Respiratory Motion Compensation for Simultaneous PET/MR Using Strongly Undersampled MR Data

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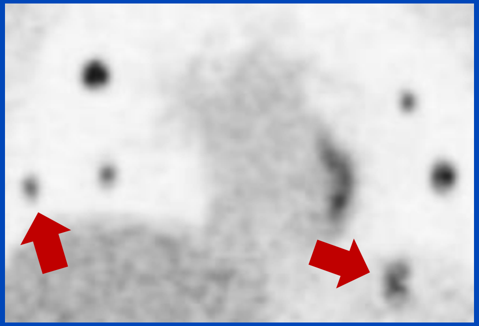
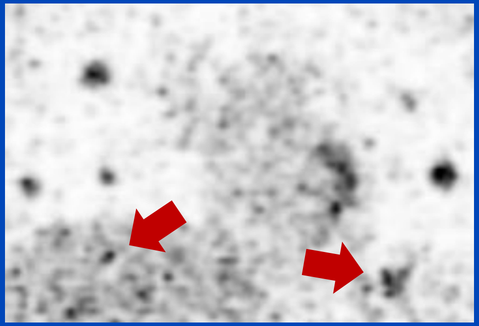
Introduction

- 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 up to 25%[1]
- Gating
  - divide motion cycle into certain gates and reconstruct data from each gate separately
  - trade-off between temporal resolution and an appropriate SNR and CNR of the PET images

3D PET



4D gated PET



- Recent approach: PET/MR motion compensation (MoCo)
  - use MR information to estimate 4D motion vector fields (MVFs)
  - 4D MoCo PET reconstruction from 100% of raw data

[1] Kinahan , Fletscher. PET/CT Standardized Uptake Values (SUVs) in Clinical Practice and Assessing Response to Therapy. Semin Ultrasound CT MR 2010.

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Aim of Work

- Develop a method for respiratory motion compensation of PET images
- Use information from a strongly undersampled radial MR sequence with an acquisition time of 1 minute
- Difficulty: obtain high-fidelity MVFs from strongly undersampled MR data

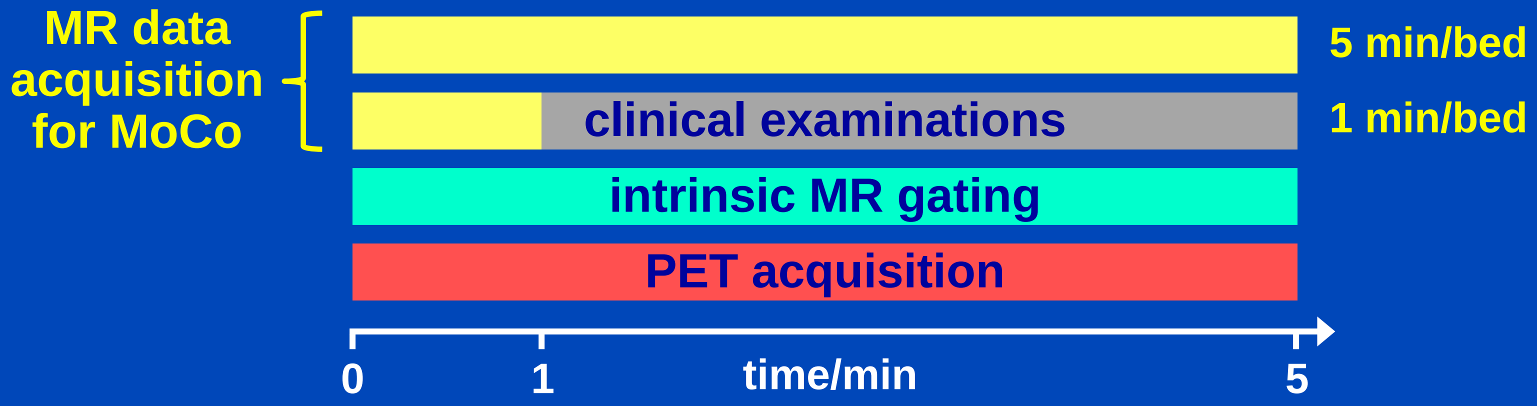
Related Work

author	MR sequence	MR acquisition time / min	voxel size / mm³	# of gates	motion estimation
Würslin et al. 2013	2D multi-slice	3.0	2.0×2.0×10.0	4	3D
Petibon et al. 2014	2D multi-slice	3.0	2.0×2.0×8.0	7	3D
Dutta et al. 2015	2D radial	5.5 to 7.0	2.0/2.3×2.0/2.3×5.0/8.0	6	3D
Fayad et al. 2015a	2D multi-slice	1.5	2.0×2.0×10.0	4	3D
Fayad et al. 2015b	2D multi-slice	3.0	2.0×2.0×10.0	4	3D
Fürst et al. 2015	radial stack-of-stars	10.0	1.7×1.7×5.0	5	3D
Grimm et al. 2015	radial stack-of-stars	3.0 to 10.0	1.7×1.7×5.0	5	3D
Manber et al. 2015	2D multi-slice	1.0 and 2.7	1.8×1.8×10.0[a]	10[b]	2D
proposed	radial stack-of-stars	1.0	1.6×1.6×4.5	20[b,c]	3D

