Respiratory Motion Compensation for Simultaneous PET/MR Based on Strongly Undersampled Radial MR Data

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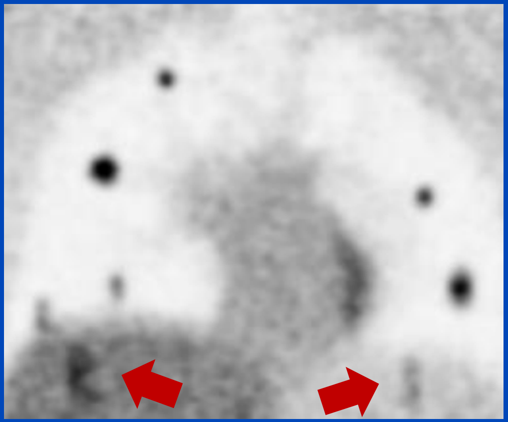
DEUTSCHES KREBSFORSCHUNGSZENTRUM IN DER HELMHOLTZ-GEMEINSCHAFT

Introduction

- One major challenge in PET image reconstruction is patient motion (respiratory, cardiac, involuntary motion)
- Motion causes image blurring and an underestimation of the reconstructed activity

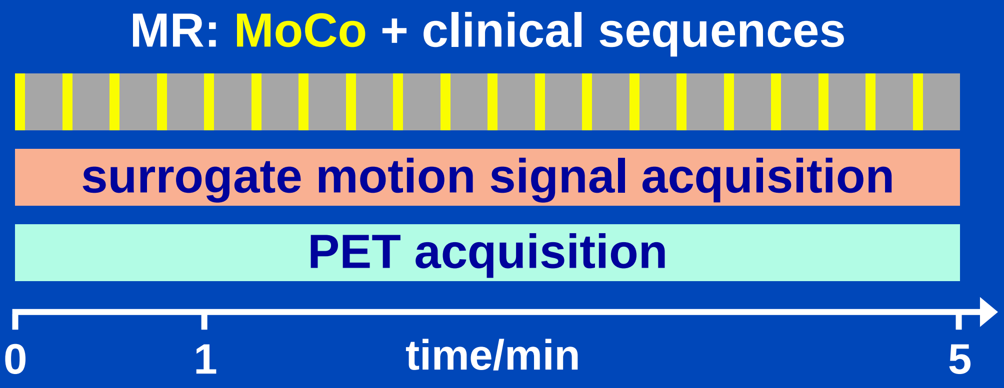


- Gating
  - divide (cyclic) motion into certain gates and reconstruct images from the data of each individual gate separately
  - trade-off between temporal resolution and an appropriate SNR and CNR of the reconstructed images
- Recent approach: PET/MR Motion Compensation (MoCo)[1,2,3]
  - use MR information to estimate 4D motion vector fields (MVFs)
  - 4D MoCo PET reconstruction from 100% of rawdata

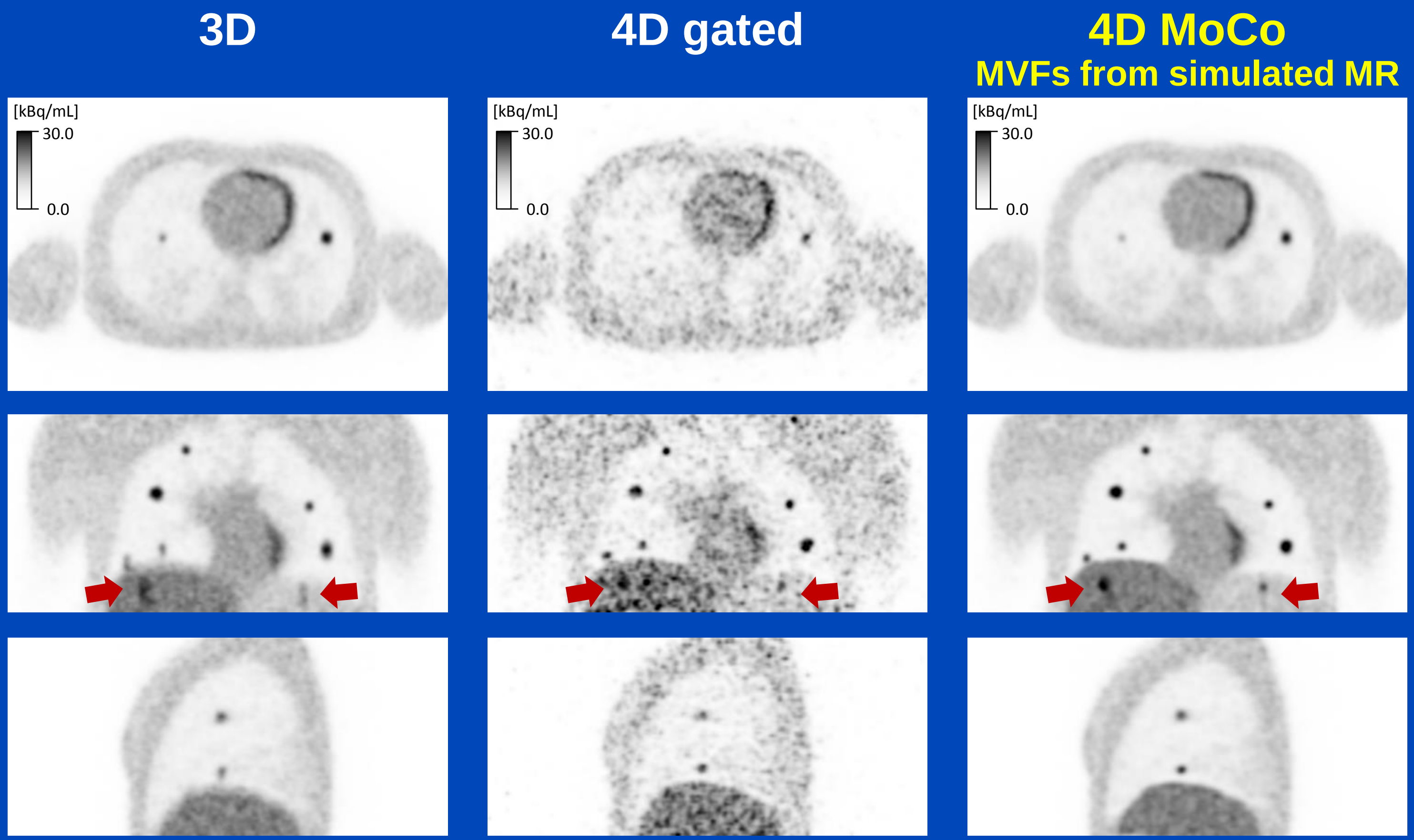
[1] Würslin et al. Respiratory motion correction in oncologic PET using T1-weighted MR imaging on a simultaneous whole-body PET/MR system. *J. Nucl. Med.* 2013.
[2] Grimm et al. Self-gated MRI motion modeling for respiratory motion compensation in integrated PET/MRI. *Med. Image Anal.* 2015.
[3] Fürst et al. Motion Correction Strategies for Integrated PET/MR. *J. Nucl. Med.* 2015.

