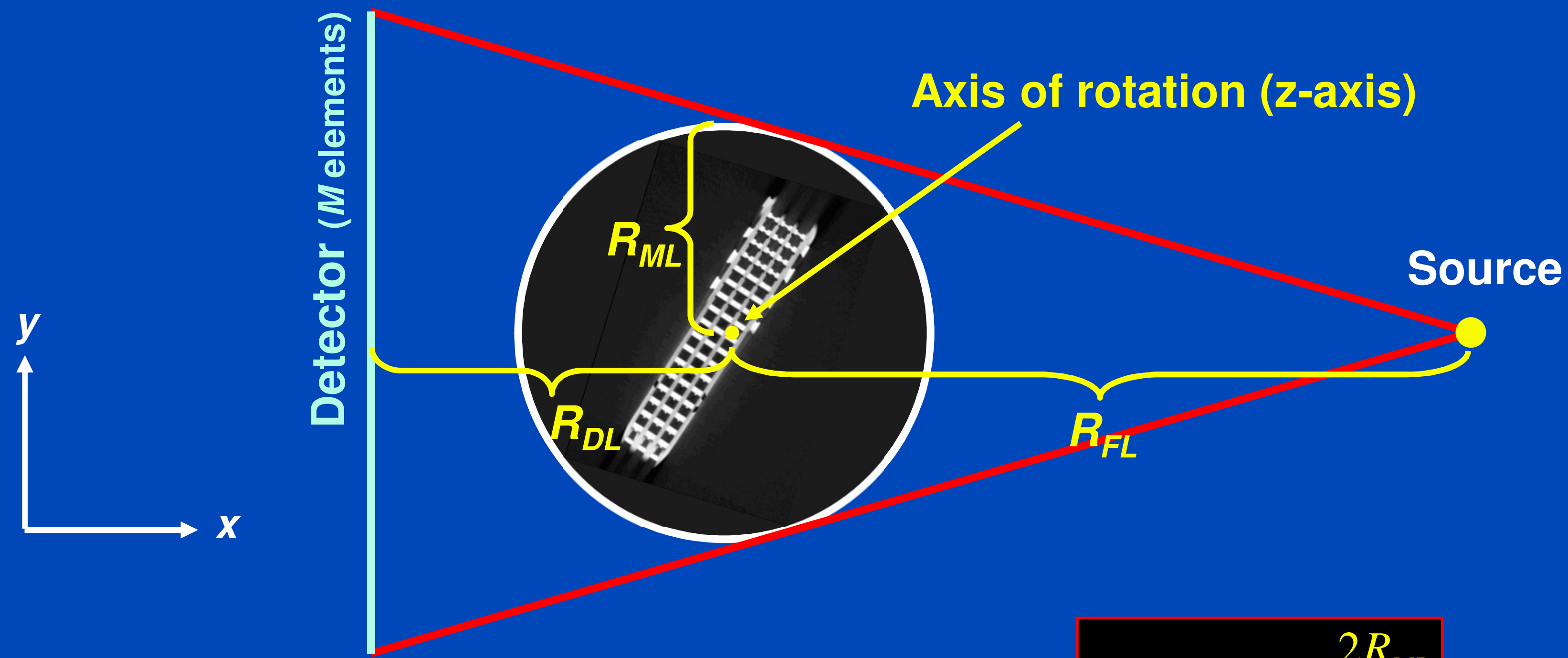
Lung Phantom Scan



Conclusions on Novel Scatter Correction Methods

- Empirical scatter correction (ESC) does not require a well-calibrated physical model
- PMSE estimates the scatter contribution during the measurement by modulating a known aperture into the images. Due to iPMSE and ECCP this aperture can be chosen rather arbitrarily, e.g. it could also be a random structure such as a foam or a coil.

