A Count Rate-Dependent Method for Spectral Distortion Correction in Photon Counting CT

Joscha Maier[a,d] , Jannis Dickmann[a,b,c], Stefan Sawall[a,d], Thomas Thüring[e], Spyridon Gkoumas[e], Christian Brönnimann[e], and Marc Kachelrieß[a,d]

[a]German Cancer Research Center (DKFZ), Heidelberg, Germany
[b]KTH Royal Institute of Technology, Stockholm, Sweden
[c]Technical University of Darmstadt, Germany
[d]University of Heidelberg, Germany
[e]Dectris Ltd., Baden, Switzerland

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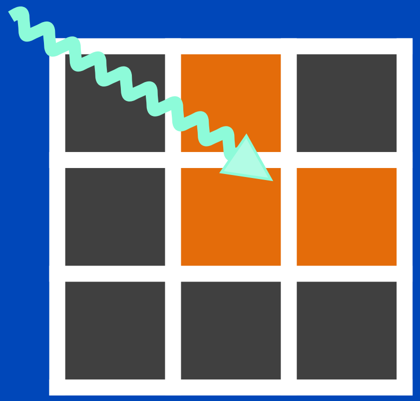
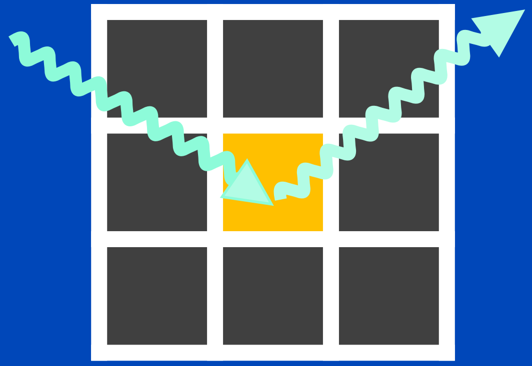
DEUTSCHES KREBSFORSCHUNGSZENTRUM IN DER HELMHOLTZ-GEMEINSCHAFT

Aim

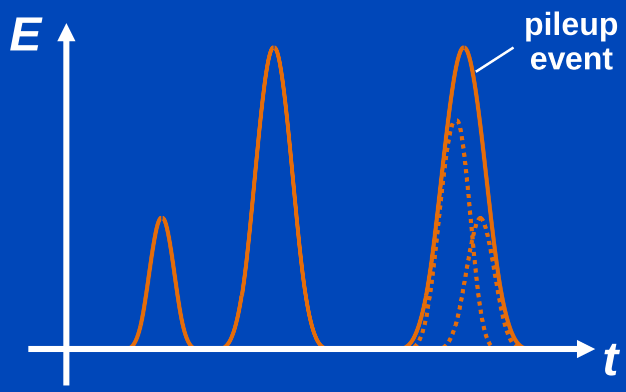
- Material decomposition of spectral CT data into contributions of two or more materials
- Rawdata-based material decomposition requires dedicated models to predict the measured counts
- Calibration of spectral response to account for…
  - Spectral distortions: charge sharing, K-escape
  - Count rate-dependent distortions: pulse pileup



Charge Sharing

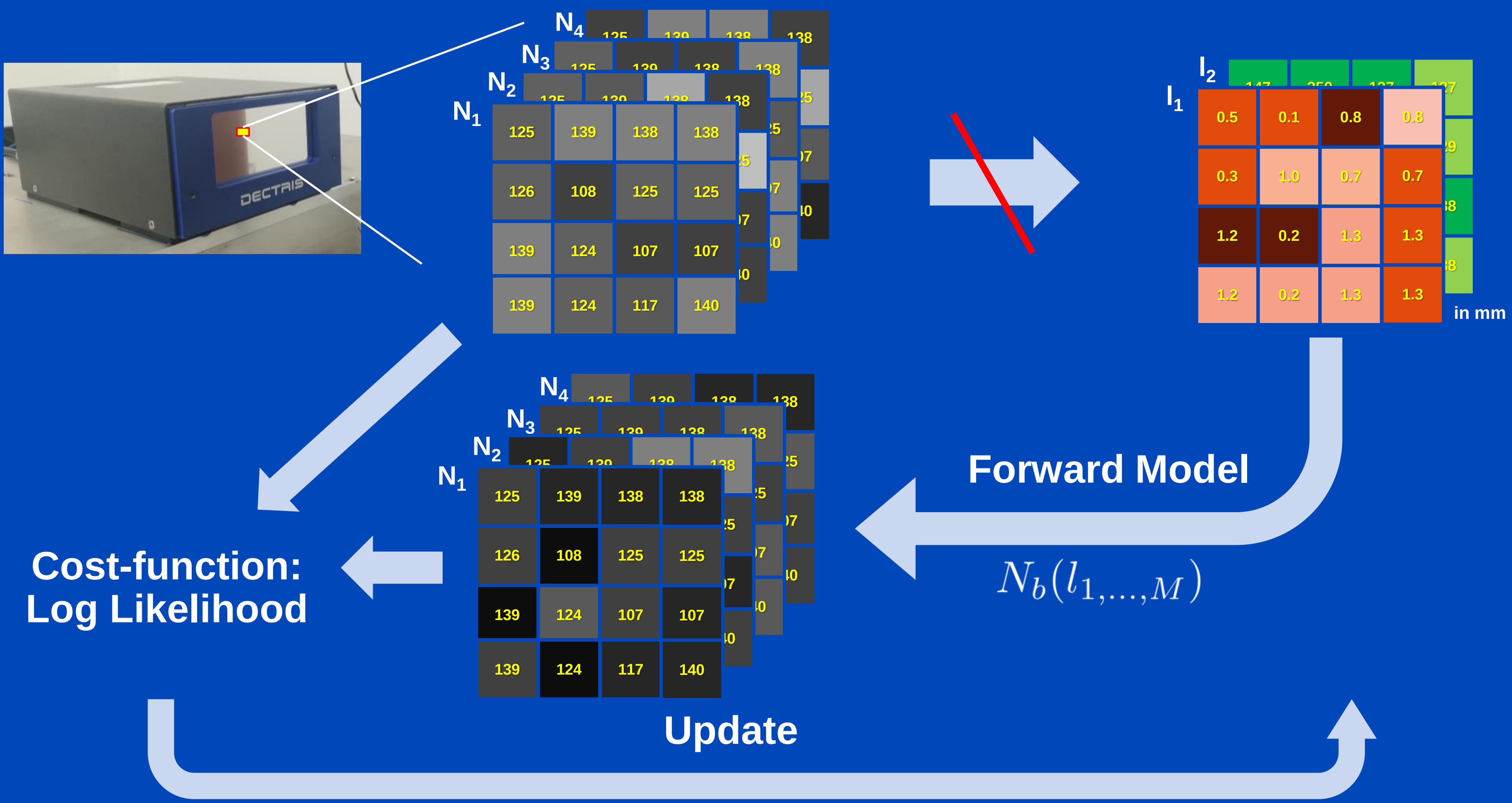


K-Escape, Compton



Pulse Pileup

Material Decomposition



Schlomka et al. (2008) “Experimental feasibility of multi-energy photon-counting K-edge imaging in pre-clinical computed tomography” *Physics in Medicine and Biology*, 53(15), 4031–4047.

