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Declaration of Financial Interests or Relationships

Christopher M Rank:

I have no financial interests or relationships to disclose with regard to the subject matter of this presentation.

Five-Dimensional Respiratory and Cardiac Motion Compensation Based on Strongly Undersampled MR Data

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Introduction

- Dynamic imaging of organs can provide valuable information for radiotherapy or for studying physiology
- Time-resolved 5D (3D + respiratory + cardiac) MR imaging requires long acquisition times, e.g. in the range of 14 to 20 min[1,2,3]

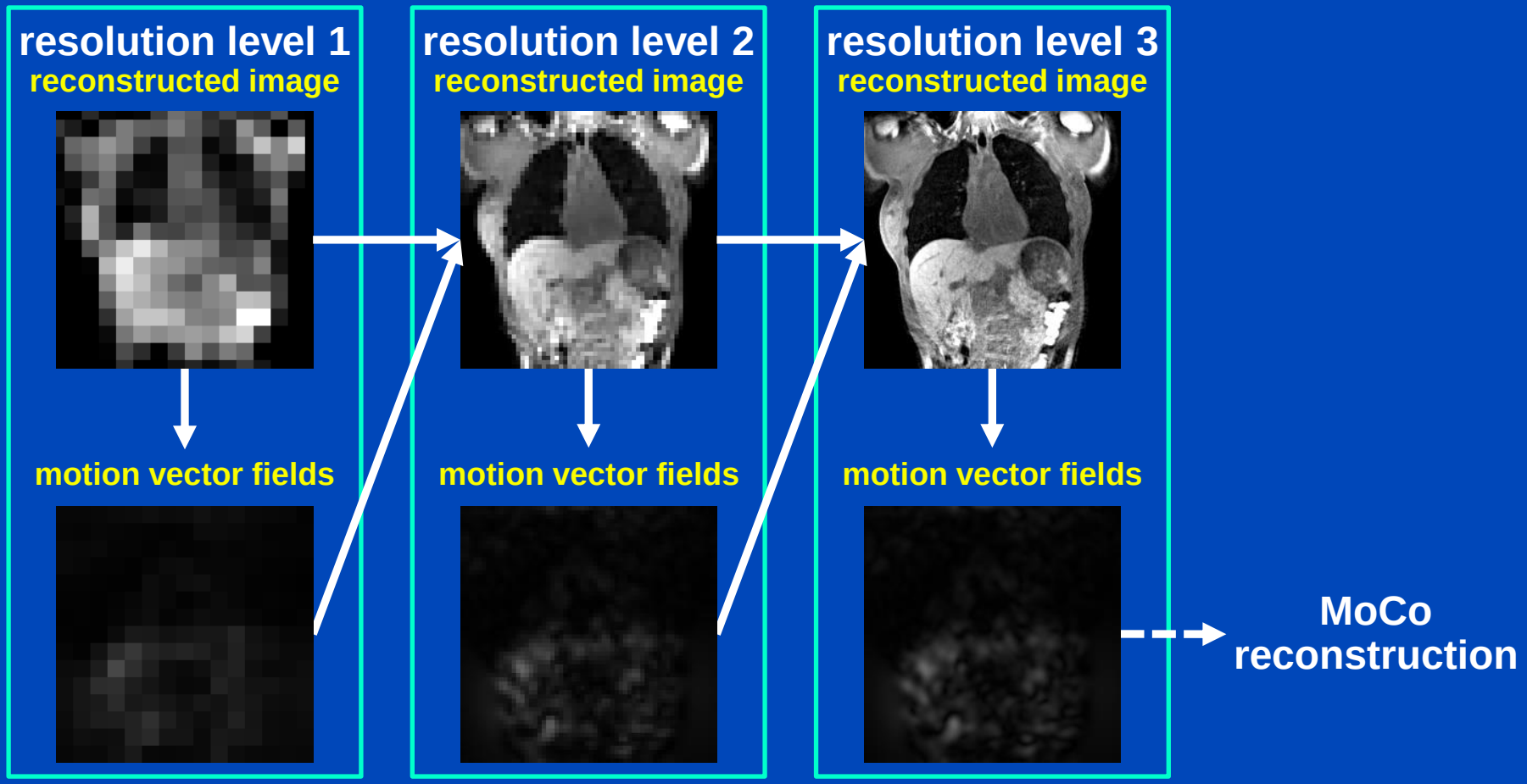
5D double-gated MR (2 min)