Aim of Work

- **Develop a framework for respiratory motion compensation of PET images**
- **Use information from a strongly undersampled radial MR sequence that**
  - **runs in parallel with the PET acquisition**
  - **requires less than 1 min of the acquisition time per bed position**
  - **can be interlaced with clinical MR sequences**

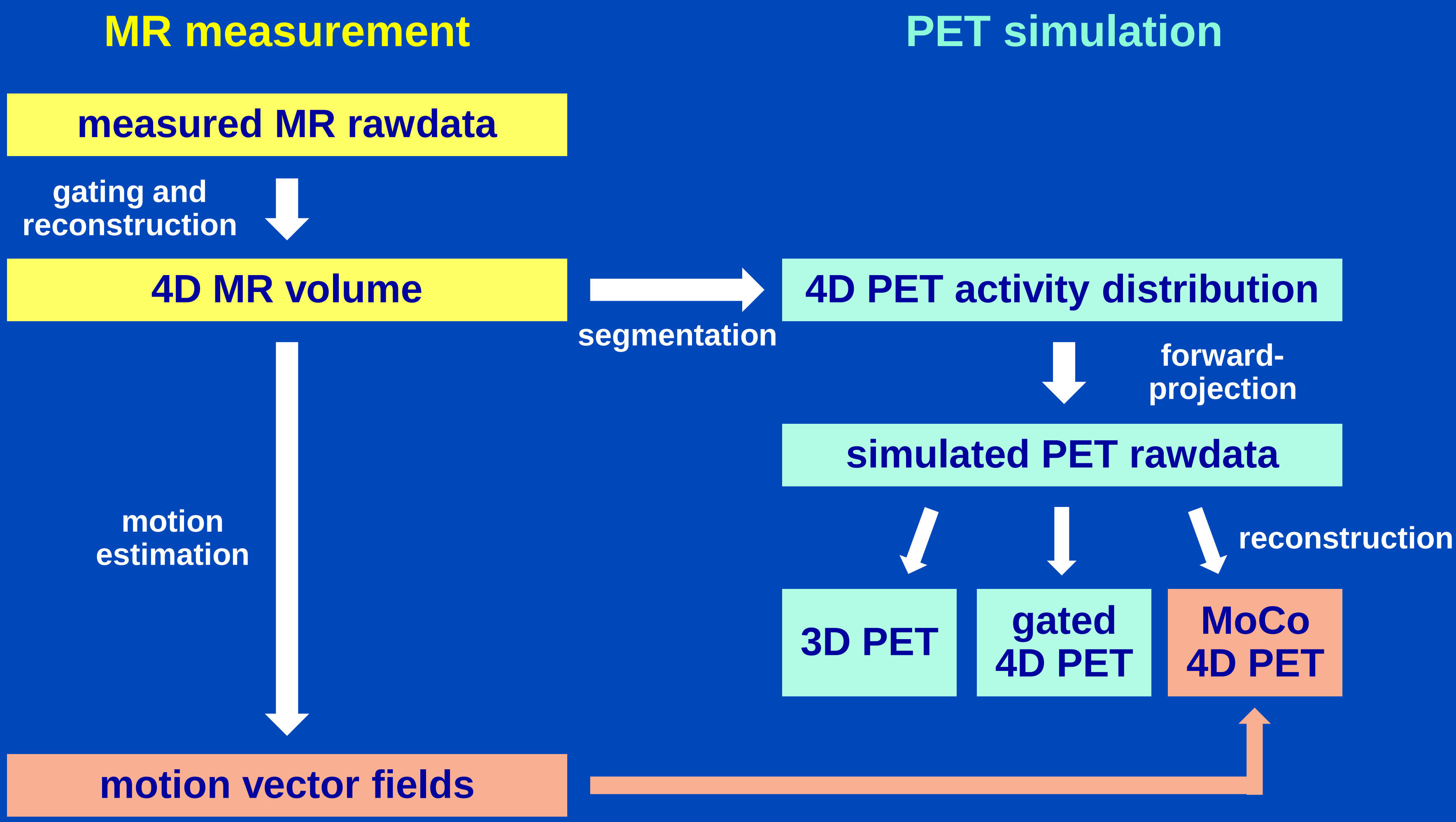


PET MoCo with Simulated MR and PET Data



Results were presented at RSNA 2014, MIC 2014, SPIE 2015.

