CT Calibration and Dose Minimization in Image-Based Material Decomposition With Energy-Selective Detectors

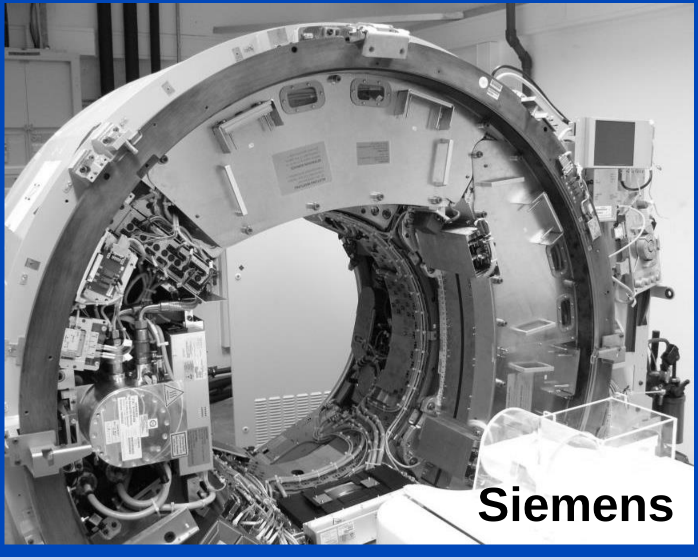
Sebastian Faby[1], Stefan Kuchenbecker[1,2], David Simons[1], Heinz-Peter Schlemmer[1], Michael Lell[2], and Marc Kachelrieß[1,2]

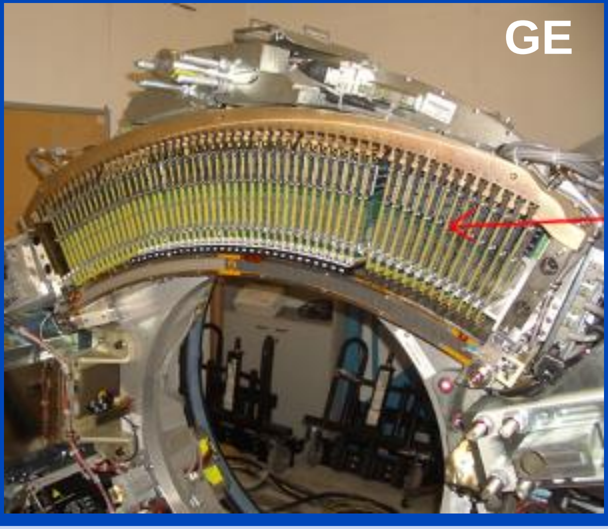
[1]German Cancer Research Center (DKFZ), Heidelberg, Germany
[2]Friedrich-Alexander-University (FAU) Erlangen-Nürnberg, Germany

DEUTSCHES KREBSFORSCHUNGSZENTRUM IN DER HELMHOLTZ-GEMEINSCHAFT

Aims

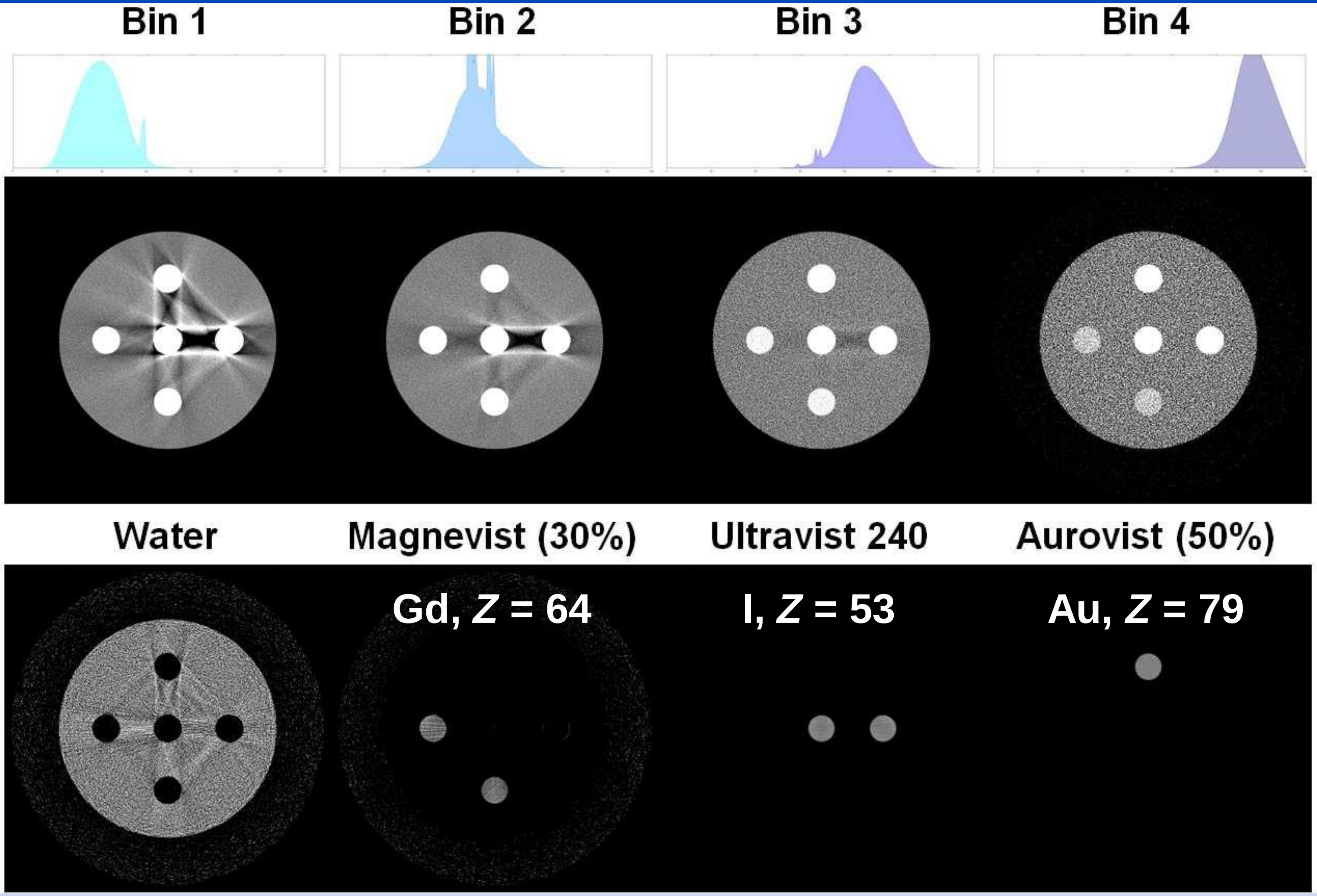
- Make use of energy data redundancies in multi energy CT
- Minimize noise in material images, i.e. reduce patient dose