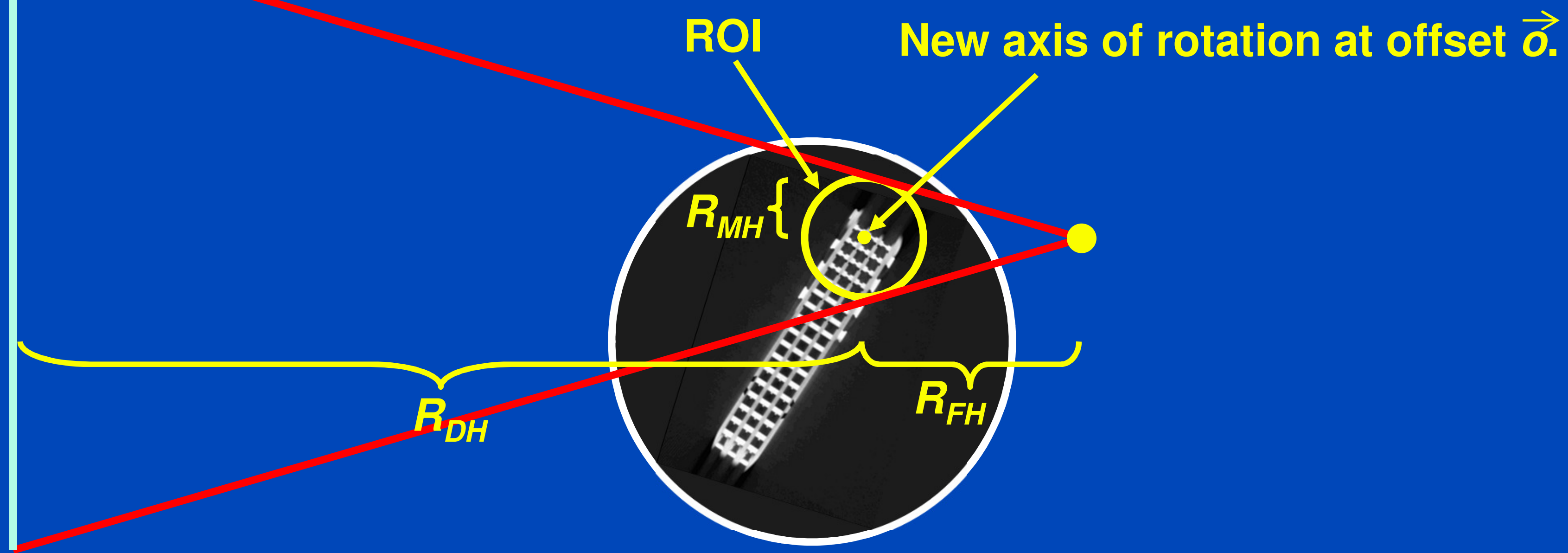
ROI Tomography



$$\text{Resolution} \cong \frac{2R_{ML}}{M}$$

$$\text{Zoom factor} = \frac{R_{FL} + R_{DL}}{R_{FL}}$$

ROI Tomography



Problems:

1. Data of ROI scan are truncated.
2. Source may not cover 360° or not even 180°.

$$\text{Resolution} \cong \frac{2R_{MH}}{M}$$

$$\text{Zoom factor} = \frac{R_{FH} + R_{DH}}{R_{FH}}$$

Aim

Achieve the same high resolution inside an ROI as it would be possible for a small object.

Idea of a "simple" ROI scan:

1. **Perform both an overview scan and an ROI scan.**
2. **Use the data of the overview scan to complete the data of the ROI scan.**

Materials and Methods

Three reconstruction methods:

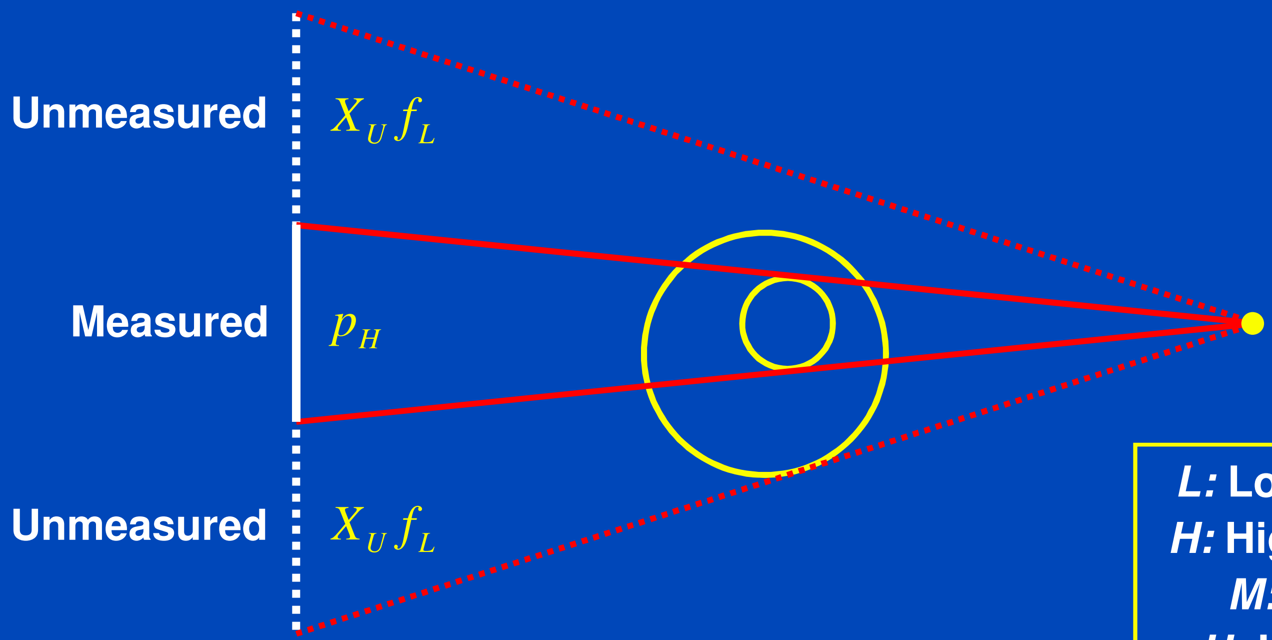
- **Data completion (gold standard)**
- **Data filtering (new)**
- **Data weighting (new)**

ROI scans were performed with a state-of-the-art dimensional CT scanner TomoScope HV Compact (Werth Messtechnik GmbH, Gießen, Germany).

Variable distances
source ↔ object and source ↔ detector.

⇒ Arbitrary, object-dependent zoom factor.

Data Completion Method



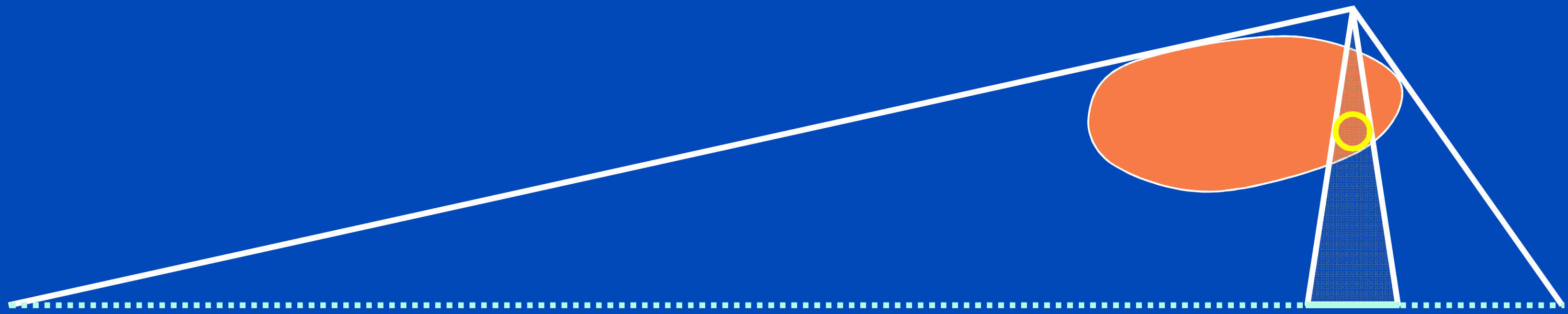
L: **Low resolution scan**
H: **High resolution scan**
M: **Measured data**
U: **Unmeasured data**

