4D and 5D Motion-Compensated (MoCo) Image Reconstruction

Marc Kachelriess

German Cancer Research Center (DKFZ)
Heidelberg, Germany
www.dkfz.de/ct

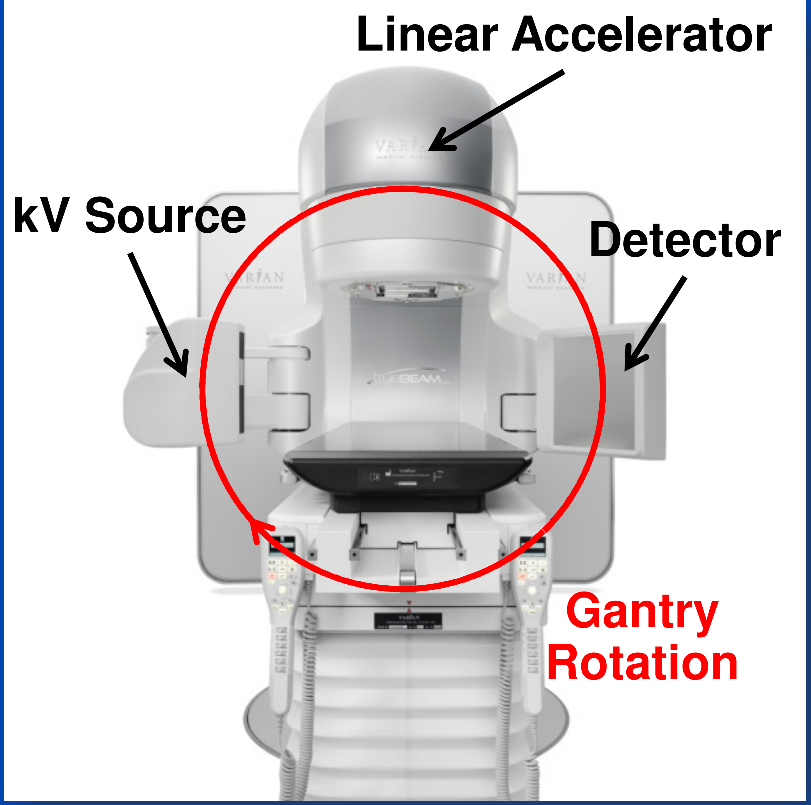
DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

Motion Compensation (MoCo)

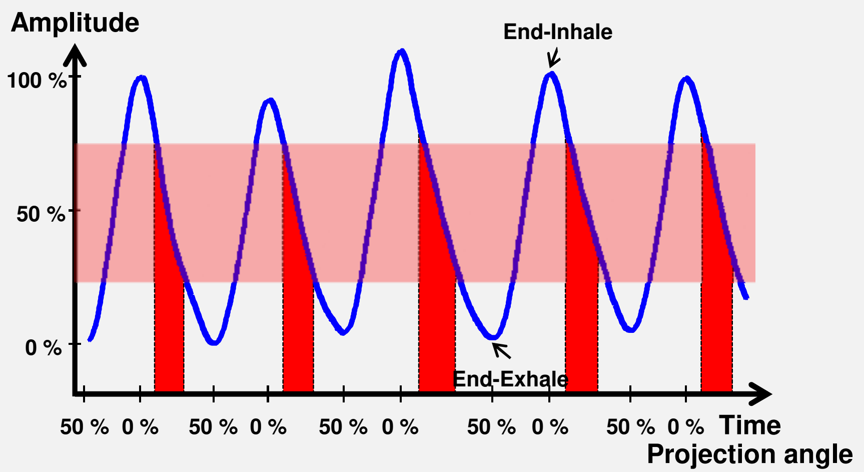
- Step 1 (difficult): Motion estimation resulting in motion vector fields (MVFs)
- Step 2 (simple): Applying the estimated MVFs during image reconstruction to compensate for the motion.
- Depending on the type of algorithm iteratively repeat these steps

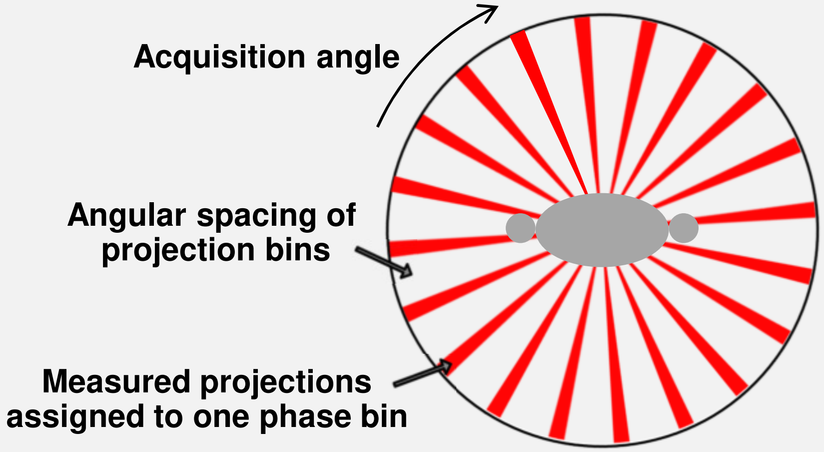
4D MoCo

Motion Management for CBCT in IGRT



4D CBCT Scan with Retrospective Gating





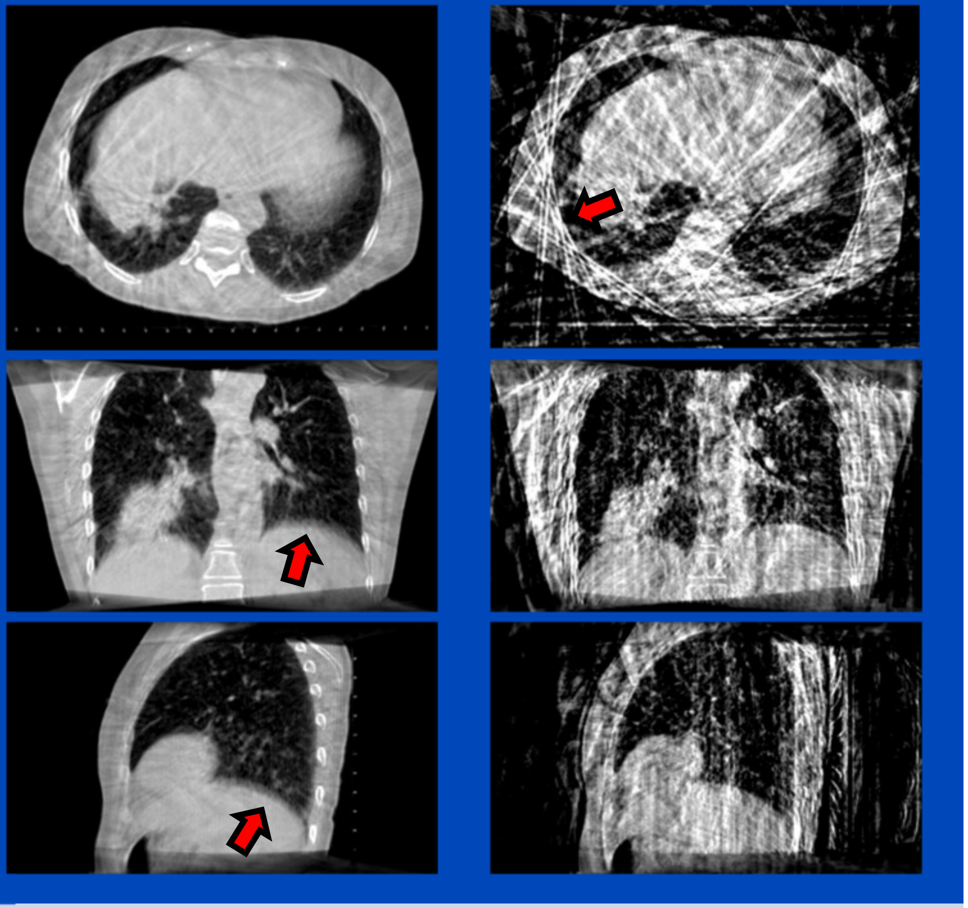
Acquisition angle

Angular spacing of projection bins

Measured projections assigned to one phase bin

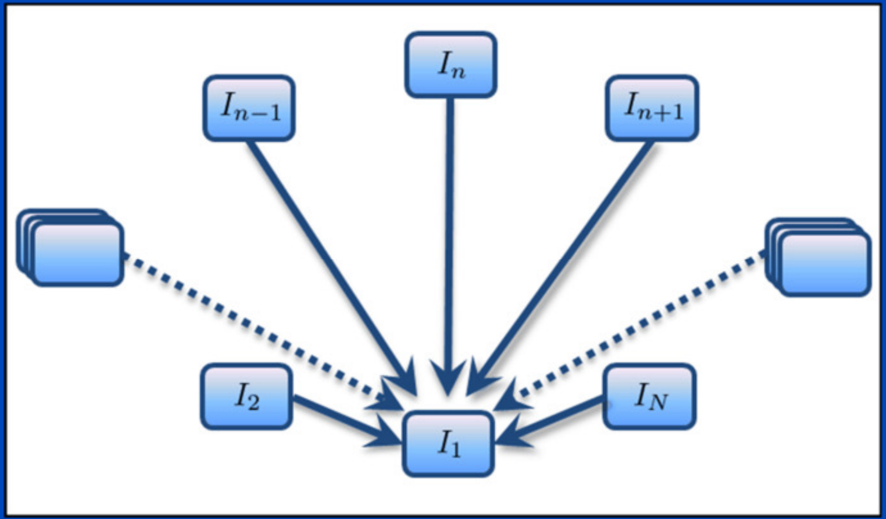
Without gating (3D): Motion artifacts

With gating (4D): Sparse-view artifacts

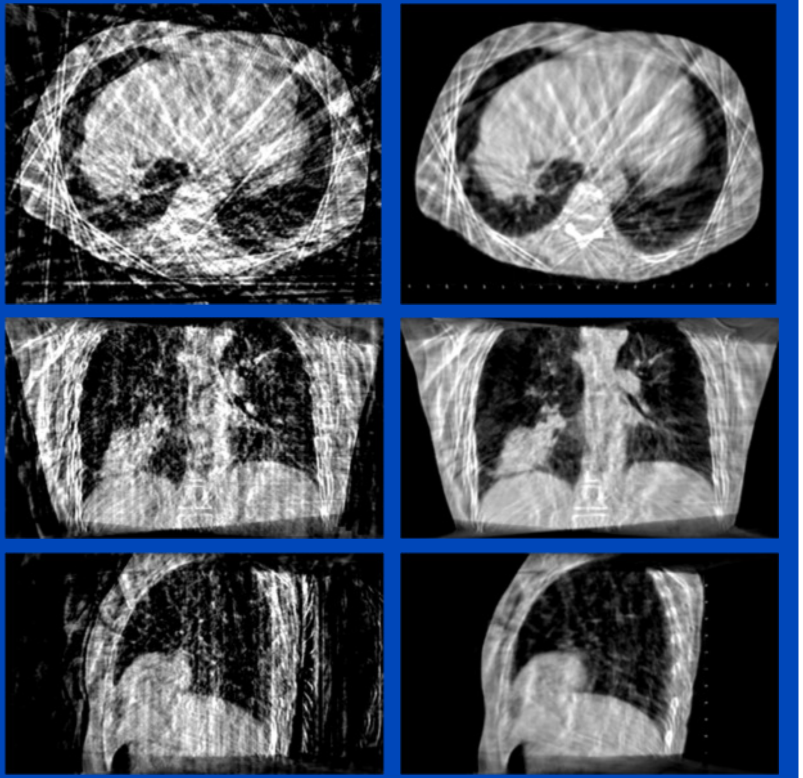


A Standard Motion Estimation and Compensation Approach (sMoCo)