Motivation

- Typical case: *B* = 4 energy bins, *M* = 4 basis materials



N. Maaß, S. Sawall, M. Knaup and M. Kachelrieß, “Empirical Multiple Energy Calibration (EMEC) for Material–Selective CT,” IEEE Imaging Conference Record, MIC21.S-177, 4222-4229, 2011.

Motivation

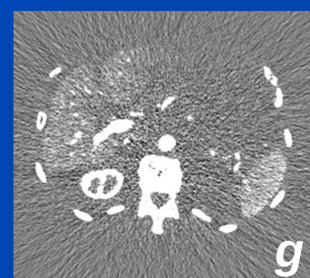
- **Without multiple high-*Z* contrast agents:**
- **Clinically interesting case only *M* = 2:**
  - **Water/soft tissue and bone/iodine**
  - **Photoelectric effect and Compton scattering**
- **Number energy bins *B* > number basis materials *M***
  → Gain in degrees of freedom, how to use it?
- **Image-based method for this task**
  - **Narrow energy bins, images show only very little beam hardening**
  - **Linear image-based methods are fast.**
- **Projection-based algorithms available**
  - **Maximum likelihood approach (Roessl and Proksa, PMB 2007)**
  - **EMEC + Dose Minimization (Maaß *et al*., MIC 2011)**

Algorithm Concept

- **Linear image weighting**
  - Material image *g*
  - Weighting coefficients *w*
  - Energy bin images *f*

$$g = \begin{pmatrix} +16.5 \\ +81.8 \\ -79.7 \\ -44.9 \end{pmatrix} \cdot \begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{pmatrix}$$

Material image *g*



Bin images *f*

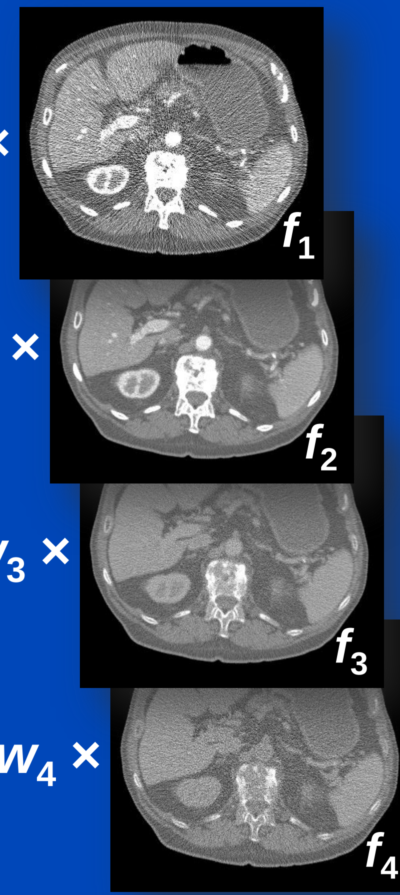
$w_1 \times$

$w_2 \times$

$w_3 \times$

$w_4 \times$

+



- **Two subsequent steps:**
  - Material decomposition calibration
  - Image noise minimization using the $K = B - M$ degrees of freedom

dkfz.