[a] 25 mm gap between slice centers
[b] discrimination between inhalation and exhalation
[c] motion phases have an overlap of 50%

Data Acquisition and Processing

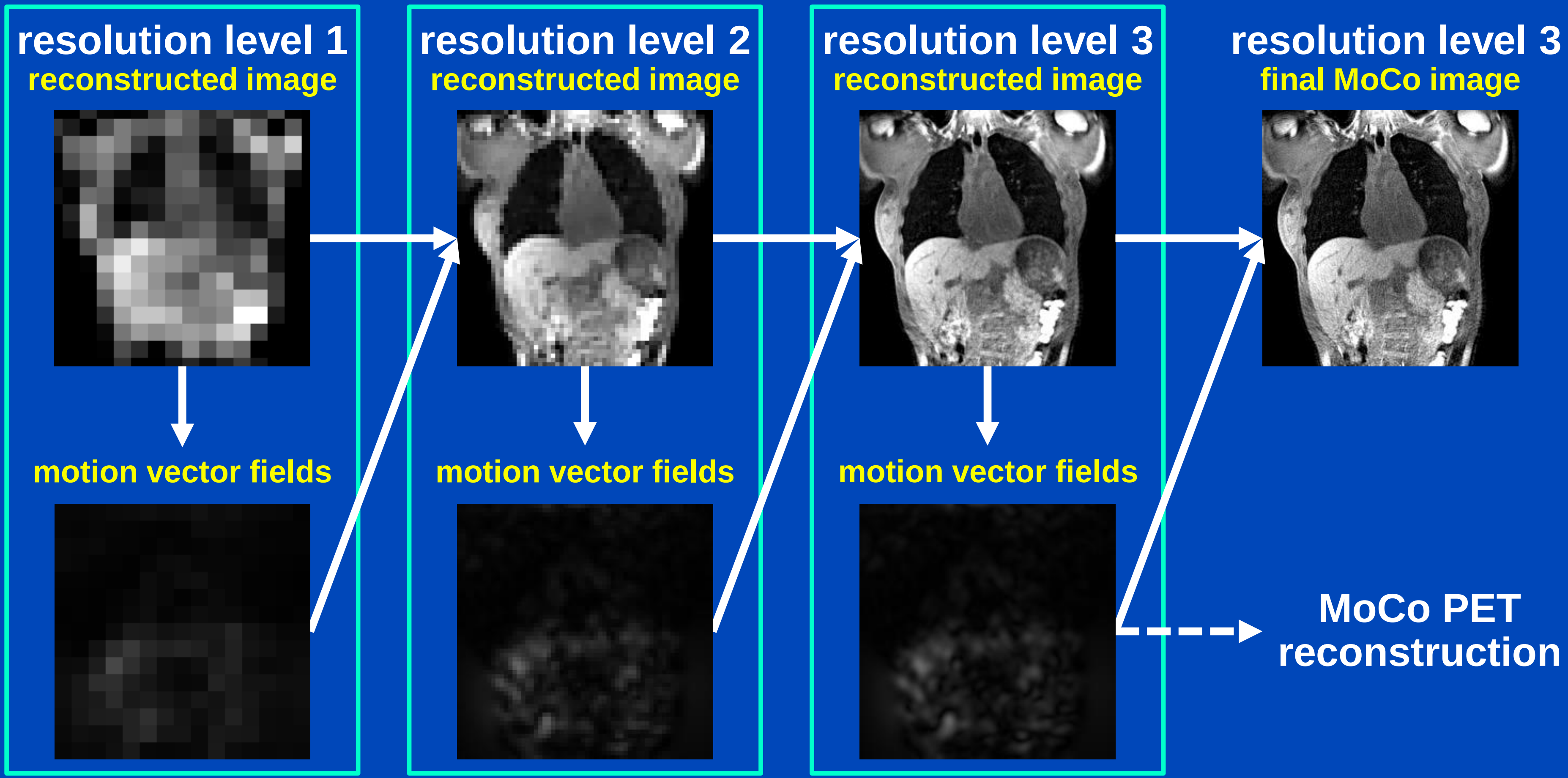
- Simultaneous PET/MR acquisition at Biograph mMR
  - tracer: fluorodeoxyglucose (^{18}F-FDG)
  - MR sequence: 3D-encoded gradient echo sequence with radial stack-of-stars sampling scheme and golden angle radial spacing
- Retrospective generation of undersampled MR raw data



- MR and PET data were sorted retrospectively into 20 overlapping motion phase bins (10% width)

Estimation of MVFs

Schematic Overview (4D joint MoCo-HDTV[1])



[1] Rank, Heußer, Buzan, Wetscherek, Freitag, Dinkel, Kachelrieß. 4D respiratory motion-compensated image reconstruction of free-breathing radial MR data with very high undersampling. *Magn Reson Med*, early view online.