- **Aim of work:**
  - Develop 5D respiratory and cardiac motion compensation to employ 100% of the measured raw data
  - Use strongly undersampled radial MR data with an acquisition time of 2 minutes
  - Difficulty: estimate high-fidelity respiratory and cardiac motion vector fields (MVFs) from strongly undersampled MR data

[1] Sigfridsson, Kvitting, Knutsson, Wigström. Five-dimensional MRI incorporating simultaneous resolution of cardiac and respiratory phases for volumetric imaging. *J. Magn. Reson. Imaging* 2007.
[2] Celicanin, Bieri. 5DMRI of Moving Organs. *Proc. Intl. Soc. Mag. Reson. Med.* 2015.
[3] Feng, Coppo, Piccini, Lim, Stuber, Sodickson, Otazo. Five-Dimensional Cardiac and Respiratory Motion-Resolved Whole-Heart MRI. *Proc. Intl. Soc. Mag. Reson. Med.* 2015.

Algorithm for Motion Estimation

4D joint MoCo-HDTV[1]



Details at electronic poster #4249: Motion Correction, Thursday, May 12, 10:30

[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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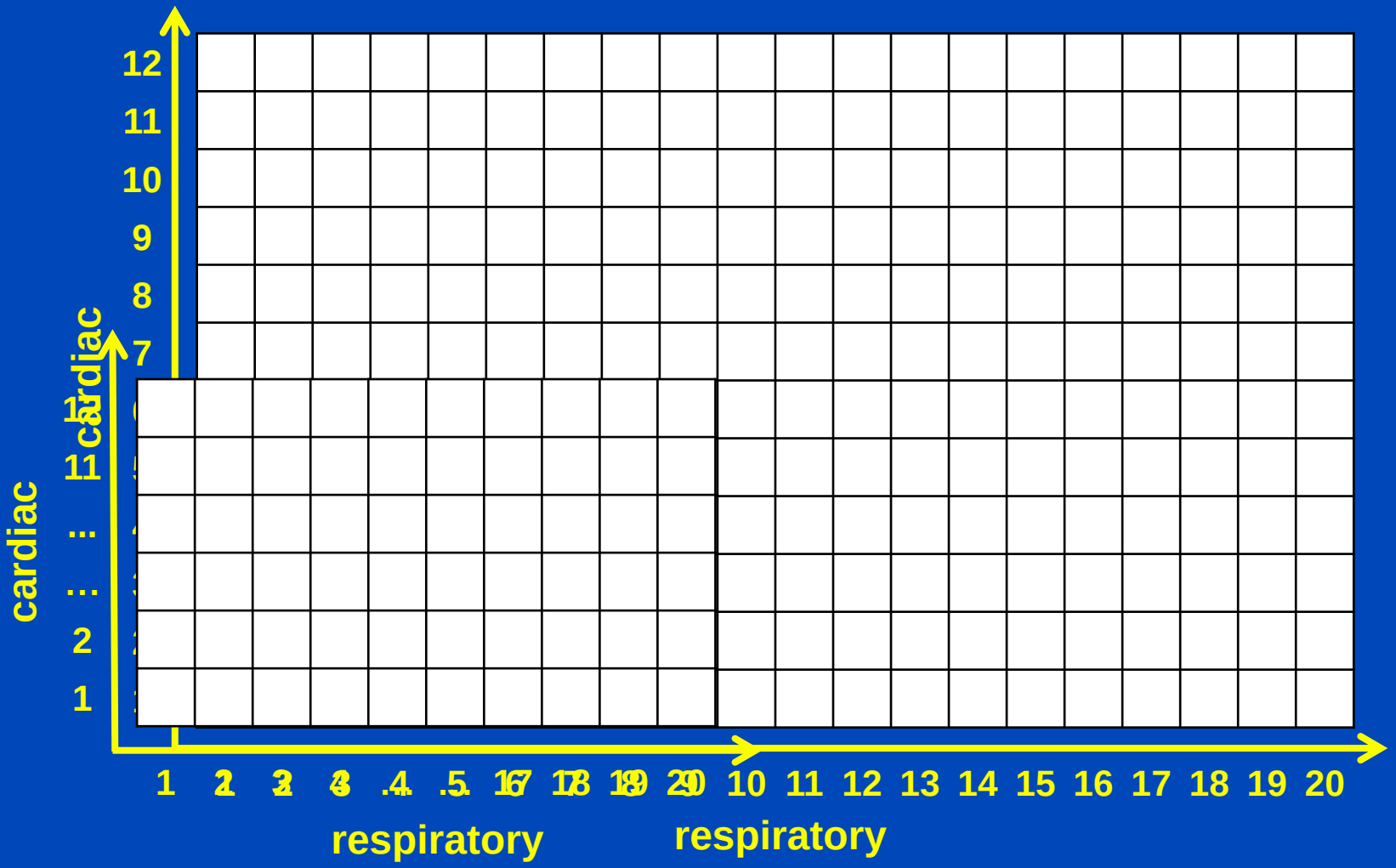
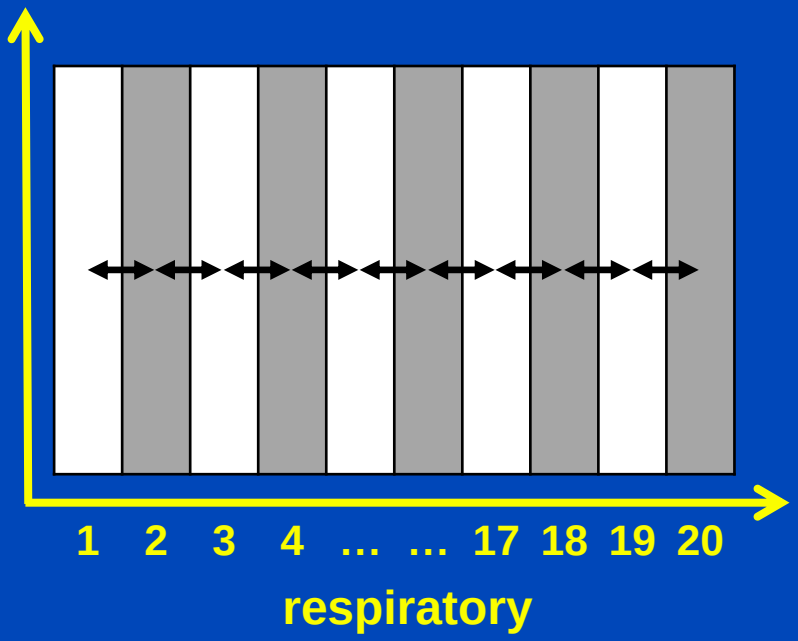
Double-Gated Raw Data Matrix



