Five-Dimensional Respiratory and Cardiac Motion Compensation for Simultaneous PET/MR

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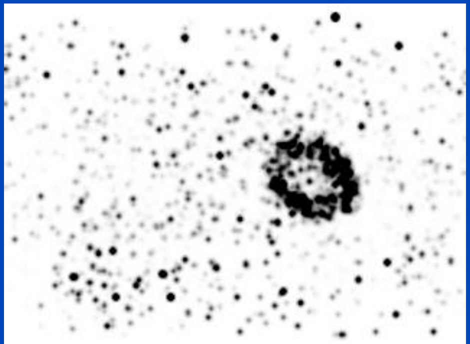
DEUTSCHES KREBSFORSCHUNGSZENTRUM IN DER HELMHOLTZ-GEMEINSCHAFT

Introduction

- One major challenge in PET image reconstruction is respiratory and cardiac patient motion
- Motion causes image blurring and an underestimation of the reconstructed activity
- Gating
  - sort data into respiratory and cardiac bins and reconstruct data from each bin separately
  - trade-off between temporal resolution and an appropriate SNR and CNR of the PET images

5D double-gated PET



- Recent approach: PET/MR motion compensation (MoCo)[1,2,3]
  - use MR information to estimate motion vector fields (MVFs)
  - MoCo PET reconstruction from 100% of raw data

[1] Petibon et al. Cardiac motion compensation and resolution modeling in simultaneous PET-MR: A cardiac lesion detection study. *Phys Med Biol* 2013.
[2] Huang et al. Accelerated acquisition of tagged MRI for cardiac motion correction in simultaneous PET-MR: phantom and patient studies. *Med Phys* 2015.
[3] Munoz et al. MR-based cardiac and respiratory motion-compensation techniques for PET-MR imaging. *PET Clin* 2016.

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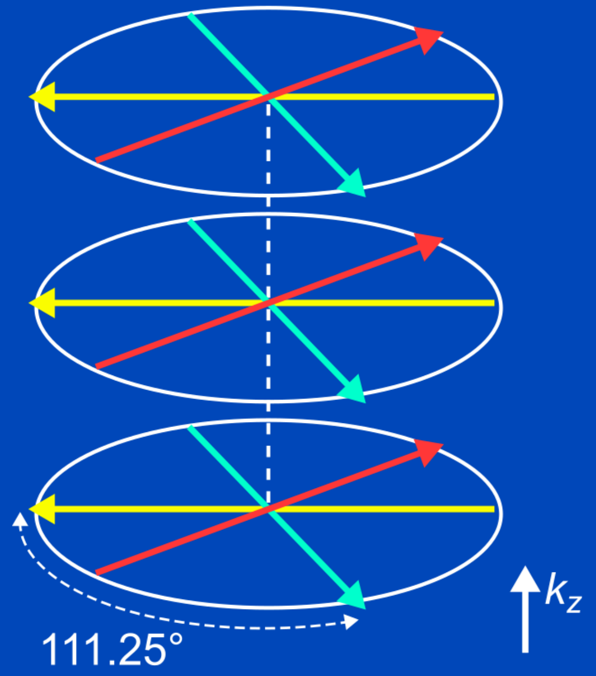
Aim of Work

- Develop a method for respiratory and cardiac motion compensation of PET images
- Use information from simultaneously acquired MR data for motion estimation
- Difficulty: efficient and robust estimation of both respiratory and cardiac MVFs

