Respiratory Motion Compensation for Simultaneous PET/MR Based on a 3D-2D Registration of Strongly Undersampled Radial MR Data

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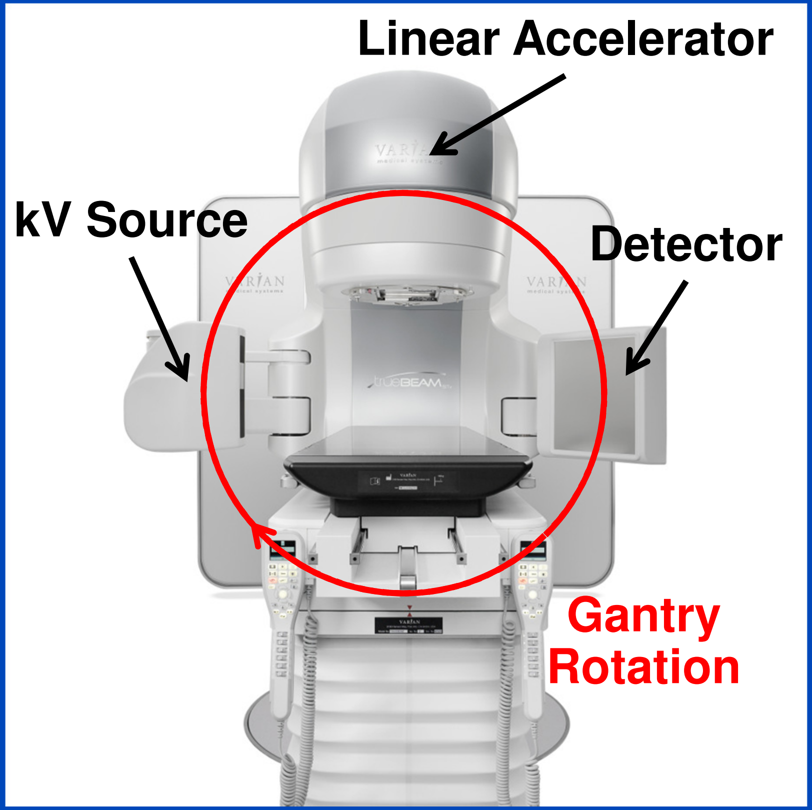
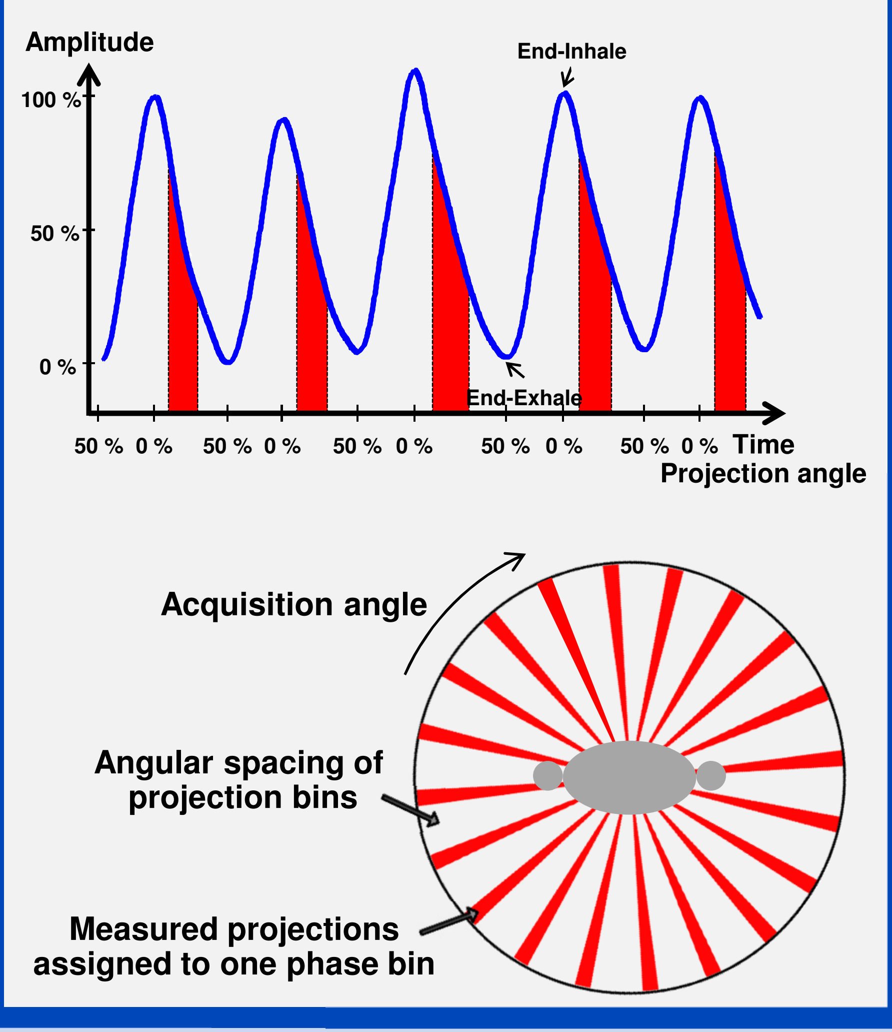
DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

