Multi-Dimensional Radial Self-Navigation with Non-Linear Reconstruction for Free-Breathing Coronary MRI

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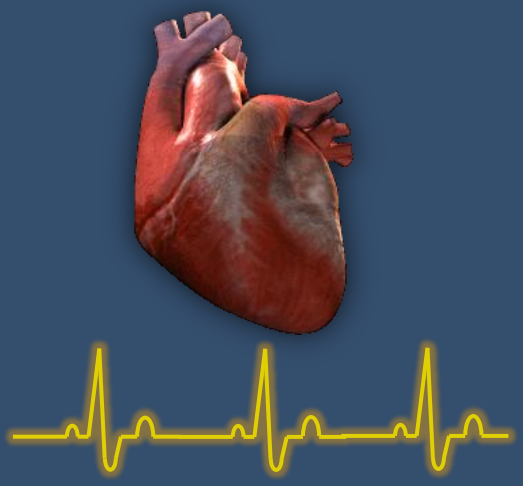
Avec le soutien de:

The Heart Motion

Is related to the displacement of a non rigid object in 3 dimensions with translational, rotational and distortion components.

Intrinsic Motion

Pulsating movement of heart



Bulk Motion

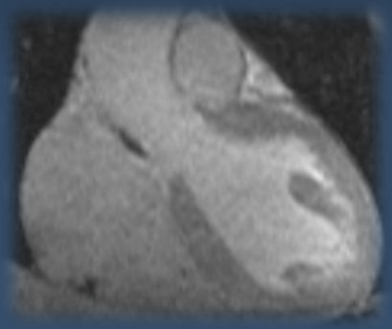
Patient movements

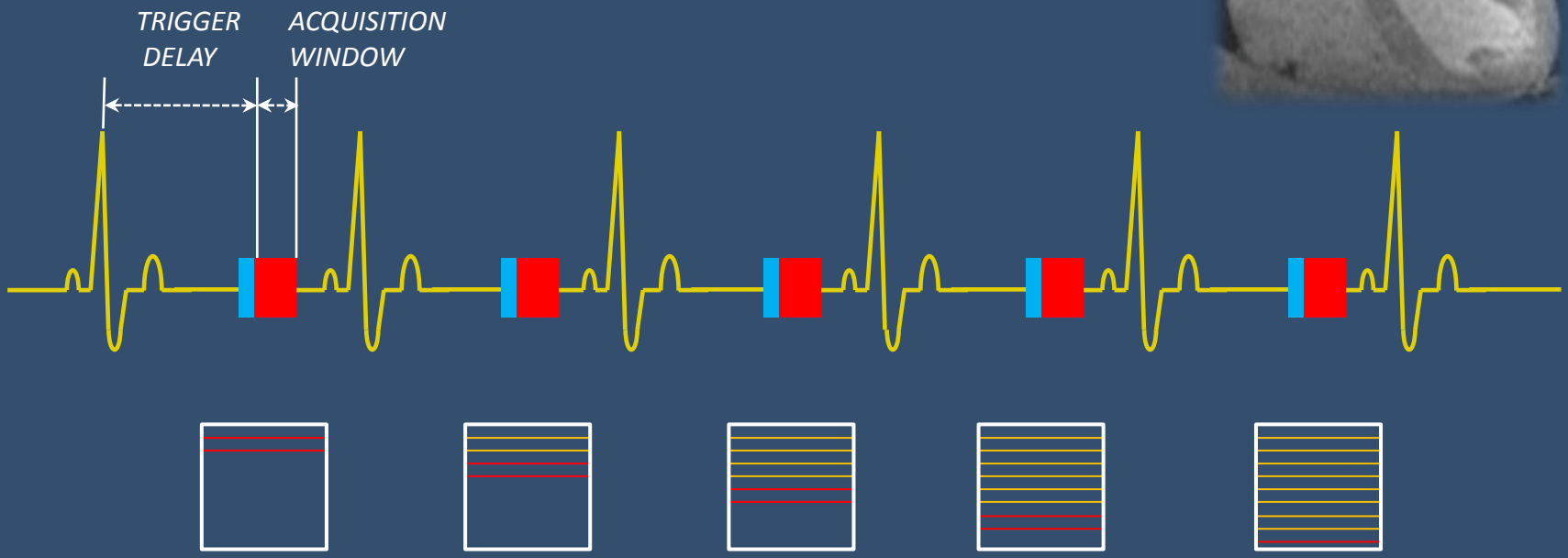
Extrinsic Motion

Respiration induced motion

Intrinsic Motion Compensation