Data Acquisition and Processing

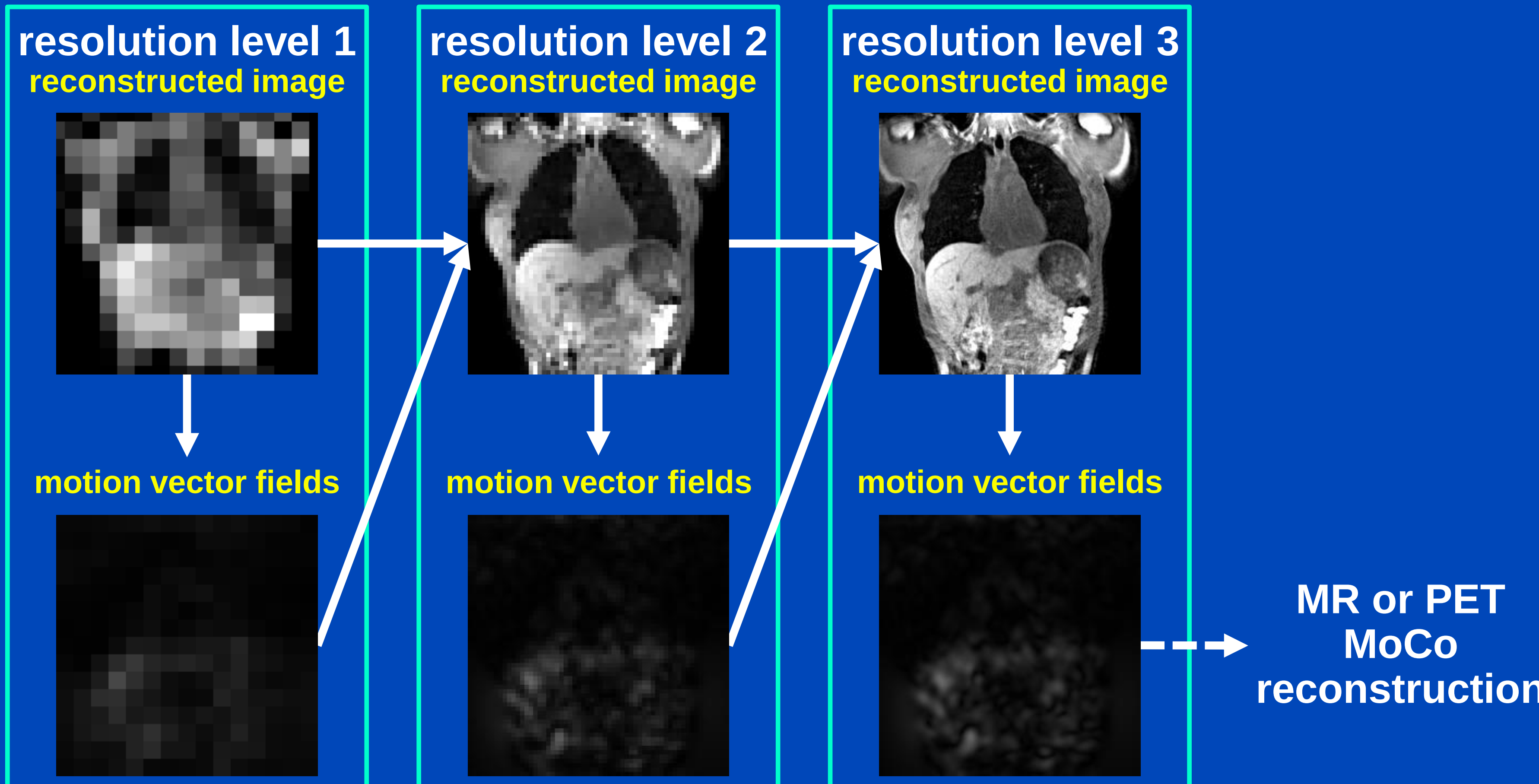
- Simultaneous PET/MR acquisition with 5 min per bed (Biograph mMR, Siemens Healthineers)
- Tracer: fluorodeoxyglucose (^{18}F-FDG)
- 3D-encoded gradient echo sequence with radial stack-of-stars sampling
- Golden angle (≈ 111.25°) radial spacing
- Intrinsic estimation of motion signals



- MR and PET data were sorted into 20 overlapping respiratory motion phases (10% width) and 12 overlapping cardiac motion phases (17% width)

Algorithm for Motion Estimation

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.

Algorithm for Motion Estimation

MR Image Reconstruction - Cost Function[1,2]

- **Cost function:**

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

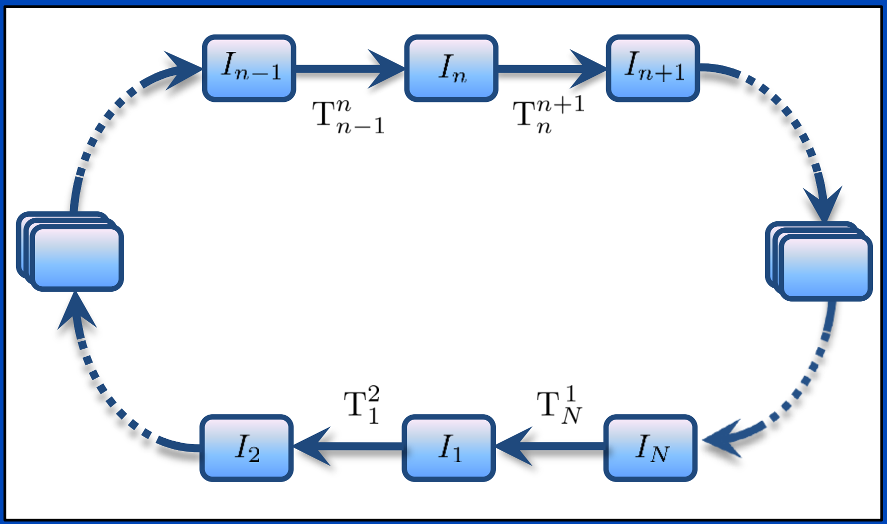
X_{pc}	: motion phase-correlated forward transform
S	: coil sensitivity profiles
f	: 4D image volume
p	: measured raw data
μ	: weight
HDTV	: spatial and temporal total variation