- Motion estimation via standard 3D-3D registration



- Has to be repeated for each reconstructed phase



Gated 4D CBCT

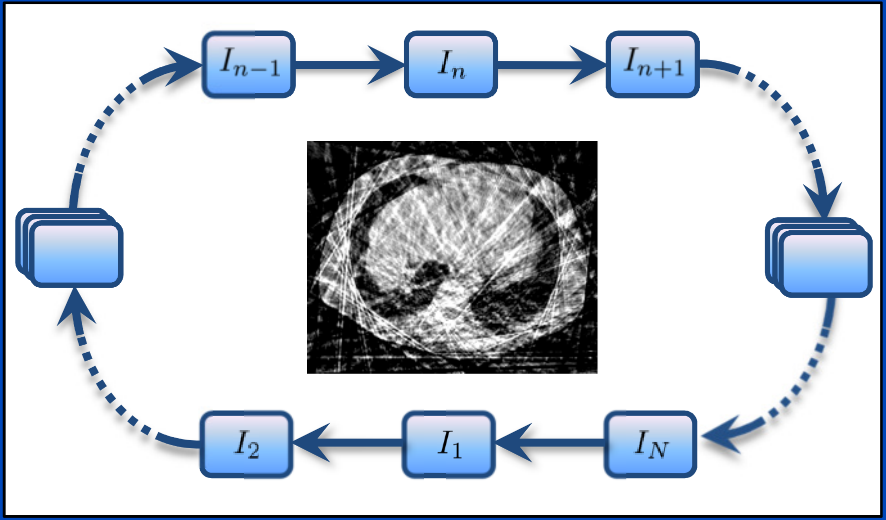
sMoCo

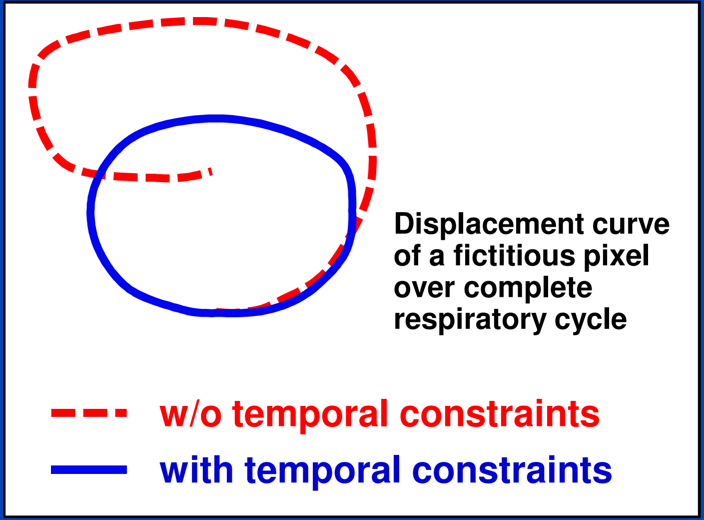
- Streak artifacts from gated reconstructions propagate into sMoCo results

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

The Cyclic Motion Estimation and Compensation Approach (cMoCo)

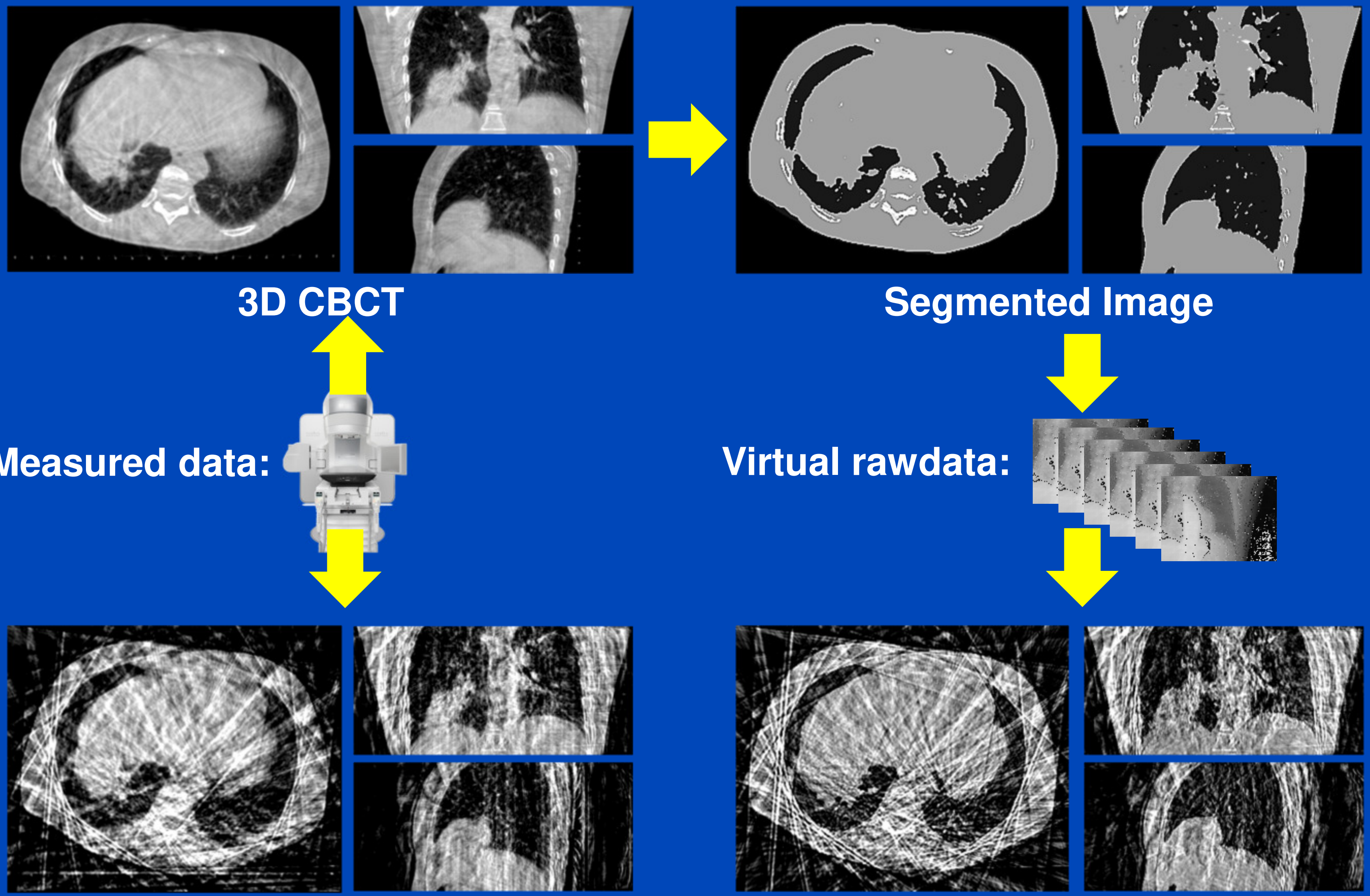
- Motion estimation only between adjacent phases
- Incorporate additional knowledge
  - A priori knowledge of quasi periodic breathing pattern
  - Non-cyclic motion is penalized
  - Error propagation due to concatenation is reduced




Displacement curve of a fictitious pixel over complete respiratory cycle

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.

Artifact Model-Based MoCo (aMoCo)



3D CBCT

Segmented Image

Measured data:

Virtual rawdata:

Gated 4D CBCT

4D Artifact Images

Brehm, Paysan, Oelhafen, and Kachelrieß, “Artifact-resistant motion estimation with a patient-specific artifact model for motion-compensated cone-beam CT” Med. Phys. 40(10):101913, 2013.

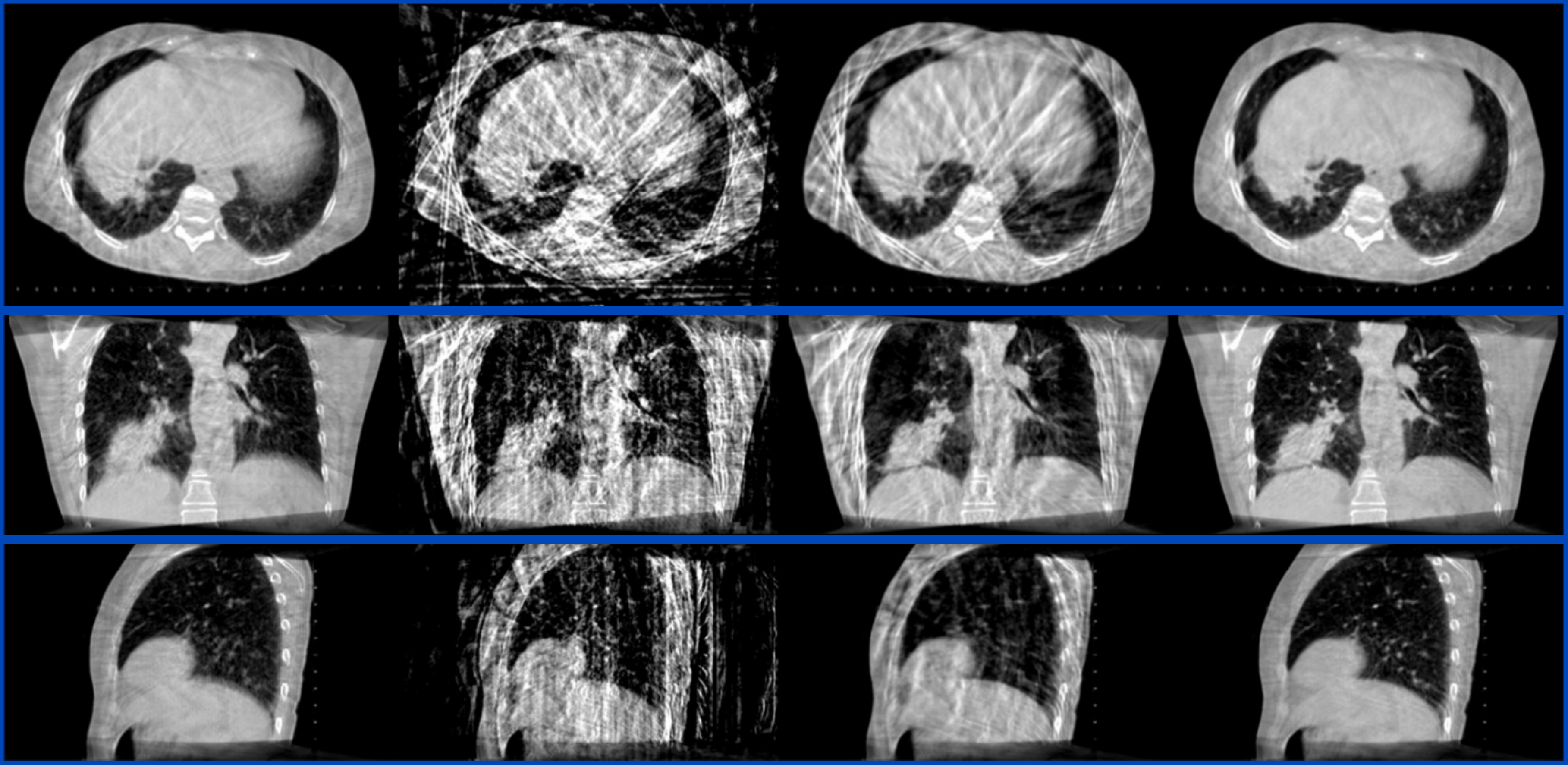
Patient Data – Results

3D CBCT
Standard

Gated 4D CBCT
Conventional
Phase-Correlated

sMoCo
Standard Motion
Compensation

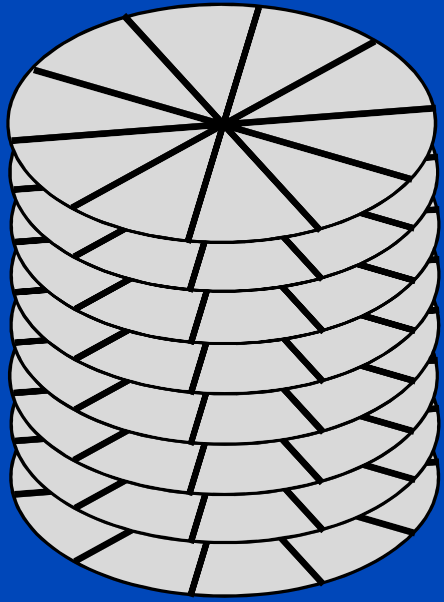
acMoCo
Artifact Model-Based
Motion Compensation



C = -200 HU, *W* = 1400 HU, displayed with 30 rpm.
Patient data provided by Memorial Sloan–Kettering Cancer Center, New York, NY.