1. **Standard reconstruction of the overview scan.** $f_L = X_L^{-1} p_L$
2. **Virtually expand the detector of the ROI scan.** $X_H = X_M + X_U$
3. **Get missing data of the ROI scan by forward projection of the overview volume.** $f_H = X_H^{-1}(p_H + X_U f_L)$

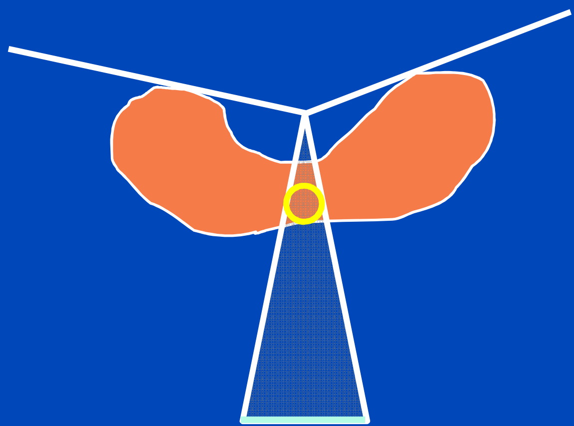
Data Completion Method

Possible problems for flat detectors:

- **Virtual detector might become VERY large.**



- **Fan angle might become > 180°.**

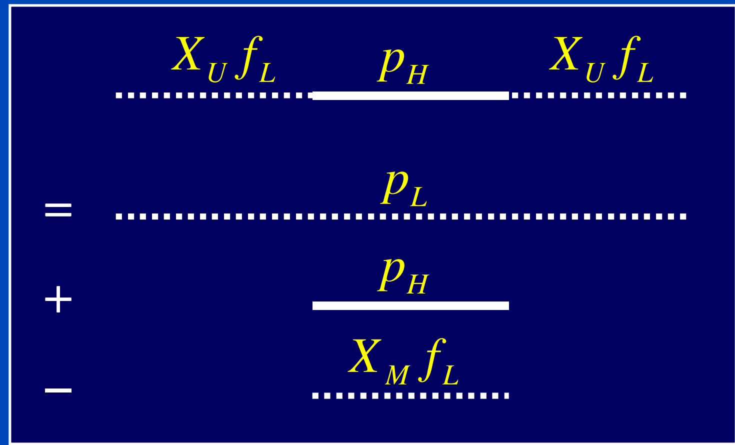


dkfz.

Data Filtering Method

We start from the data completion method:

$$f_H = X_H^{-1}(p_H + X_U f_L)$$



Using $X_U = X_H - X_M$

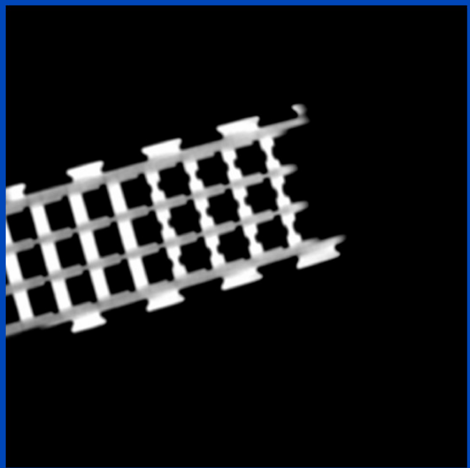
we get

$$f_H = X_H^{-1}(p_H + X_H f_L - X_M f_L)$$
$$= f_L + X_H^{-1}(p_H - X_M f_L)$$

Subtracting the low frequencies equates high-pass filtering:

$$f_H = f_L + X_H^{-1}(h * p_H)$$

Data Filtering Method



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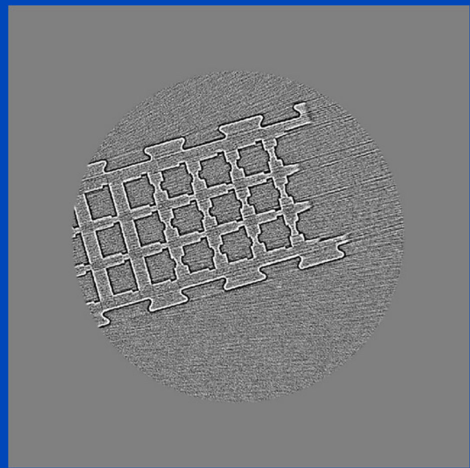