Estimation of MVFs
Image Reconstruction - Cost Function[1,2]

- **Cost function:**

$$C = \underbrace{\|\mathrm{X}_{\mathrm{pc}} S f - p\|_2^2}_{\text{raw data fidelity}} + \underbrace{\mu \,\mathrm{HDTV}\, f}_{\text{total variation}}$$

X_{pc} : motion phase-correlated forward transform
S : coil sensitivity profiles
f : 4D image volume
p : measured raw data
μ : weight
HDTV : spatial and temporal total variation

- **The first term optimizes the raw data fidelity**
- **The second term improves the image sparsity 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, Sawall, Knaup, Hess, Kachelrieß. Iterative 4D cardiac micro-CT image reconstruction using an adaptive spatio-temporal sparsity prior. *Phys. Med. Biol.* 2012.
[2] Rank, Heußer, Buzan, Wetscherek, Freitag, Dinkel, Kachelrieß. 4D respiratory motion-compensated image reconstruction of free-breathing radial MR data with very high undersampling. *Magn Reson Med,* early view online.

Estimation of MVFs

Image Reconstruction - Update Equation[1]

- **Update equation from raw data comparison for motion phase *t*:**

$$u_t^{(i+1)} = S^\dagger \mathsf{X}_{\mathrm{pc},t}^\dagger (\mathsf{X}_{\mathrm{pc},t} S f_t^{(i)} - p_t)$$

- **Modified update of image volume for motion phase *t*:**

$$f_t^{(i+1)} = f_t^{(i)} + \alpha \left(\underbrace{(1-\beta) u_t^{(i+1)}}_{\text{direct update}} + \underbrace{\beta \frac{1}{N_t} \sum_{t'} T_{t'}^t u_{t'}^{(i+1)}}_{\text{MoCo update}} \right)$$

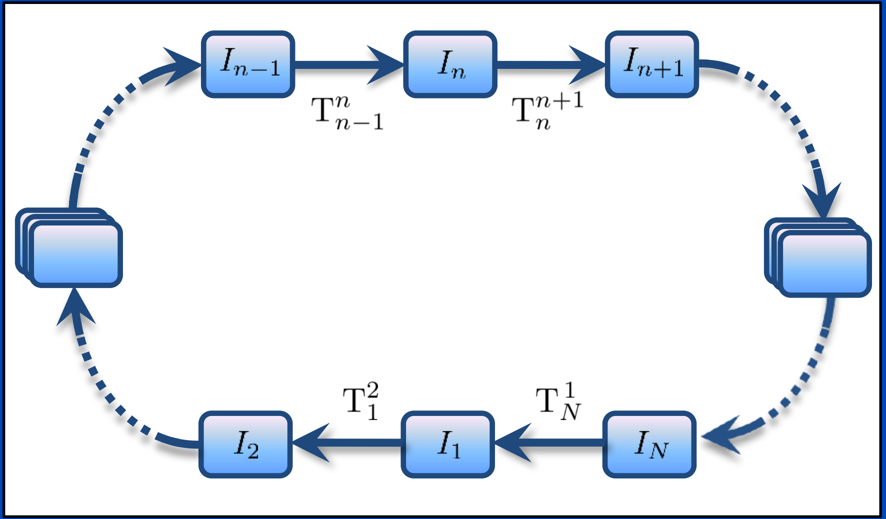
$u_t^{(i)}$: update at iteration *i*
t, t' : indices of motion phases
S, $S^\dagger$: coil sensitivity profiles and pseudo-inverse operator
$\mathsf{X}_{\mathrm{pc},t}$, $\mathsf{X}_{\mathrm{pc},t}^\dagger$: system matrix including motion phase-correlated forward and pseudo-inverse transform

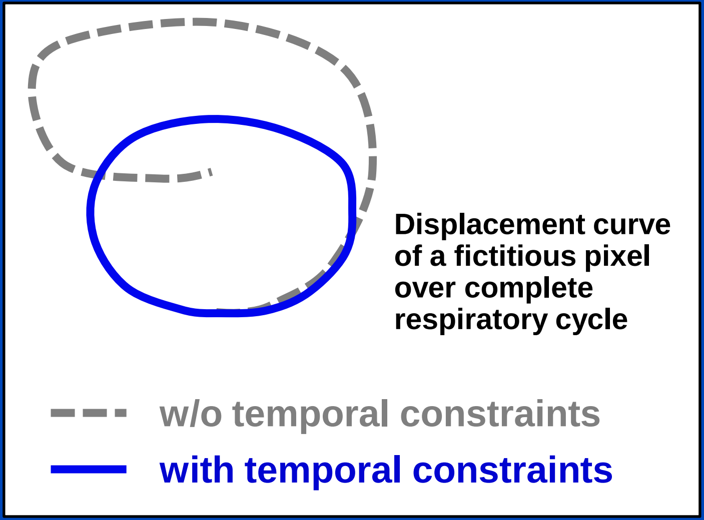
$f_t^{(i)}$: image at iteration *i*
p_t : measured raw data
$T_{t'}^t$: warping operation mapping volume of motion phase *t'* to *t*
α, β : weights
N_t : number of motion phases

[1] Rank, Heußer, Buzan, Wetscherek, Freitag, Dinkel, Kachelrieß. 4D respiratory motion-compensated image reconstruction of free-breathing radial MR data with very high undersampling. *Magn Reson Med,* early view online.