Where we come from:
Motion Management for IGRT

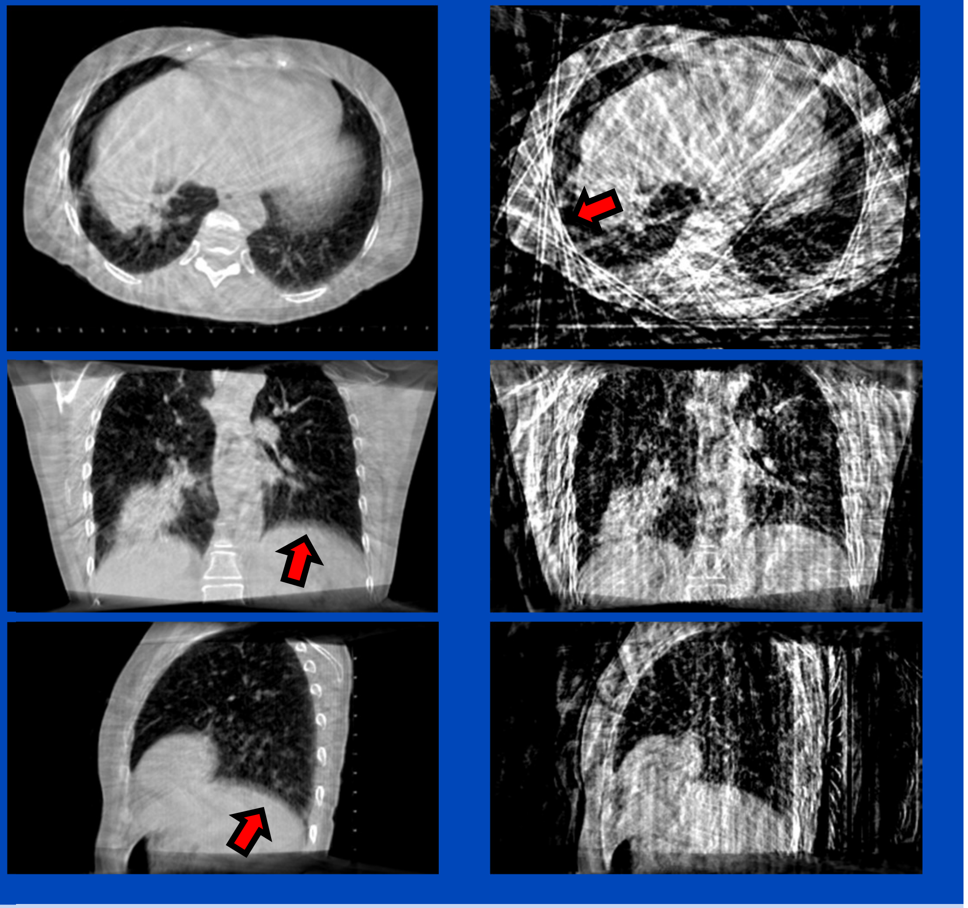


Retrospective Gating



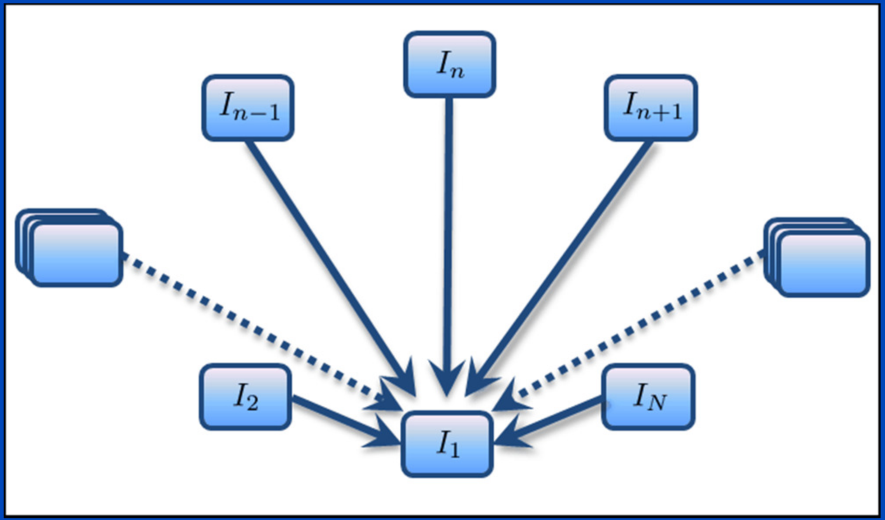
Without gating (3D): Motion artifacts

With gating (4D): Sparse-view artifacts

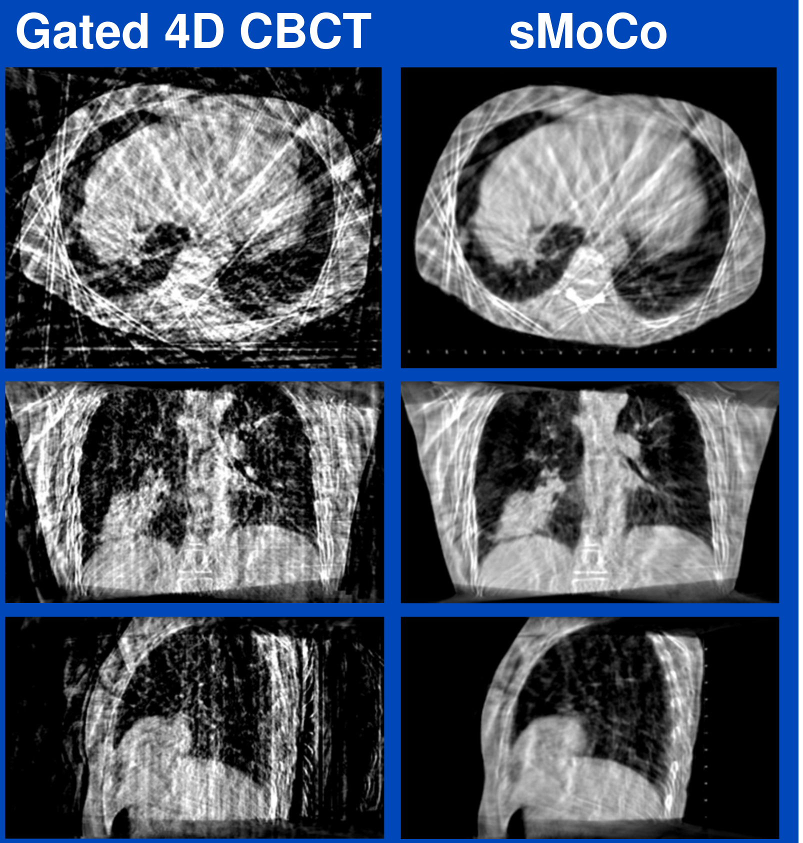


A Standard Motion Estimation and Compensation Approach (sMoCo)

- Motion estimation via standard 3D-3D registration



- Has to be repeated for each reconstructed phase

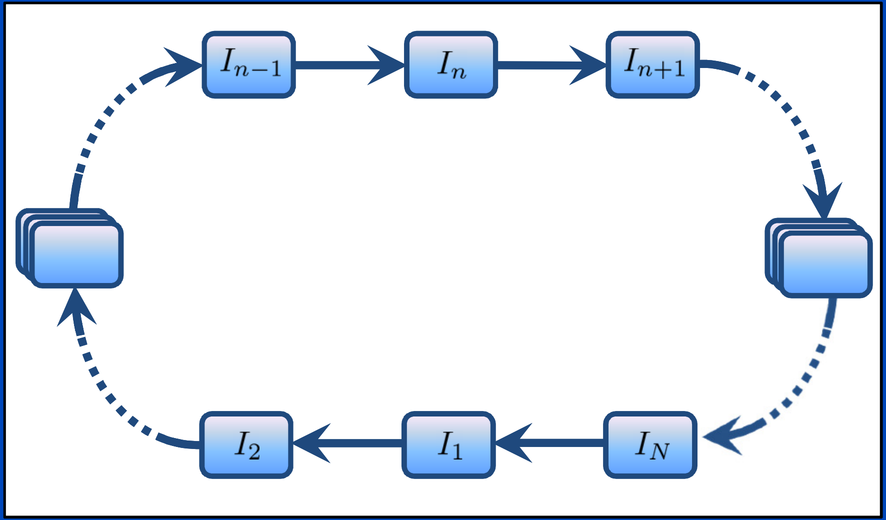


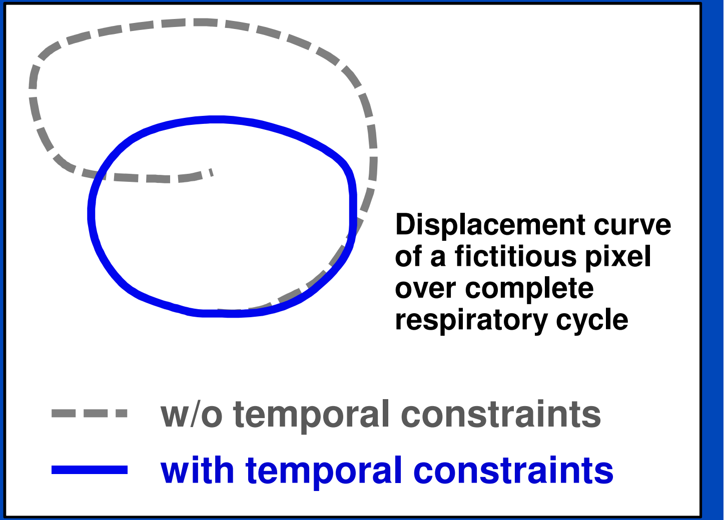
- Streak artifacts from gated reconstructions propagate into sMoCo results

Li, Koong, and Xing, “Enhanced 4D cone–beam CT with inter–phase motion model,” Med. Phys. 51(9), 3688–3695 (2007).