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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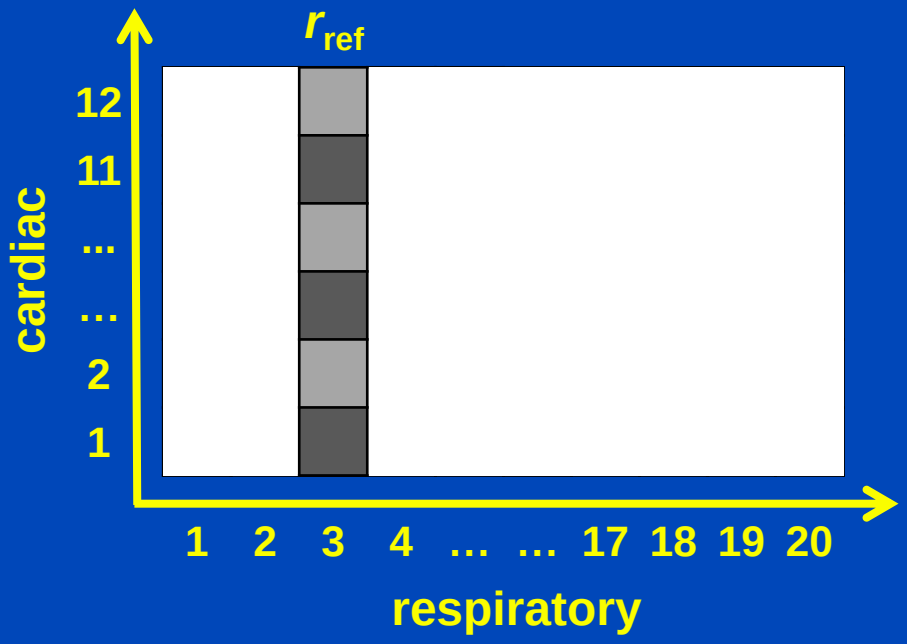
Generation of Respiratory MoCo Raw Data