Material Decomposition Calibration

- Example for *M* = 2: water and iodine
- *N* = 2 calibration measurements using ROIs
- Determine weighting coefficients *w*
  - *M*×*B* coefficients, but *M*×*N* equations

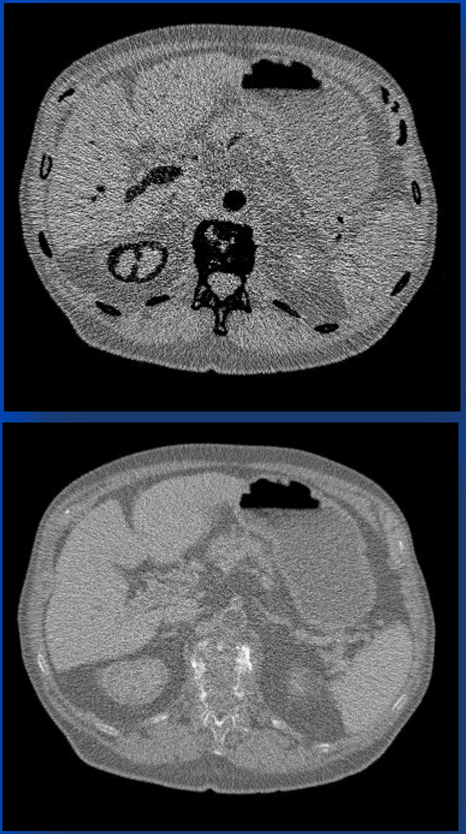
WATER

Water, Iodine: $$\begin{pmatrix}1\\0\end{pmatrix} \overset{!}{=} \begin{pmatrix} w_{\mathrm{W},1} \dots w_{\mathrm{W},B} \\ w_{\mathrm{I},1} \dots w_{\mathrm{I},B}\end{pmatrix} \cdot \begin{pmatrix} f_{\mathrm{W},1}\\ \vdots \\ f_{\mathrm{W},B}\end{pmatrix} \quad \begin{pmatrix}0\\1\end{pmatrix}$$

Target values — ROI values

IODINE

Water, Iodine: $$\begin{pmatrix}1\\1\end{pmatrix} \overset{!}{=} \begin{pmatrix} w_{\mathrm{W},1} \dots w_{\mathrm{W},B} \\ w_{\mathrm{I},1} \dots w_{\mathrm{I},B}\end{pmatrix} \cdot \begin{pmatrix} f_{\mathrm{I},1}\\ \vdots \\ f_{\mathrm{I},B}\end{pmatrix} \quad \begin{pmatrix}1\\1\end{pmatrix}$$



- Case studied in the simulations

Material Decomposition Calibration

- Problem separable for the *M* basis materials
- *N* ≥ *M* calibration measurements to determine *w*:

$$g_n = \sum_b f_{nb} w_b \qquad \boldsymbol{g} = \boldsymbol{F} \cdot \boldsymbol{w}$$

- In general *N* ≠ *B*, least squares approach:

$$\boldsymbol{w} = \mathrm{argmin}_{\boldsymbol{w}} (\boldsymbol{F} \cdot \boldsymbol{w} - \boldsymbol{g})^2$$

- Linear system for *w*:

$$\underbrace{\boldsymbol{F}^{\mathrm{T}} \boldsymbol{F}} \cdot \boldsymbol{w} = \underbrace{\boldsymbol{F}^{\mathrm{T}} \boldsymbol{g}}$$

B × *B* matrix, rank at most *M* — Vector of dim. *B*

- Singular value decomposition:

$$\boldsymbol{w}(\alpha_k) = \boldsymbol{w}_0 + \sum_{k=1}^{K} \alpha_k \boldsymbol{w}_k \ , \forall \, \alpha_k \in \mathbb{R}$$

Rank *M* solution ($\boldsymbol{w}_0$) — Null space, dimension *K* = *B* - *M* ($\boldsymbol{w}_k$)

Image Noise Minimization

- **Exploit free parameters α_k of the null space**

$$\boldsymbol{w}(\alpha_k) = \boldsymbol{w}_0 + \sum_k \alpha_k \boldsymbol{w}_k$$

- **Noise minimization = maximizing CNR**
- **Covariance matrix C of all bin images:**

$$C_{bb'} = \frac{1}{P-1} \sum_{p \in \mathrm{ROI}} (f_b(p) - \overline{f}_b)(f_{b'}(p) - \overline{f}_{b'})$$

- **Error propagation:**

$$\mathrm{Var}\ g = \boldsymbol{w}^{\mathrm{T}}(\alpha_k) \cdot \boldsymbol{C} \cdot \boldsymbol{w}(\alpha_k)$$

- **Minimize variance:** $\frac{\partial \mathrm{Var}\ g}{\partial \alpha_j} = 0$
- **Resulting linear system $\boldsymbol{A} \cdot \boldsymbol{\alpha} = \boldsymbol{b}$ with:**