A Cyclic Motion Estimation and Compensation Approach (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

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

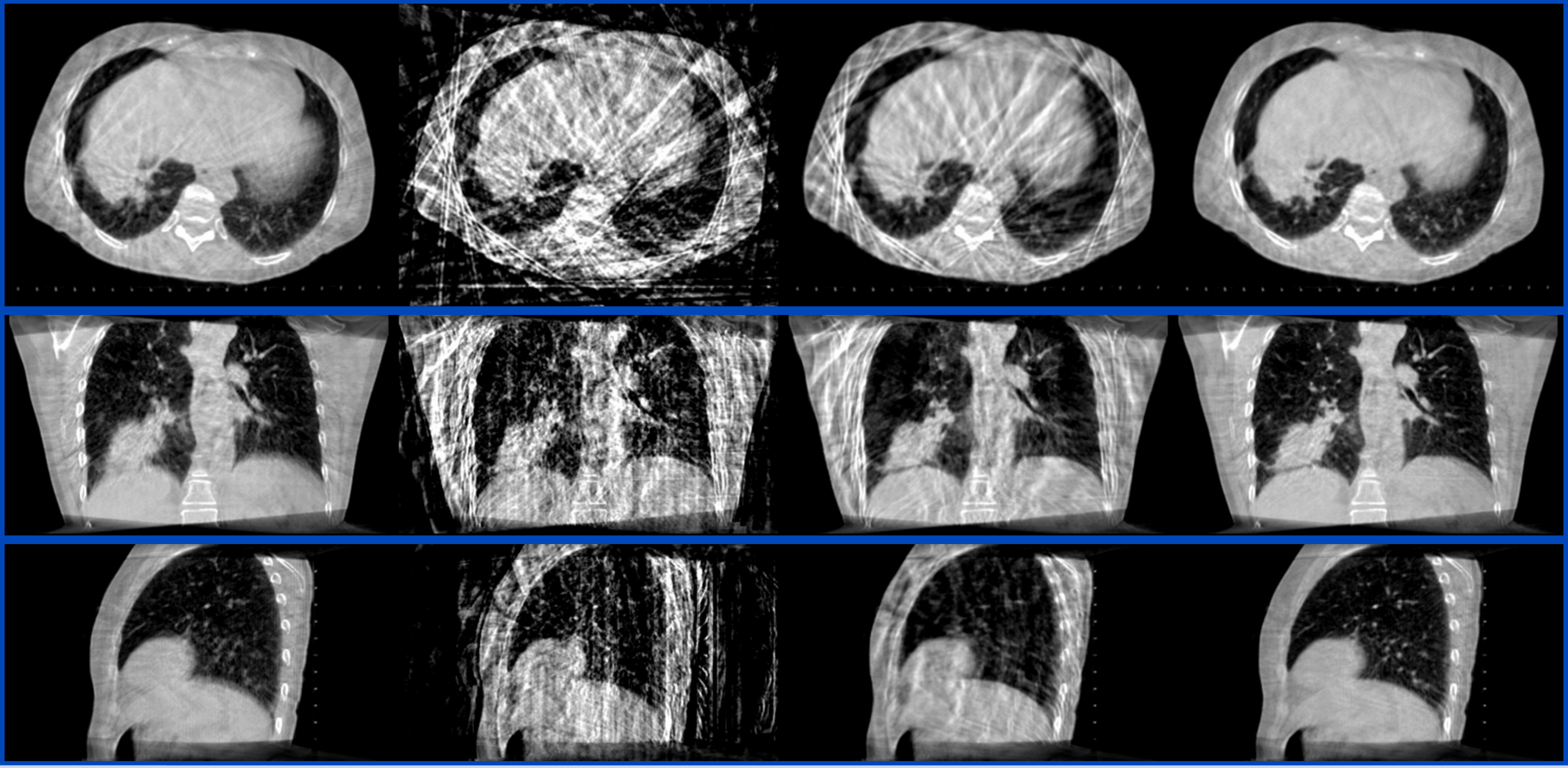
Results (Varian Patient Data)

3D CBCT
Standard

Gated 4D CBCT
Conventional
Phase-Correlated

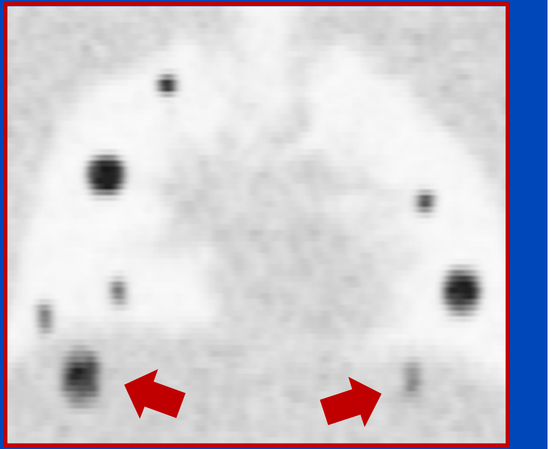
sMoCo
Standard Motion
Compensation

acMoCo
Artifact Model-Based
Motion Compensation



C = -200 HU, W = 1400 HU

Introduction



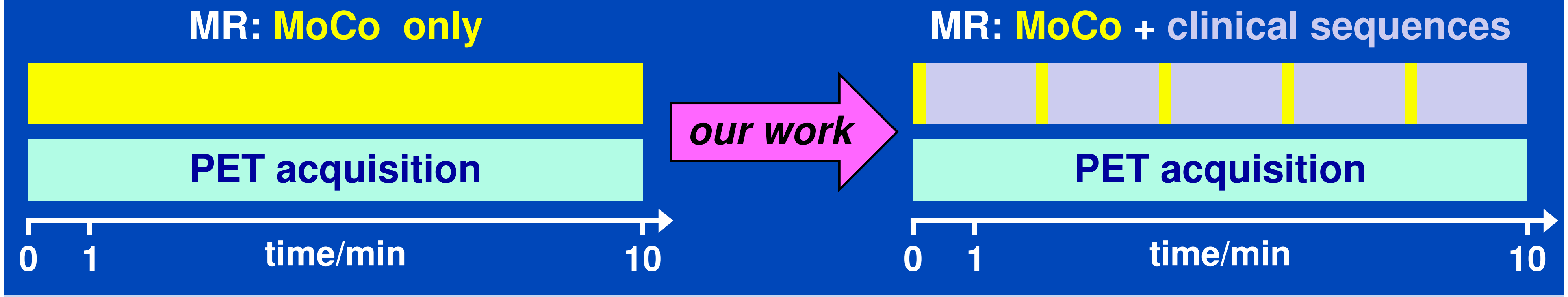
- One major obstacle in PET image reconstruction is patient motion (respiratory, cardiac, involuntary motion)
- Motion causes image blurring and an underestimation of the reconstructed activity
- Gating
  - divide (cyclic) motion into certain gates and reconstruct images from the data of each individual gate separately
  - trade-off between temporal resolution and an appropriate SNR and CNR of the reconstructed images
- Recent approaches: Motion Compensation (MoCo)[1,2]
  - use MR information to estimate 4D motion vector fields (MVFs)
  - 4D MoCo PET reconstruction using 100% of the PET 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.