Forward Model

- The detection process of a PCD is described using the bin sensitivity function $S_b(E)$.

$$N_b(l_{1,\ldots,M}) \propto N_0 \int dE \;\; w(E) \cdot S_b(E) \cdot \exp\left(-\sum_{m=1}^{M} \mu_m(E) \cdot l_m\right)$$

Total number of x-rays

X-ray spectrum

Bin sensitivity

Interaction with the sample

Bin Sensitivity

Ideal Detector

- **The detection process of a PCD is described using the bin sensitivity function $S_b(E)$.**

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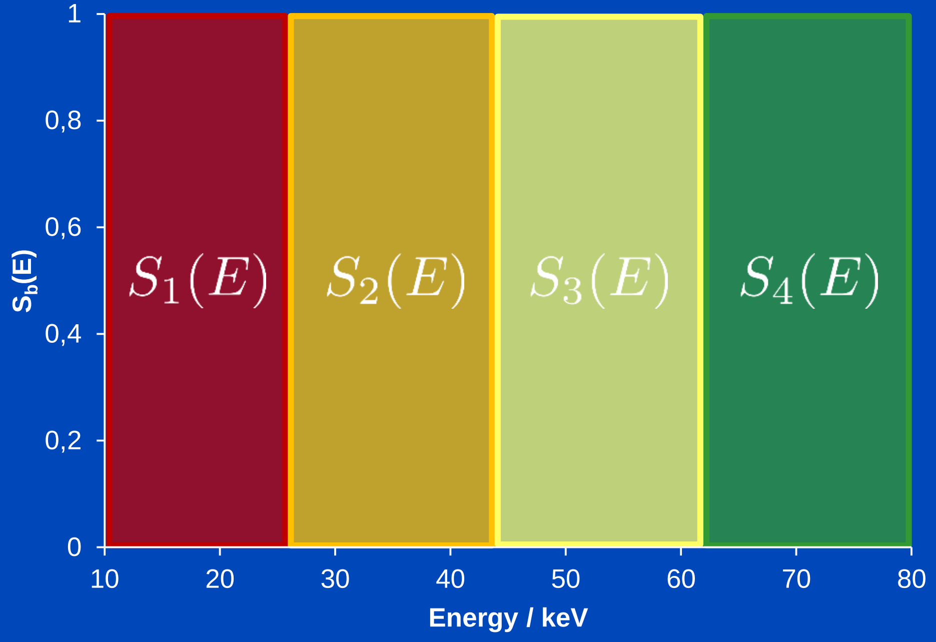

Bin Sensitivity
Real Detector

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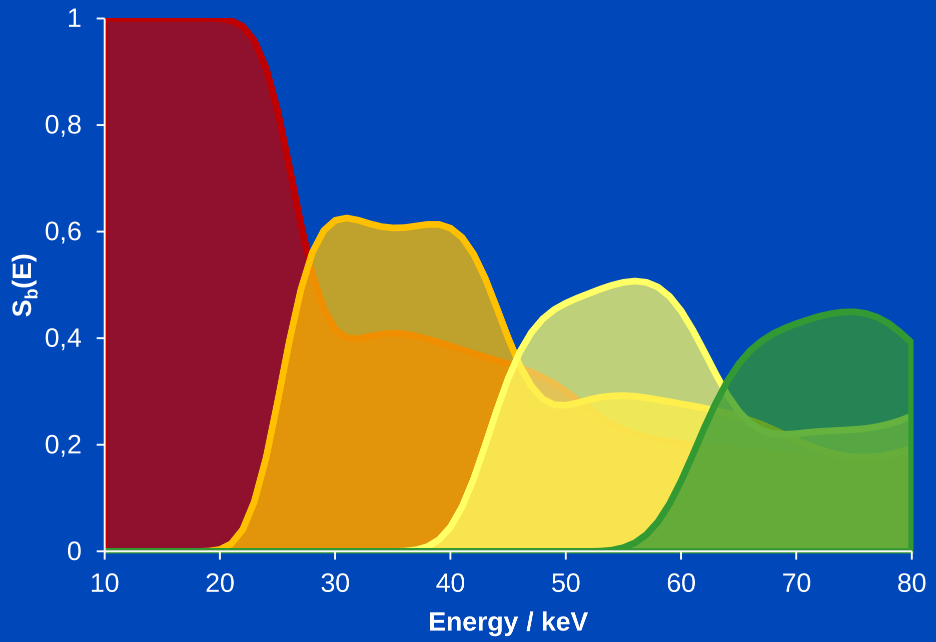