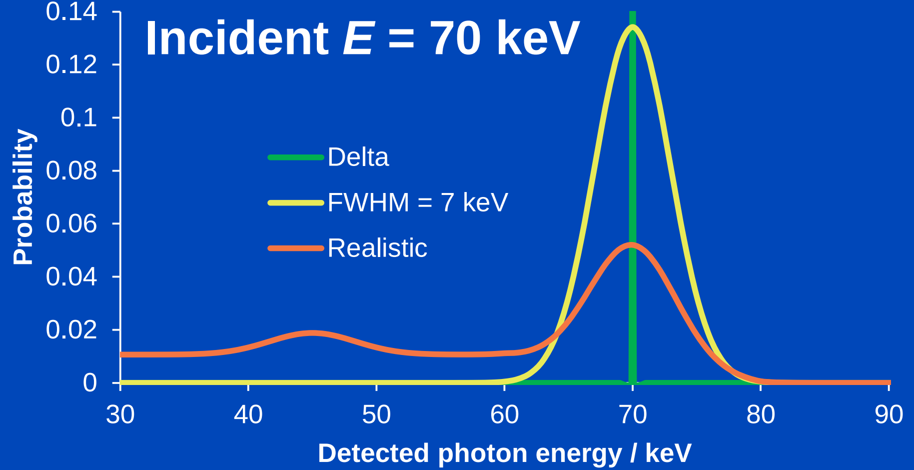
$$A_{jk} = \sum_b \sum_{b'} w_{jb} w_{kb'} C_{bb'} \text{ and } b_j = -\sum_b \sum_{b'} w_{jb} w_{0b'} C_{bb'}$$

Simulations

- Asses the proposed algorithm
- Study typical dual energy CT (DECT) application:
  - Material decomposition into a water-equivalent and an iodine material image
- Comparison of:
  - Dual energy technique, energy integrating (EI) detectors
  - Energy-selective photon counting (PC) detectors
- Based on patient data set with low noise
  - Averaged over 8 thin slices
  - Separation into water and bone
  - Forward projection to obtain material-specific sinograms for polychromatic simulation