- ECG gating & *k*-space segmentation





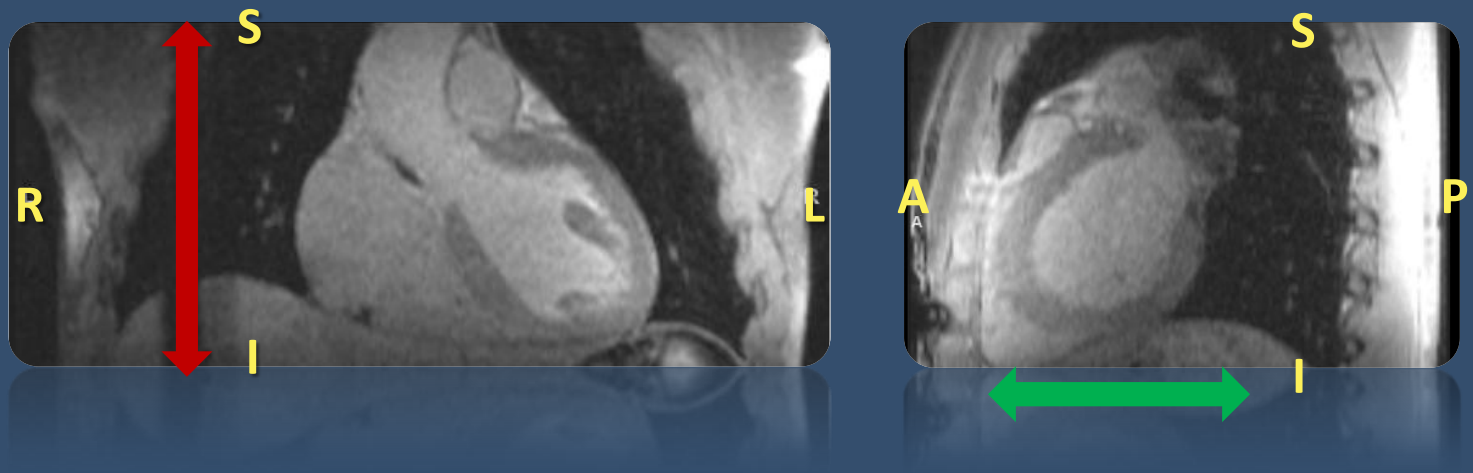
→ Imaging is performed during the period of minimal Coronary Motion!

Extrinsic Motion

Respiratory induced displacement:

SI = 20 mm

AP = 10 mm



Respiratory Motion is one of the major challenges in cardiovascular MRI !

Respiratory Motion Compensation

1) Breath holding - *Advantages*

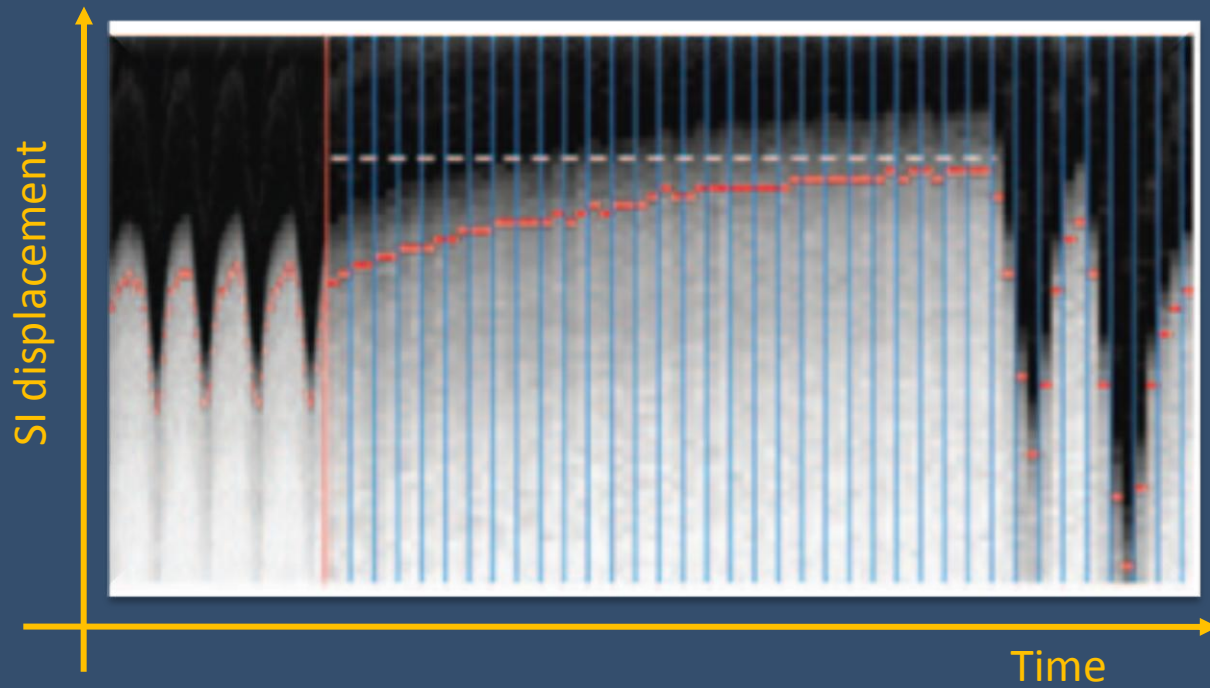
- ✓ Constrains Coronary Artery motion within 0.5 mm! [1]
- ✓ Easy to implement in well motivated subjects
- ✓ Preferred for functional, perfusion, late enhancement
- ✓ Short scanning times