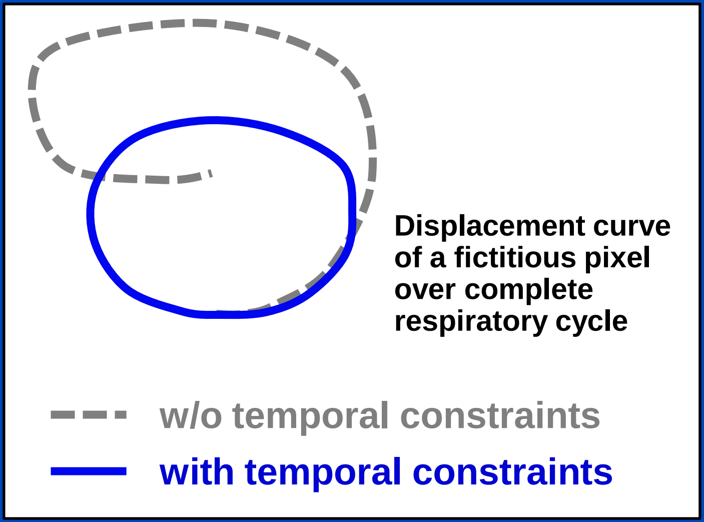
- **The first term optimizes the raw data fidelity**
- **The second term improves the image sparsity by optimizing the spatial and temporal total variation**
- **Both terms are optimized in an alternating manner**
- **The cost function is optimized for the complete 4D volume including all motion phases**

[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.

Algorithm for Motion Estimation
Cyclic Deformable Registration[1]

- Motion estimation only between adjacent phases
  - all other motion vector fields given by concatenation

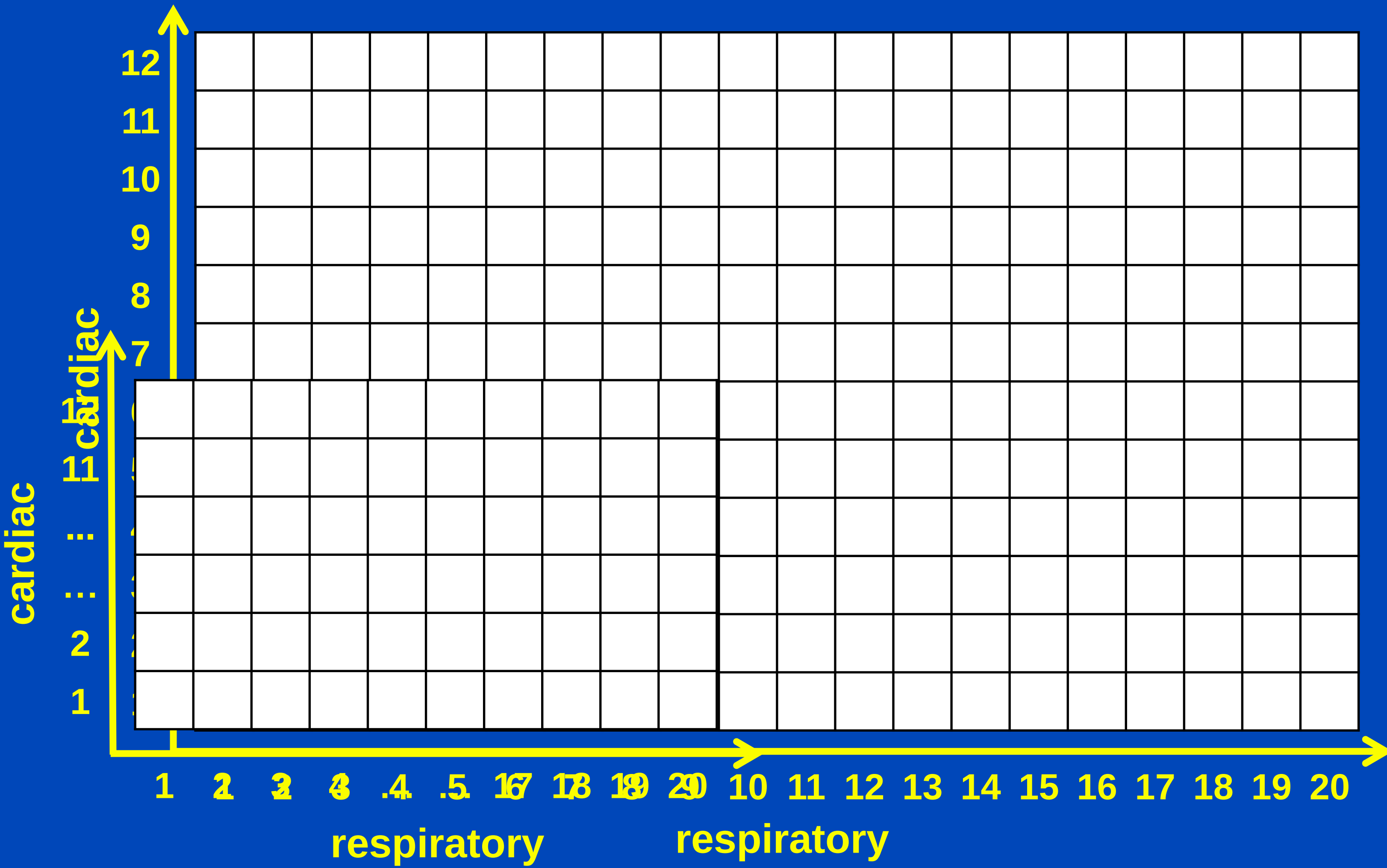




- Incorporate additional knowledge
  - a priori knowledge of quasi periodic breathing pattern
  - non-cyclic motion is penalized
  - error propagation due to concatenation is reduced