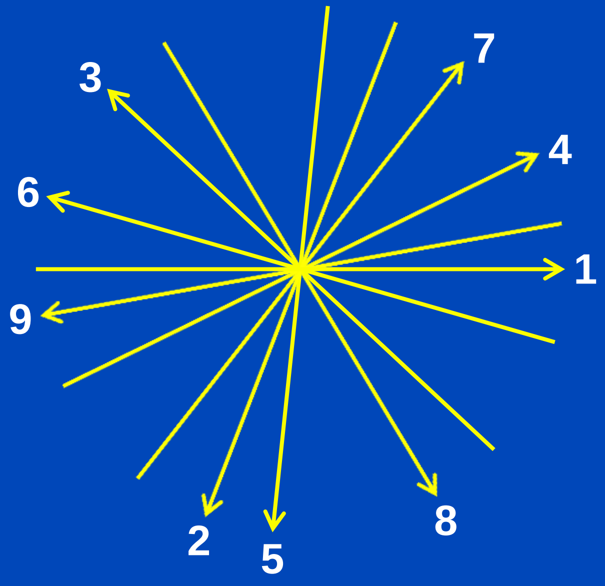
Overview of Study



Measurement of MR Rawdata

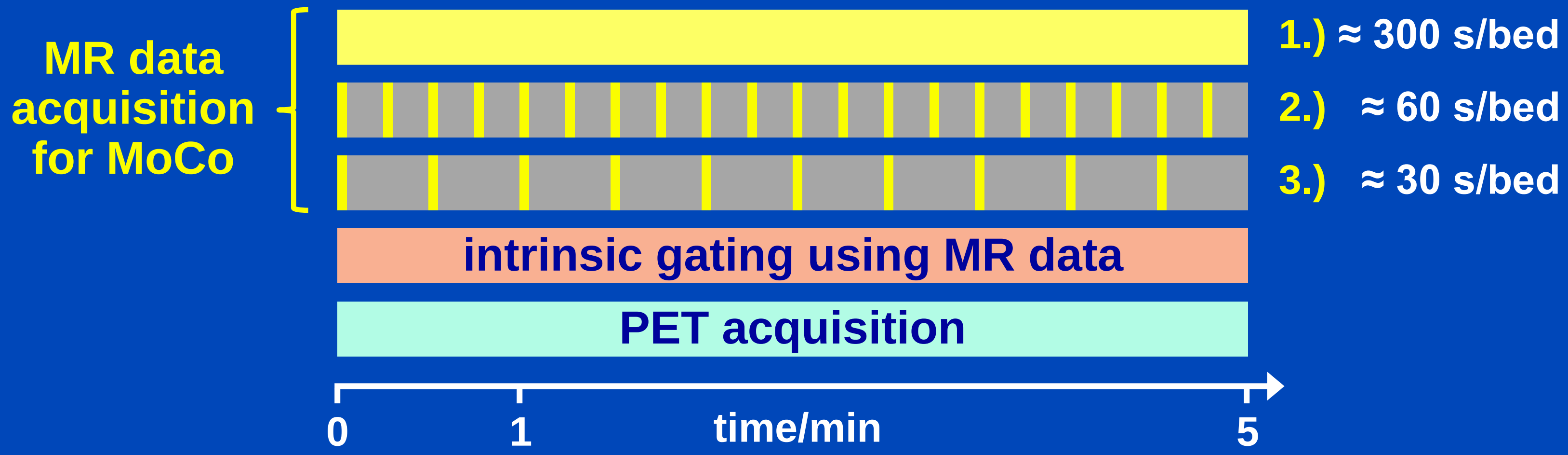
- **MR volunteer measurements of free-breathing thorax and upper abdomen at Siemens Biograph mMR**
- **3D encoded gradient echo sequence with radial stack-of-stars sampling scheme**
- **Radial sampling in sagittal or coronal plane**
- **Golden angle radial spacing**

$$\mathrm{d}\theta = \frac{2\pi}{1+\sqrt{5}} \approx 111.25^\circ$$



Generation of Sparse MR Datasets and Binning to Motion Phases

- Retrospective generation of three MR rawdata sets reproducing an interlaced MR acquisition



- Intrinsic gating: motion amplitudes were estimated from measured MR data
- MR data were sorted retrospectively into 20 overlapping motion phase bins (10% width)

Iterative MR Reconstruction (HDTV)[1,2]