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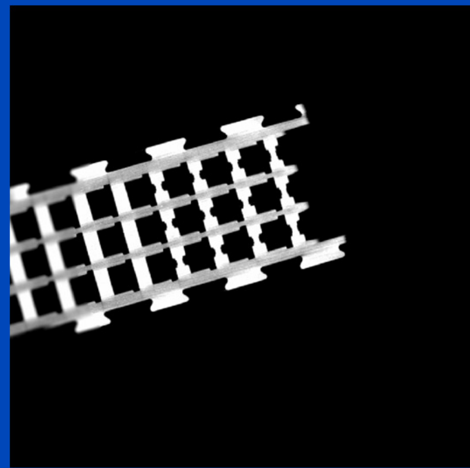
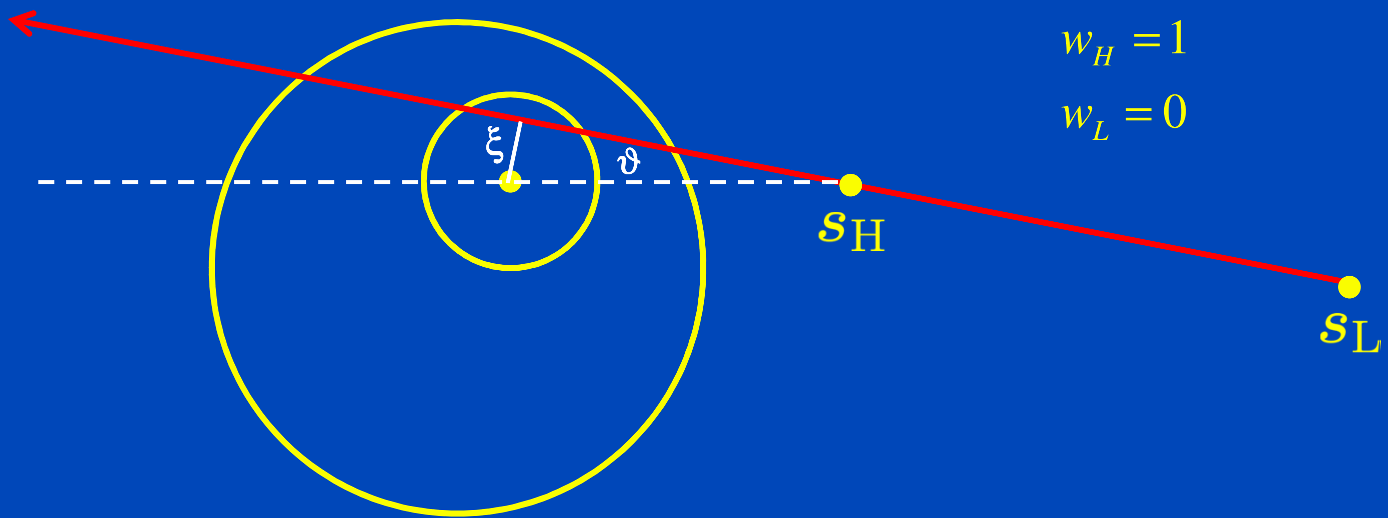


$$f_L \quad + \quad X_H^{-1}(h * p_H) \quad = \quad f_H$$

Data Weighting Method

Perform appropriate weighting to overview and ROI scan and add the reconstructed images:

$$f_H = X_L^{-1}(p_L w_L) + X_H^{-1}(p_H w_H)$$



Example:

$w_H = 1$

$w_L = 0$

Data Weighting Method

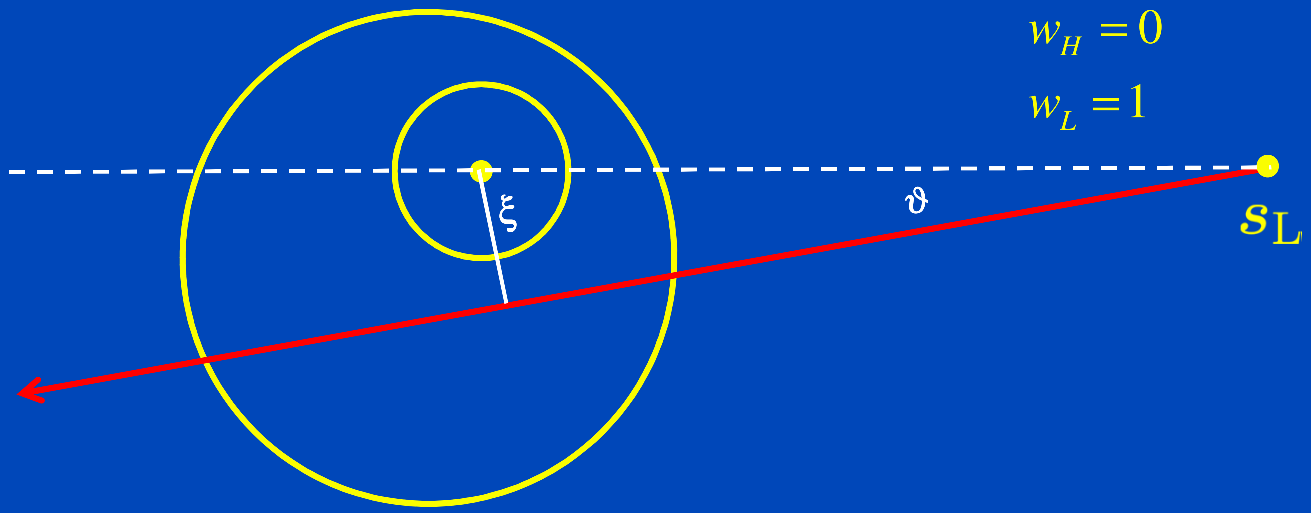
Perform appropriate weighting to overview and ROI scan and add the reconstructed images:

$$f_H = X_L^{-1}(p_L w_L) + X_H^{-1}(p_H w_H)$$

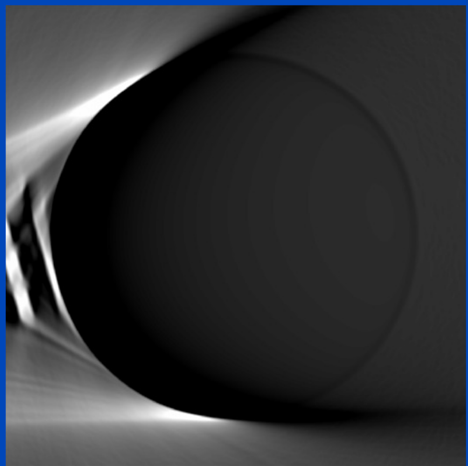
Example:

$w_H = 0$

$w_L = 1$



Data Weighting Method



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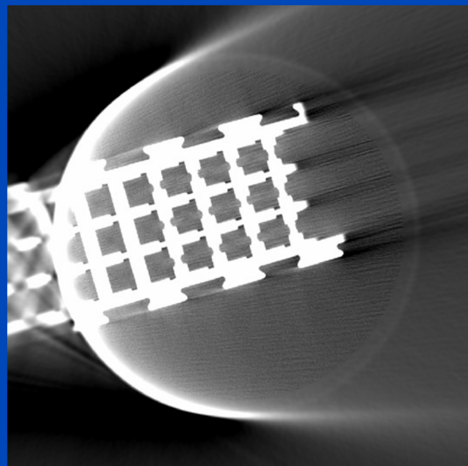

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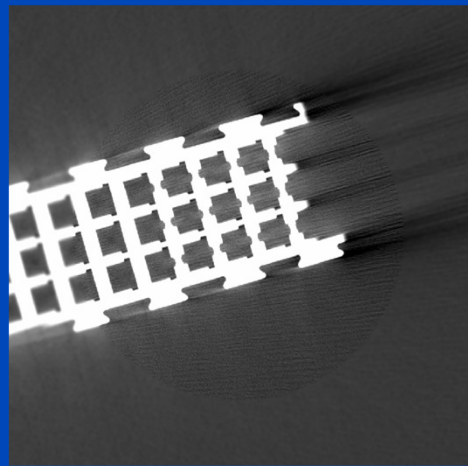


$$X_L^{-1}(p_L w_L) \quad + \quad X_H^{-1}(p_H w_H) \quad = \quad f_H$$

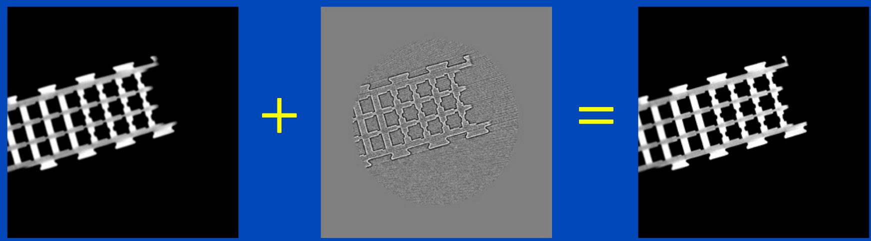
Recapitulation

Data completion method (gold standard):

$$f_H = X_H^{-1}(p_H + X_U f_L)$$

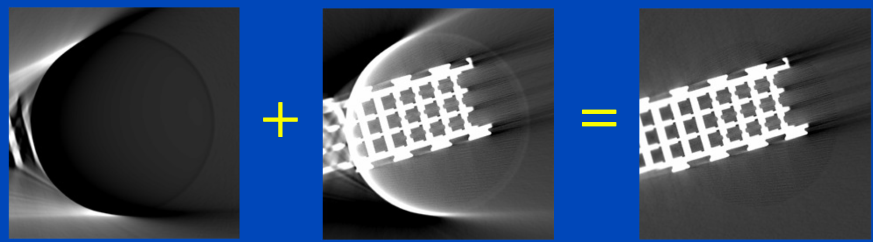
Data filtering method (new):

$$f_H = f_L + X_H^{-1}(h * p_H)$$



Data weighting method (new):