Spin-Off Effects?

What about MoCo in MR, in PET/MR, or in MR-guided RT?



- MR acquisition is slow
- 4D MR acquisiton is even slower
- Thus:
  Develop a framework for MR-MoCo
- Use motion vector fields
  - to compensate the motion from clinical sequences
  - to compensate the motion from other modalities
  - for tracking the tumor position
- Using dedicated image reconstruction and registration techniques, allows to cope with highly undersampled data.[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 77(3):1170-1183, 2017.

Joint MoCo-HDTV Algorithm for MR

Cost Function[1,2]

- **Cost function:**

$$C = \underbrace{\|\mathrm{X}_{\mathrm{pc}} S f - p\|_2^2}_{\text{raw data fidelity}} + \underbrace{\mu \|\mathrm{HDTV}\, f\|_1}_{\text{total variation}}$$

X_{pc} : phase-correlated forward transform
S : coil sensitivity profiles
f : 4D image volume
p : raw data
μ : weight
$\|\mathrm{HDTV}\cdot\|_1$: 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**
- **An optimal weighting μ of the raw data fidelity and total variation step is calculated in each iteration[1]**

---

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

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

Joint MoCo-HDTV Algorithm for MR

Update Equation

- **Modified update equation of the raw data fidelity step for phase *i*:**

$$u_{t,(n+1)} = S^{-1}\mathsf{X}_{\mathrm{pc},t}^{-1}(\mathsf{X}_{\mathrm{pc},t} S f_{t,(n)} - p_t)$$

$u_t^{(n)}$: update of phase *t* at iteration *n*
$f_t^{(n)}$: image of phase *t* at iteration *n*
X_{pc} : phase-correlated forward transform
$\mathrm{X}_{\mathrm{pc}}^{-1}$: phase-correlated inverse transform
p_t : measured raw data of phase *t*
$T_{t'}^{t}$: warping operation mapping volume of motion phase *t'* to *t*
α : weight
β : MoCo update weight

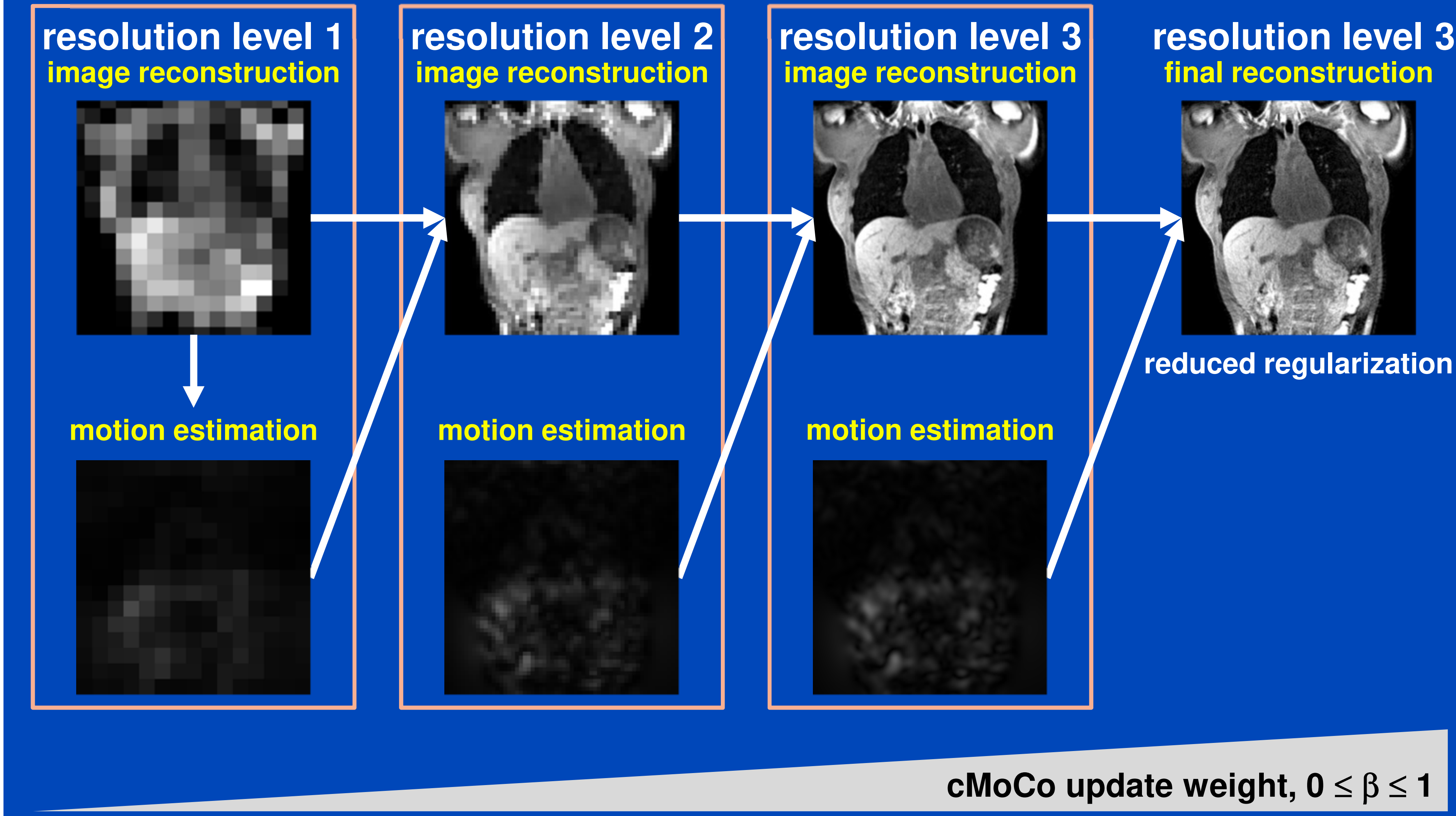
$$f_{t,(n+1)} = f_{t,(n)} + \alpha \left(\underbrace{(1-\beta) u_{t,(n+1)}}_{\text{direct update}} + \underbrace{\beta \frac{1}{N_t} \sum_{t'} T^{t}_{t',(n)} u_{t',(n+1)}}_{\text{cMoCo update}} \right)$$

cMoCo update weight, 0 ≤ β ≤ 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 77(3):1170-1183, 2017.

Joint MoCo-HDTV Algorithm for MR

Schematic Overview



resolution level 1
image reconstruction
motion estimation

resolution level 2
image reconstruction
motion estimation

resolution level 3
image reconstruction
motion estimation

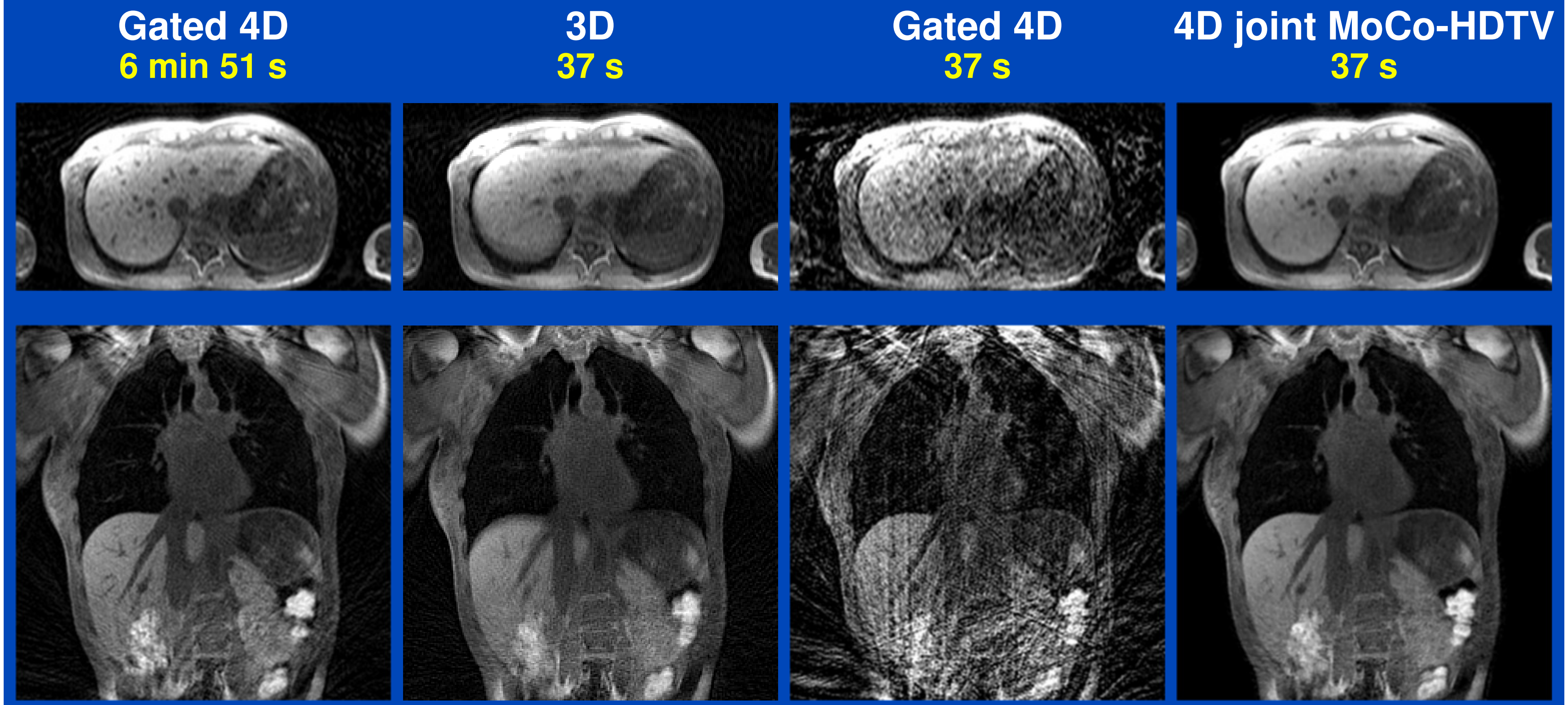
resolution level 3
final reconstruction
reduced regularization

cMoCo update weight, $0 \leq \beta \leq 1$

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 77(3):1170-1183, 2017.