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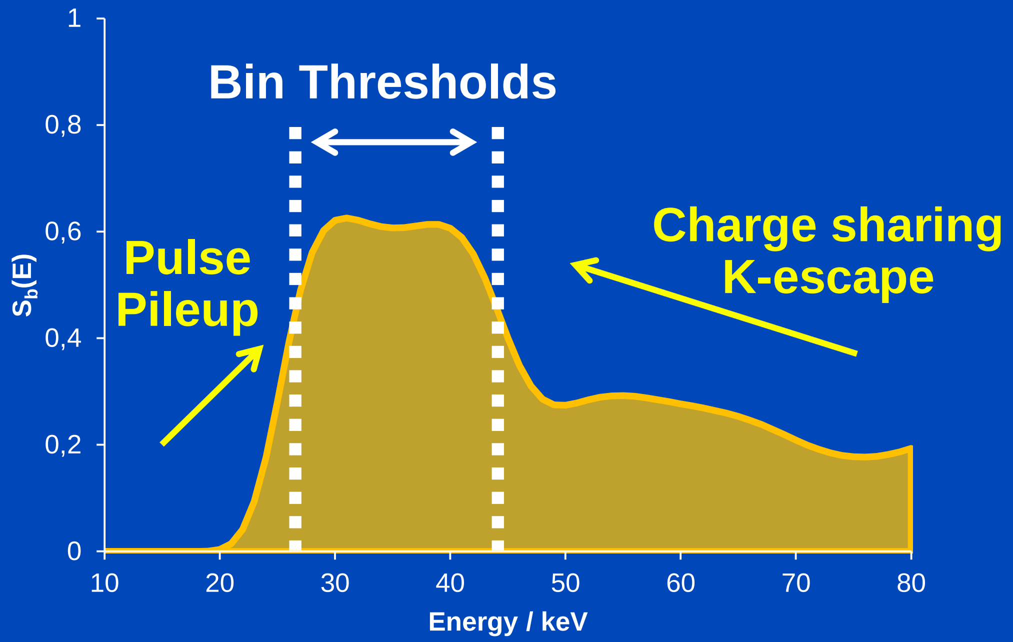
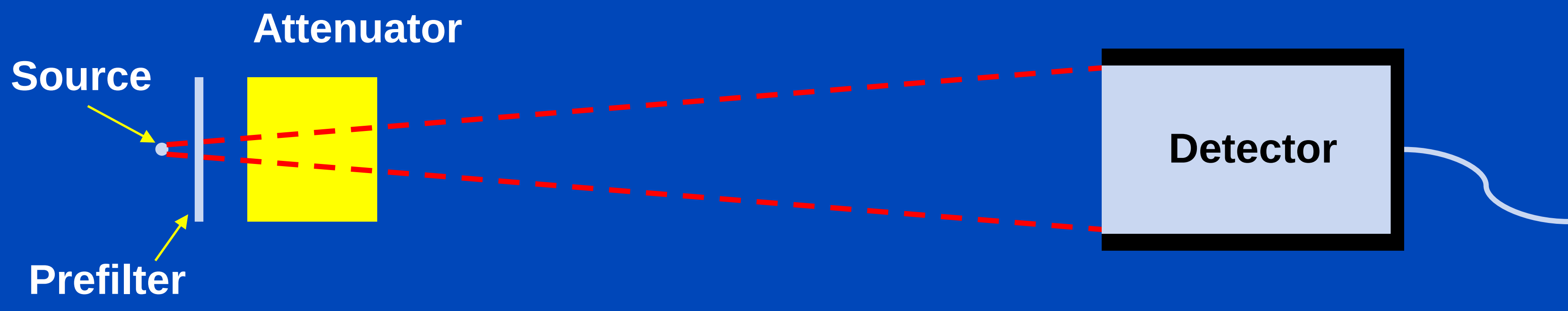


Schlomka et al. (2008) "Experimental feasibility of multi-energy photon-counting K-edge imaging in pre-clinical computed tomography" *Physics in Medicine and Biology*, 53(15), 4031–4047.

Calibration Measurements

- Measure transmission through slabs of aluminum and POM
- Adapt forward model such that it reproduces the calibration measurement



Calibration
Reference Methods

- **Method 1** by Liu et al. (2015)

$$N_b(l_{1,\ldots,M}) \propto N_0 \cdot C_b\Big(\int dE \;\; w(E) \cdot S_b(E) \cdot \exp\Big(-\sum_{m=1}^{M} \mu_m(E) \cdot l_m\Big)\Big)$$

$$C_b(N) = \frac{\alpha_b + \beta_b \cdot N}{1 + \gamma_b \cdot N}$$

- **Method 2** by Sidky et al. (2005)

$$N_b(l_{1,\ldots,M}) \propto N_0 \cdot \int dE \;\; \underbrace{w(E) \cdot S_b(E)}_{= w_b(E)} \cdot \exp\Big(-\sum_{m=1}^{M} \mu_m(E) \cdot l_m\Big)$$

Liu, et al. (2015) "Spectral response model for a multibin photon-counting spectral computed tomography detector and its applications". *Journal of Medical Imaging*, 33502

Sidky et al. (2005) "A robust method of x-ray source spectrum estimation from transmission measurements: Demonstrated on computer simulated, scatter-free transmission data". *Journal of Applied Physics*, 97(12), 124701.

Count Rate-Dependent Spectral Calibration

- Include a multiplicative correction function $P_b(E,N_b)$ to account for spectral distortions and effects depending on the count-rate N_b

$$N_b(l_{1,\ldots,M}) \propto N_0 \int dE \;\; w(E) \cdot S_b(E) \cdot P_b(E, N_b) \cdot \exp\left(-\sum_{m=1}^{M} \mu_m(E) \cdot l_m\right)$$

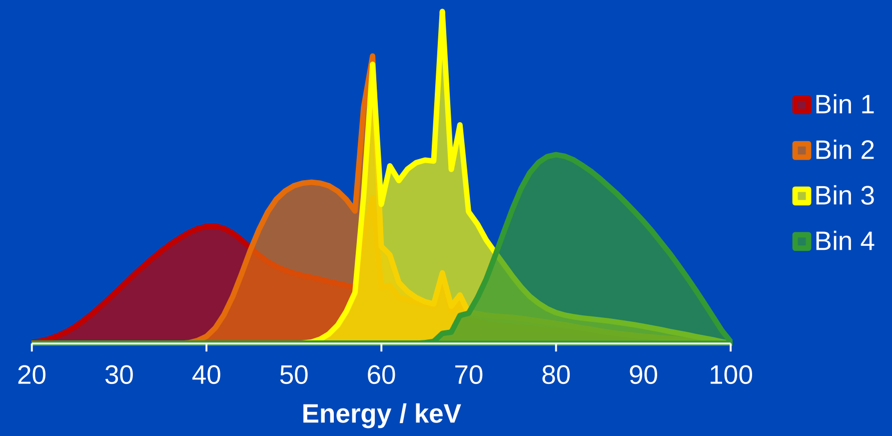
- Model the correction function as a polynomial of order K

$$P_b(E, N_b) = 1 + (E - E_{\min})(E - E_{\max}) \cdot \sum_{k=0}^{K-2} c_{kb}(N_b) E^k$$