- **Cost function:**

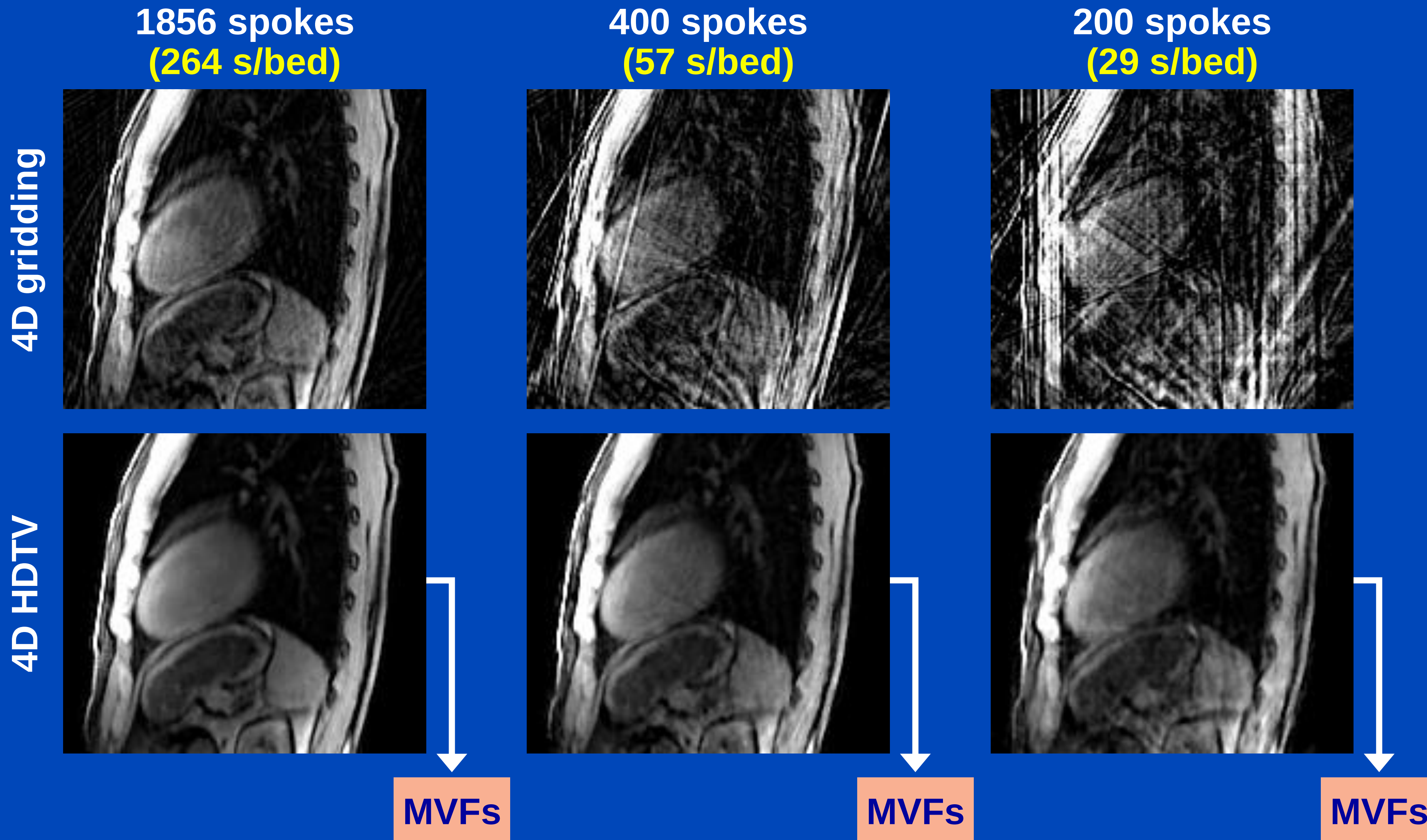
$$C = \underbrace{\|\mathrm{X}Sf - p\|_2^2}_{\text{rawdata fidelity}} + \underbrace{\alpha\|f\|_{\mathrm{TV,\,xyzt}}}_{\text{total variation}}$$

X:	forward transform
S:	coil sensitivity profiles
f:	4D image volume
p:	rawdata
α:	weight
$\|\cdot\|_{\mathrm{TV,\,xyzt}}$:	spatial and temporal total variation

- **The first term optimizes the rawdata fidelity**
- **The second term improves the image smoothness by optimizing the spatial and temporal total variation**
- **Both terms are optimized in an alternating manner**
- **The cost function is optimized for the complete 4D volume including all motion phases**

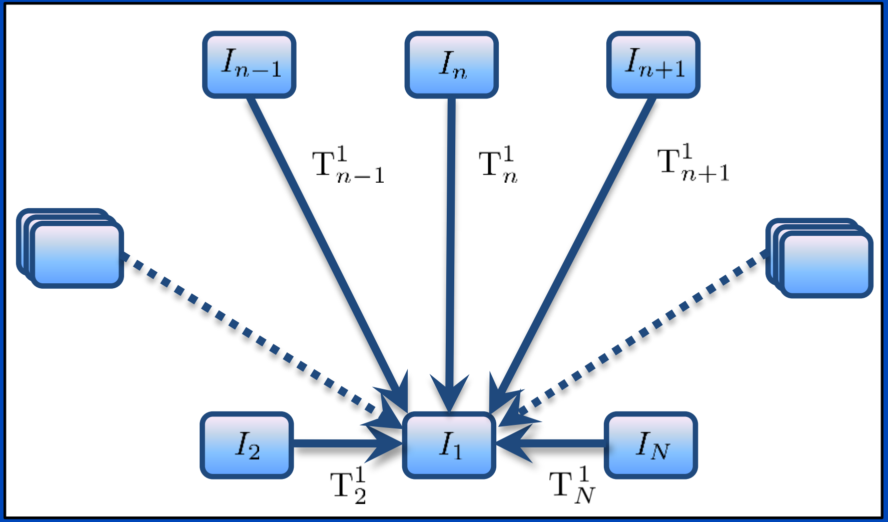
1 Ritschl, Bergner, Fleischmann, Kachelrieß. Improved total variation-based CT image reconstruction applied to clinical data. *Phys. Med. Biol.* 2011.
2 Ritschl, Sawall, Knaup, Hess, Kachelrieß. Iterative 4D cardiac micro-CT image reconstruction using an adaptive spatio-temporal sparsity prior. *Phys. Med. Biol.* 2012.