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

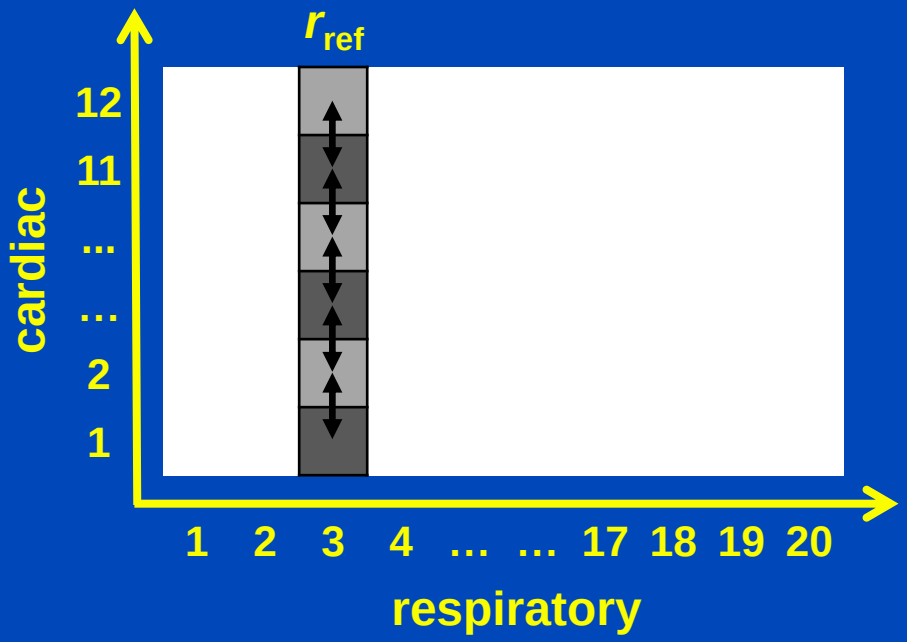
$$p^{\text{resp MoCo}}_{r_{\text{ref}},c} = \mathrm{X} \sum_{r} D^{r_{\text{ref}}}_{r} \mathrm{X}^{\dagger} G_r G_c \, p$$



r, *c*	: indices of respiratory and cardiac phases
X, X†	: 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 using the respiratory MoCo 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.

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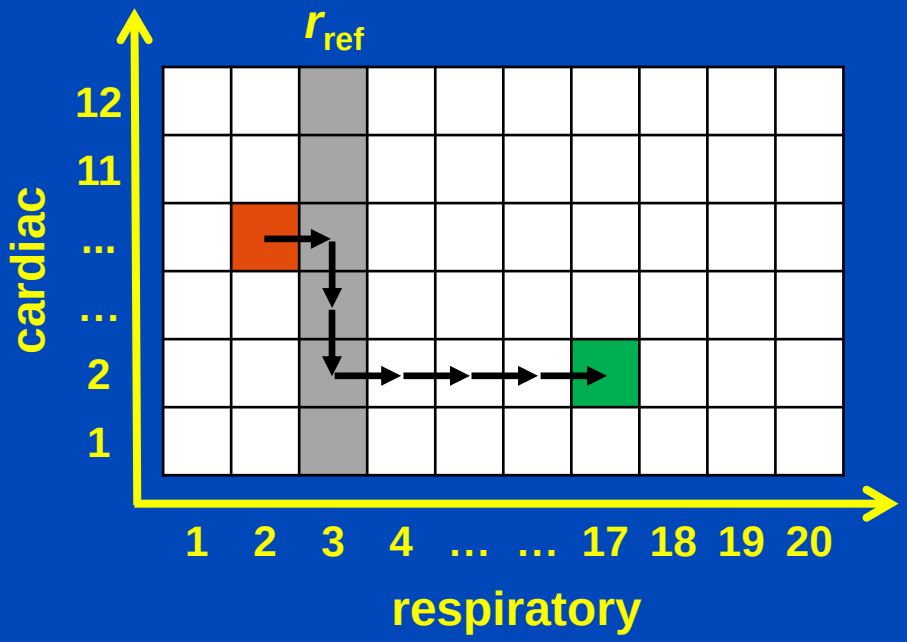
5D MoCo Reconstruction