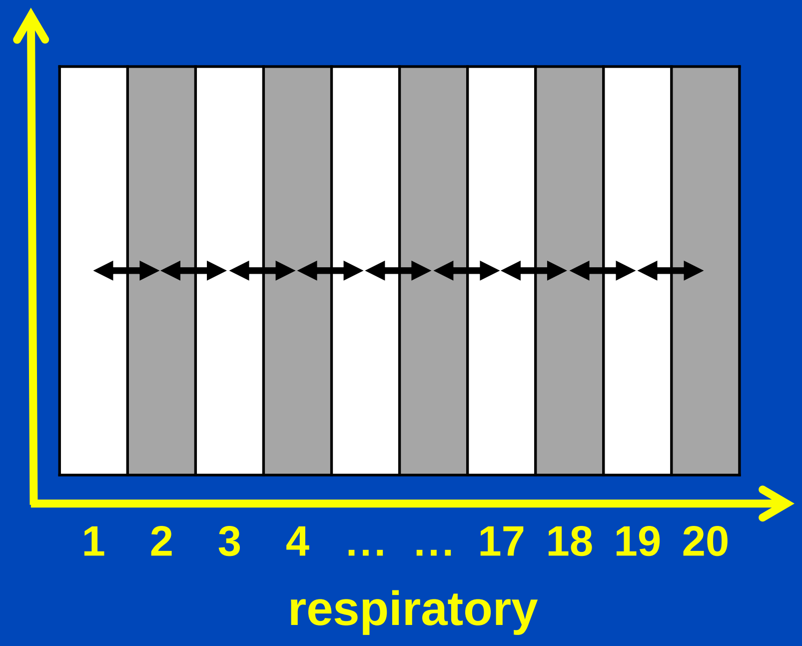
[1] Brehm, Paysan, Oelhafen, Kunz, Kachelrieß. Self-adapting cyclic registration for motion-compensated cone-beam CT in image-guided radiation therapy. *Med. Phys.* 2012.

Double-Gated Raw Data Matrix



Respiratory Motion Estimation

- Respiratory MVFs are estimated neglecting the effect of cardiac motion
- The 4D joint MoCo-HDTV[1] algorithm is employed for motion estimation in the respiratory dimension



[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.

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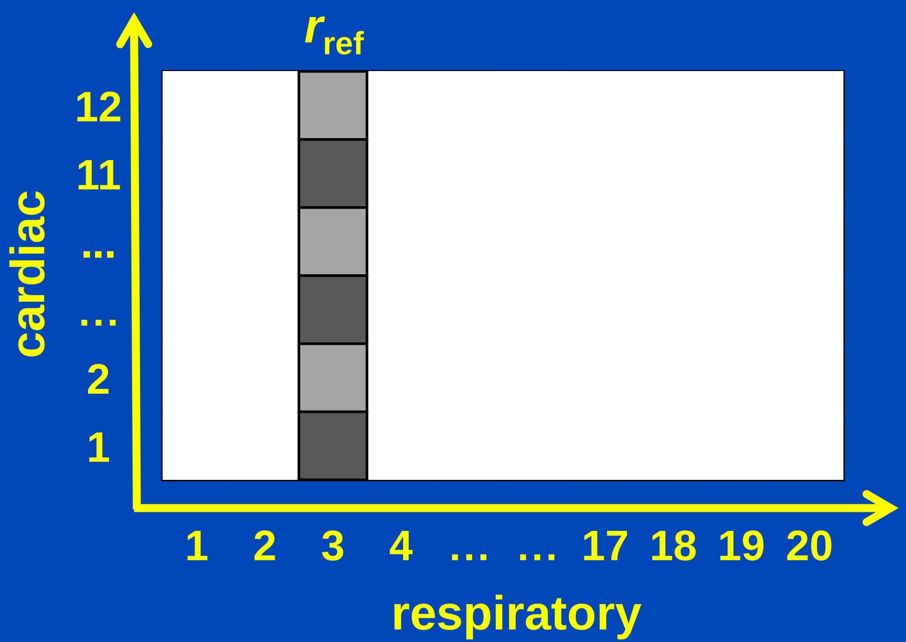
Generation of Respiratory MoCo MR Raw Data

- **Respiratory MoCo MR raw data for cardiac phase *c* at the respiratory reference phase:**