4D MR Motion Compensation

Results Volunteer p8



Gated 4D
6 min 51 s

3D
37 s

Gated 4D
37 s

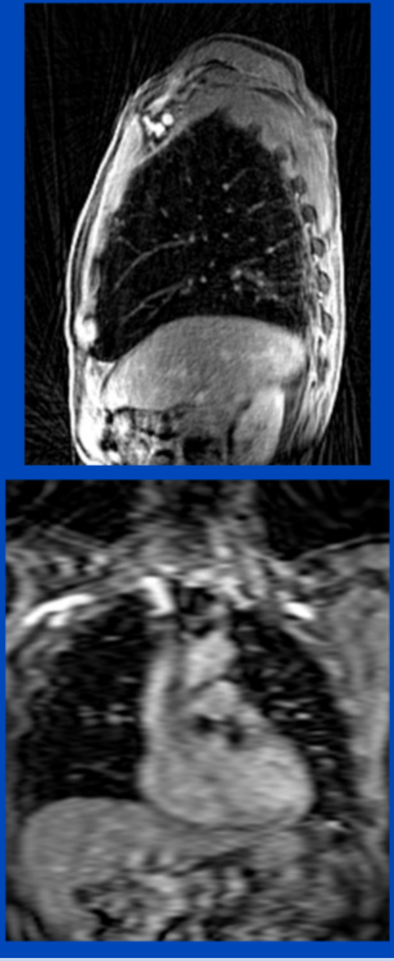
4D joint MoCo-HDTV
37 s

Magnetom Aera at Thoraxklinik, Radial VIBE WIP 528K
$R = 20$, $\Delta r = 10\%$

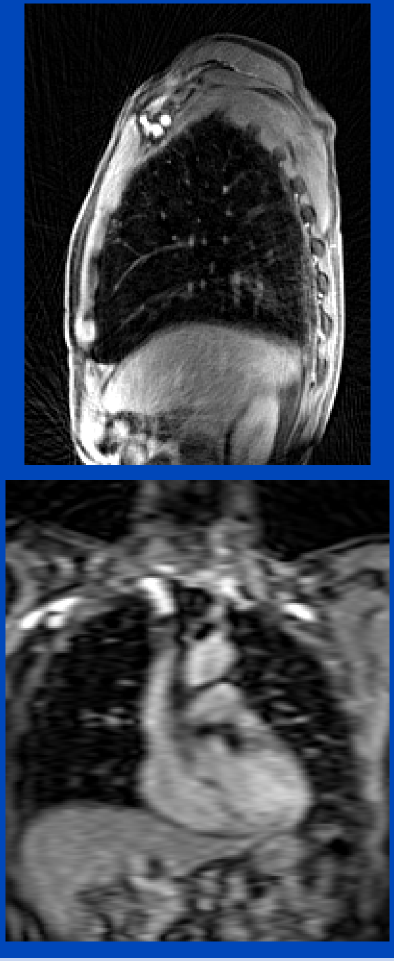
4D MR Motion Compensation

Results Patient c24

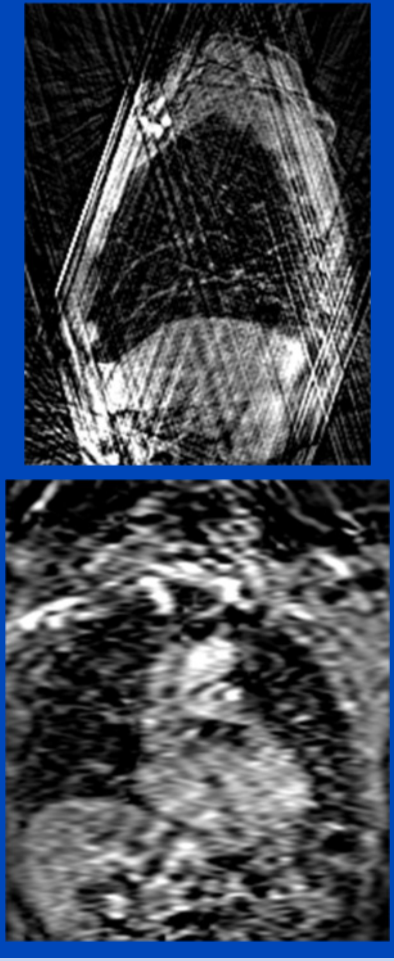
Gated 4D
5 min 50 s



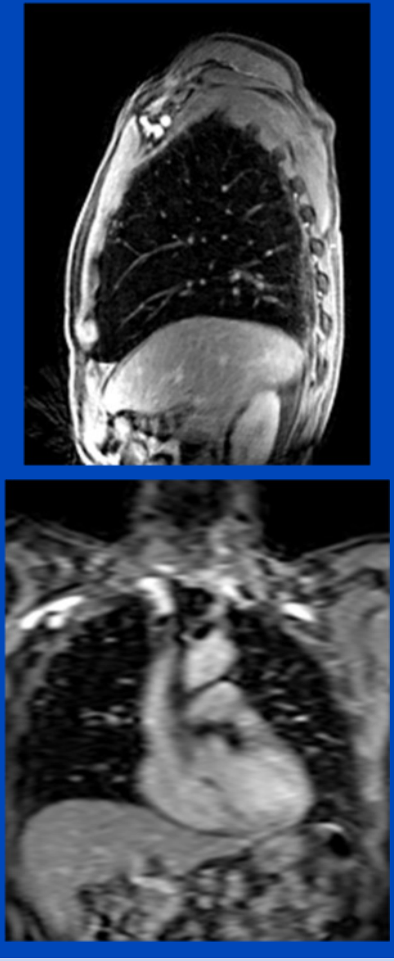
3D
41 s



Gated 4D
41 s



4D joint MoCo-HDTV
41 s



Magnetom Aera at Thoraxklinik, Radial VIBE WIP 528K
$R = 20$, $\Delta r = 10\%$

MoCo PET Image Reconstruction[1]

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

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

n:	iteration index
M, M^{T}:	system matrix including forward-/backprojection
a:	attenuation correction factors
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**

---

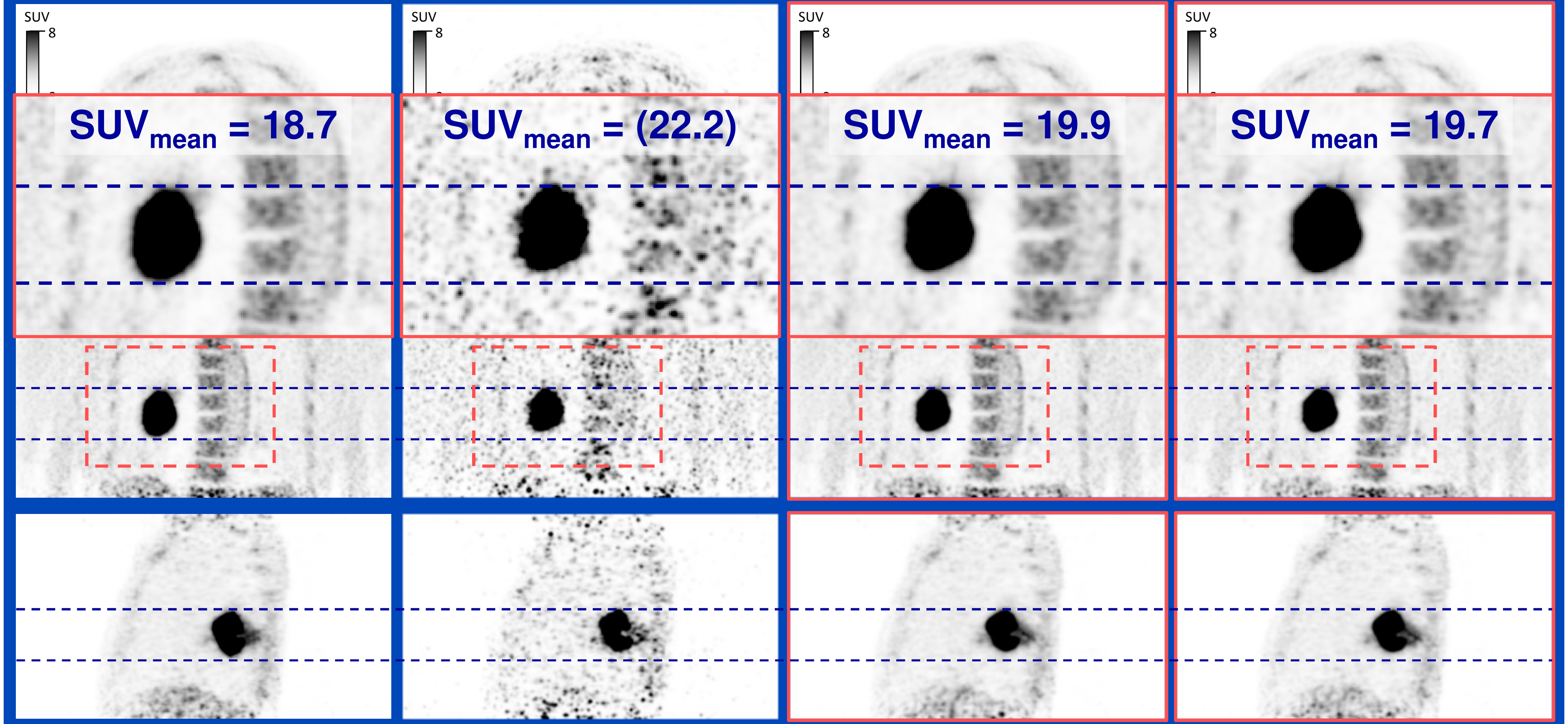
[1] Qiao, Pan, Clark, Mawlawi. A motion-incorporated reconstruction method for gated PET studies. Phys. Med. Biol. 2006.

4D PET/MR Motion Compensation

PET Results Patient s01

4D cMoCo

3D | Gated 4D | MR: 5 min / bed | MR: 1 min / bed



SUV$_{mean}$ = 18.7

SUV$_{mean}$ = (22.2)

SUV$_{mean}$ = 19.9

SUV$_{mean}$ = 19.7

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

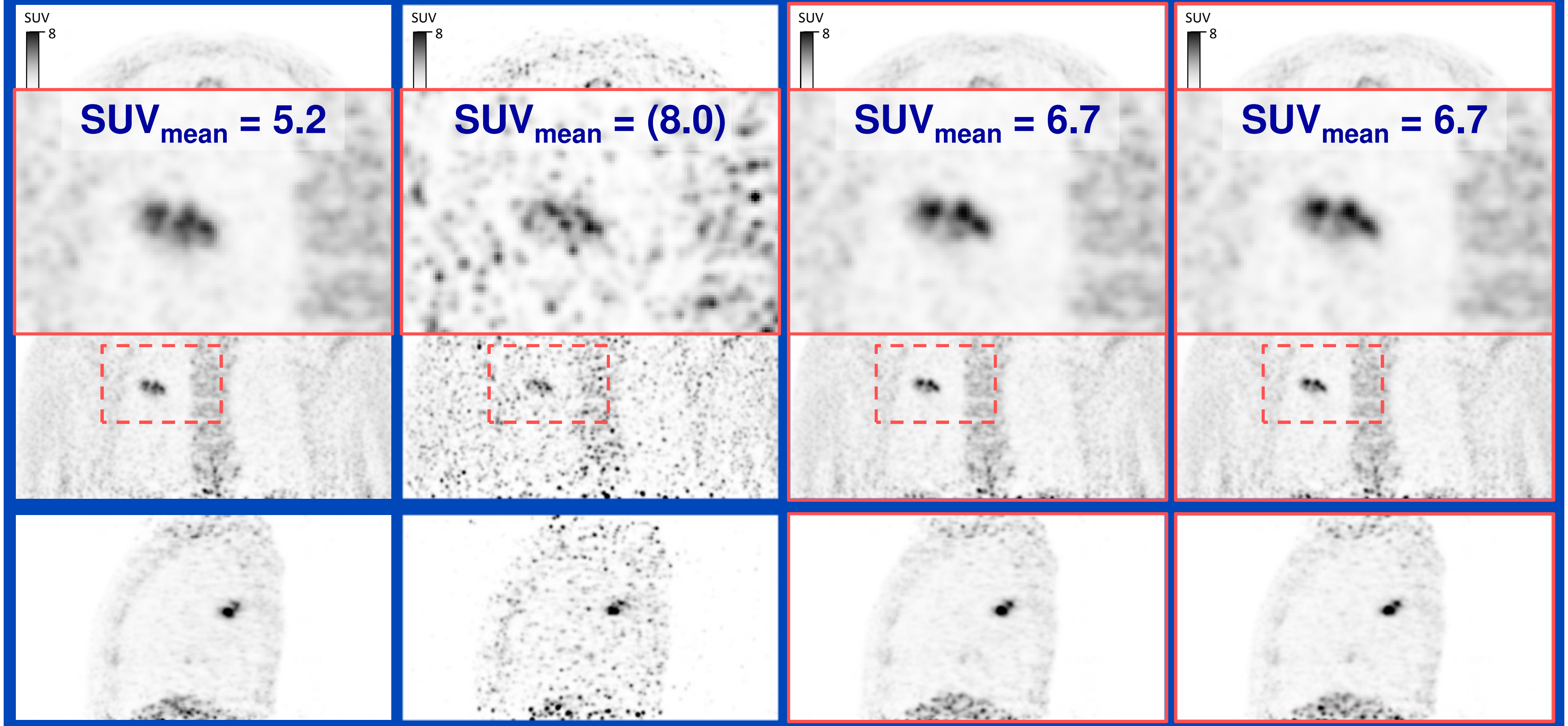
C. Rank, T. Heußer, A. Wetscherek, M. Freitag, O. Sedlaczek, H.-P. Schlemmer, and M. Kachelrieß. Respiratory motion compensation for simultaneous PET/MR based on highly undersampled MR data. Med. Phys. 43(12):6234-6245, December 2016.