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**



MR: MoCo only

PET acquisition

0 1 time/min 10

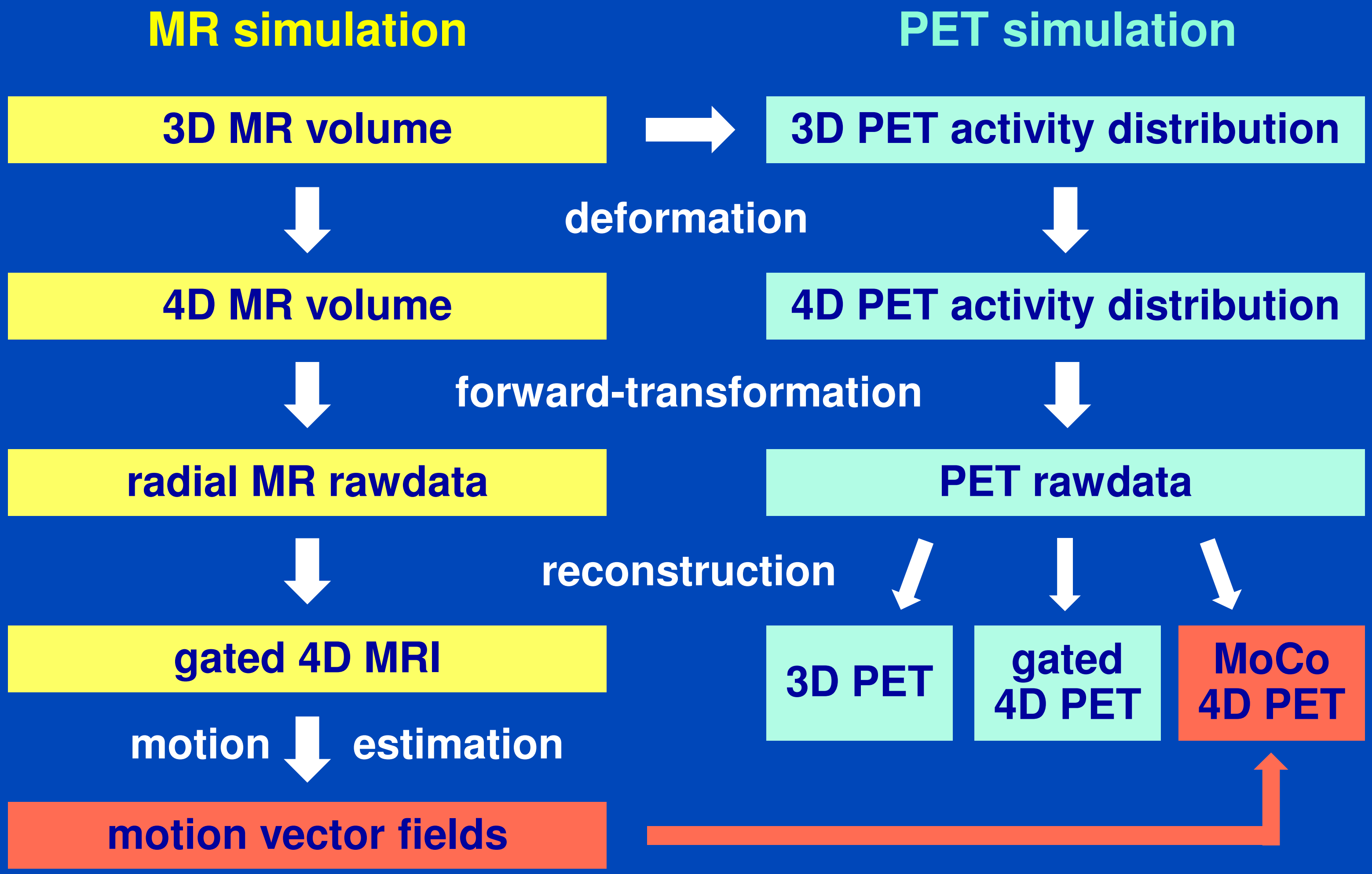
our work

MR: MoCo + clinical sequences

PET acquisition

0 1 time/min 10

Overview



MR simulation

PET simulation

3D MR volume

3D PET activity distribution

deformation

4D MR volume

4D PET activity distribution

forward-transformation

radial MR rawdata

PET rawdata

reconstruction

gated 4D MRI

3D PET

gated 4D PET

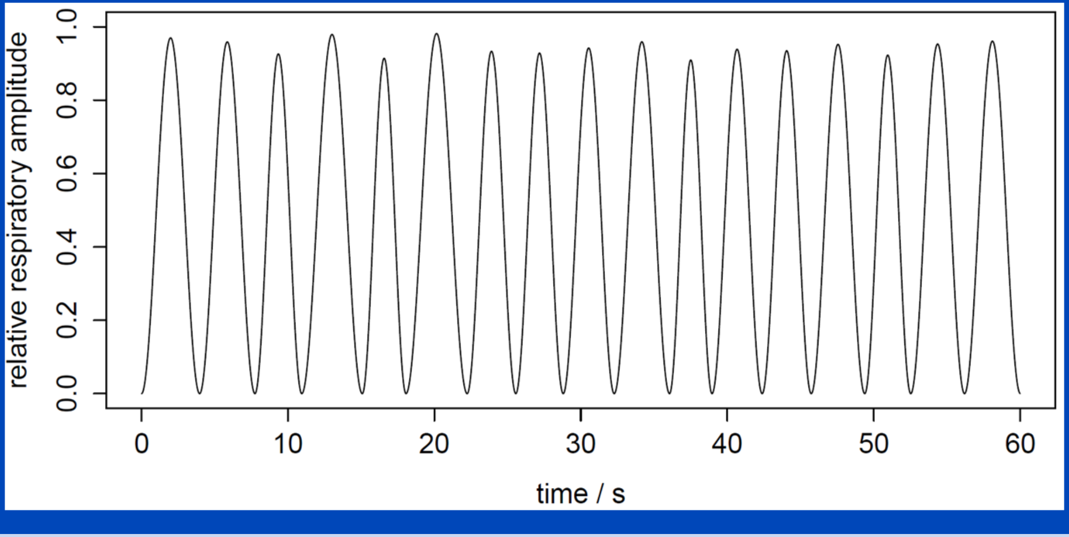
MoCo 4D PET

motion estimation

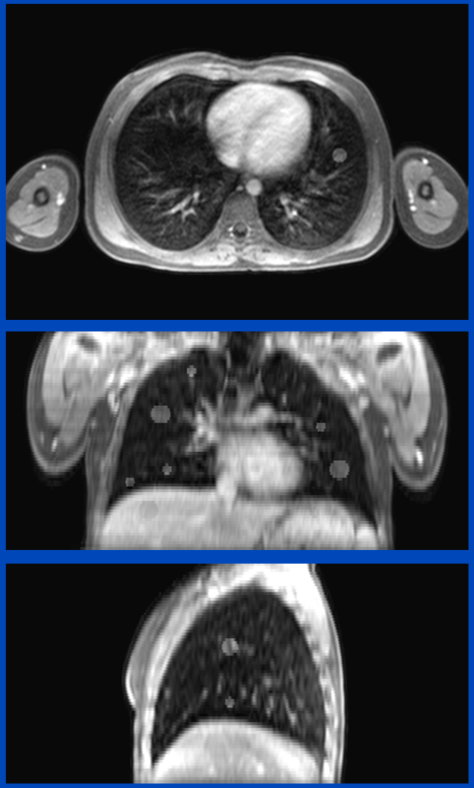
motion vector fields

Simulation of Undersampled Data

- Respiratory motion was generated by applying artificially generated DVFs to a static 3D MR volume
- For simulation of an MR measurement during free breathing, the time evolution of a respiratory motion curve was considered

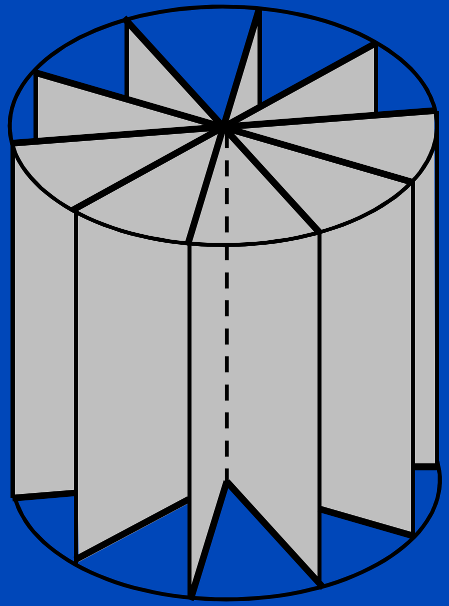


motion simulation



K-Space Sampling Scheme

Simulation	Measurement
160 radial spokes per slice	480 radial spokes per slice
3D encoded radial stack-of-stars sequence	
radial sampling in transversal plane	radial sampling in coronal or sagittal plane
acquisition time: 38 s	acquisition time: 57 – 69 s
data sorted retrospectively into 20 overlapping motion phases (10% width of respiratory cycle, 5% steps)	
reordered interleaved angle increment	interleaved Golden angle increment