Results of MR Reconstruction



Standard Motion Estimation (sMoCo)

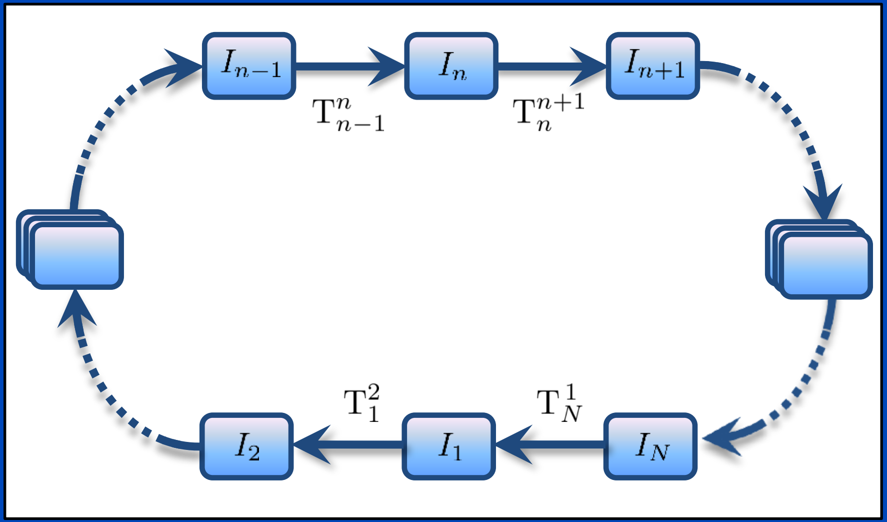
- Motion estimation via standard 3D-3D registration
  - all motion phases are registered to each individual phase

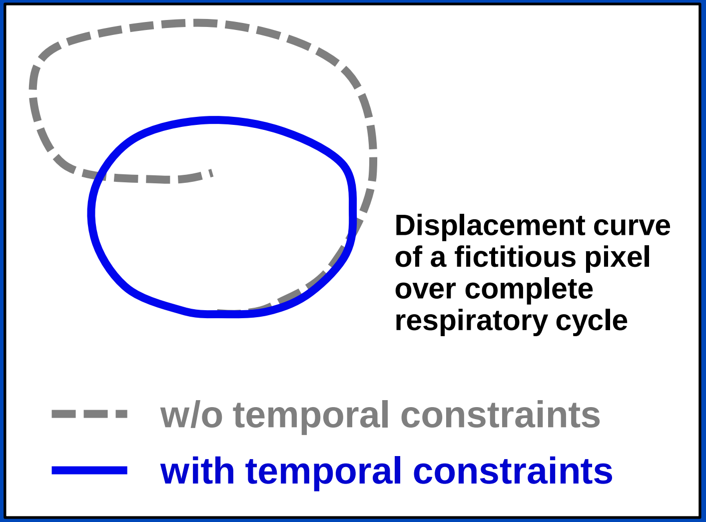


- *N* (*N*-1) registration steps are required

Cyclic Motion Estimation[1] (cMoCo)

- Motion estimation only between adjacent phases
  - all other MVFs given by concatenation





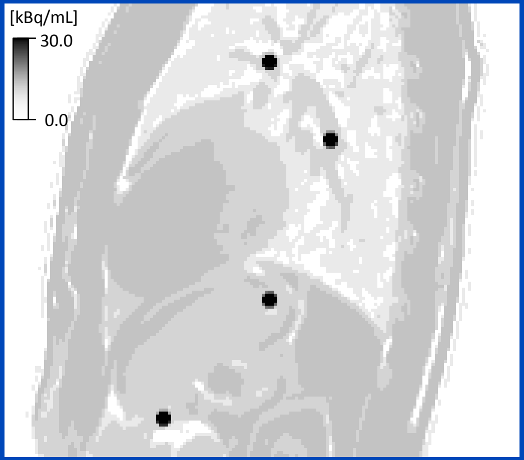
- Incorporate additional knowledge
  - a priori knowledge of quasi periodic breathing pattern
  - non-cyclic motion is penalized
  - error propagation due to concatenation is reduced

1 Brehm, Paysan, Oelhafen, Kunz, Kachelrieß. Self-adapting cyclic registration for motion-compensated cone-beam CT in image-guided radiation therapy. *Med. Phys.* 2012.

PET Simulation and Reconstruction

- **4D activity distribution**
  - soft tissue (*A* = 5-7 kBq/mL)
  - lungs (*A* = 2.5 kBq/mL)
  - 4 artificial hot lesions (spheres with 8 mm diameter and *A* = 36 kBq/mL)
- **Rawdata simulation**
  - forward project activity distribution
  - add Poisson noise and scatter
  - total number of counts: $\approx 10^8$
  - effect of attenuation was excluded
  - geometry of Siemens Biograph mMR
- **Iterative reconstruction**
  - 3D OSEM using 3 iterations and 21 subsets
  - Gaussian smoothing after each iteration (FWHM = 3.3 mm)
  - incorporation of MVFs into system matrix for 4D MoCo reconstruction

4D PET
activity distribution



MoCo PET Image Reconstruction[1]

- **MoCo MLEM update equation of motion phase *i*:**

$$\lambda_i^{(n+1)} = \lambda_i^{(n)} \frac{1}{\sum_{i'} T_{i'}^{i} M^{\mathrm{T}} \mathbf{1}} \sum_{i'} T_{i'}^{i} M^{\mathrm{T}} \frac{p_{i'}}{M T_i^{i'} \lambda_i^{(n)} + r_{i'} + s_{i'}}$$

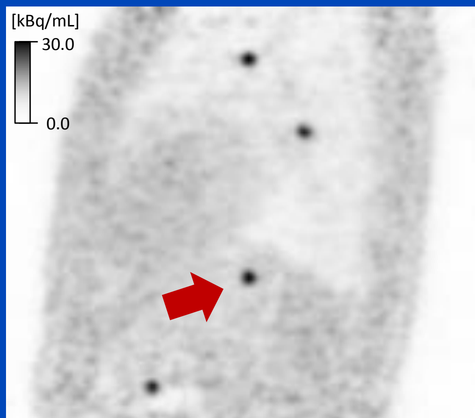
n:	iteration index
M, M^{T}:	system matrix including forward-/backprojection
p:	measured rawdata (prompts)
r:	estimated randoms
s:	estimated scatter
$\lambda^{(n)}$:	image estimate at iteration n
i, i':	indices of motion phases
$T_i^{i'}$:	warping operation mapping motion phase *i* to *i'*