Estimation of MVFs
Cyclic Deformable Registration[1]

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



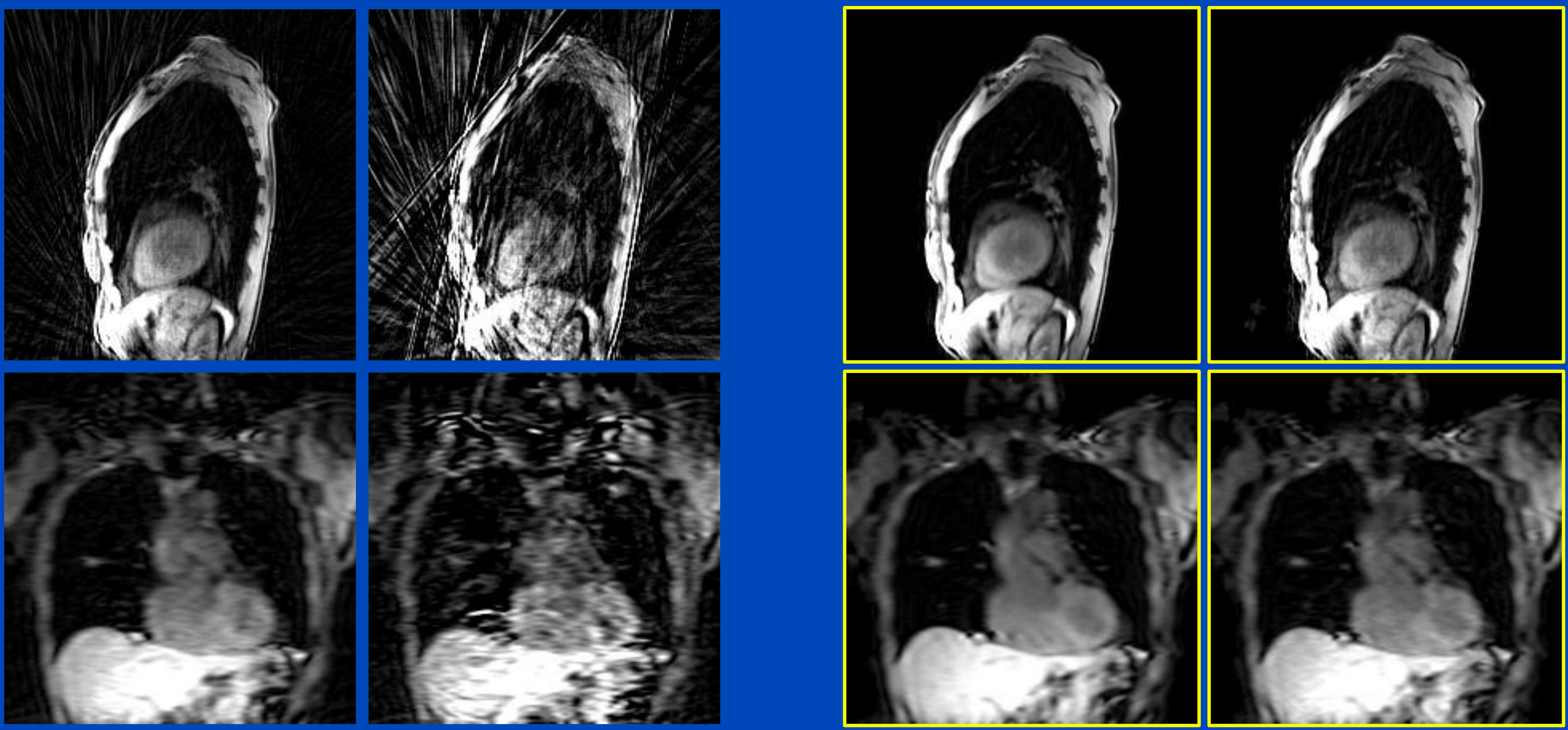


- Incorporate additional knowledge
  - a priori knowledge of quasi periodic breathing pattern
  - non-cyclic motion is penalized
  - error propagation due to concatenation is reduced

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

Results of MR Reconstruction

4D gated gridding		4D MoCo[1]	
5 min / bed	1 min / bed	5 min / bed	1 min / bed



		MVFs	MVFs

[1] Rank, Heußer, Buzan, Wetscherek, Freitag, Dinkel, Kachelrieß. 4D respiratory motion-compensated image reconstruction of free-breathing radial MR data with very high undersampling. *Magn Reson Med,* early view online.