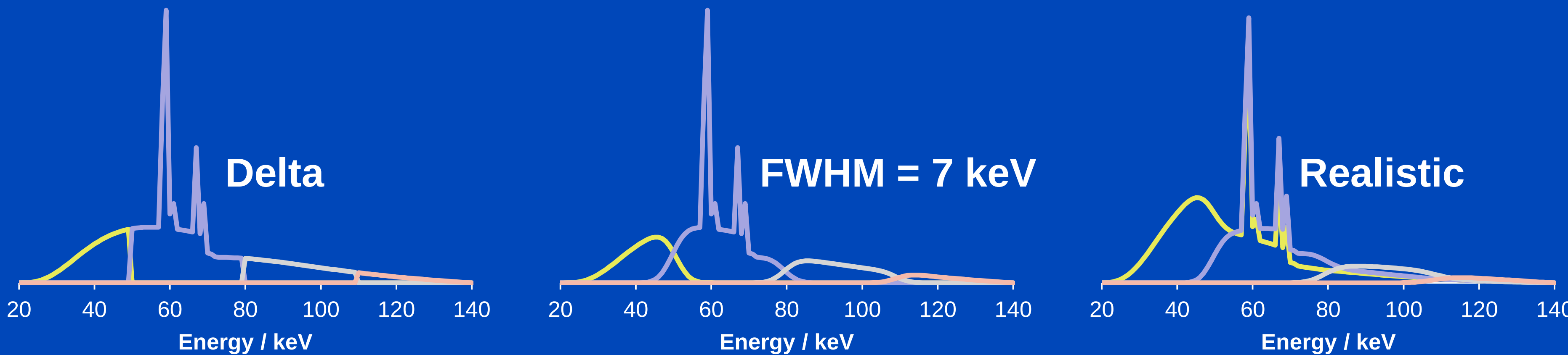
Simulations

- **Spectral response:**



Energy bins placed equidistantly from 20 keV to 140 keV

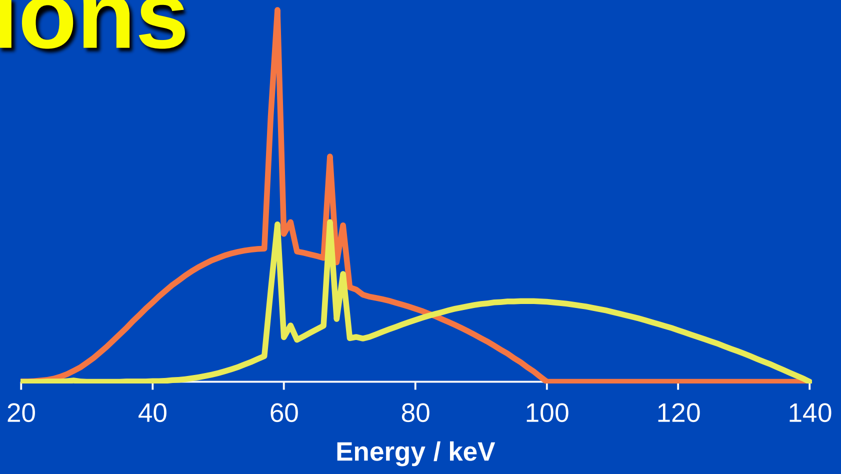
- **Energy bin spectra for *B* = 4:**

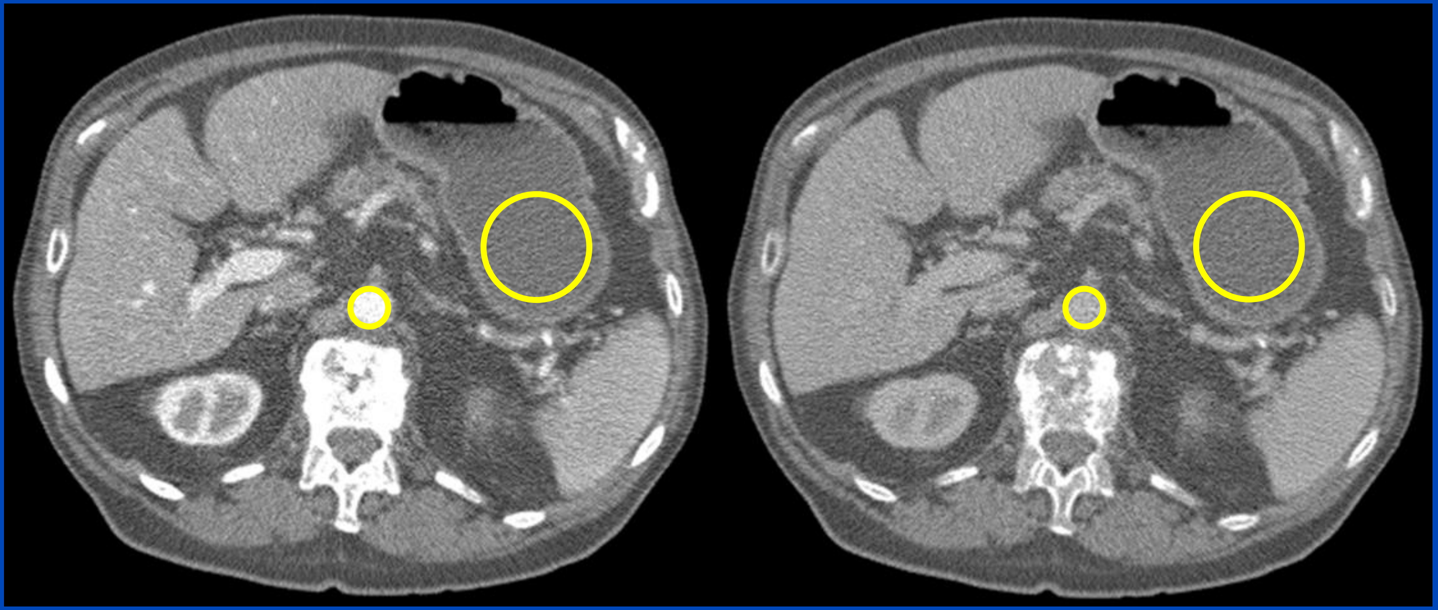


[J. P. Schlomka, E. Roessl, R. Dorscheid, S. Dill, G. Martens, T. Istel, C. Bäumer, C. Herrmann, R. Steadman, G. Zeitler, A. Livne and R. Proksa, "Experimental feasibility of multi-energy photon-counting K-edge imaging in pre-clinical computed tomography," Phys. Med. Biol. 53, 4031-4047, 2008.]