- **To reduce computation time, an ordered subset implementation (OSEM) was used**

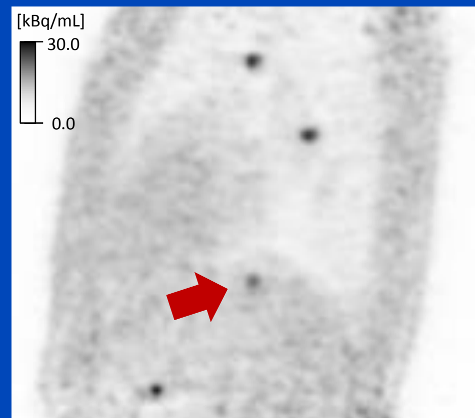
1 Qiao, Pan, Clark, Mawlawi. A motion-incorporated reconstruction method for gated PET studies. Phys. Med. Biol. 2006.

Results of PET Reconstruction

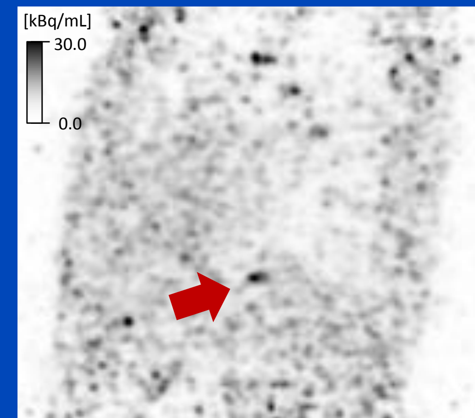
4D reference gated
ten-fold PET acquisition time



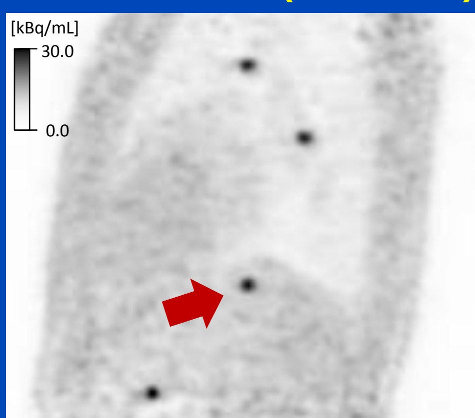
3D



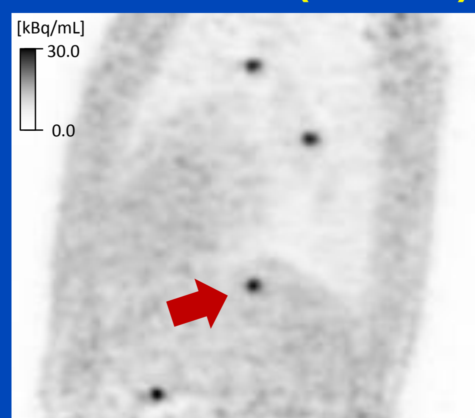
4D gated



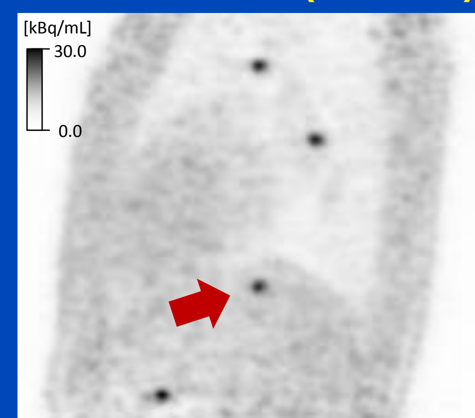
4D MoCo
MVFs from MR (264 s/bed)



4D MoCo
MVFs from MR (57 s/bed)

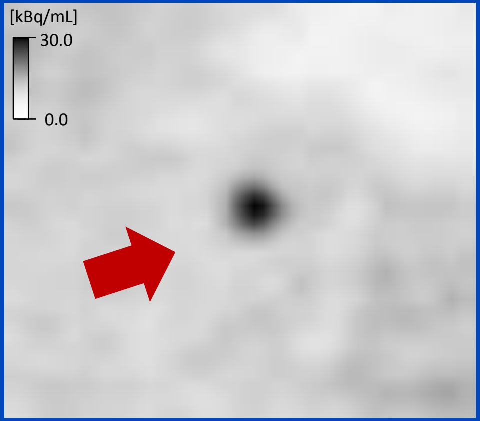


4D MoCo
MVFs from MR (29 s/bed)

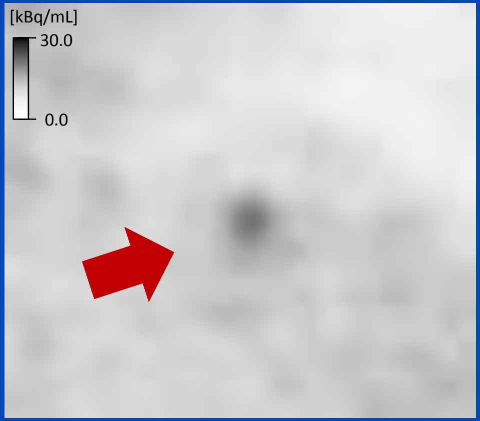


Results of PET Reconstruction

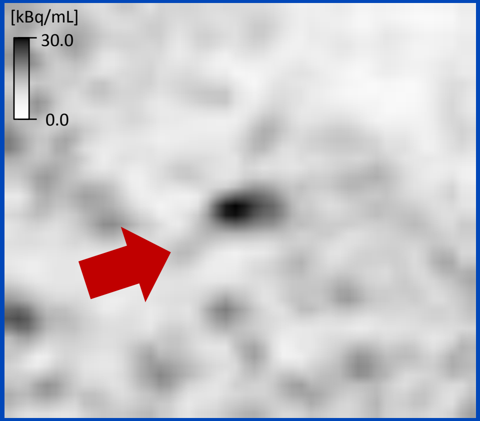
4D reference gated
ten-fold PET acquisition time