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

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



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
$X^{\dagger}$	: pseudo-inverse transform
G_r, G_c	: gating operators
p	: measured raw data

5D MoCo Reconstruction

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

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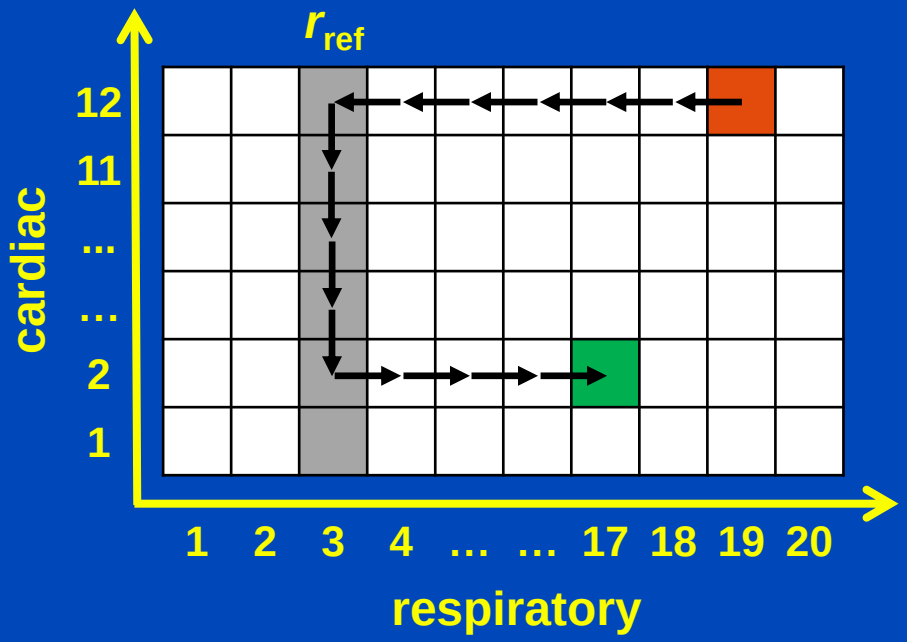

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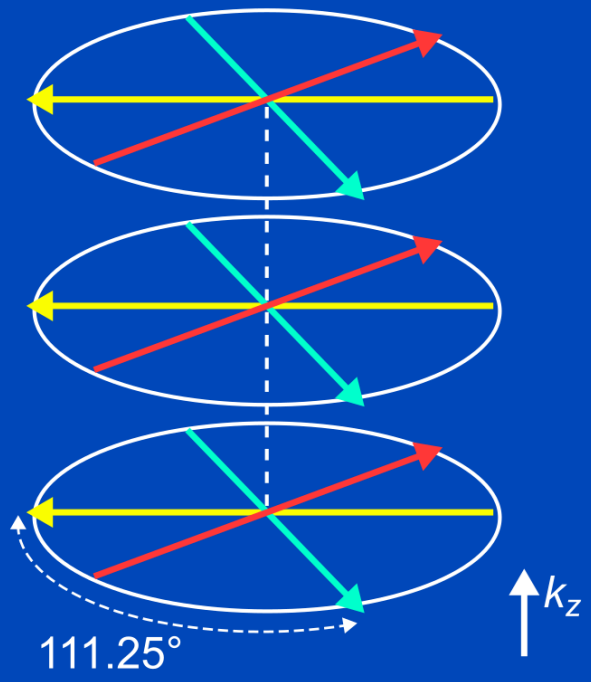
G_r, G_c	: gating operators
p	: measured raw data

Data Acquisition and Processing

- Patient measurements of free-breathing thorax and upper abdomen at 1.5 T (Magnetom Aera, Siemens Healthcare)
- 3D-encoded gradient echo sequence with radial stack-of-stars sampling
- Radial sampling in read-out plane, Cartesian sampling in slice direction
- Golden angle (≈ 111.25°) radial spacing
- Intrinsic estimation of motion signals