Simulations

- **Dual source DECT:**
  - **100 kV**
  - **140 kV + 0.4 mm Sn**





100 kV **140 kV Sn**

***C* = 0 HU / *W* = 700 HU**

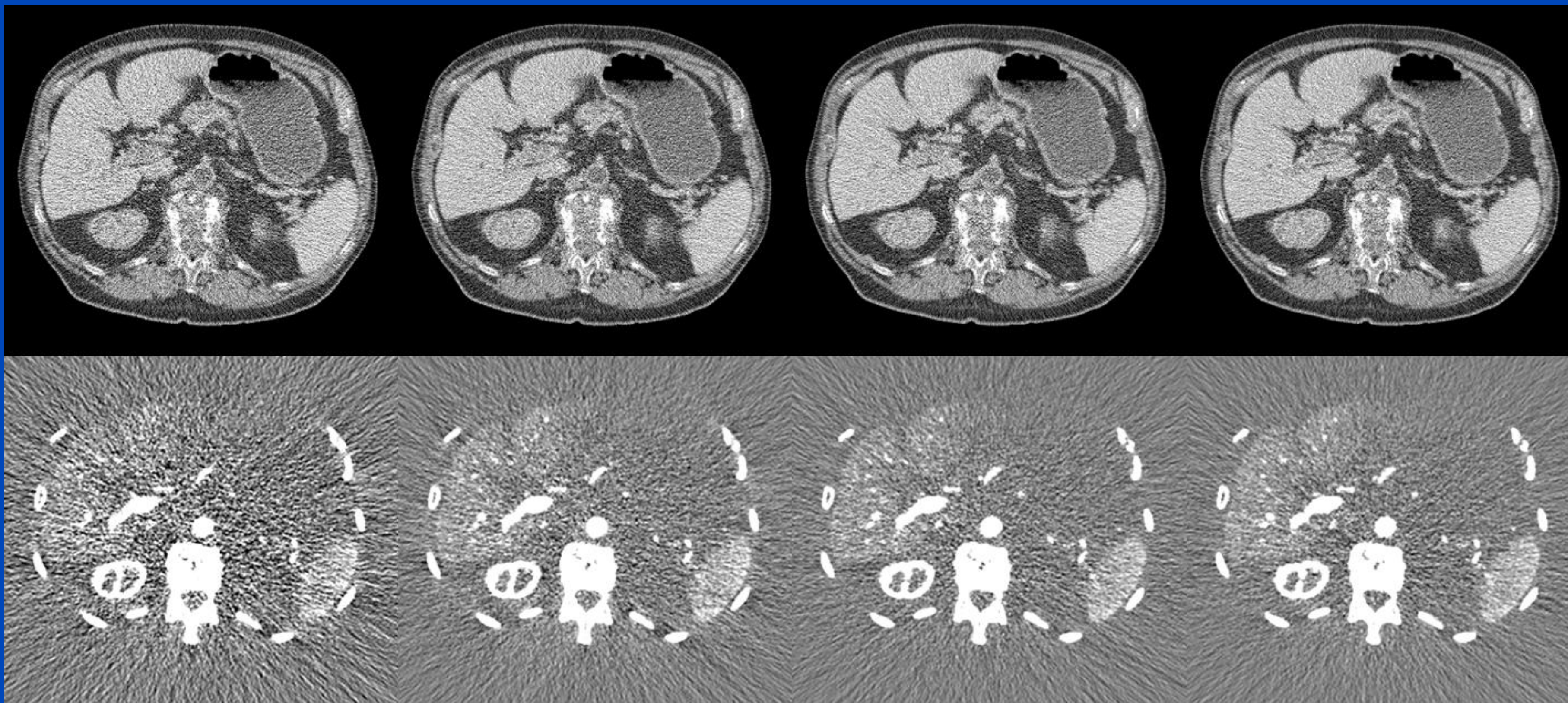
dkfz.

Results – Delta Model

DECT | PC 2 Bins | PC 4 Bins | PC 8 Bins

Water

Iodine



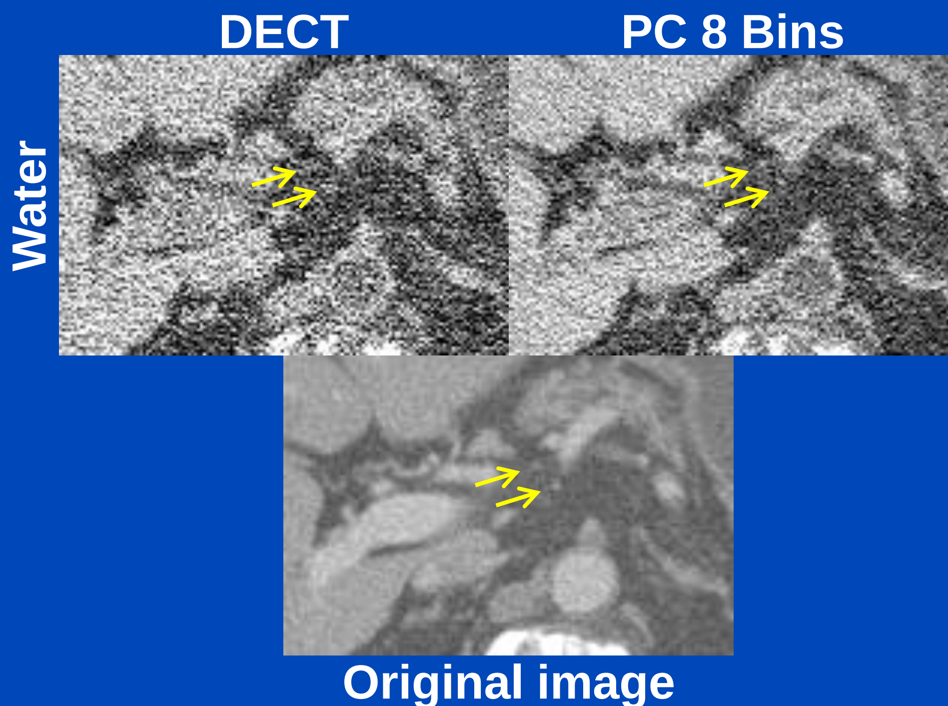
		2 bins	4 bins	8 bins	12 bins
Water	Noise rel. to DECT	-16%	-22%	-27%	-29%
Iodine	Noise rel. to DECT	-37%	-43%	-49%	-52%

$$\frac{\sigma_{\mathrm{PC}}}{\sigma_{\mathrm{DECT}}} - 1$$

Water: C = 1 / W = 0.4
Iodine: C = 0 / W = 0.4

dkfz.