$$f_H = X_L^{-1}(p_L w_L) + X_H^{-1}(p_H w_H)$$



Head Phantom Inner Ear

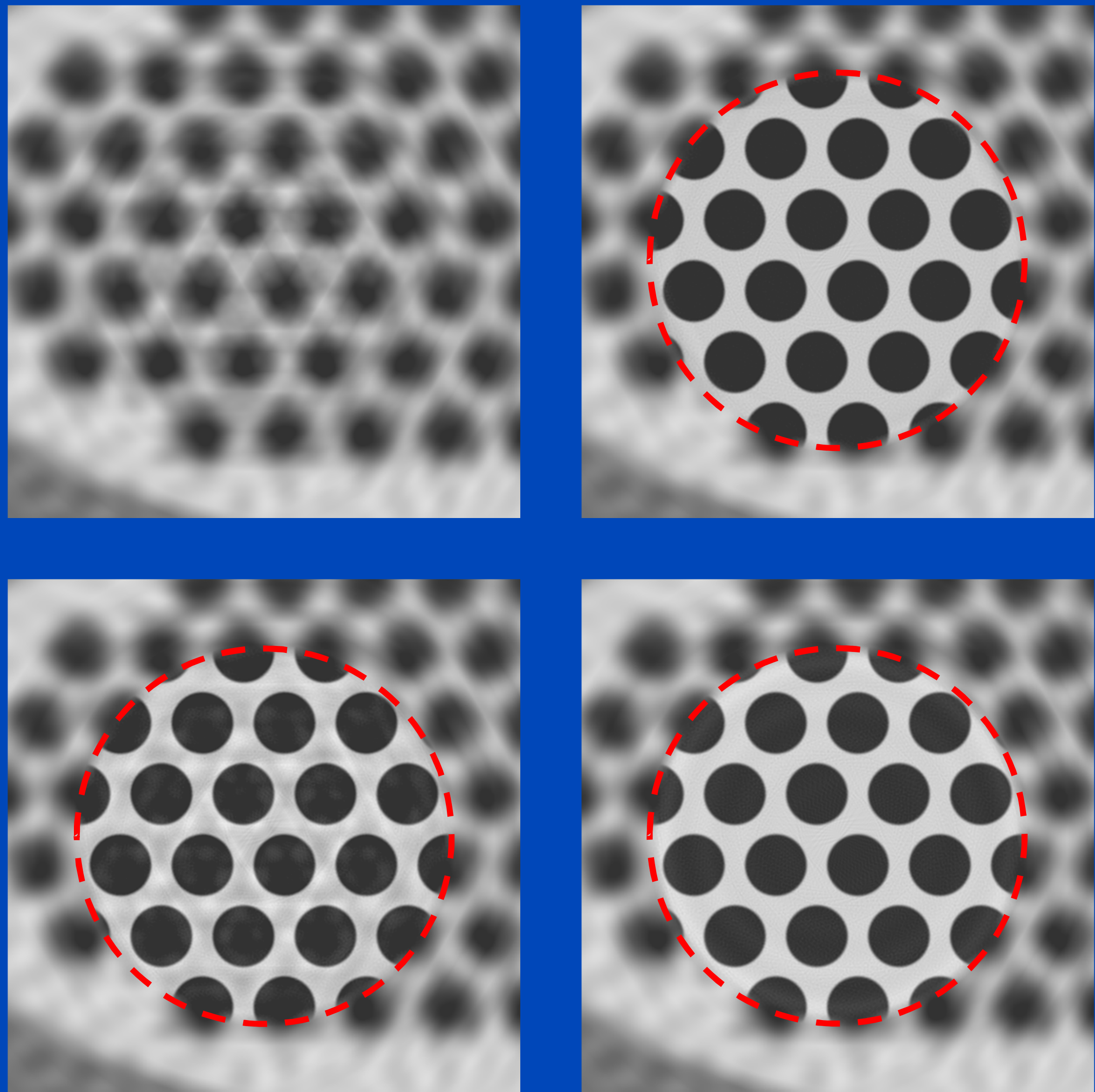
Head Phantom Inner Ear

Overview

Data completion

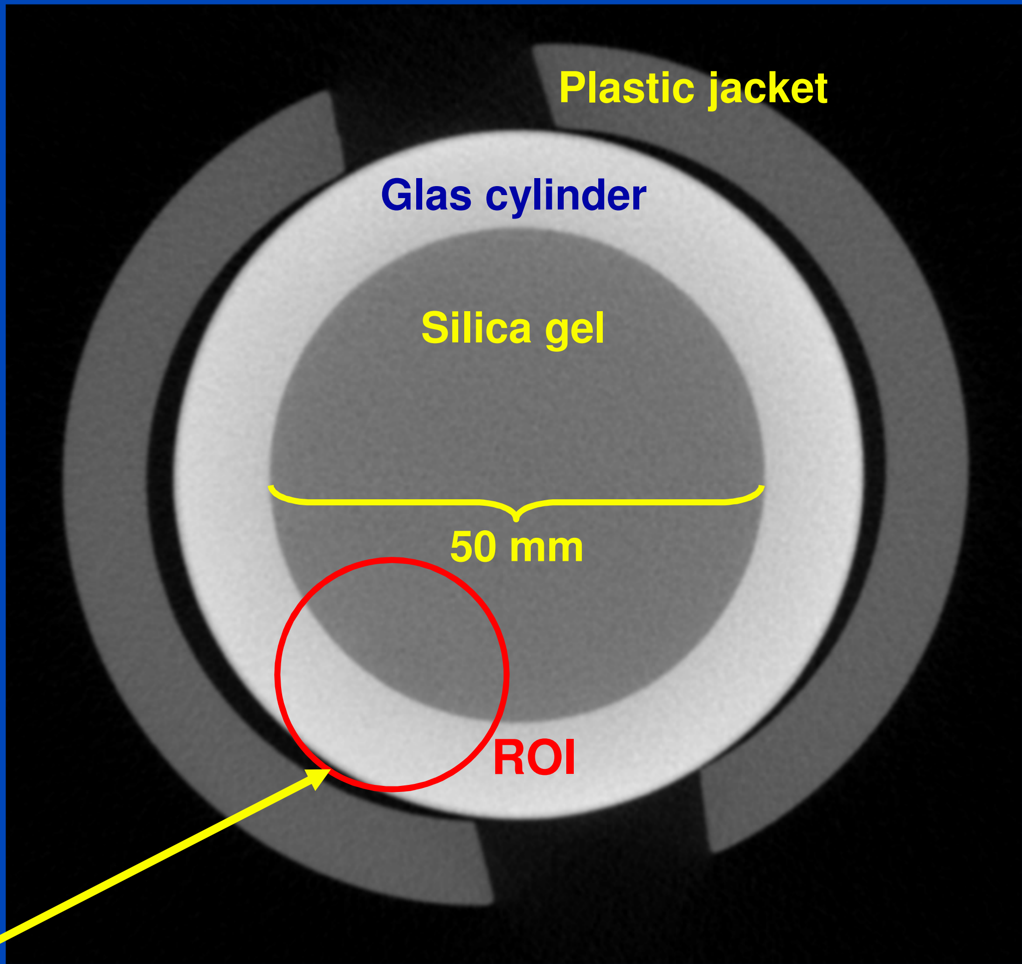
Data filtering

Data weighting



C/W = 200/4000 HU

Measurements: Chromatography Column

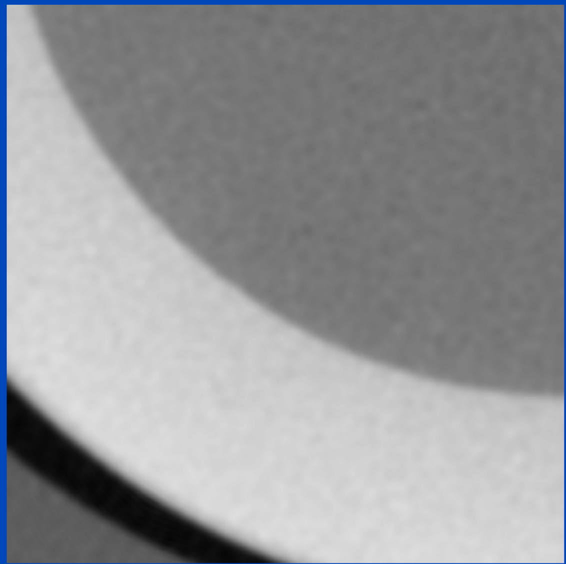


0.5 mm splinter shield
(not visible in the overview scan)