MoCo PET Image Reconstruction[1]

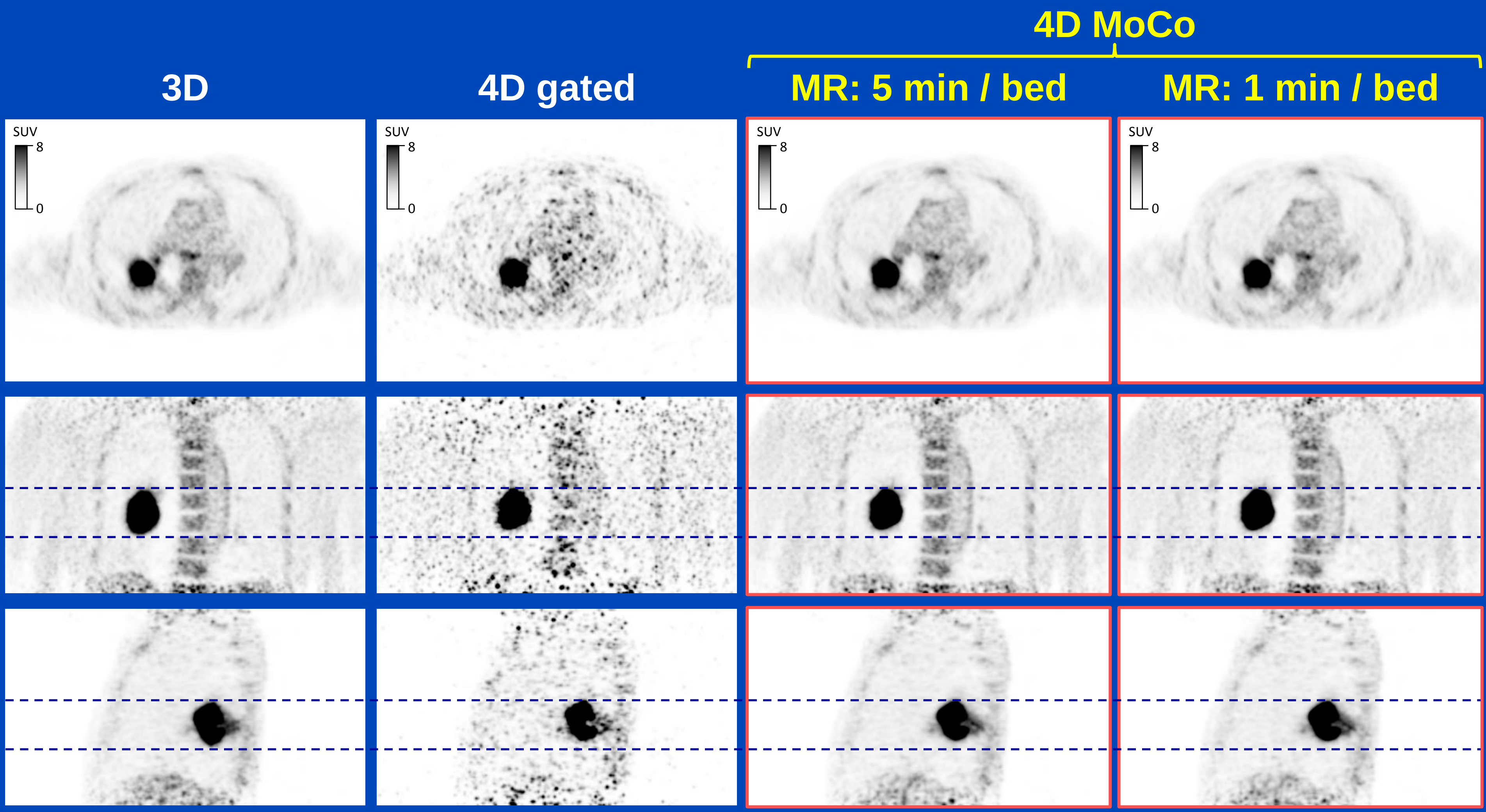
- **MoCo OSEM update equation of motion phase *t*:**

$$\lambda_t^{(i+1)} = \lambda_t^{(i)} \frac{1}{\sum_{t'} T_{t'}^{t} M_k^{\mathrm{T}} (\frac{1}{a_{t'} n})} \sum_{t'} T_{t'}^{t} M_k^{\mathrm{T}} \frac{p_{t'}}{(M_k T_t^{t'} \lambda_t^{(i)}) + a_{t'}(r_{t'} n + s)}$$