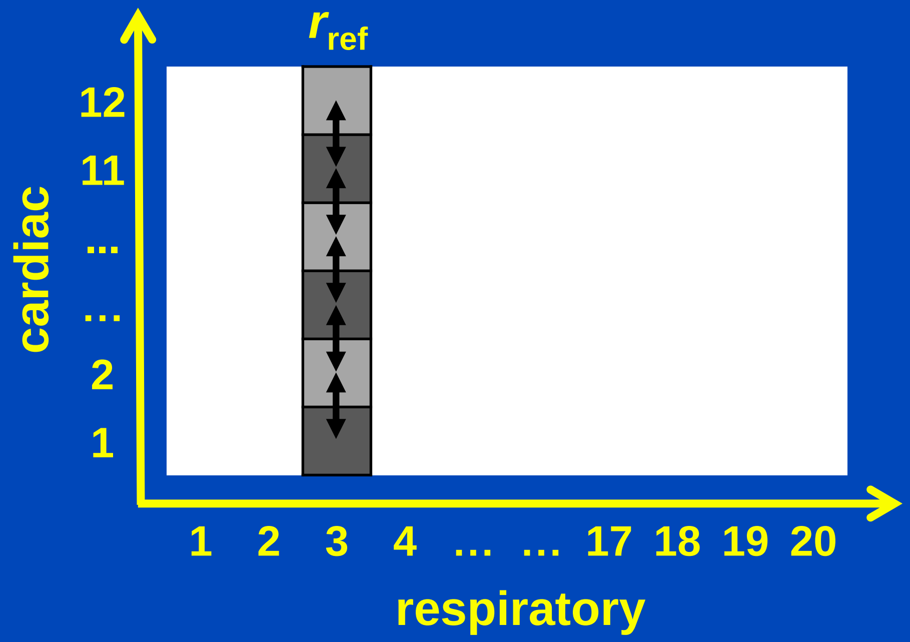
$$p_{r_{\mathrm{ref}},c}^{\mathrm{resp\ MoCo}} = \mathsf{X} \sum_r D_r^{r_{\mathrm{ref}}} \mathsf{X}^{\dagger} G_r G_c \, p$$



r, c	: indices of respiratory and cardiac phases
X, $\mathsf{X}^{\dagger}$	: forward and pseudo-inverse transform
$D_{r'}^{r}$	: warping operation mapping volume of phase r' to r
G_r, G_c	: gating operators
p	: measured raw data

Cardiac Motion Estimation

- Cardiac MVFs are estimated for the respiratory MoCo MR raw data at the respiratory reference phase
- The 4D joint MoCo-HDTV[1] algorithm is employed for motion estimation in the cardiac dimension

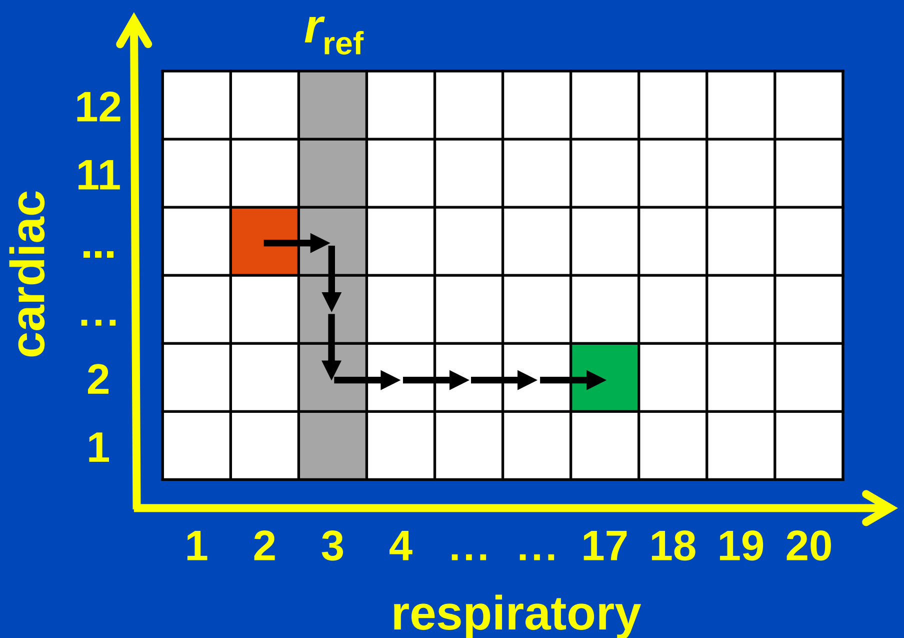


[1] Rank, Heußer, Buzan, Wetscherek, Freitag, Dinkel, Kachelrieß. 4D respiratory motion-compensated image reconstruction of free-breathing radial MR data with very high undersampling. *Magn Reson Med,* early view online.