Iterative Reconstruction (HDTV)[1,2]

- **Cost function**

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

X:	Forward transform
f:	image
p:	rawdata
α:	weight
$\|\cdot\|_{\text{TV, xyzt}}$:	total variation

- **The rawdata fidelity and the spatial and temporal smoothness of the image are optimized in an alternating manner**
- **Instead of X^T we precondition and use X^{-1}, i.e. gridding followed by inverse Cartesian Fourier transform.**
- **The cost function is optimized for the complete 4D volume including all motion phases**

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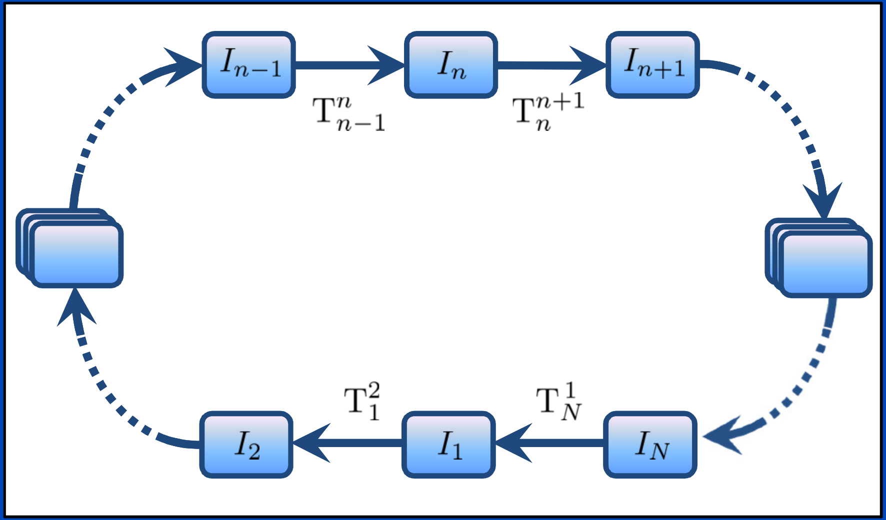
[1] Ritschl, Bergner, Fleischmann, Kachelrieß. Improved total variation-based CT image reconstruction applied to clinical data. *Phys. Med. Biol.* 2011.

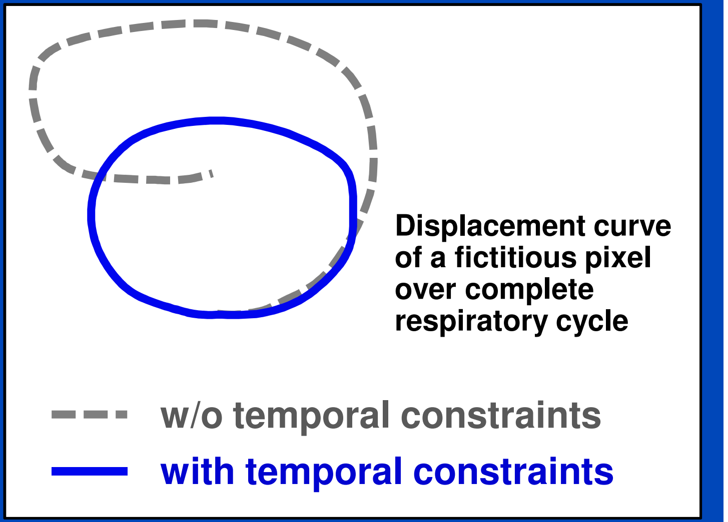
[2] Ritschl, Sawall, Knaup, Hess, Kachelrieß. Iterative 4D cardiac micro-CT image reconstruction using an adaptive spatio-temporal sparsity prior. *Phys. Med. Biol.* 2012.

MoCo

Cyclic Motion Estimation[1] (cMoCo)

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




Displacement curve of a fictitious pixel over complete respiratory cycle

- Incorporate additional knowledge
  - A priori knowledge of quasi periodic breathing pattern
  - Non-cyclic motion is penalized
  - Error propagation due to concatenation is reduced

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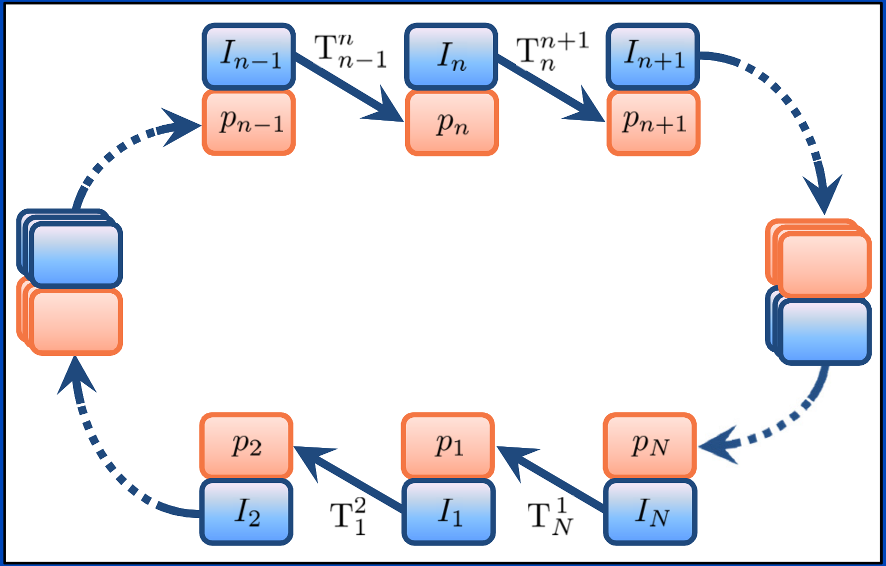
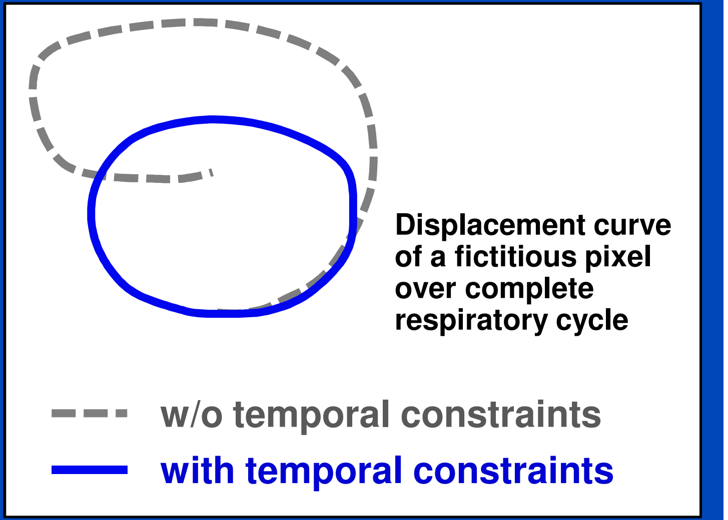
[1] Brehm, Paysan, Oelhafen, Kunz, Kachelrieß. Self-adapting cyclic registration for motion-compensated cone-beam CT in image-guided radiation therapy. *Med. Phys.* 2012.

Cyclic Motion Estimation[1] (3D-2D[2] cMoCo)

- Motion estimation only between adjacent phases
  - Deform image I_n in such a way that it matches the rawdata p_{n+1}

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

[2] Flach, Brehm, Sawall, Kachelrieß. Deformable 3D-2D registration for CT and its application to low dose tomographic fluoroscopy. Phys. Med. Biol. 2014.