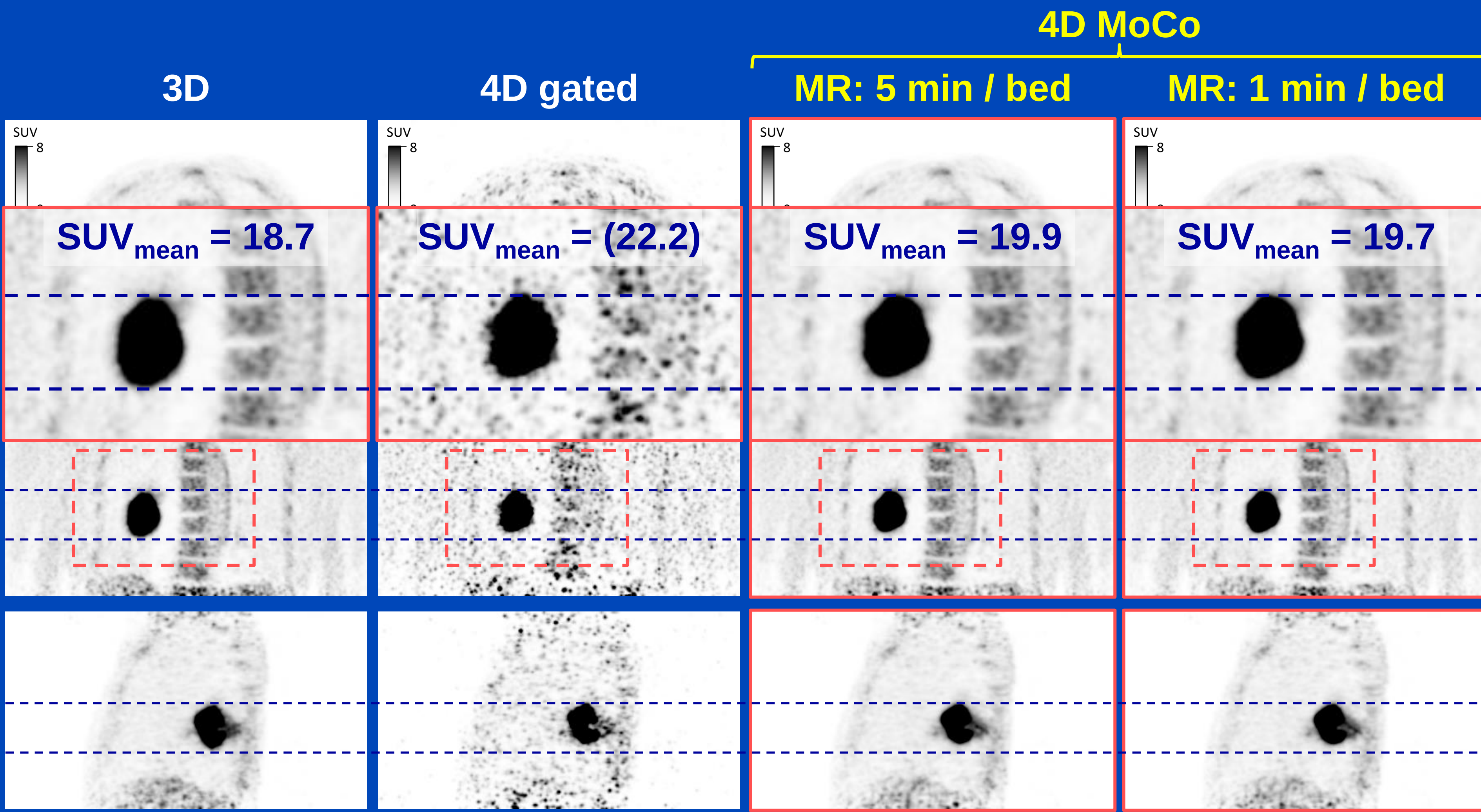
$\lambda_t^{(i)}$: image estimate at subiteration *i*
t, *t'* : indices of motion phases
i : subiteration index
k : subset index, *k* = *i* mod *K*
K : total number of subsets
M_k, M_k^{T} : system matrix including forward-/backprojection of subset *k*
a_t : attenuation correction factors
p_t : measured raw data (prompts)
r_t : estimated randoms
s : estimated scatter
n : normalization factors
$T_t^{t'}$: warping operation mapping motion phase *t* to *t'*

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

Results of PET Reconstruction (I)