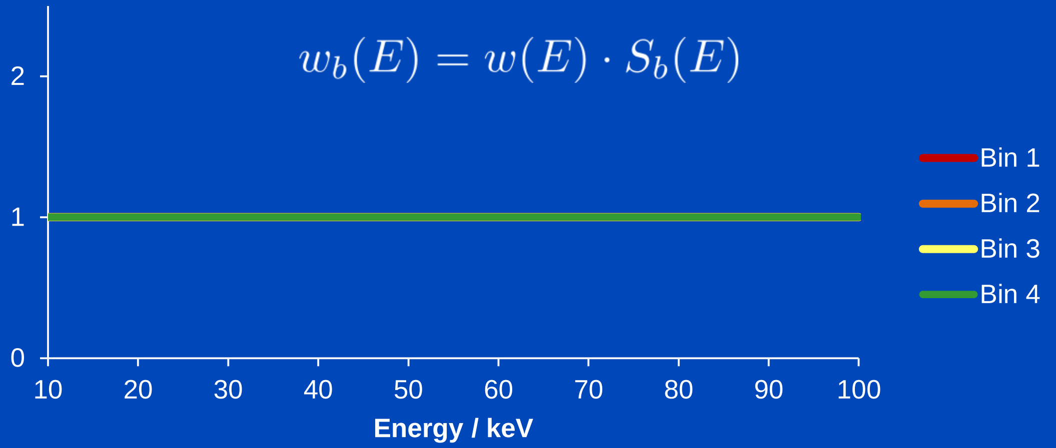
where the coefficients depend linearly on the count-rate

$$c_{kb}(N_b) = c_{kb}^{(0)} + c_{kb}^{(1)} \cdot N_b$$

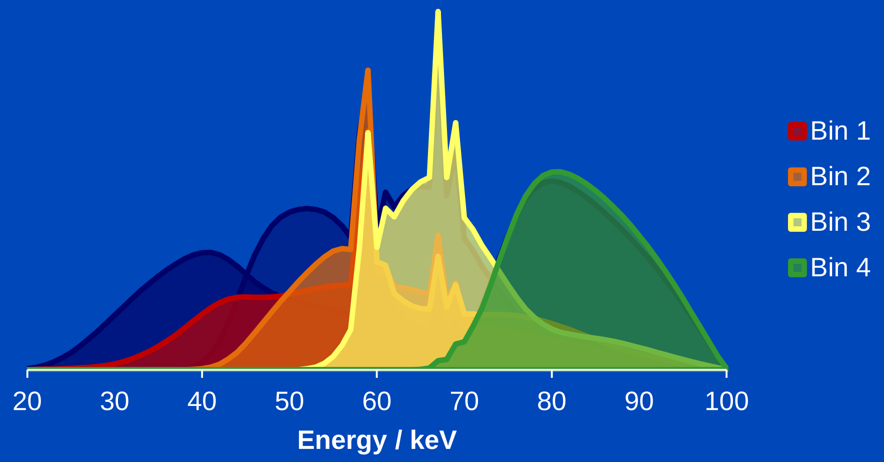
Count Rate-Dependent Spectral Calibration