MoCo
Deformable 3D-2D Registration[1]

- Deform image $m(\boldsymbol{r})$ such that it matches the rawdata p:
  - Displacement vector field (DVF): $\boldsymbol{u}(\boldsymbol{r}) = (u_1(\boldsymbol{r}), u_2(\boldsymbol{r}), u_3(\boldsymbol{r}))^{\mathrm{T}}$
  - Deformed image: $m_{\boldsymbol{u}}(\boldsymbol{r}) = m(\boldsymbol{r} + \boldsymbol{u}(\boldsymbol{r})) = (m \circ (\mathrm{Id} + \boldsymbol{u}))(\boldsymbol{r})$
  - Matching criterion: $S[\boldsymbol{u}] = \|\mathsf{X}m(\boldsymbol{r} + \boldsymbol{u}(\boldsymbol{r})) - p\|_2^2$ (rawdata fidelity)
  - Velocity vector field: $\boldsymbol{v}(\boldsymbol{r}) = (v_1(\boldsymbol{r}), v_2(\boldsymbol{r}), v_3(\boldsymbol{r}))^{\mathrm{T}} = \partial_t \boldsymbol{u}(\boldsymbol{r})$
  - Smoothness of a vector field $\boldsymbol{w}(\boldsymbol{r}) = (w_1(\boldsymbol{r}), w_2(\boldsymbol{r}), w_3(\boldsymbol{r}))^{\mathrm{T}}$ achieved by optimizing $R[\boldsymbol{w}] = \sum_{d=1}^{3} \sum_{\boldsymbol{r}} \langle \boldsymbol{\nabla}_{\boldsymbol{r}} w_d(\boldsymbol{r}), \boldsymbol{\nabla}_{\boldsymbol{r}} w_d(\boldsymbol{r}) \rangle$
  - Diffusive regularization: $R[\boldsymbol{u}]$
  - Fluid regularization: $R[\boldsymbol{v}] = R[\partial_t \boldsymbol{u}]$
- Search DVF u minimizing the following cost function:

$$C[\boldsymbol{u}] = S[\boldsymbol{u}] + \beta R[\boldsymbol{u}] + \gamma R[\partial_t \boldsymbol{u}]$$

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[1] Flach, Brehm, Sawall, Kachelrieß. Deformable 3D-2D registration for CT and its application to low dose tomographic fluoroscopy. Phys. Med. Biol. 2014.

MoCo

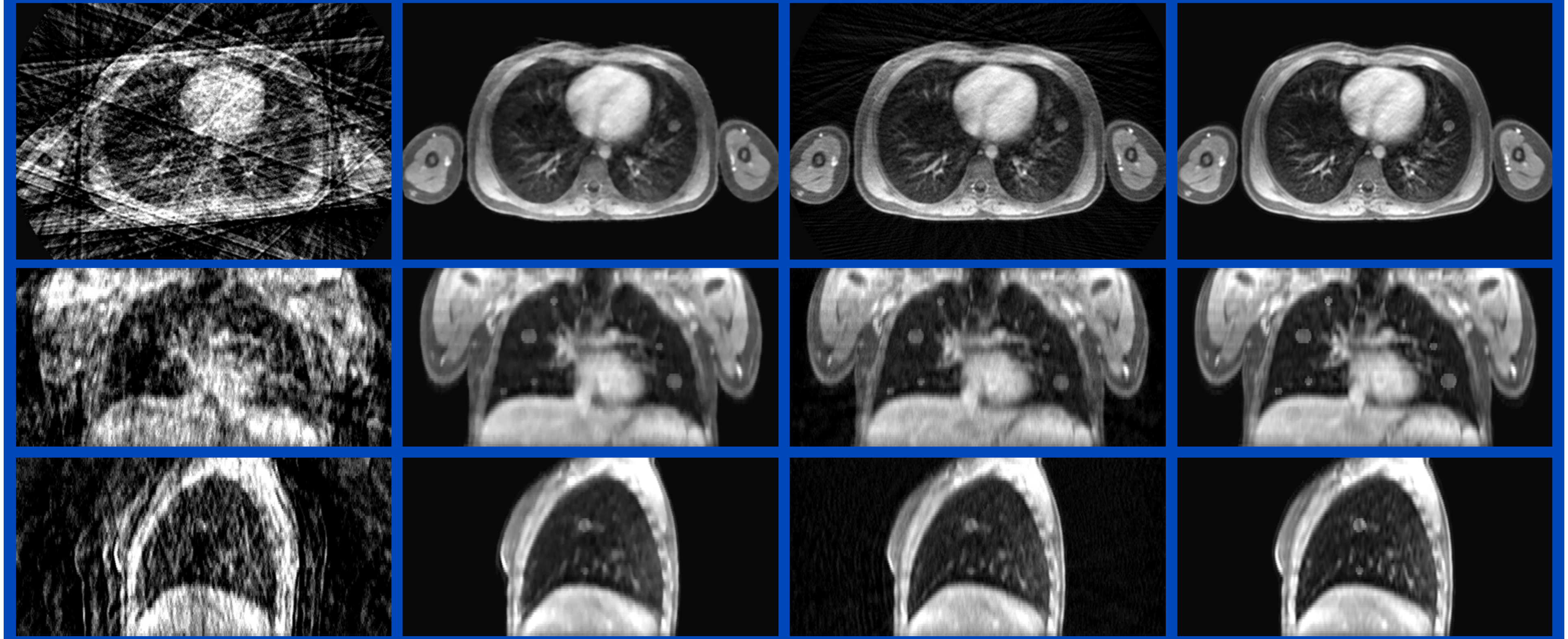
Results of Motion Compensation

4D gated
gridding

4D gated HDTV

4D MoCo
MVF from 3D-2D cMoCo

4D ground truth



< 1 min/bed

< 1 min/bed

< 1 min/bed

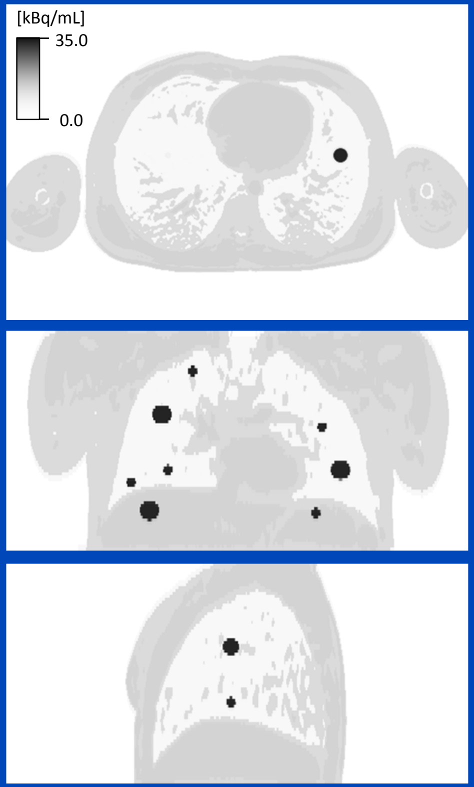
PET

Simulation and Reconstruction

- **4D activity distribution**
  - soft tissue (*A* = 5-6 kBq/mL)
  - lungs (A = 1 kBq/mL)
  - 8 artificial hot lesions (*A* = 30 kBq/mL)
- **Rawdata simulation**
  - forward project activity distribution
  - add Poisson noise
  - geometry of Siemens Biograph mMR
- **Iterative reconstruction**
  - 3D OSEM using 2 iterations and 21 subsets
  - incorporation of MVFs into system matrix for 4D MoCo reconstruction

4D PET

activity distribution



PET
MoCo Image Reconstruction[1]