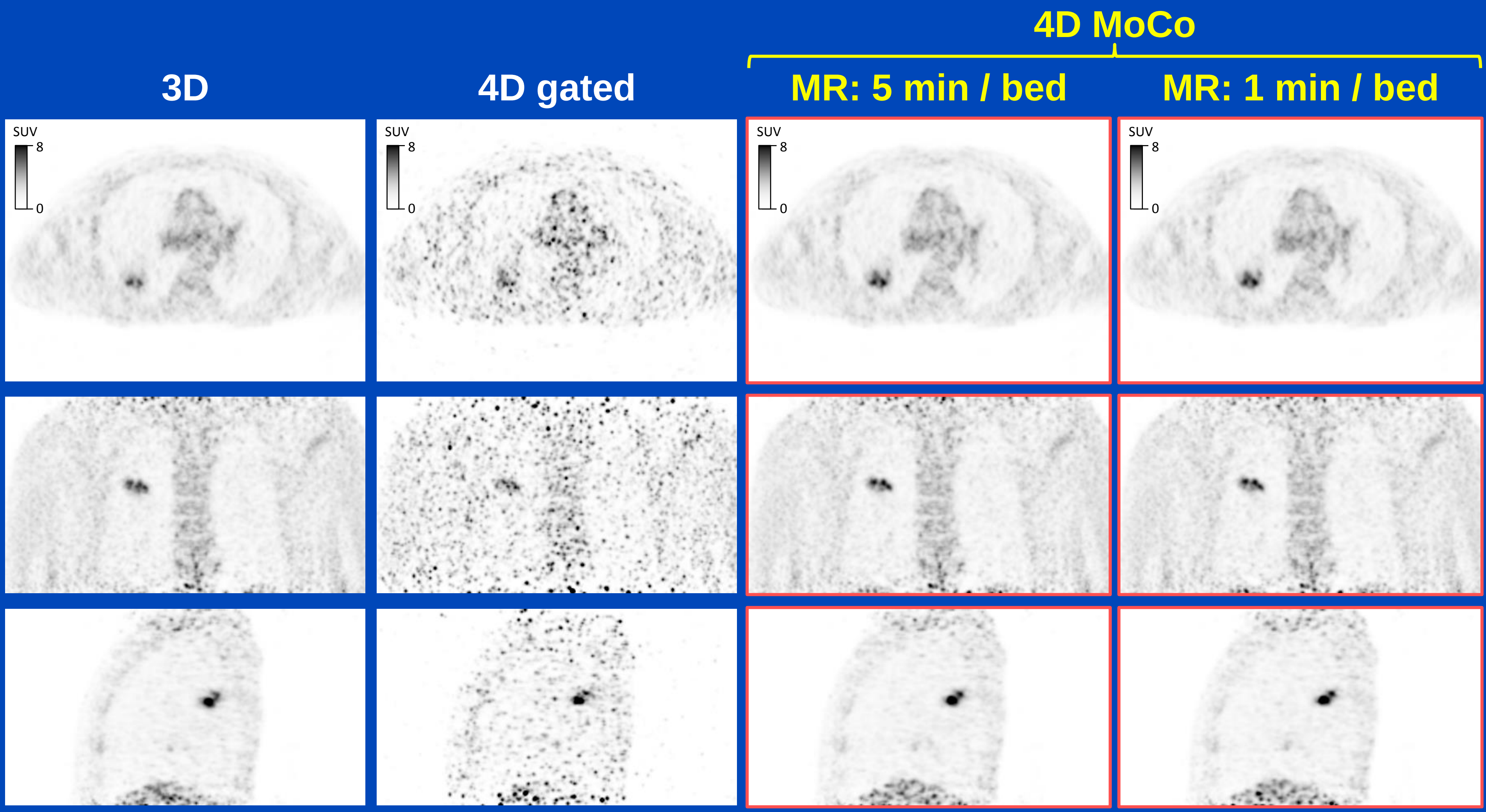


Results of PET Reconstruction (I)