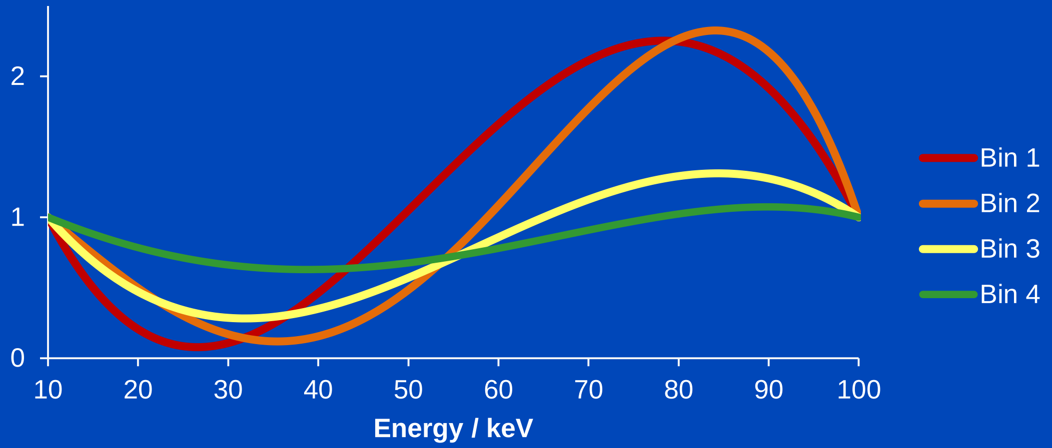


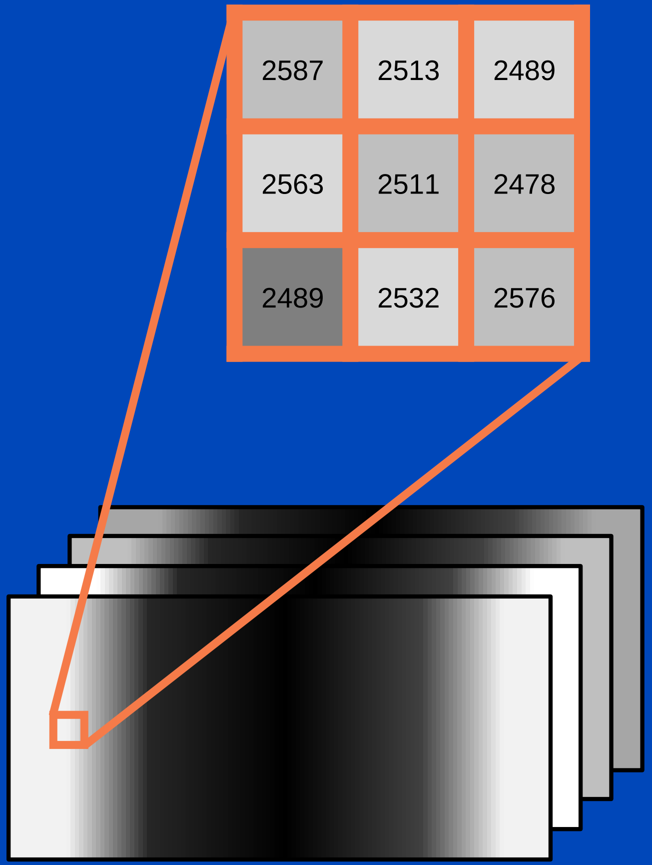
$$w_b(E) = w(E) \cdot S_b(E)$$



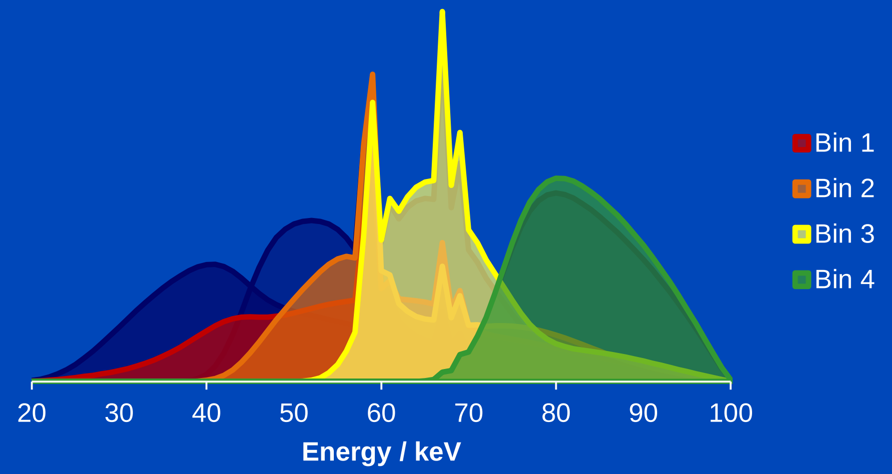
Count Rate-Dependent Spectral Calibration

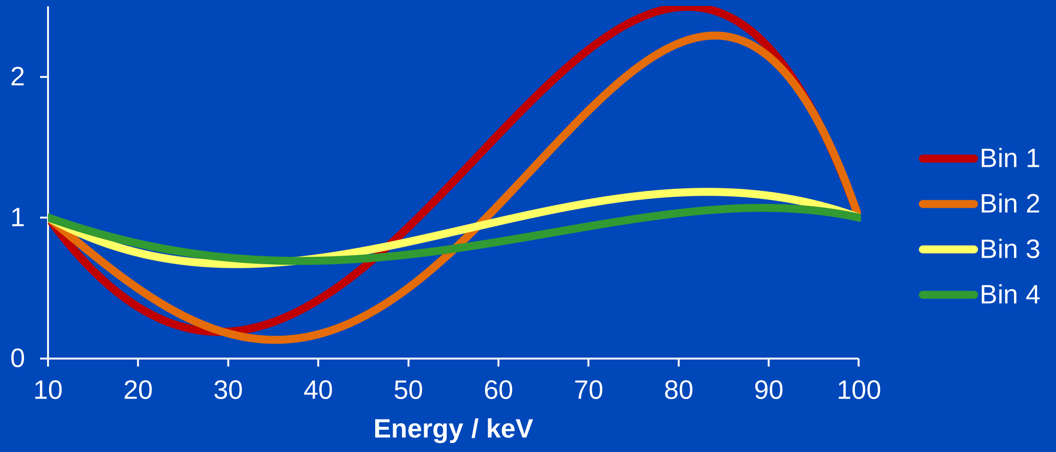


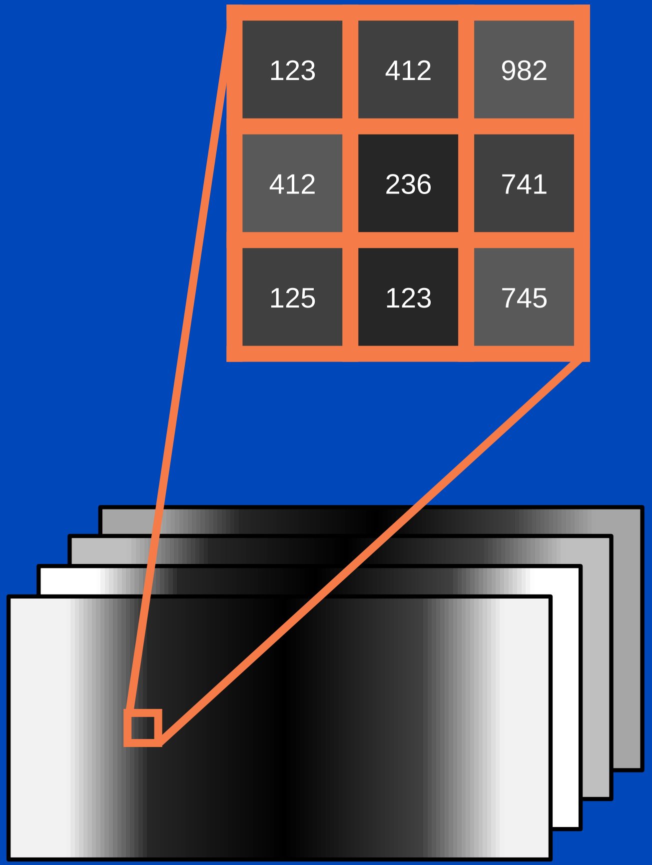




Count Rate-Dependent Spectral Calibration





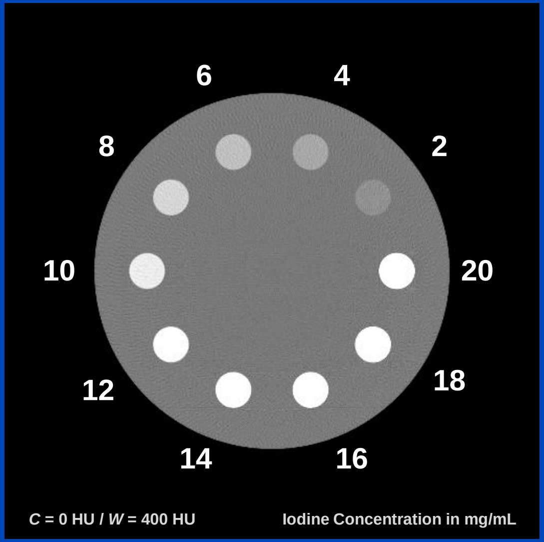


Simulation Study

- Material decomposition into iodine and water
- Spectrum 80 kV, 6 mm Al prefiltration

a) Distorted bin sensitivity function for decomposition

b) Simulated pulse pileup for paralyzable detector and rectangular shaped pulses



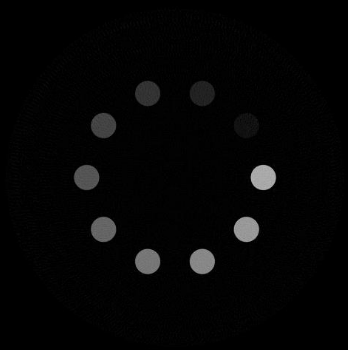
Faby et. al. (2016). "An efficient computational approach to model statistical correlations in photon counting x-ray detectors". *Medical Physics*, 43(7), 3945–3960