4D PET/MR Motion Compensation

PET Results Patient s09

4D cMoCo

3D | Gated 4D | MR: 5 min / bed | MR: 1 min / bed



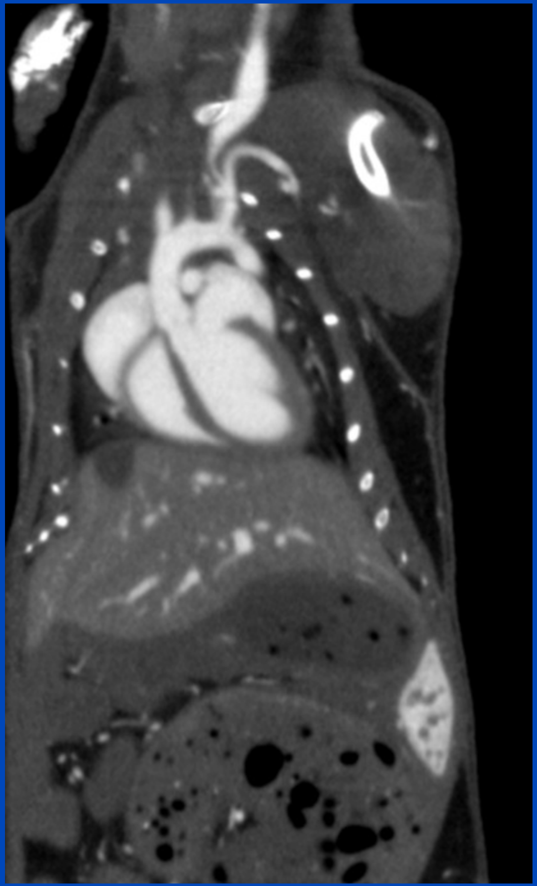
due to the high noise level of 4D gated PET,
SUV_{mean} was systematically overestimated

Conclusion and Outlook

- Quasi-periodic motion can be accurately assessed from very sparse data.
- MVFs can continuously be updated, wich is important for MR-based RT.
- Non-periodic motion can be compensated using deformable 3D-2D registration[1] (not shown here).

[1] B. Flach, M. Brehm, S. Sawall, and M. Kachelrieß. Deformable 3D-2D Registration for CT and ist Application to Low Dose Tomographic Fluoroscopy. PMB59:7865-7887, November 2014.

Is There More?

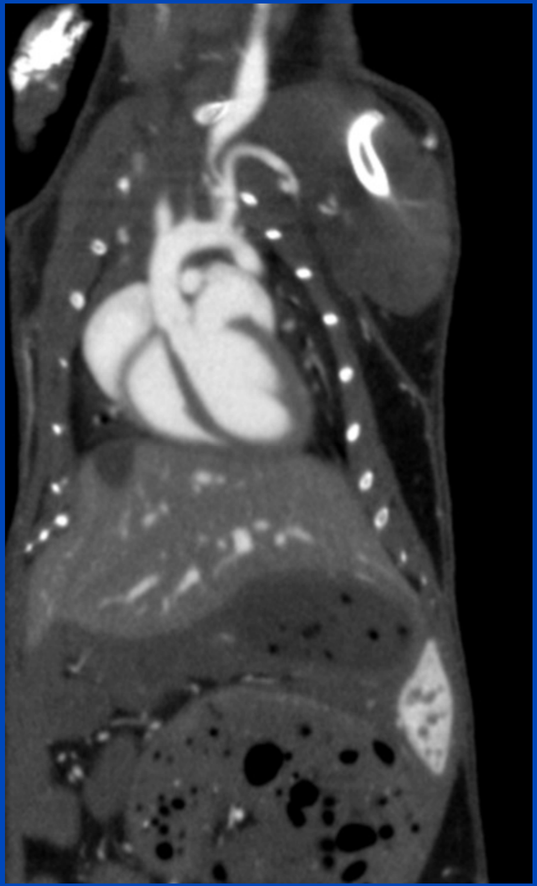


Data displayed as:

Heart: 280 bpm

Lung: 150 rpm

Mouse with 150 rpm and 280 bpm.

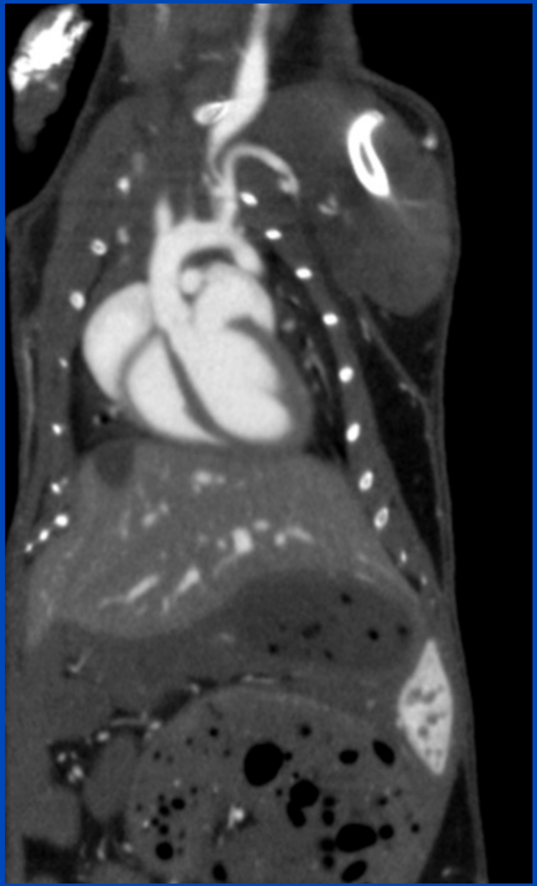


Data displayed as:

Heart: 90 bpm

Lung: 90 rpm

Mouse with 180 rpm and 240 bpm.

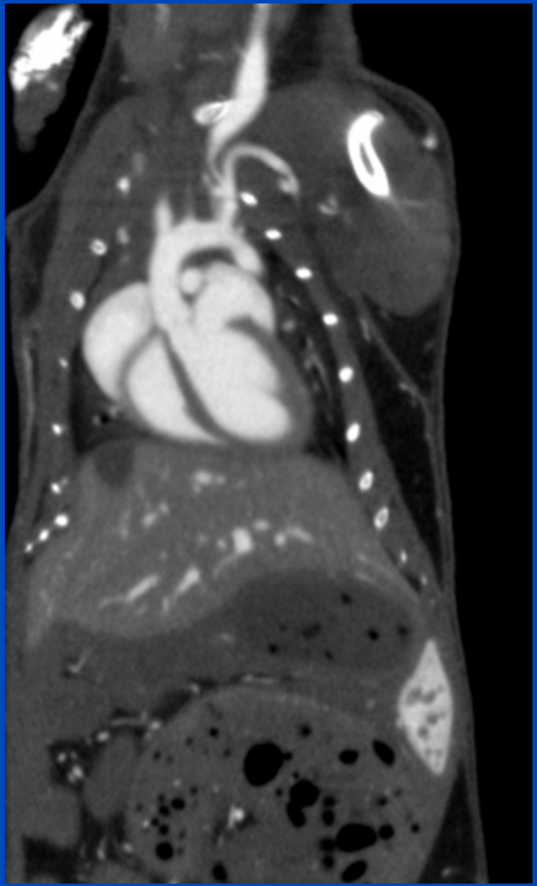


Data displayed as:

Heart: 0 bpm

Lung: 90 rpm

Mouse with 180 rpm and 240 bpm.



Data displayed as:

Heart: 90 bpm

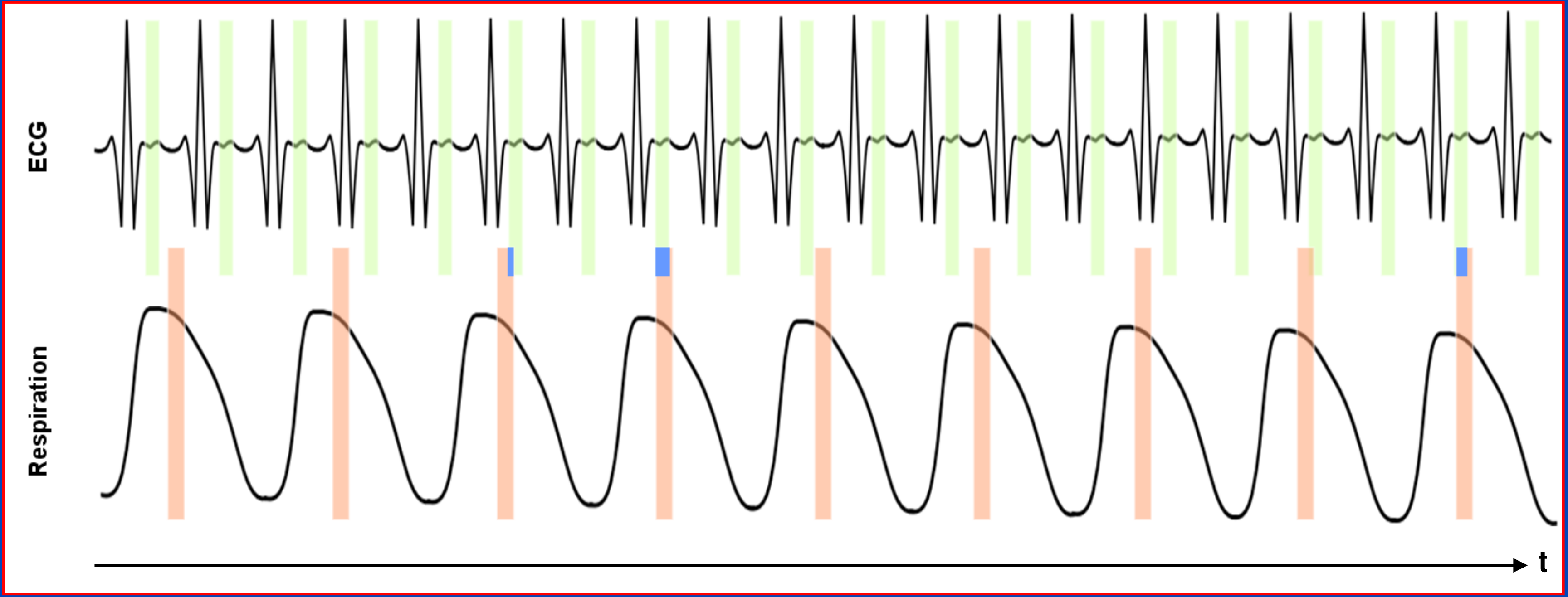
Lung: 0 rpm

Mouse with 180 rpm and 240 bpm.