5D MoCo MR Reconstruction

- **Employing 5D double-gated MR images, any arbitrary combination of respiratory and cardiac phase can be reconstructed:**

$$f_{r,c} = \sum_{r',c'} D_{r',c'}^{r,c} S^{\dagger} \mathrm{X}^{\dagger} G_{r'} G_{c'}\, p$$



r, *c*	: indices of respiratory and cardiac phases
$D_{r',c'}^{r,c}$	: warping operation mapping volume of phase (*r'*,*c'*) to (*r*, *c*)
$S^{\dagger}$	: coil combination
$\mathrm{X}^{\dagger}$	: pseudo-inverse transform
G_r, G_c	: gating operators
p	: measured raw data

5D MoCo MR Reconstruction

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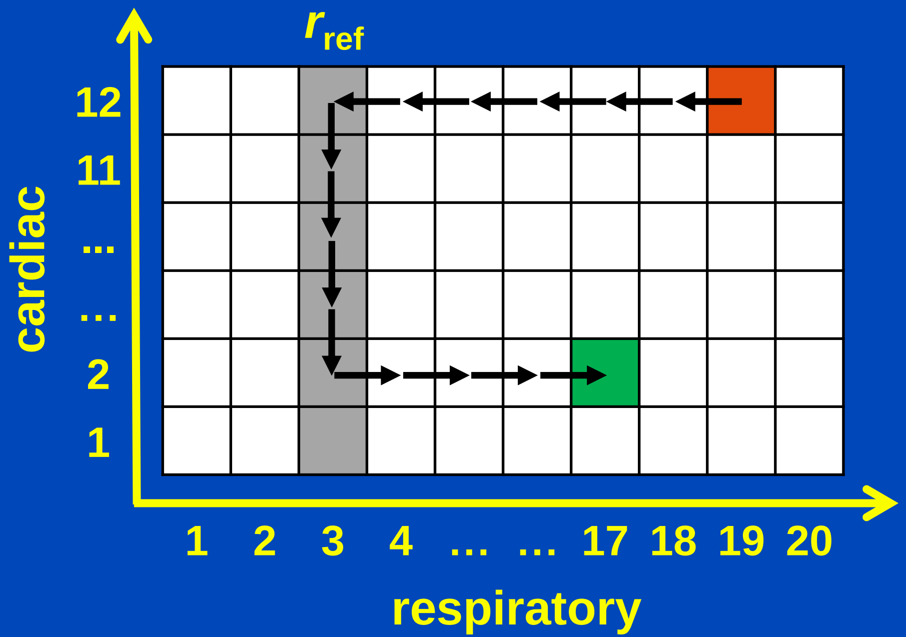


r, c	: indices of respiratory and cardiac phases
$D_{r',c'}{}^{r,c}$	: warping operation mapping volume of phase (r',c') to (r, c)
$S^{\dagger}$	: coil combination
$\mathrm{X}^{\dagger}$	: pseudo-inverse transform
G_r, G_c	: gating operators
p	: measured raw data

5D MoCo PET Reconstruction

- **MoCo OSEM update equation of subiteration *i*+1 and motion phase (*r*, *c*):**

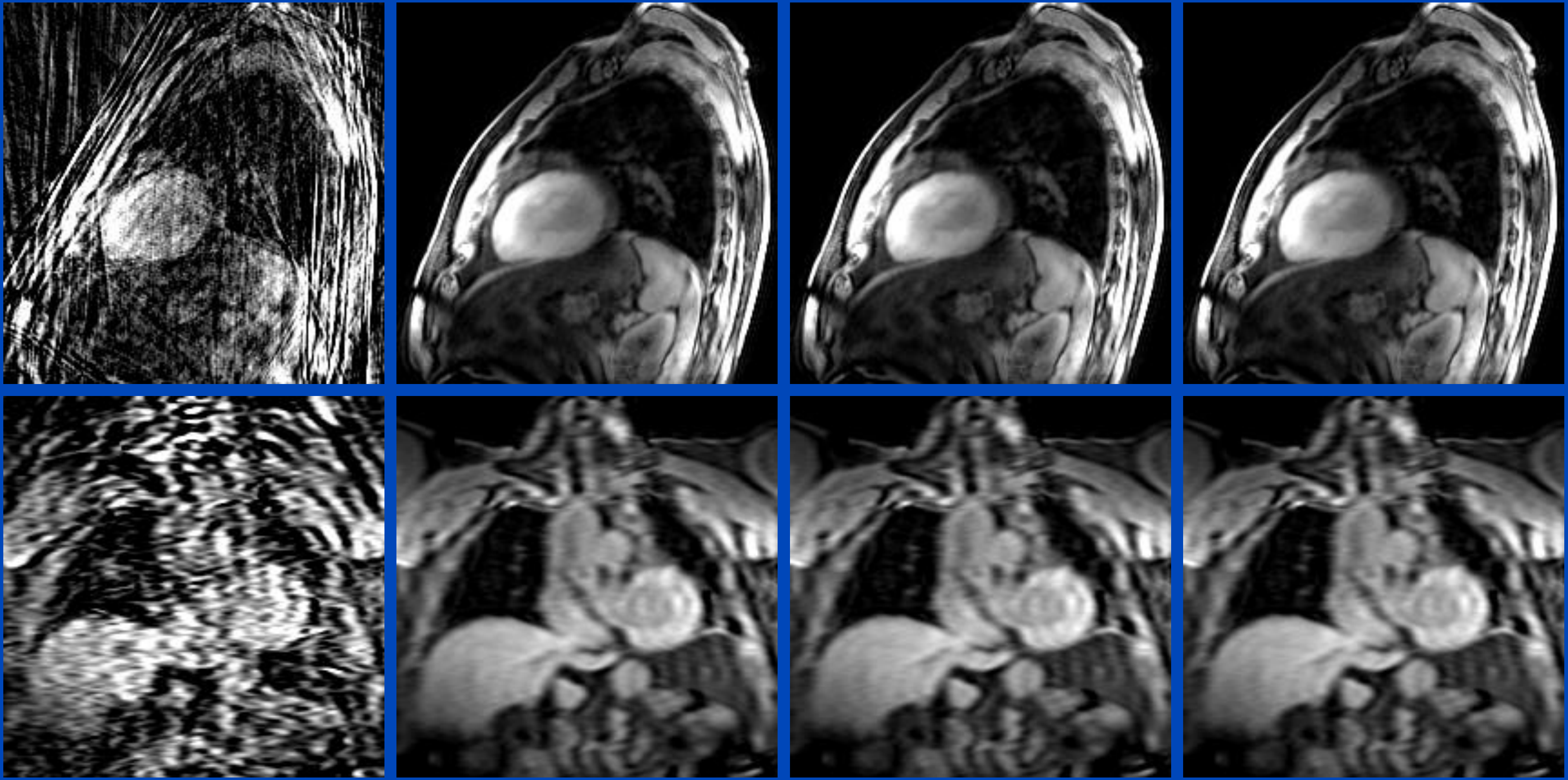
$$\lambda_{r,c,(i+1)} = \lambda_{r,c,(i)} \frac{1}{N_c \sum_{r'} D_{r',c'}^{r,c} M_k^{\mathrm{T}} (\frac{1}{a_{r'} n})} \sum_{r',c'} D_{r',c'}^{r,c} M_k^{\mathrm{T}} \frac{G_{r'} G_{c'} p}{(M_k D_{r,c}^{r',c'} \lambda_{r,c,(i)}) + a_{r'}(d\,n + s)}$$