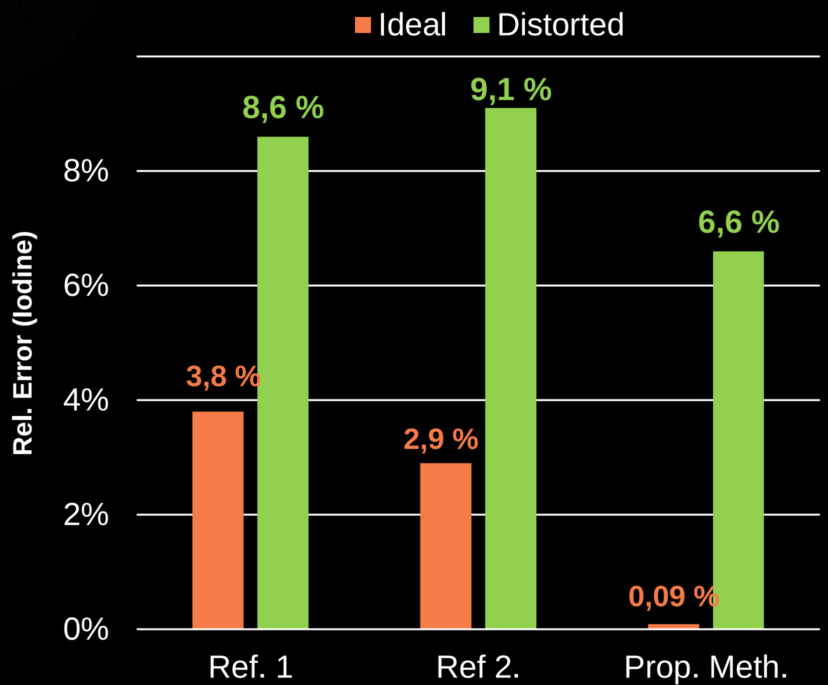
Schlomka et. al. (2008) "Experimental feasibility of multi-energy photon-counting K-edge imaging in pre-clinical computed tomography" *Physics in Medicine and Biology*, 53(15), 4031–4047

Frey et. al. (2007). "Investigation of the use of photon counting x-ray detectors with energy discrimination capability for material decomposition in micro-computed tomography". *Proceedings of SPIE Medical Imaging*, 65100A