- Sorting into 20 overlapping respiratory phases (10% width) and 12 overlapping cardiac phases (17% width)

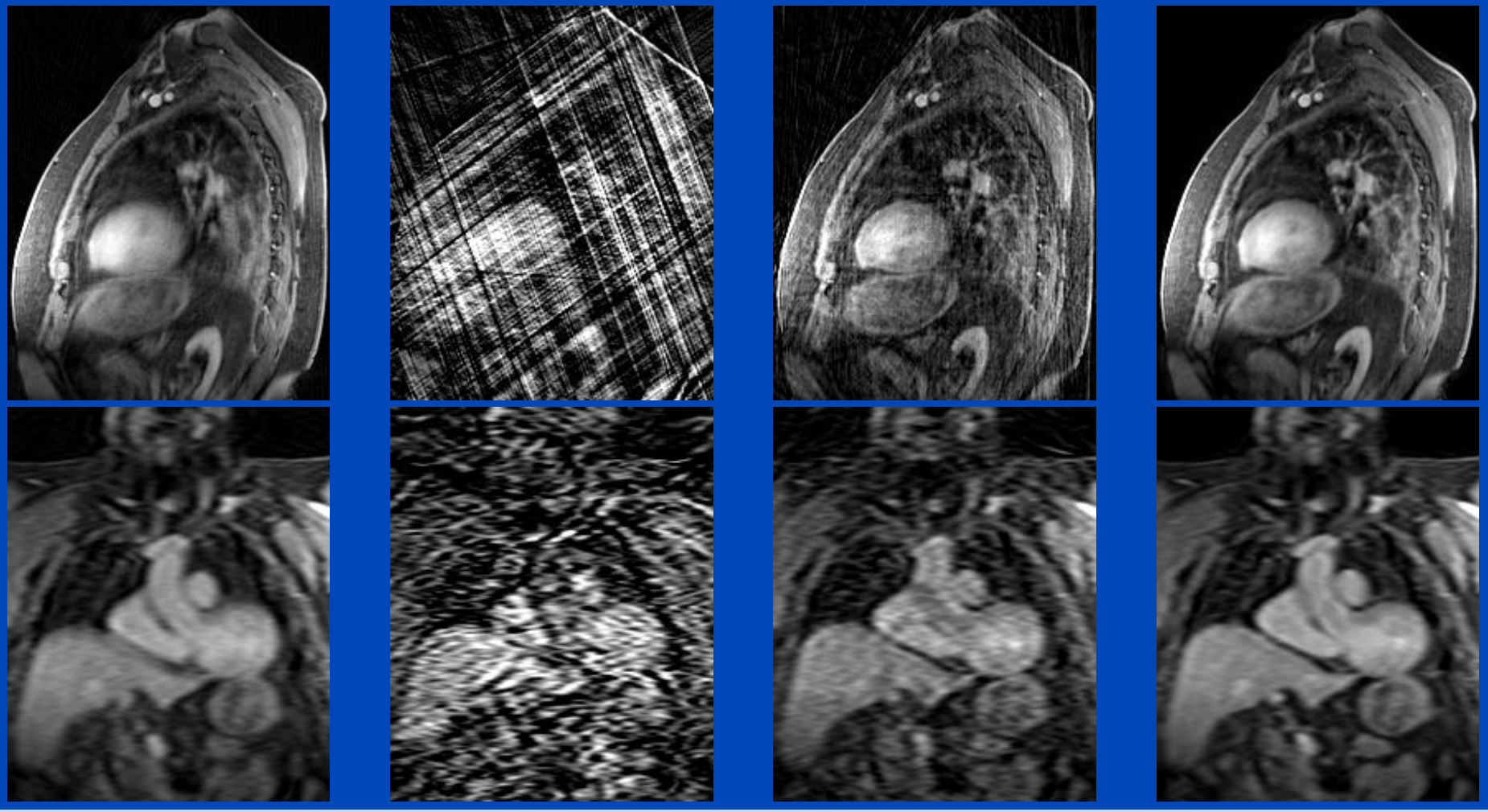
Results of 5D Reconstructions (I)