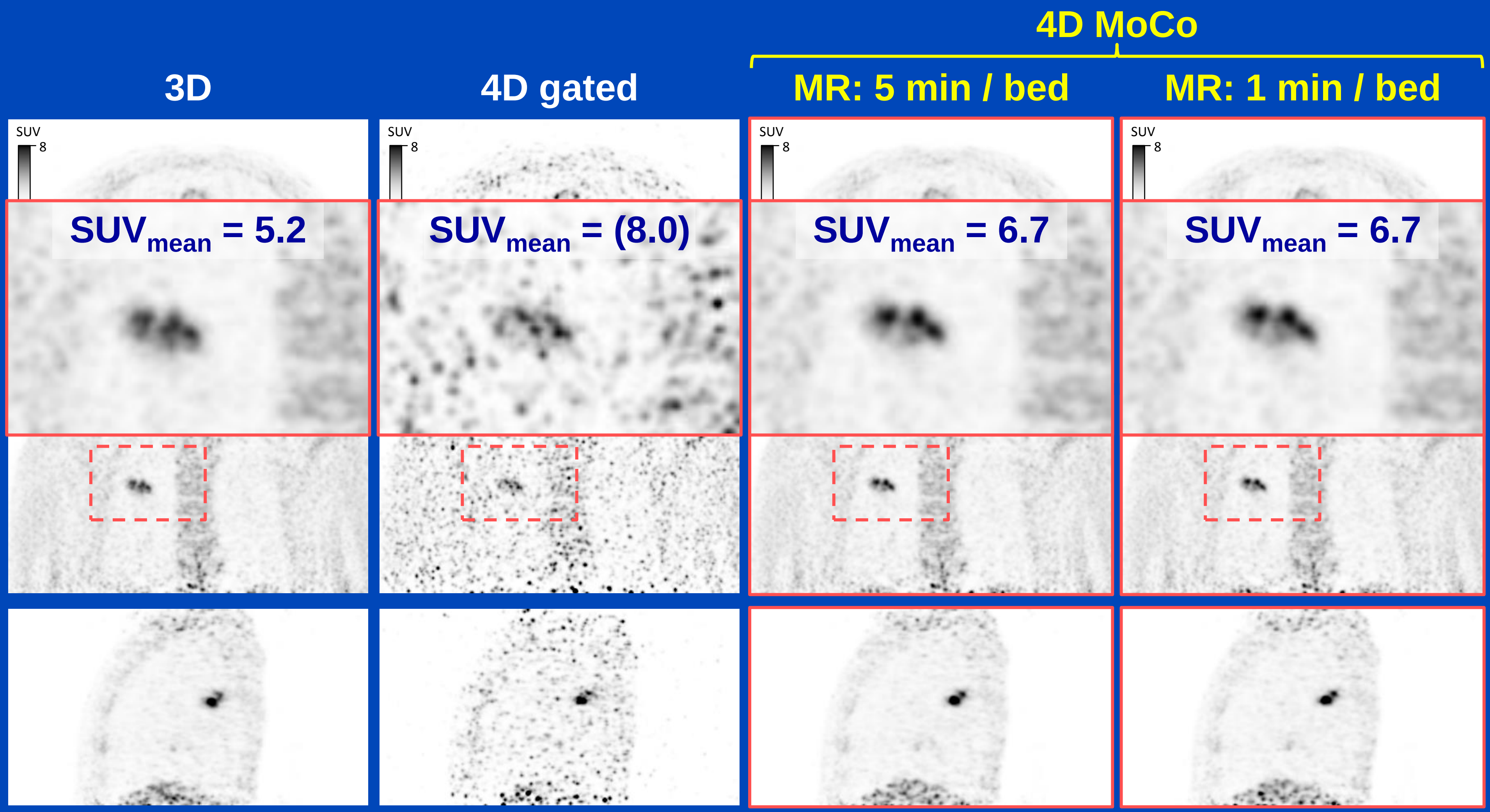


due to the high noise level of 4D gated PET,
SUV_{mean} was systematically overestimated

Results of PET Reconstruction (II)



Results of PET Reconstruction (II)



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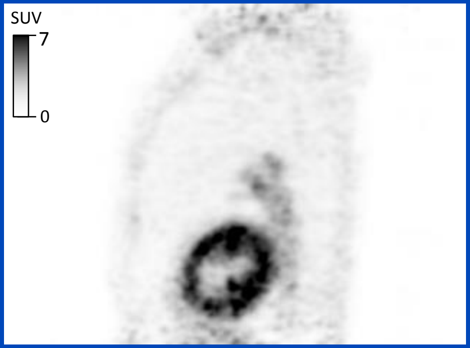
Summary and Outlook

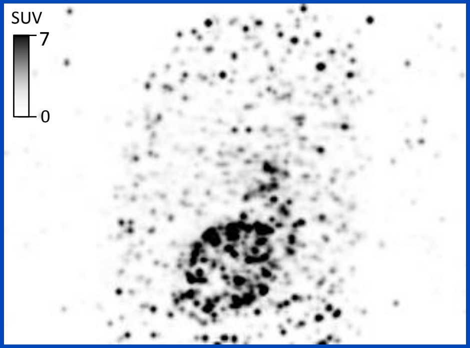
- **High quality PET respiratory MoCo is possible based on a 1 minute MR acquisition**
- **The strong undersampling requires to reconstruct MVFs and MR images in an alternating manner**
- **MoCo for PET improves PET quantification, image quality, temporal resolution and noise level**

- **Outlook: extension to 5D respiratory and cardiac MoCo**

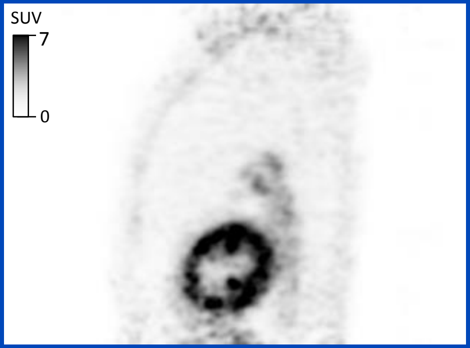
3D PET



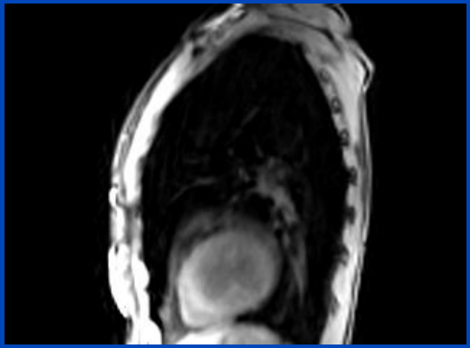
5D double-gated PET



5D MoCo PET



5D MoCo MR



Thank You!

The 4th International Conference on

Image Formation in X-Ray Computed Tomography

Conference Chair

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

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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.

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