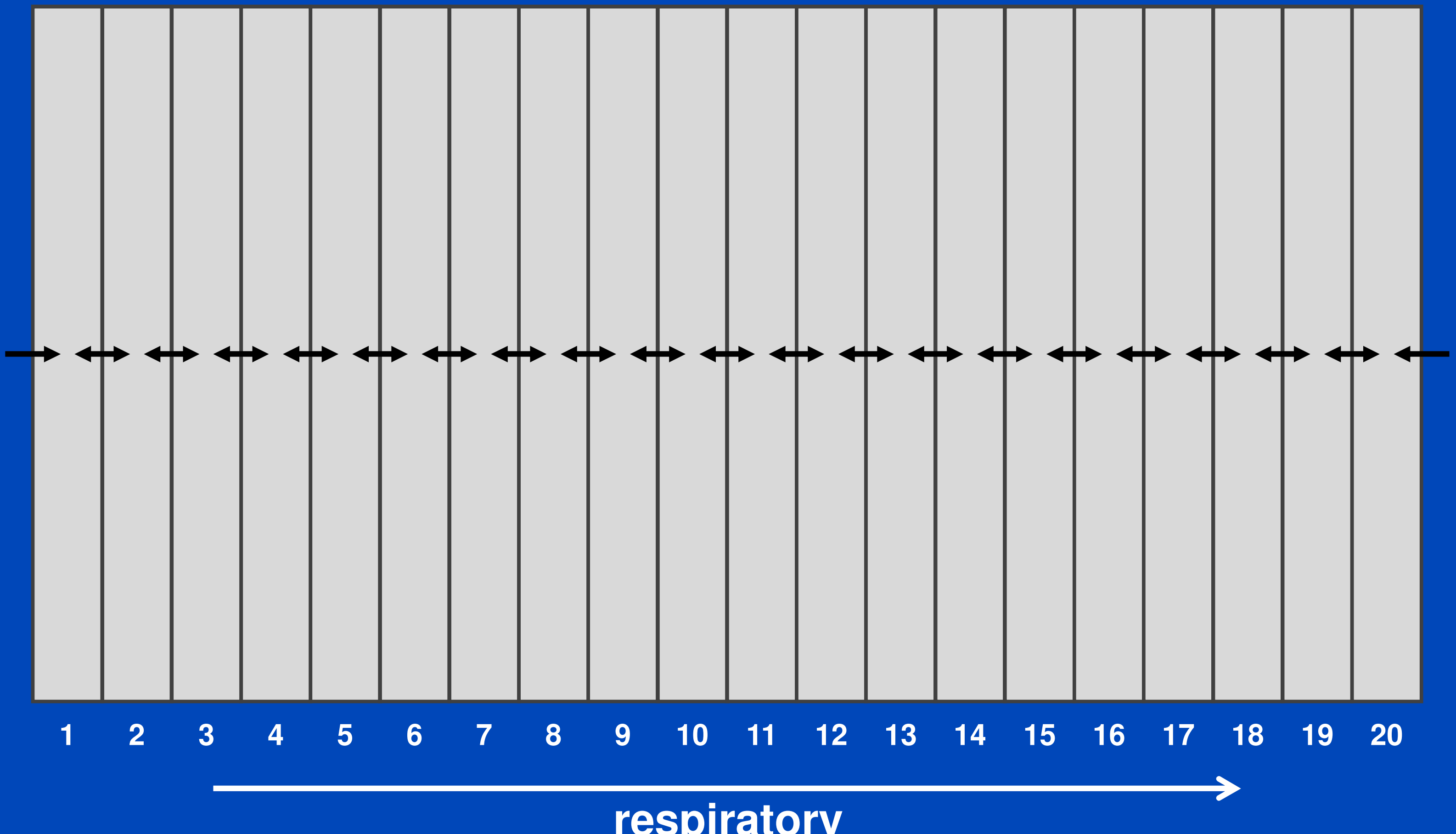
5D with Double Gating?

Double gating example:

- Cardiac window width: 20%
- Respiratory window width: 10%
- Only 2% of all projections per reconstructed volume

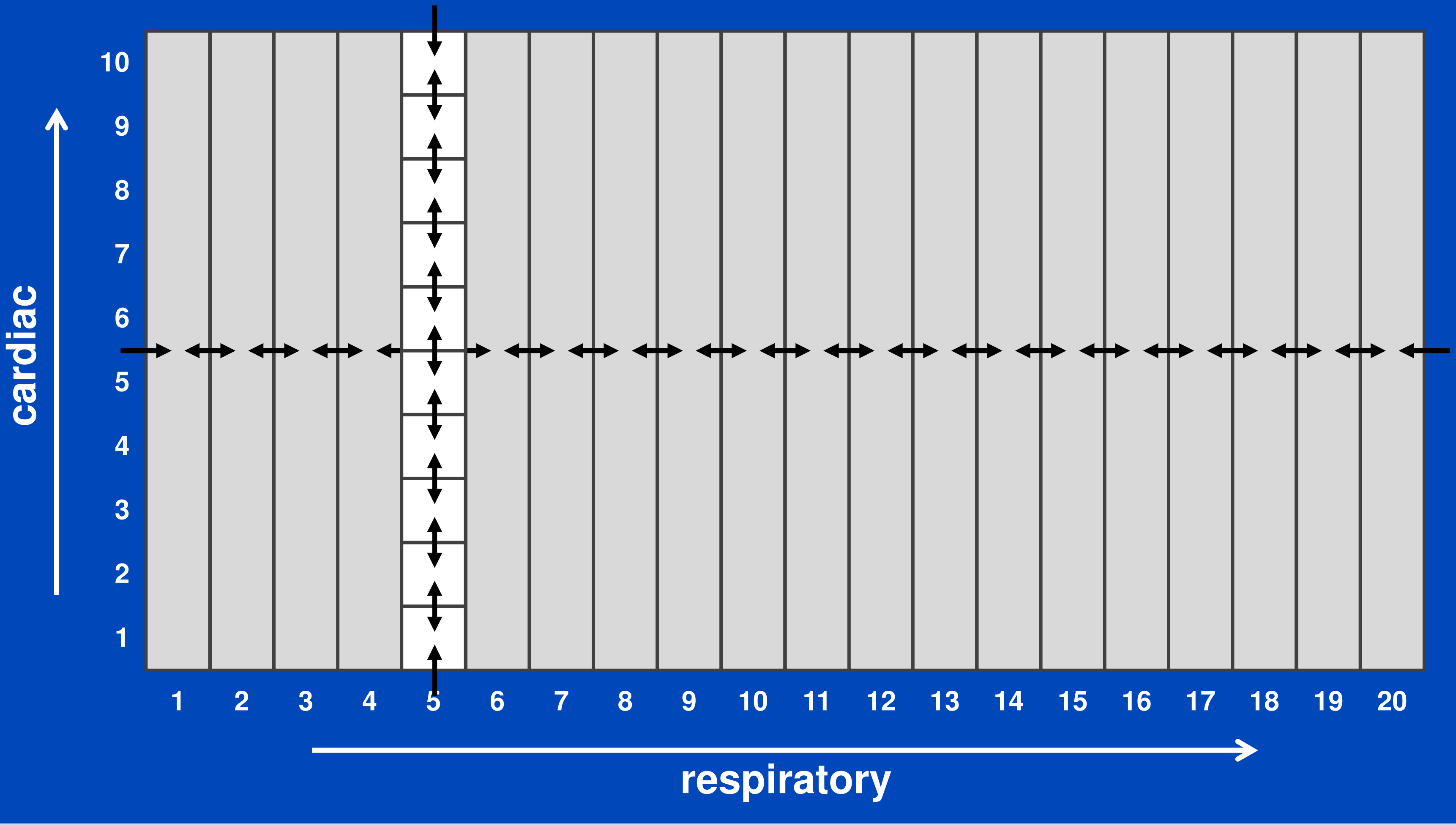


5D Motion Compensation



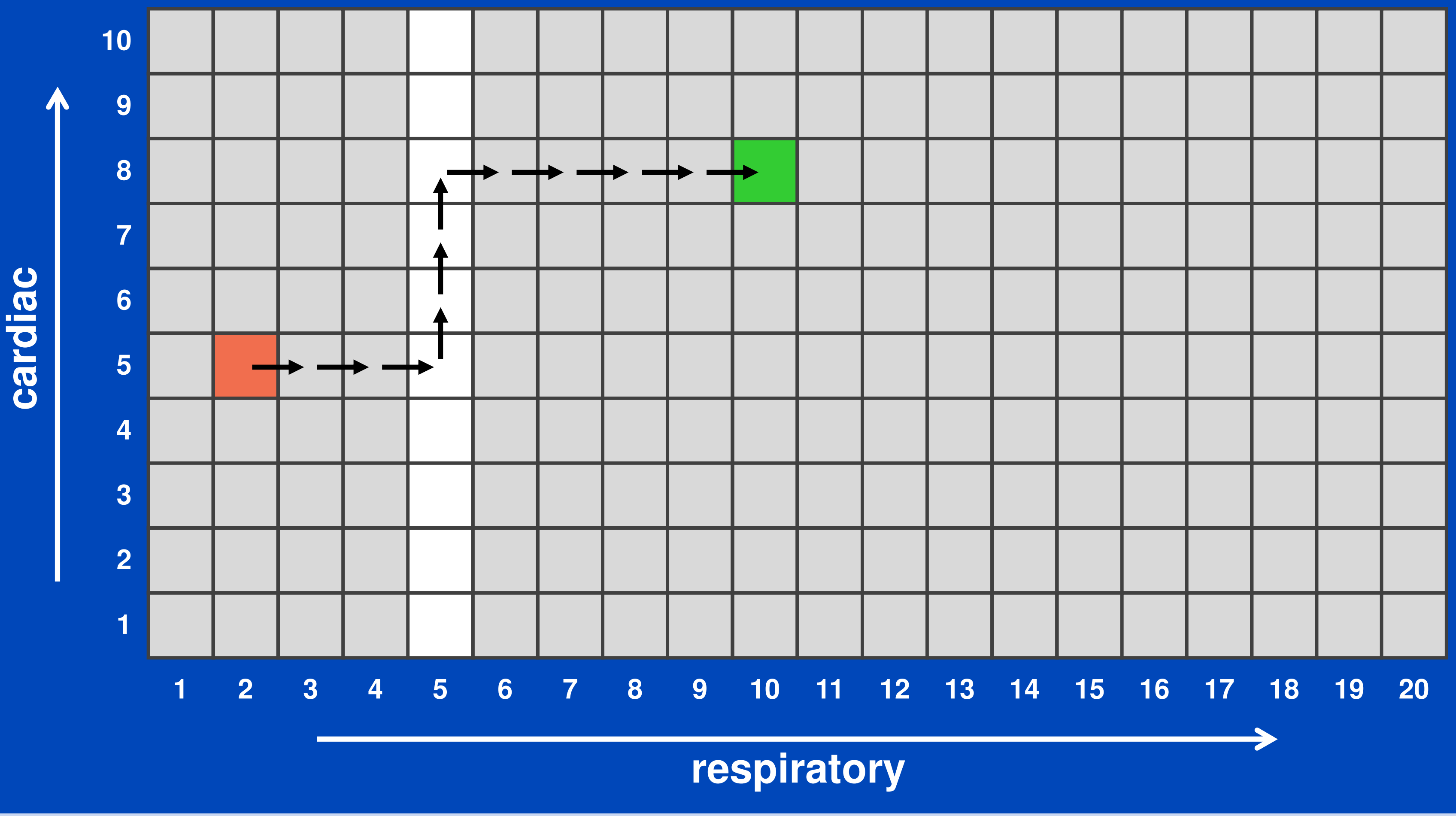
Brehm, Sawall, Maier, and Kachelrieß, “Cardio-respiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation” Med. Phys. 42(4):1948-1958, 2015.