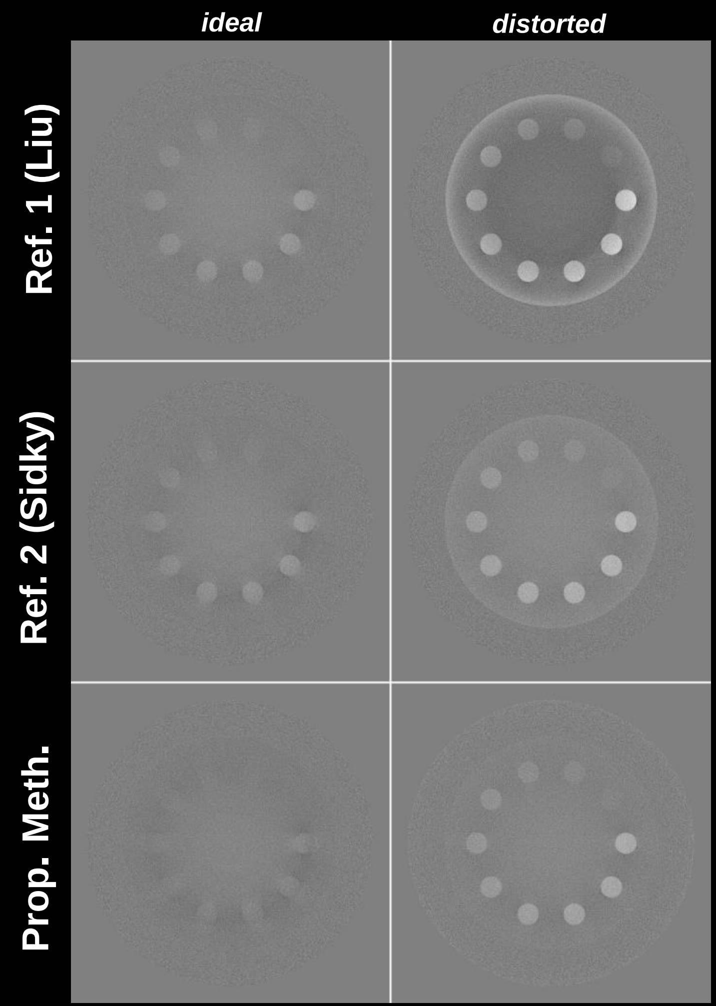
Simulation Study

Ground Truth





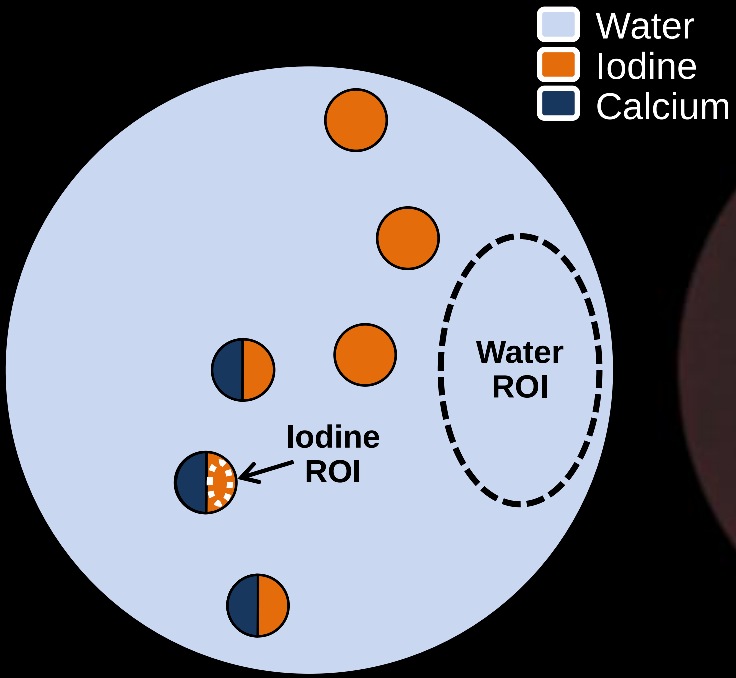
With pulse pileup

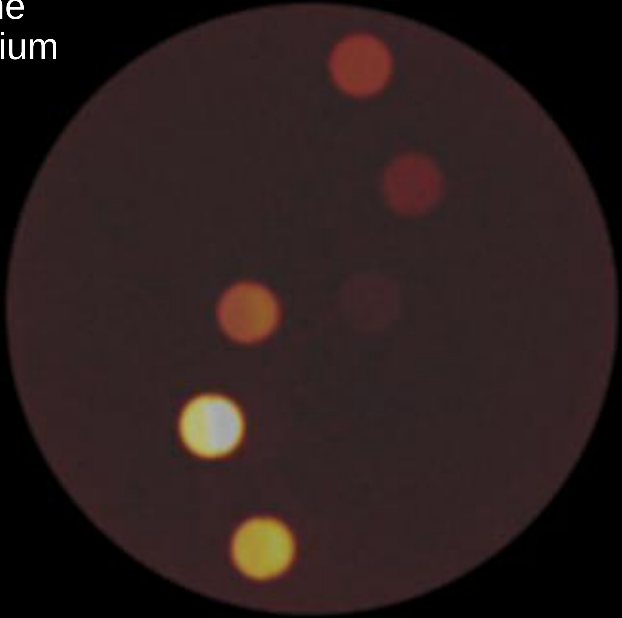


C = 0 mg/mL, *W* = 4 mg/mL

Phantom Measurements

- **QRM dual energy phantom DEP-002.**
- **Reference concentration determined with Siemens Somatom Definition Flash scanner.**