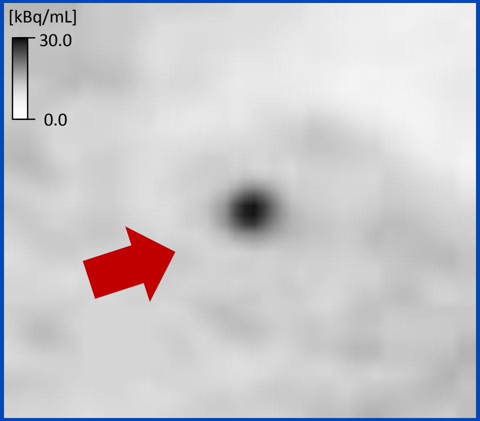
3D



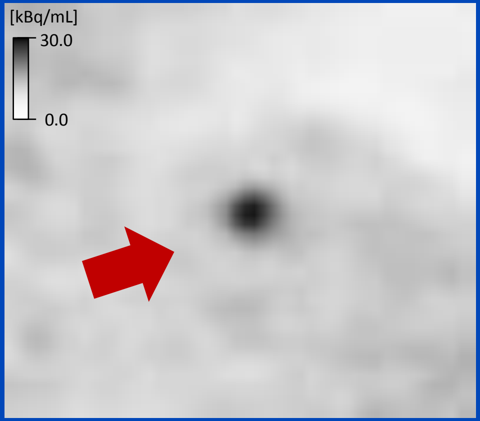
4D gated



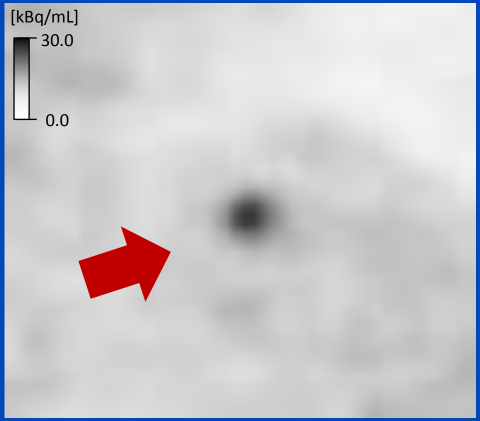
4D MoCo
MVFs from MR (264 s/bed)



4D MoCo
MVFs from MR (57 s/bed)