5D Motion Compensation



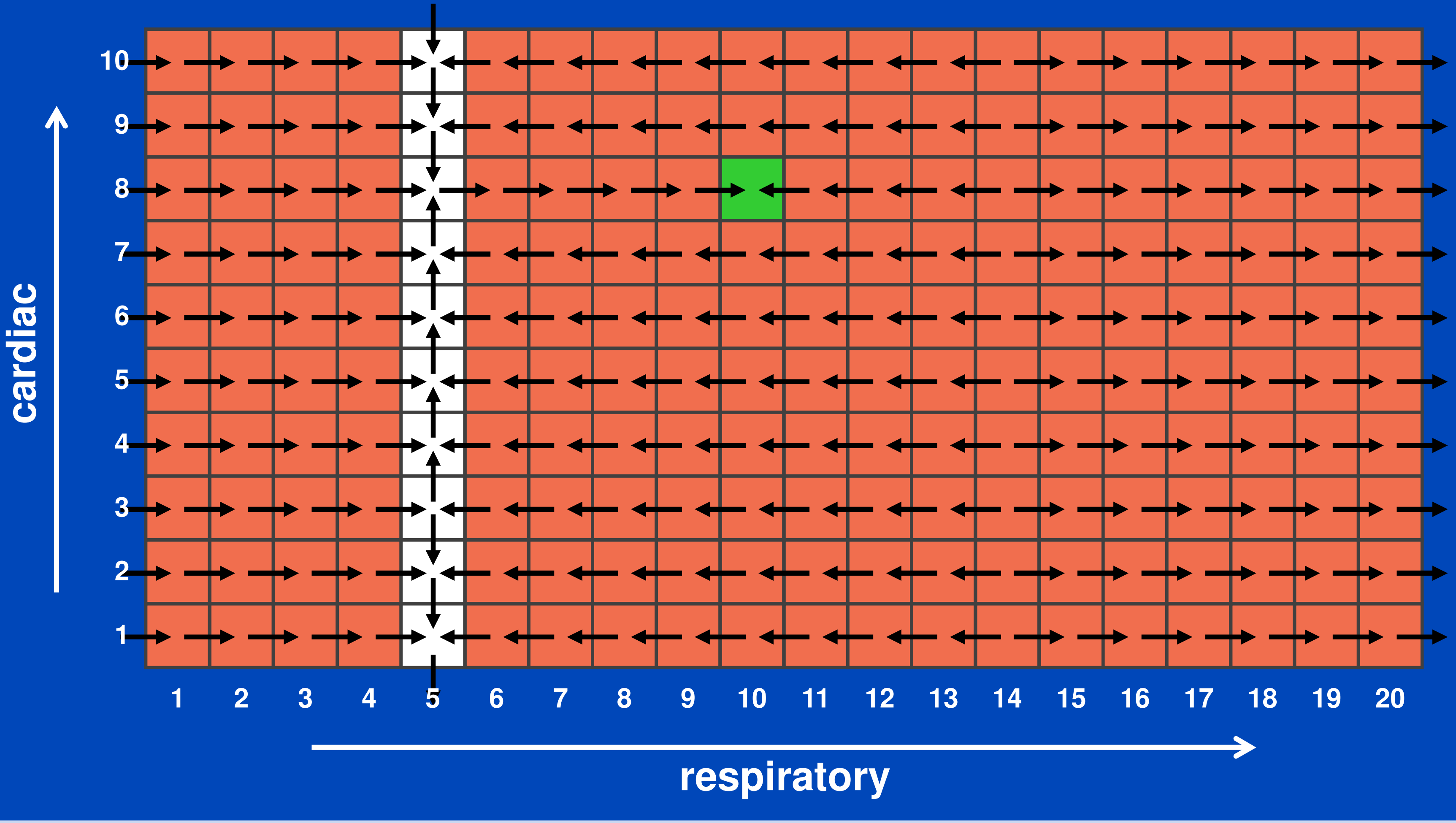
Brehm, Sawall, Maier, and Kachelrieß, “Cardio-respiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation” Med. Phys. 42(4):1948-1958, 2015.

5D Motion Compensation



Brehm, Sawall, Maier, and Kachelrieß, "Cardio-respiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation" Med. Phys. 42(4):1948-1958, 2015.

5D Motion Compensation



Brehm, Sawall, Maier, and Kachelrieß, "Cardio-respiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation" Med. Phys. 42(4):1948-1958, 2015.

5D MR Motion Compensation

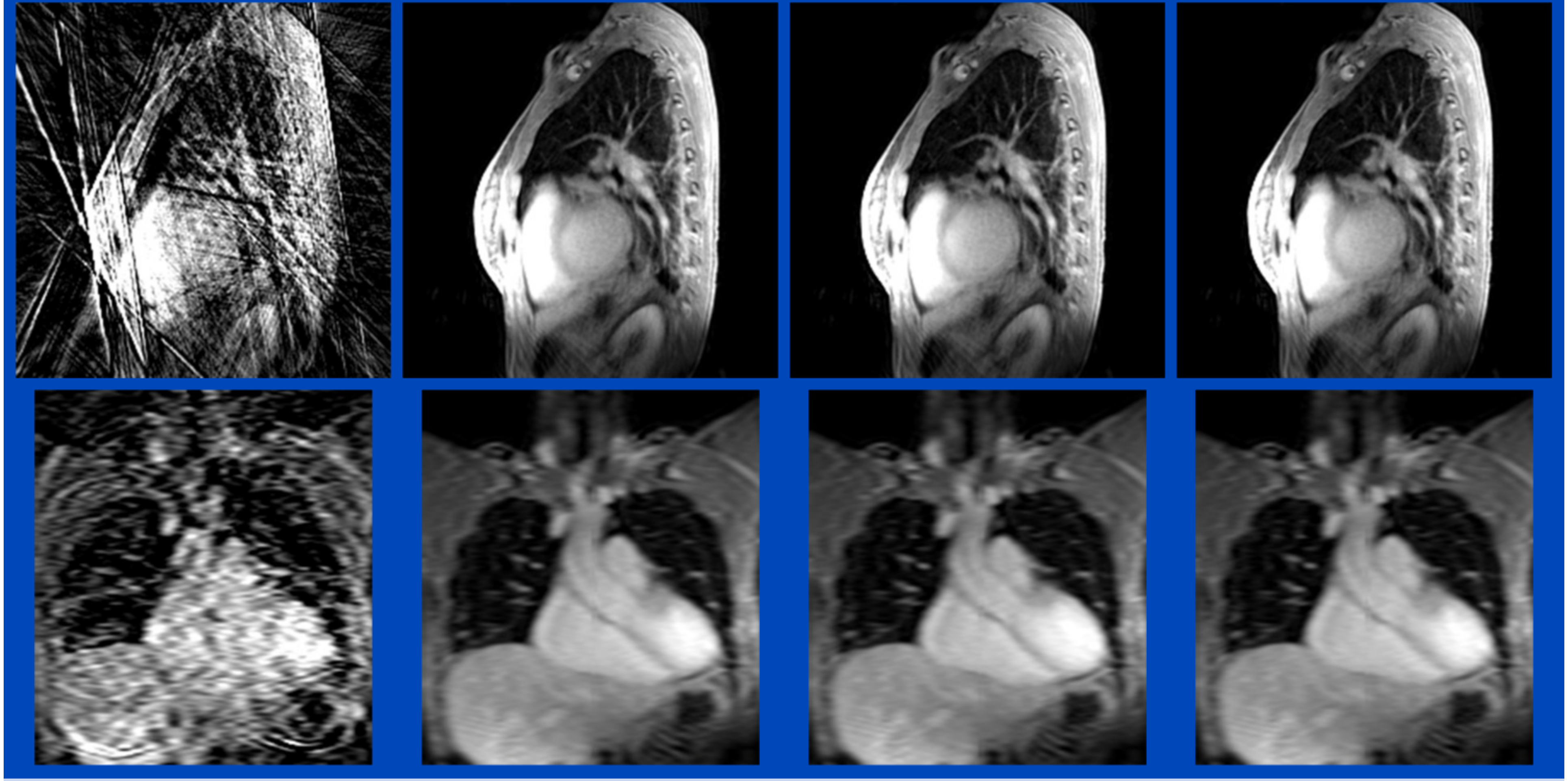
Results Patient c11 (Acquisition Time: 2 min)

5D double-gated
72 bpm, 18 rpm

5D MoCo
72 bpm, 18 rpm

5D MoCo
0 bpm, 18 rpm

5D MoCo
72 bpm, 0 rpm



Magnetom Aera at Thoraxklinik, Radial VIBE WIP 528K
$R = 20$, $\Delta r = 10\%$, $C = 10$, $\Delta c = 20\%$, radial undersampling = 27.9