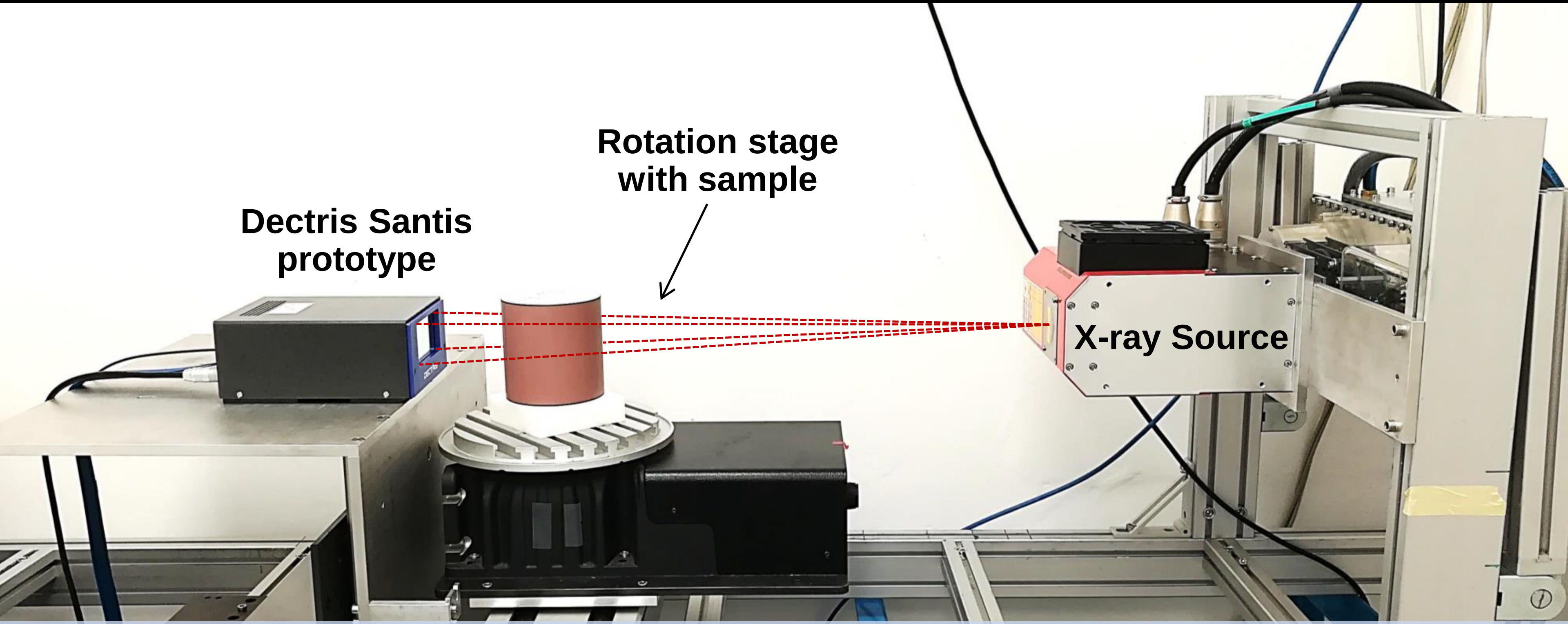




2 cm

Iodine ROI: 21.5 mg/mL
Water ROI: 0.6 mg/mL

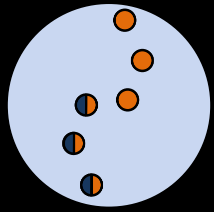
Table-Top Photon Counting CT

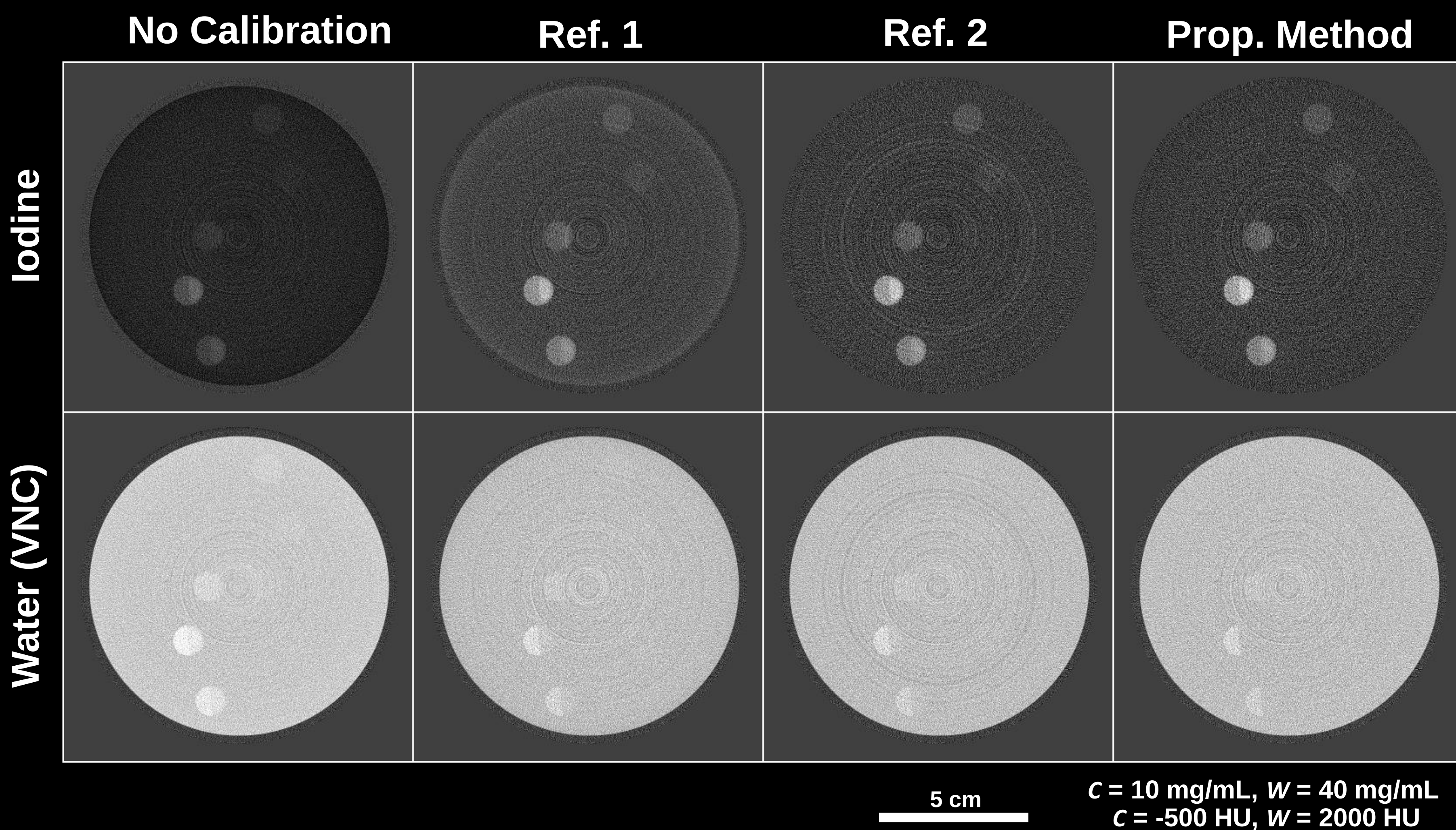


Pixel	512 x 256
Pixel size	150 x 150 µm^2
Sensor thickness	1.0 mm CdTe

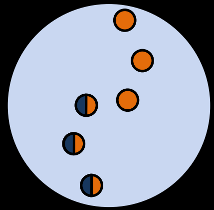
dkfz.

Phantom Measurements

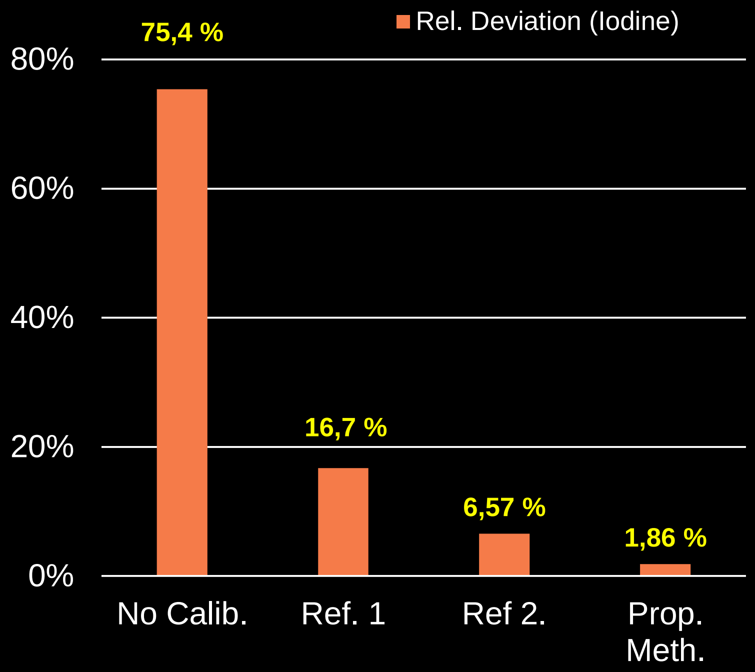




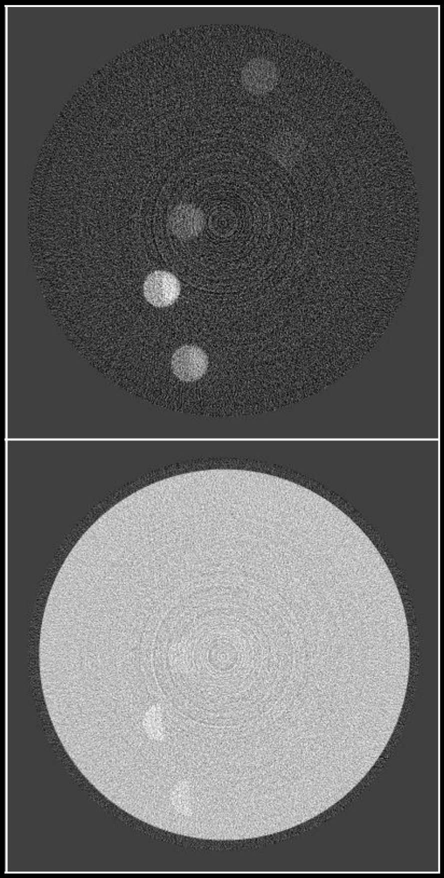
Phantom Measurements



Deviation from Reference Scan



Prop. Method



5 cm

C = 10 mg/mL, W = 40 mg/mL
C = -500 HU, W = 2000 HU

Conclusions

- The count rate-dependent spectral calibration can accommodate both for spectral distortions and count rate-dependent effects.
- In measurements, artifacts in material images were down to noise level.
- Agreement with clinical CT system within 2% for iodine quantification.

Thank You!

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

Job opportunities through DKFZ's international Fellowship programs (marc.kachelriess@dkfz.de).

Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.
The prototype photon-counting x-ray detectors were provided by Dectris Ltd., Baden, Switzerland.