- **MoCo MLEM reconstruction of gate *g*:**

$$\lambda_g^{(n+1)} = \lambda_g^{(n)} \frac{1}{\sum_{g'} T_{g',g}^{\mathrm{T}} M^{\mathrm{T}} \mathbf{1}} \sum_{g'} T_{g',g}^{\mathrm{T}} M^{\mathrm{T}} \frac{p_{g'}}{M T_{g',g} \lambda_g^{(n)}}$$

n:	iteration index
M, M^{T}:	system matrix including forward-/backprojection
p:	measured rawdata
$\lambda^{(n)}$:	image estimate at iteration n
g, g':	gate indices
G:	total number of gates
$T_{g',g}$, $T^{\mathrm{T}}_{g',g}$:	forward/backward warping operation mapping gate g to g' and vice versa

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

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

PET

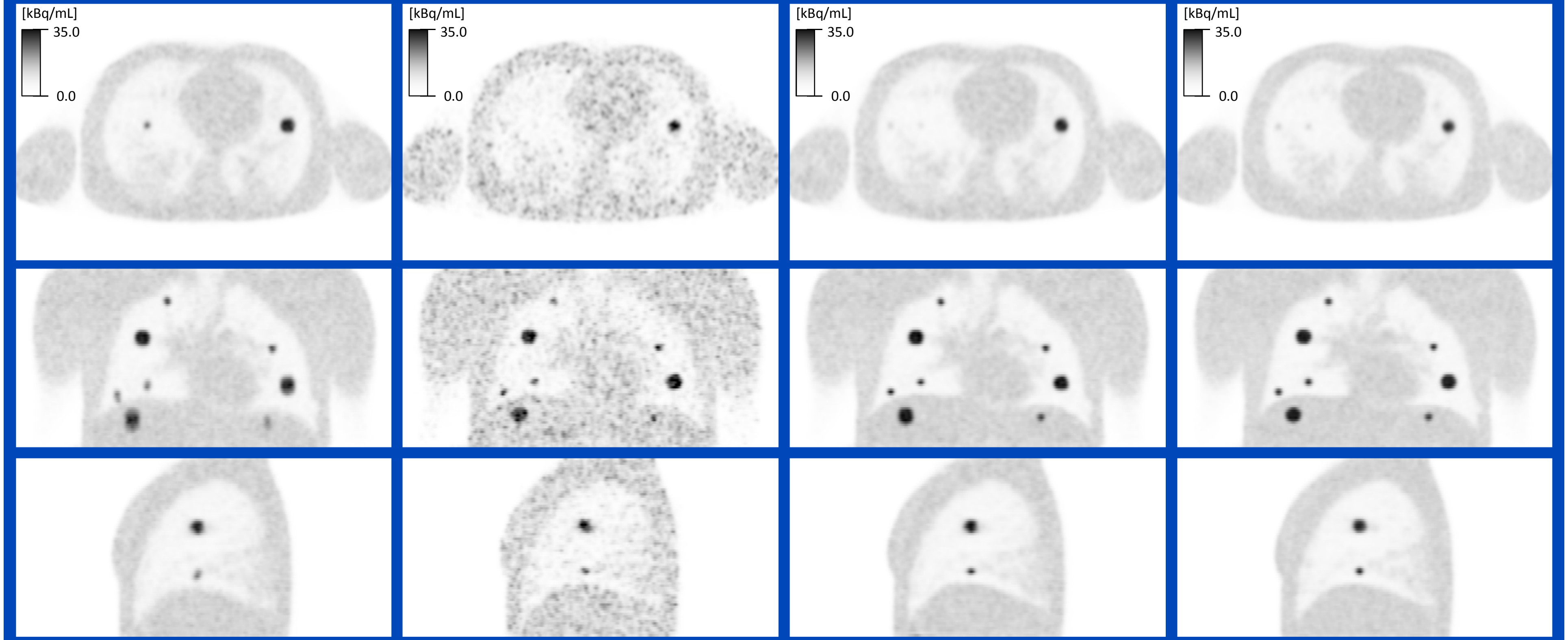
Results of Motion Compensation

3D

4D gated

4D MoCo
MVF from 3D-2D cMoCo

4D ref gated
reference



10 min/bed

10 min/bed

10 min/bed

100 min/bed
same statistics as 3D due to ten-fold measurement time

PET

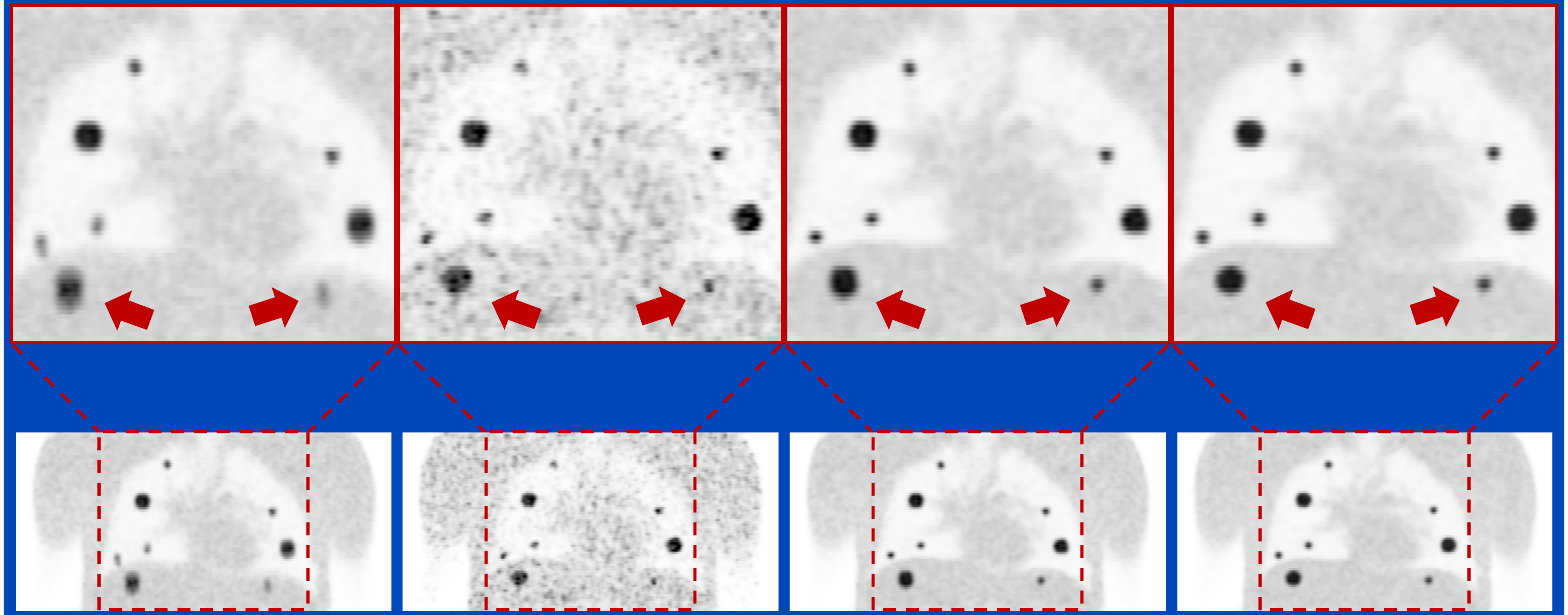
Results of Motion Compensation

3D

4D gated

4D MoCo
MVF from 3D-2D cMoCo

4D ref gated
reference



10 min/bed