5D MR Motion Compensation

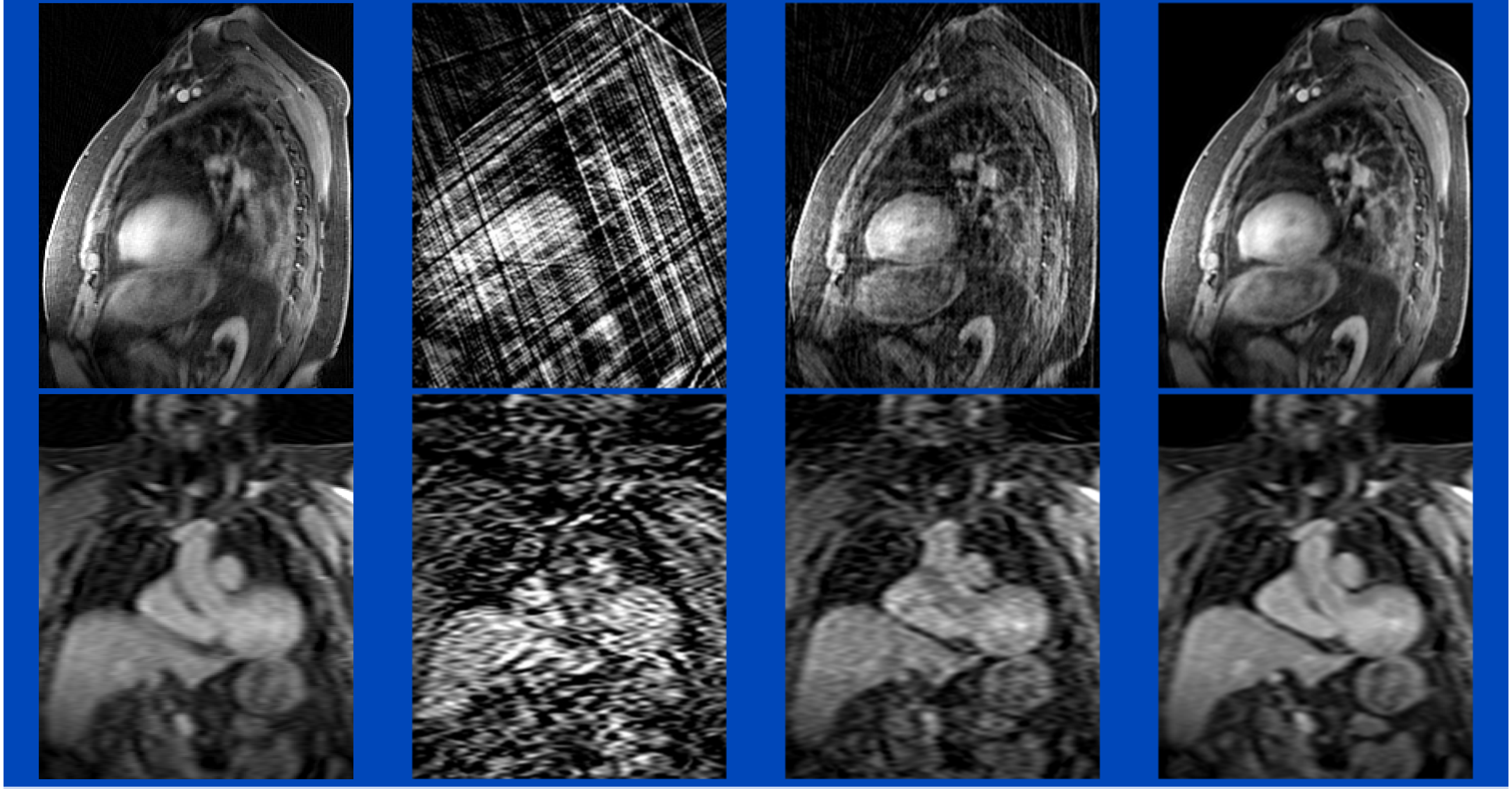
Results Patient c12

3D reconstruction
motion average

5D reconstruction
resp & card gated
$r = 1$, c-loop

5D reconstruction
resp MoCo & card gated
$r = 1$, c-loop

5D MoCo
resp & card MoCo
$r = 1$, c-loop



total acquisition time: 1 min 55 s, radial undersampling = 36

5D MR Motion Compensation

Results Patient c19

3D reconstruction
motion average

5D MoCo
resp & card MoCo
$r = 1$, c-loop

5D MoCo
resp & card MoCo
r-loop, $c = 1$

5D MoCo
resp & card MoCo
r-loop, c-loop

total acquisition time: 1 min 55 s, radial undersampling = 36

5D PET/MR Motion Compensation

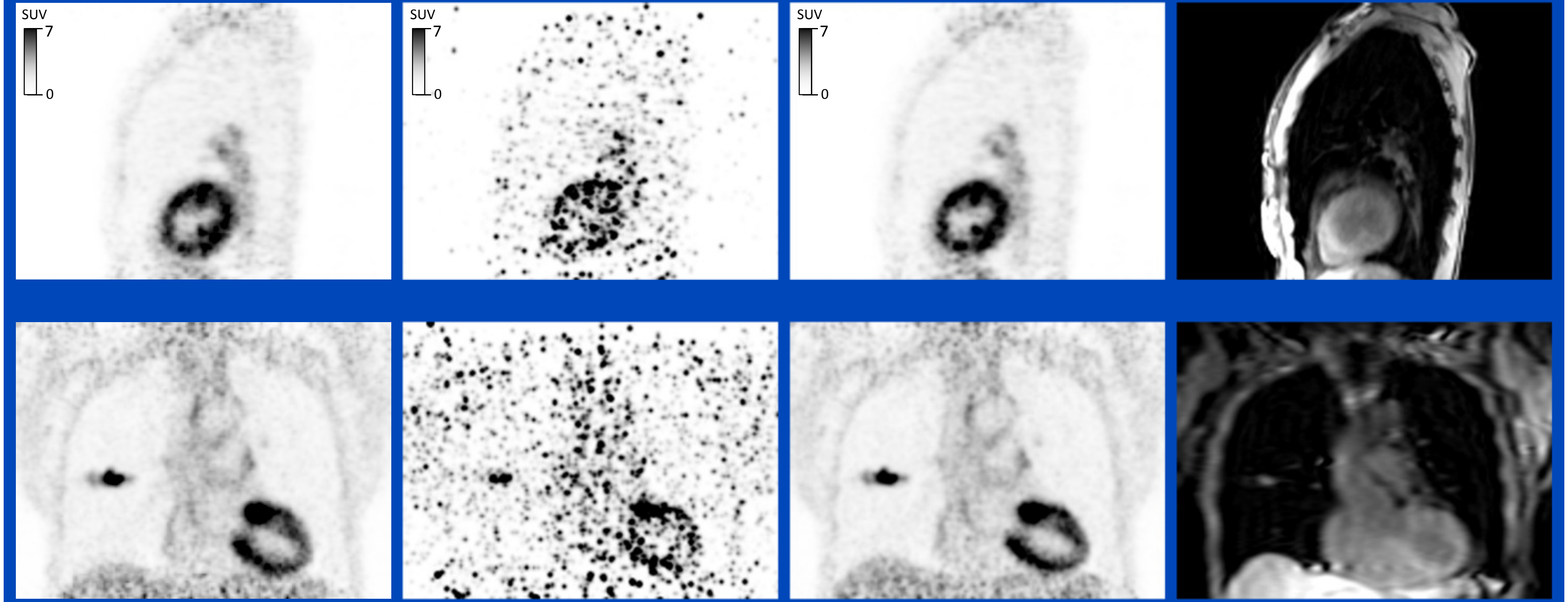
Results Patient s04

3D PET
motion average

5D double-gated PET
r = 1, *c*-loop

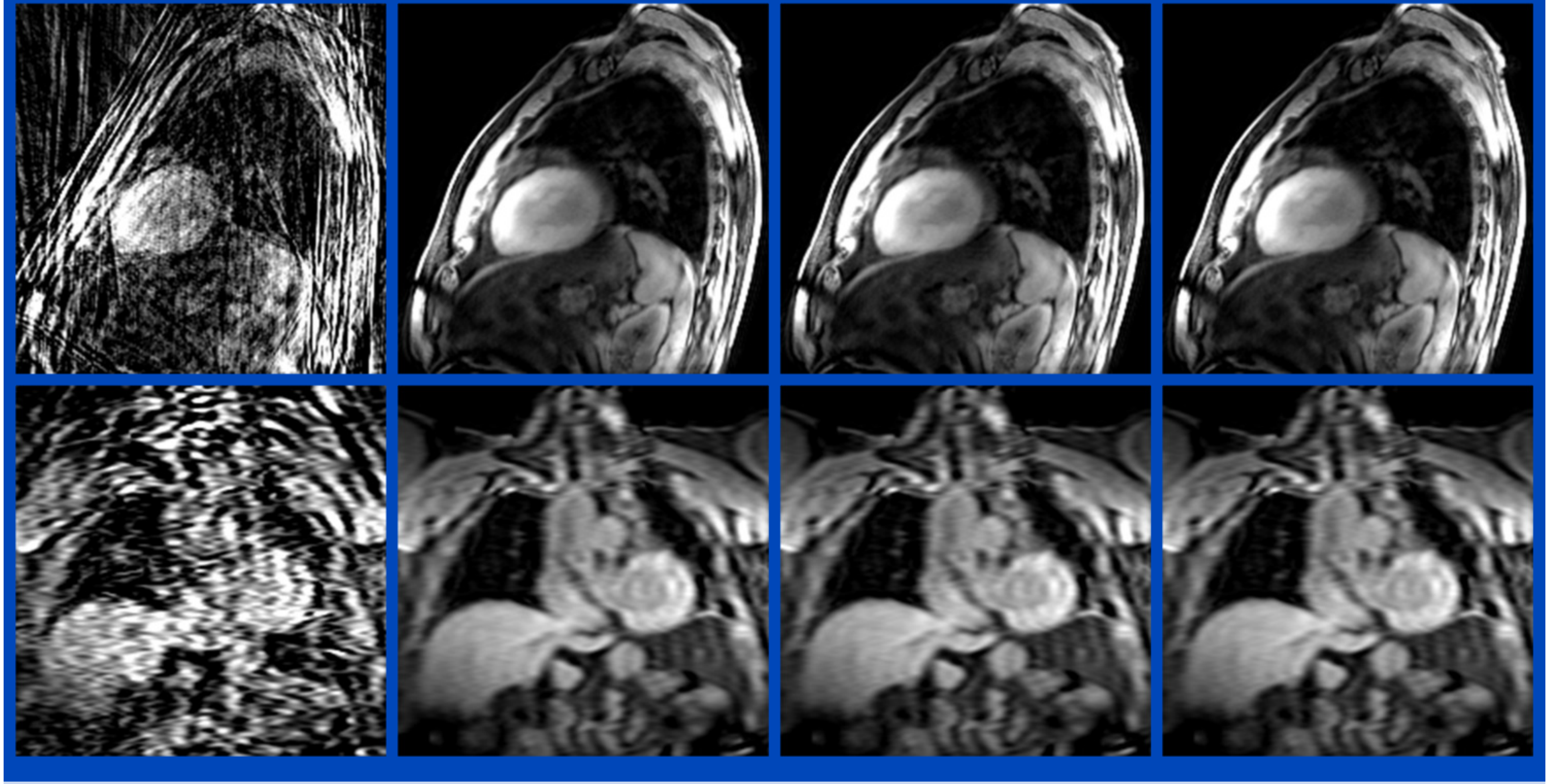
5D MoCo PET
r = 1, *c*-loop

5D MoCo MR
r = 1, *c*-loop



5D MR Motion Compensation

Results Patient s10



5D double-gated MR
$r = 1$, c-loop

5D MoCo MR
$r = 1$, c-loop

5D MoCo MR
r-loop, $c = 1$

5D MoCo MR
r-loop, c-loop

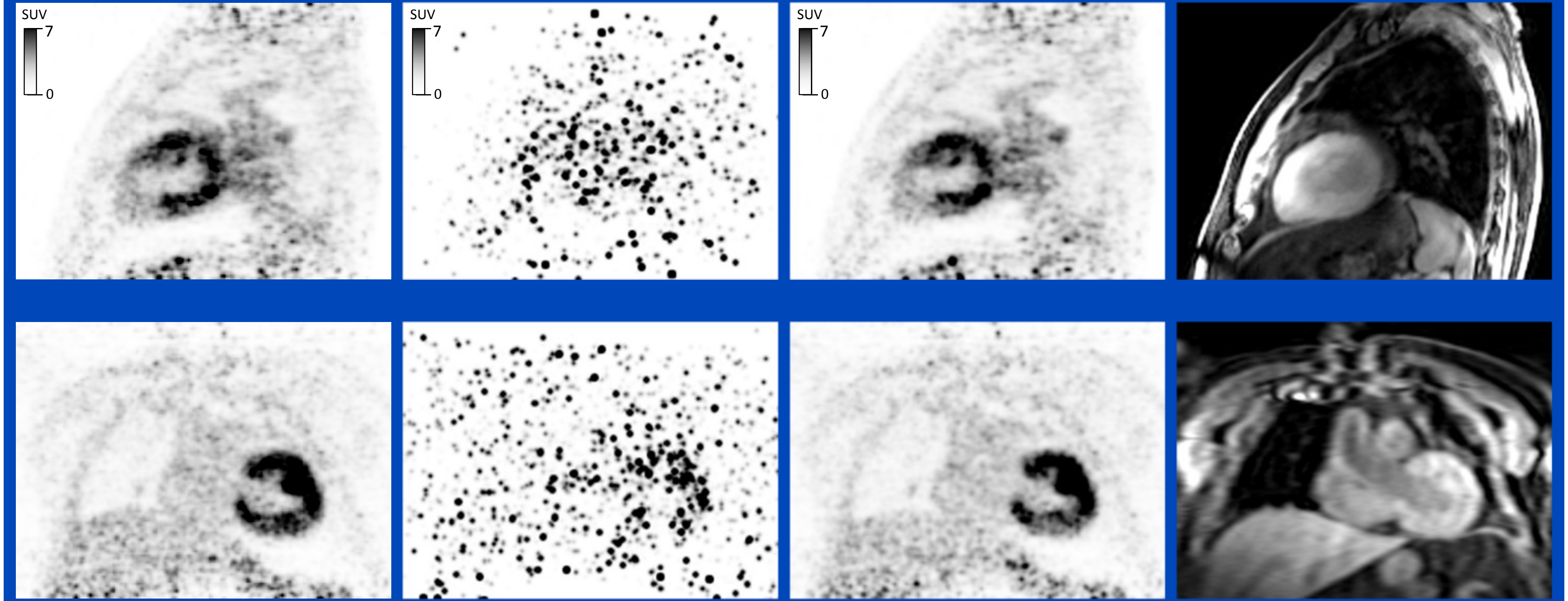
total acquisition time: 5 min

dkfz.

5D PET/MR Motion Compensation

Results Patient s10

3D PET	**5D double-gated PET**	**5D MoCo PET**	**5D MoCo MR**
motion average	$r = 1$, c-loop	$r = 1$, c-loop	$r = 1$, c-loop



total acquisition time: 5 min

Thank You!

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

Job opportunities through DKFZ's international PhD or Postdoctoral Fellowship programs (www.dkfz.de), or directly through Marc Kachelriess (marc.kachelriess@dkfz.de).

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