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

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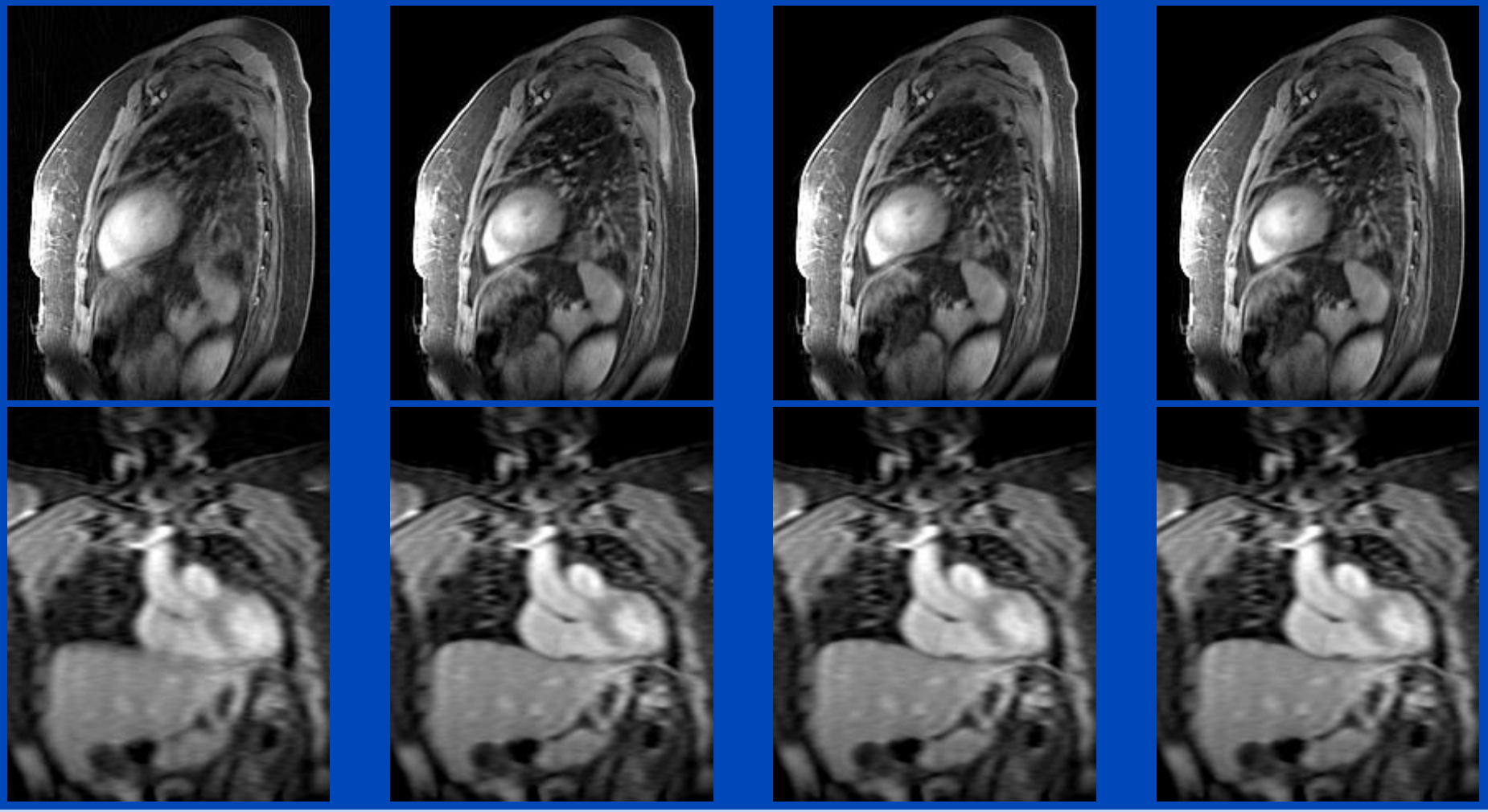
Results of 5D Reconstructions (II)

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

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Summary and Outlook

- Respiratory and cardiac MVFs are estimated sequentially employing the 4D joint MoCo-HDTV[1] algorithm
- 5D MoCo allows for reconstruction of any arbitrary combination of respiratory and cardiac phase with low noise and streak artifact levels
- **Next steps:**
  - Application to cardiac MRI, e.g. increase temporal and spatial resolution
  - Reduction of computation time
  - Usage of MVFs for 5D respiratory and cardiac PET MoCo

[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.

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.

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