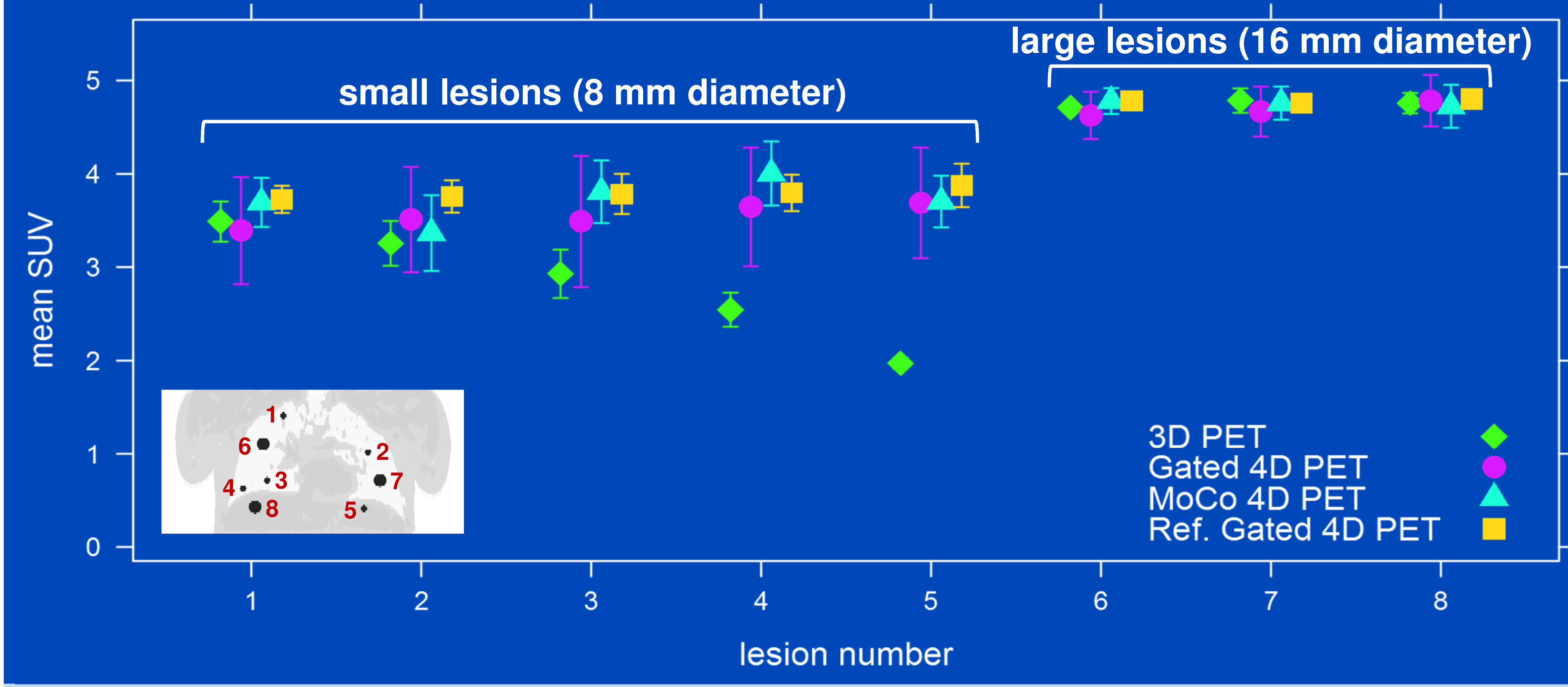
10 min/bed

10 min/bed

100 min/bed
same statistics as 3D due to
ten-fold measurement time

Quantitative Analysis

- **Mean SUV values were measured for all 20 motion phases and for all 5 noise realizations.**
- **Mean and standard deviation were calculated**

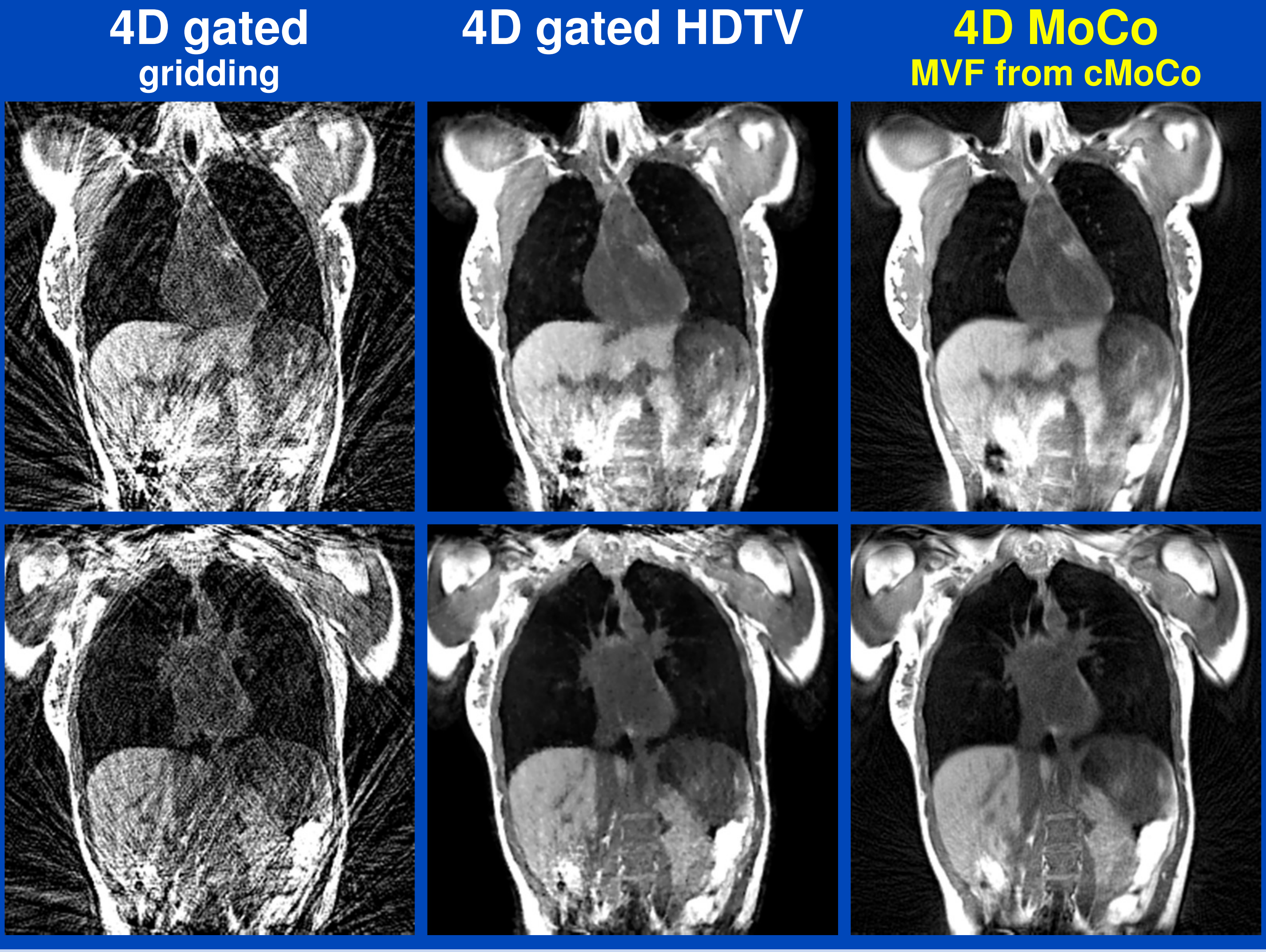


dkfz.

Summary

- PET respiratory MoCo based on strongly undersampled radial MR data acquired in less than 1 min
- 3D-2D cyclic registration for estimation of MVFs
- 4D MoCo PET reconstruction
- Significant improvement of PET image quality in terms of temporal resolution or noise level

Outlook: Results of Measured MR Data



480 radial spokes per slice, 20 overlapping phases, acquisition time: 57 s

Thank You!

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Image Formation in X-Ray Computed Tomography

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Conference Chair
Marc Kachelrieß, German Cancer Research Center (DKFZ), Heidelberg, Germany

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