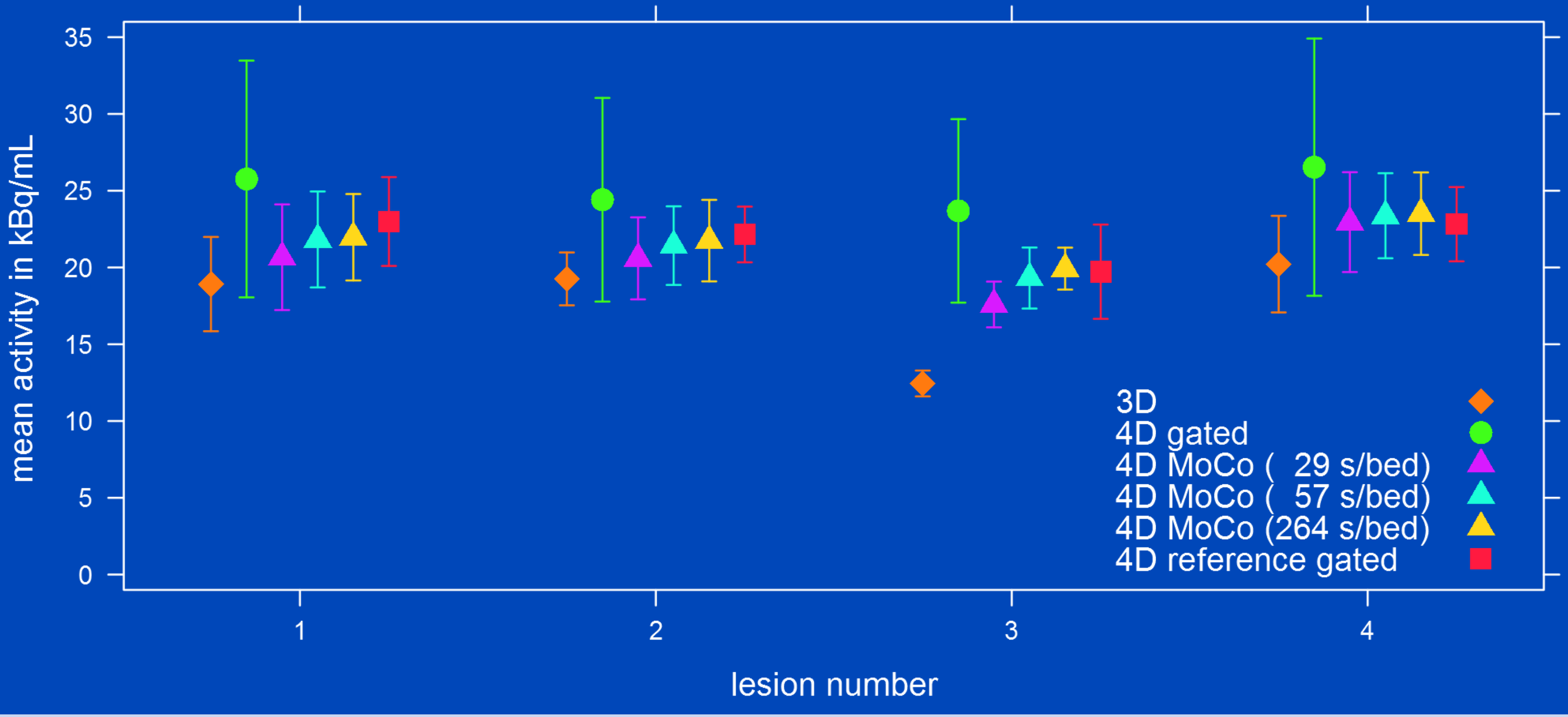


4D MoCo
MVFs from MR (29 s/bed)



Quantitative Analysis of PET Images

- Mean activities of lesions were measured for all motion phases and the average and standard deviation were calculated

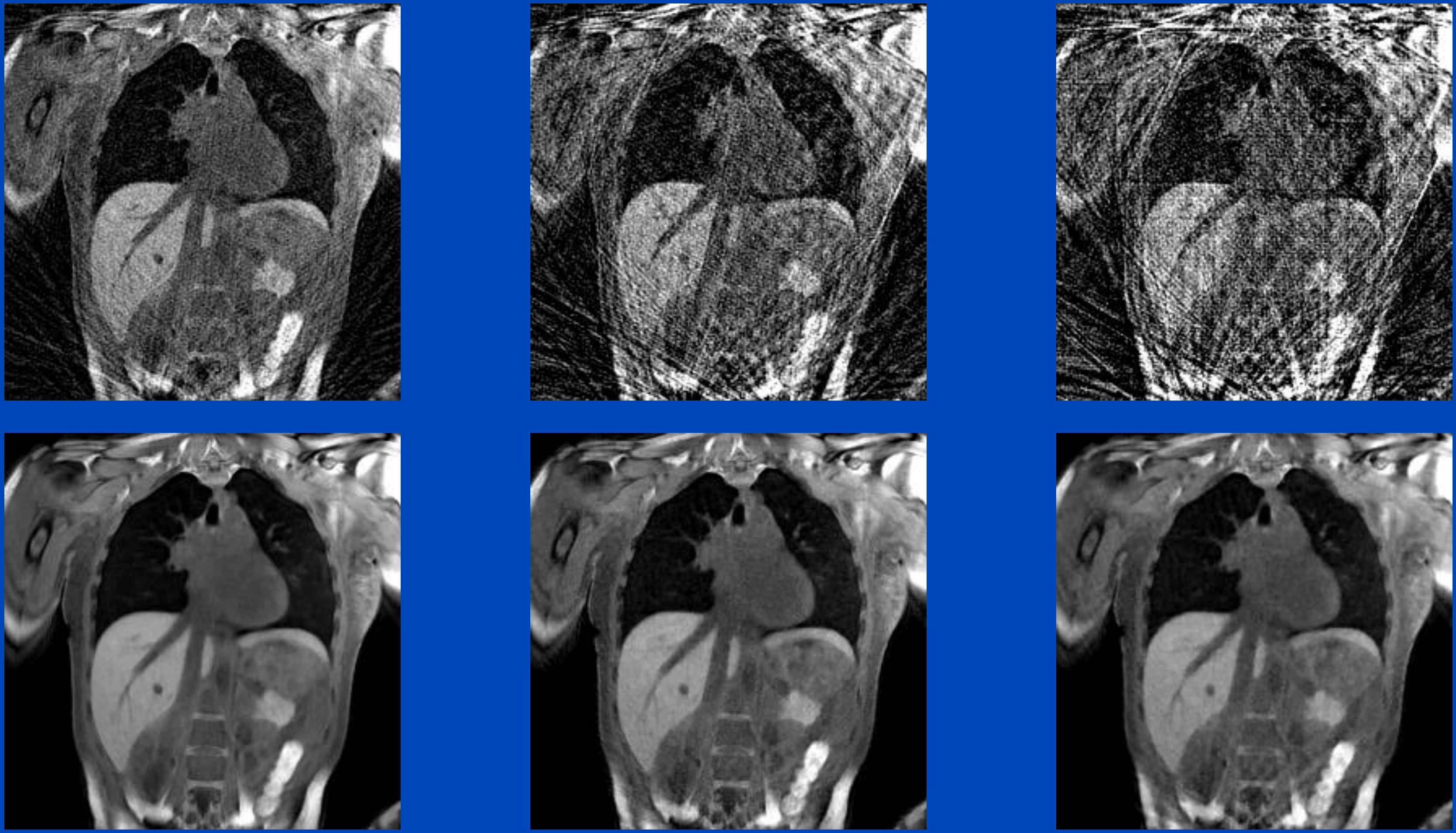


MoCo MR Image Reconstruction

1590 spokes (191 s/bed) | 400 spokes (48 s/bed) | 200 spokes (24 s/bed)

4D gridding

4D MoCo-HDTV



Summary

- PET respiratory MoCo based on measured radial MR data with high sparsity acquired in less than 1 min
- 3D encoded radial stack-of-stars MR sampling scheme with iterative MR reconstruction
- Cyclic registration for estimation of MVFs
- 4D MoCo PET reconstruction
- Significant improvement of PET image quality in terms of temporal resolution or noise level and of PET quantification
- 4D MoCo MR reconstruction possible

- Outlook: verification with measured PET patient data

Thank You!

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

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