Results – Delta Model

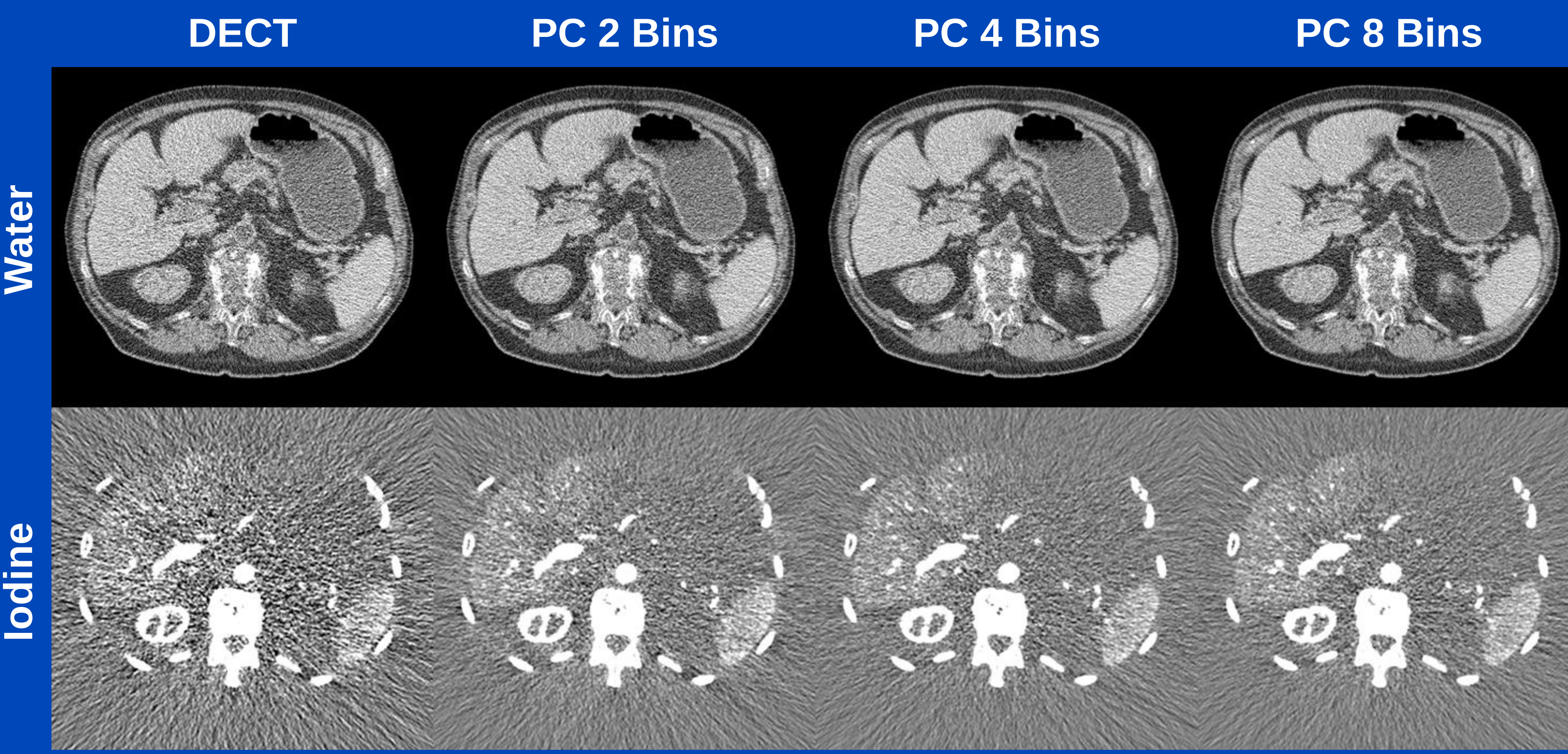


		2 bins	4 bins	8 bins	12 bins
Water	Noise rel. to DECT	-16%	-22%	-27%	-29%
Iodine	Noise rel. to DECT	-37%	-43%	-49%	-52%

$$\frac{\sigma_{\mathrm{PC}}}{\sigma_{\mathrm{DECT}}} - 1$$

Water: C = 1 / W = 0.4
Iodine: C = 0 / W = 0.4

Results – FWHM = 7 keV Model



		2 bins	4 bins	8 bins	12 bins
Water	Noise rel. to DECT	-15%	-21%	-26%	-27%
Iodine	Noise rel. to DECT	-37%	-43%	-48%	-49%