- **Parameters:**
  - **3 iterations, 21 subsets**
  - **Gaussian smoothing with FWHM = 3.2 mm after each iteration**

i:	subiteration index
k:	subset index: $k = i \bmod K$
r, r':	indices of respiratory motion phases
c, c':	indices of cardiac motion phases
M_k, M_k^{T}:	system matrix including forward-/backprojection of subset k
p:	measured raw data
d:	estimated randoms
s:	estimated scatter
$\lambda_{(i)}$:	image estimate at subiteration i
$D_{r',c'}^{r,c}$:	warping operation mapping volume of phase (r',c') to (r, c)

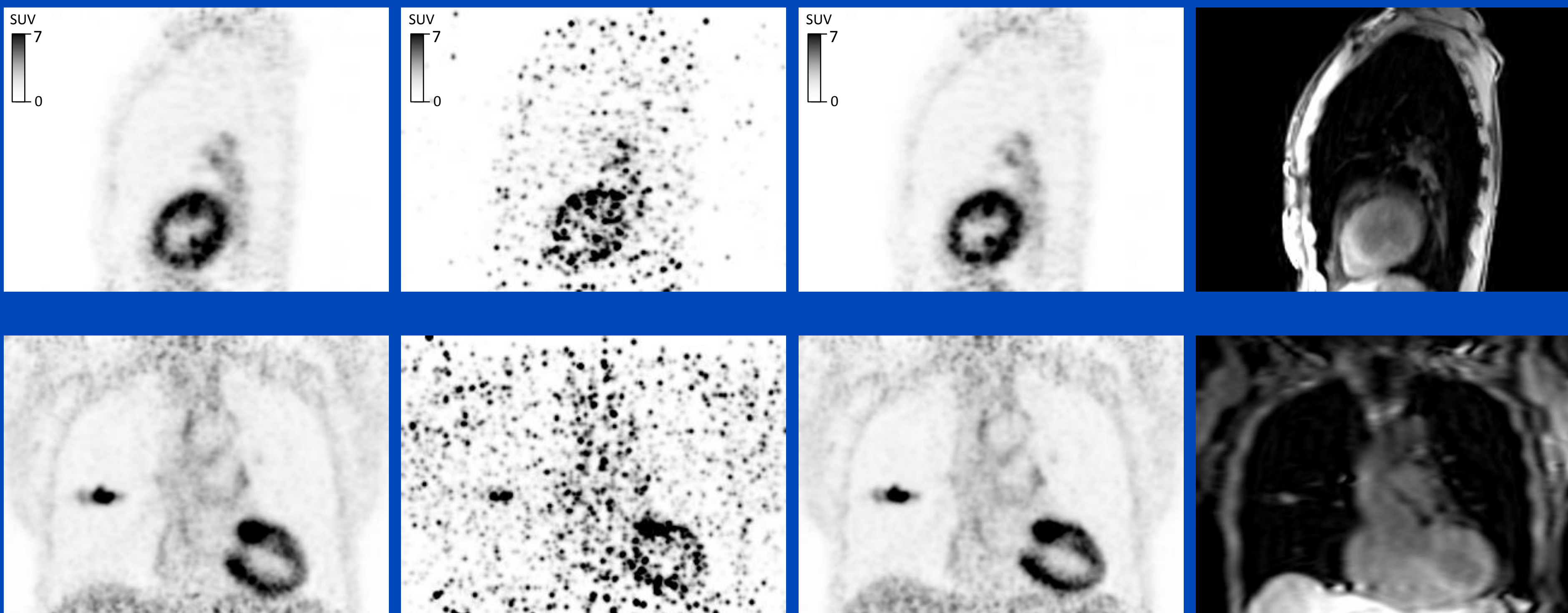
Results of 5D MR Reconstructions

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

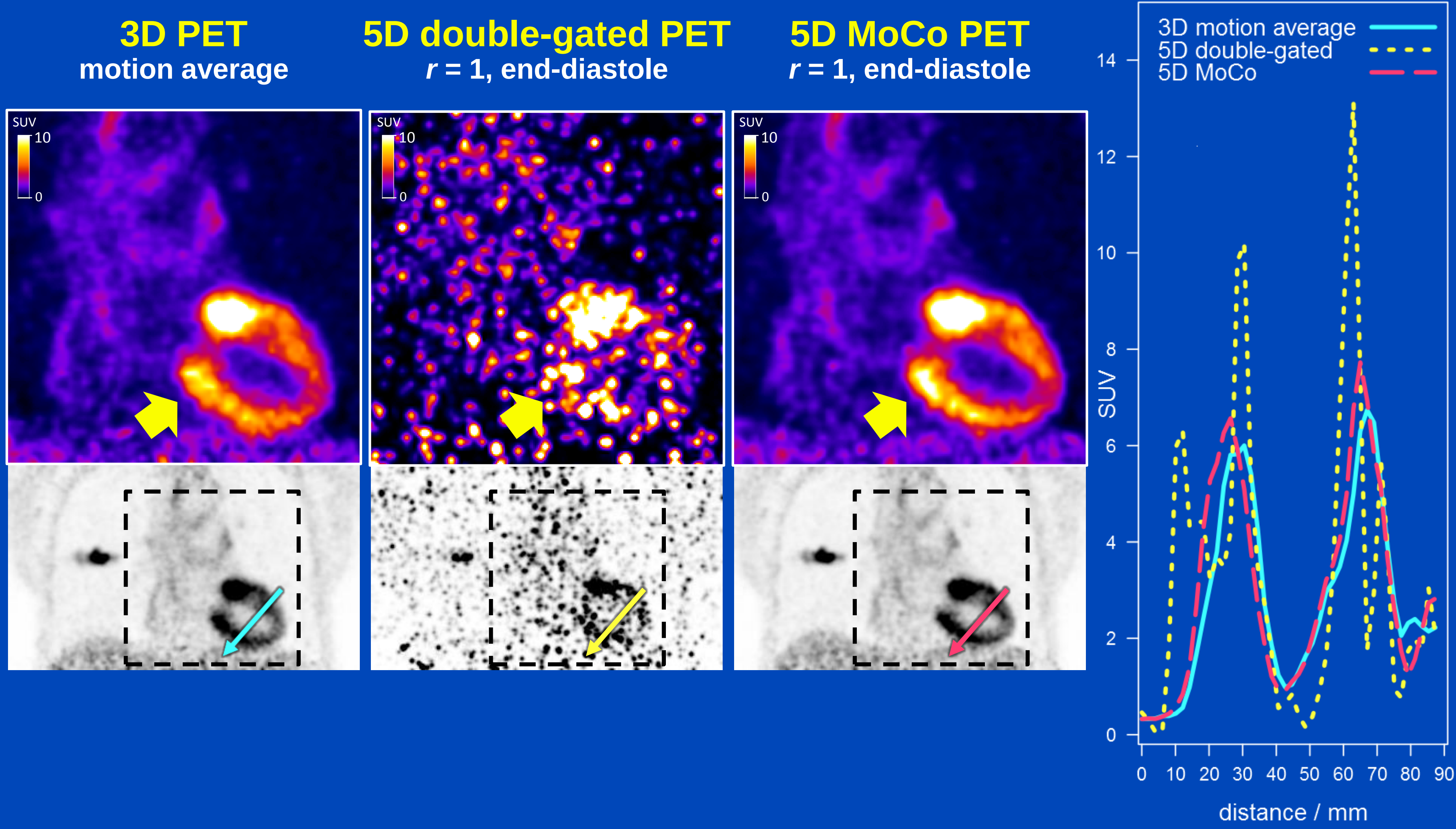


Results of 5D PET Reconstructions (I)

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



Results of 5D PET Reconstructions (II)



Summary and Outlook

- Novel method which sequentially estimates respiratory and cardiac MVFs from MR data
- 5D MoCo allows for PET or MR reconstruction of any arbitrary combination of respiratory and cardiac phase
- MoCo for PET improves PET quantification, image sharpness and noise level
- Next steps:
  - Verification of results with patients having cardiac disease
  - Optimization of workflow and performance

Thank You!

This work was supported by the Helmholtz International Graduate School for Cancer Research, Heidelberg, Germany.

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

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