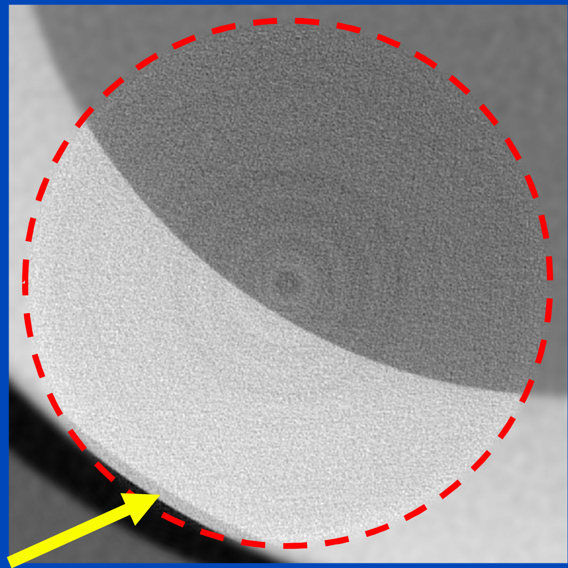
C/W = 0/2000 HU

Measurements: Chromatography Column

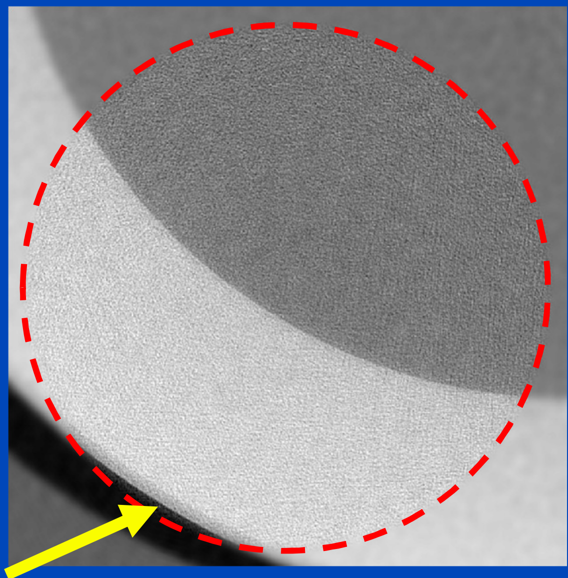
Overview



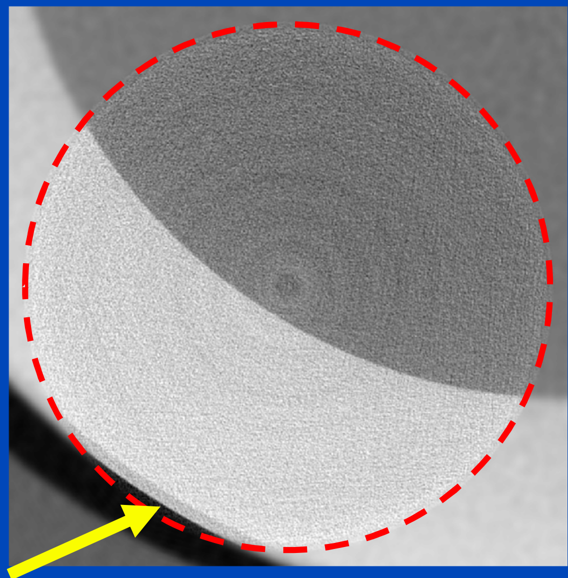
Data completion



Data filtering

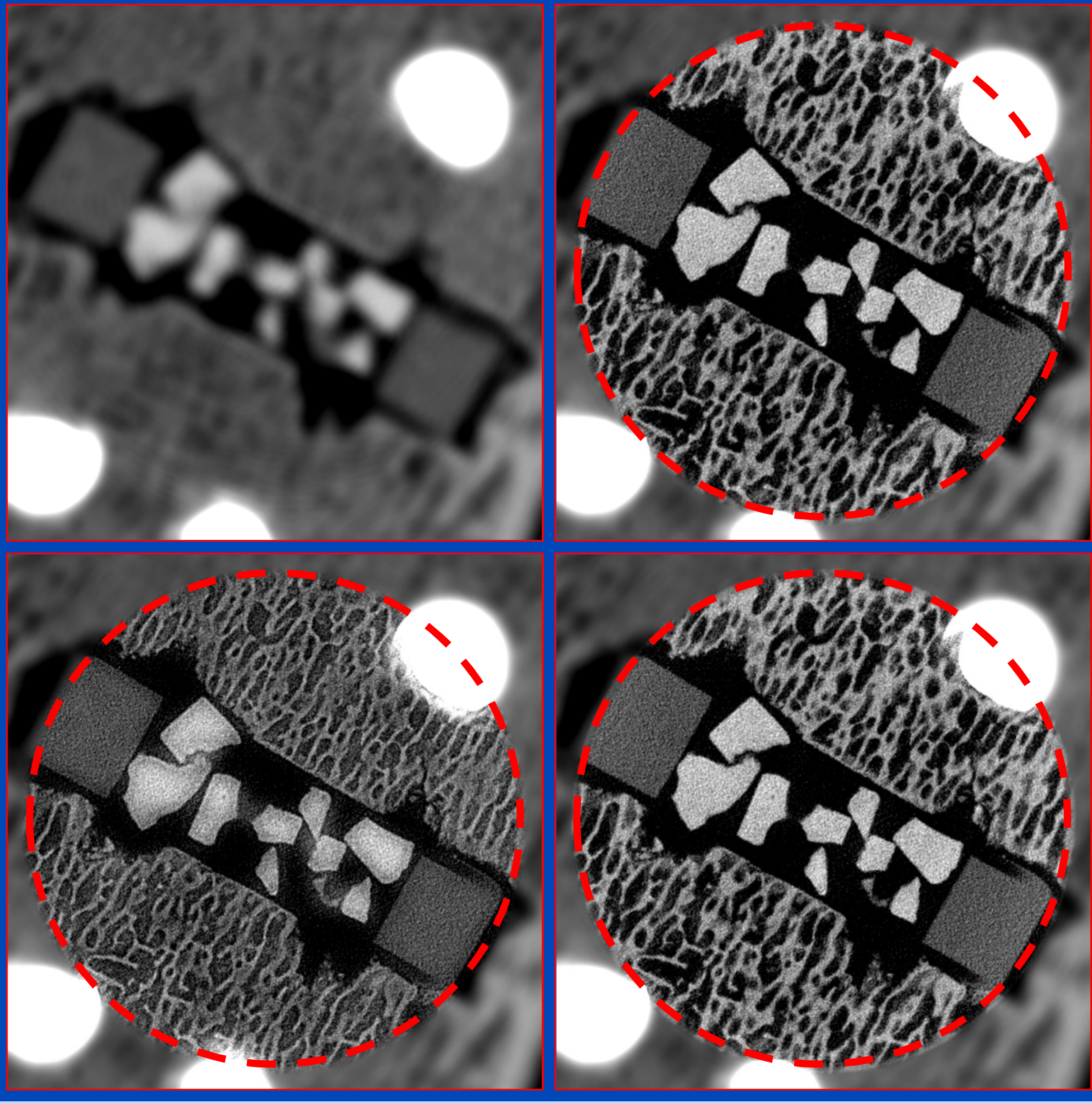


Data weighting



C/W = 0/2000 HU

Spinal Disk Implant Results



Low Resolution

Data Completion

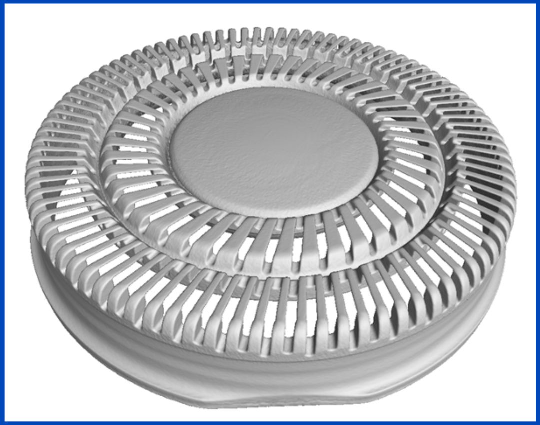
Data Filtering

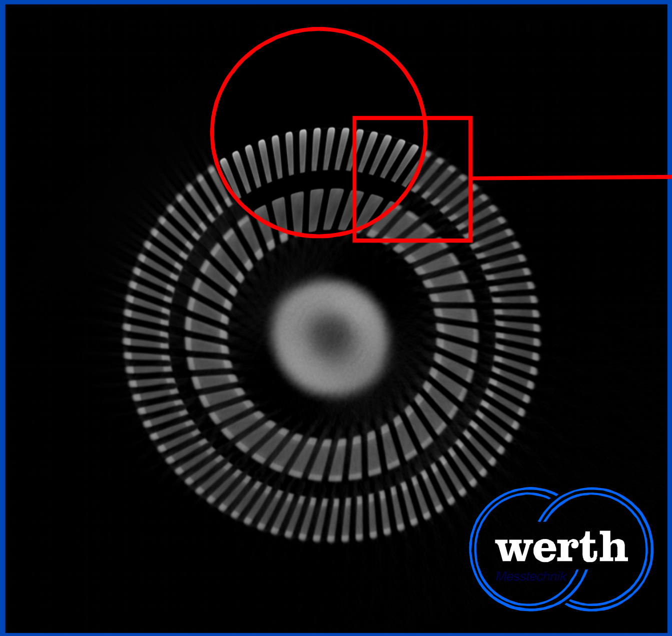
Data Weighting

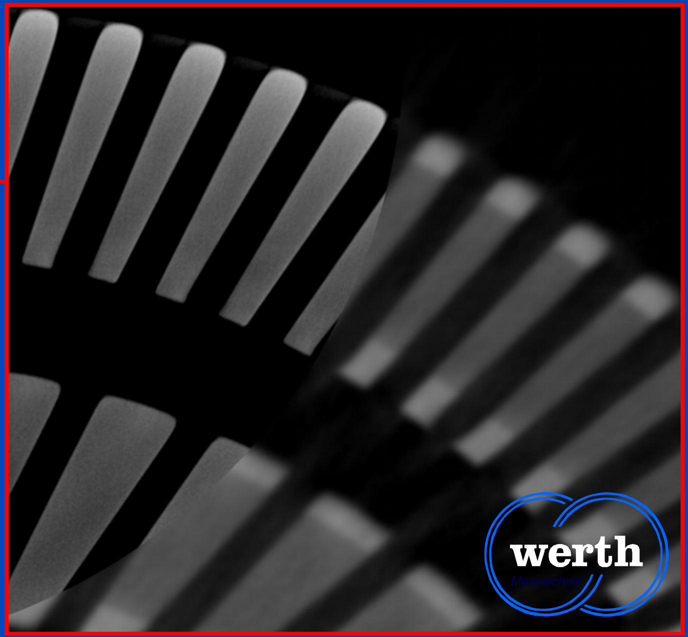
C/W = 1000/1000 HU

dkfz.

Shear Blade







Conclusions on ROI Tomography

- Combination of a low-resolution overview scan and a high-resolution ROI scan allows a high-resolution reconstruction of the ROI.
- Three different reconstruction methods were presented:

Data completion

- Highly accurate.
- Computationally expensive if the virtual detector gets very large.
- Does not work for fan angles $\geq 180°$.

Data filtering

- High computational performance.
- Does not compensate for noise and artifacts of the overview scan.

Data weighting

- Highly accurate.
- High computational performance.
- Compensates for noise and artifacts of the overview scan.

- Results from simulation studies as well as from real measurements were shown.


Thank You!
Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.
This presentation will soon be available at www.dkfz.de/ct.