$$\frac{\sigma_{\mathrm{PC}}}{\sigma_{\mathrm{DECT}}} - 1$$

Water: $C = 1$ / $W = 0.4$
Iodine: $C = 0$ / $W = 0.4$

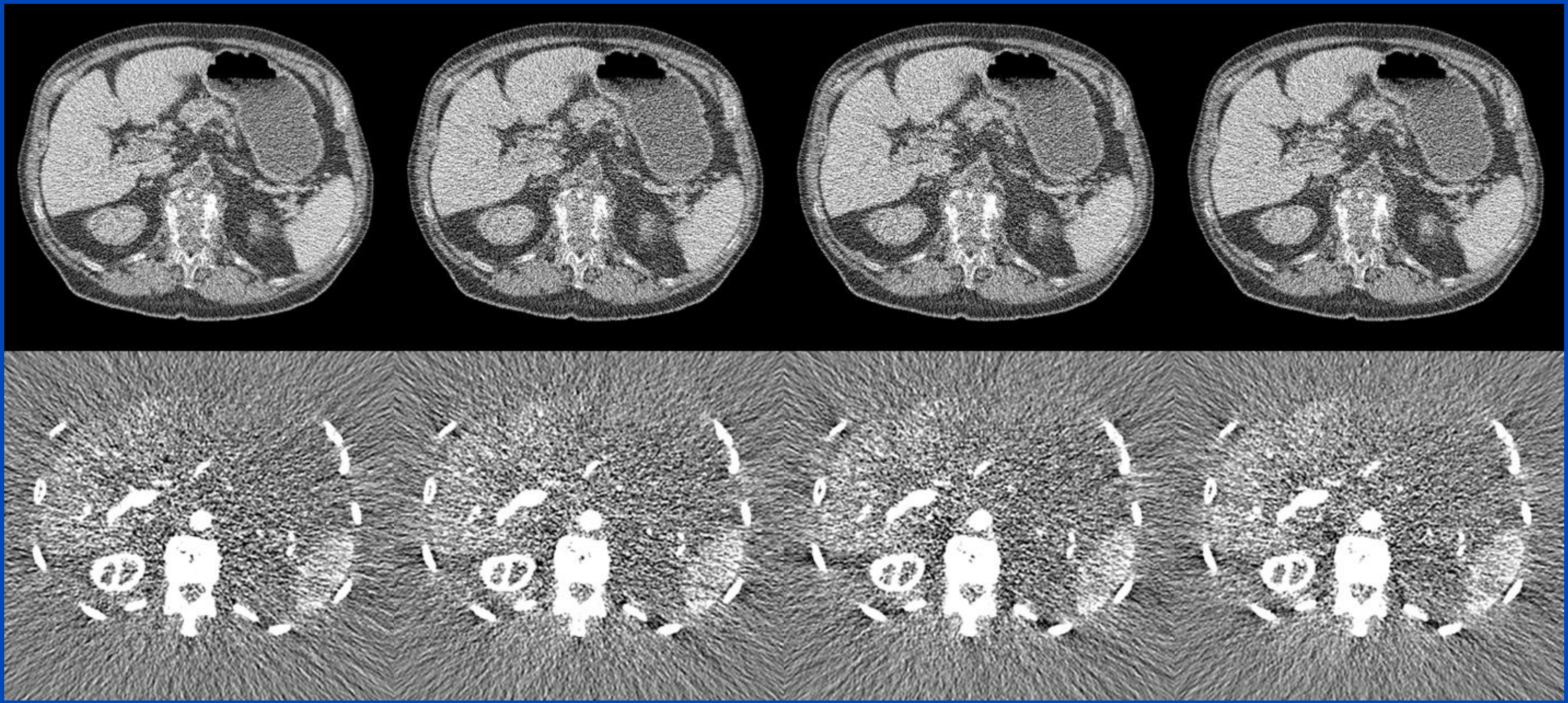
dkfz.

Results – Realistic Model

DECT | **PC 2 Bins** | **PC 4 Bins** | **PC 8 Bins**

Water

Iodine



		2 bins	4 bins	8 bins	12 bins
Water	Noise rel. to DECT	+27%	+23%	+15%	+15%
Iodine	Noise rel. to DECT	+6%	+2%	-6%	-6%

$$\frac{\sigma_{\mathrm{PC}}}{\sigma_{\mathrm{DECT}}} - 1$$

Water: C = 1 / W = 0.4
Iodine: C = 0 / W = 0.4

Conclusions

- Good performance of image noise minimization step
- Ideal:
  - PC detector with B = 2 already better than DECT (no image noise minimization possible in this case)
  - Noise reduction significant with B = 8: Water image -27%, iodine image -49%
- Realistic:
  - Finite energy resolution of PC detector not a problem
  - Low energy tail of realistic model vitiating all advantages of PC detector, DECT performing better than PC detector
- Shortcoming: Correlations not taken into account for realistic detector scenario, results will be presented in a later publication

Thank You!

This work was supported by Eurostars project E! 7308 DCXScan, by the Deutsche Forschungsgemeinschaft (DFG) under grant KA 1678/5-1 and LE 2763/1, and by the German Government, Bundesministerium für Bildung und Forschung (01EX1012B, Spitzencluster Medical Valley).

This presentation will soon be available at www.dkfz.de/ct.

Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.