1) Fischer et al. *Mag.Reg.Med.* 55:612–618 (2006)

Respiratory Motion Compensation

1) Breath holding - *Disadvantages*

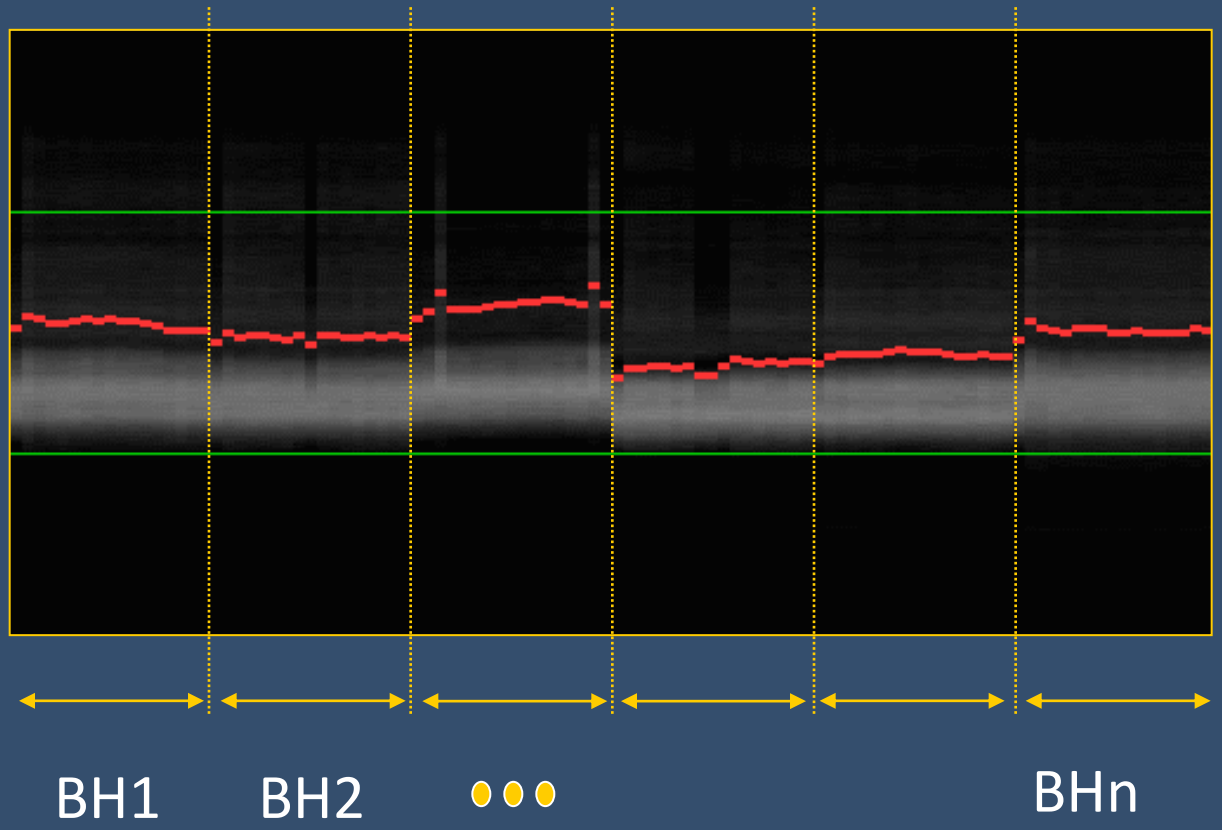
Diaphragmatic drift during breath-holding



Jahnke et al. Radiology 2006, 239, 71-78.

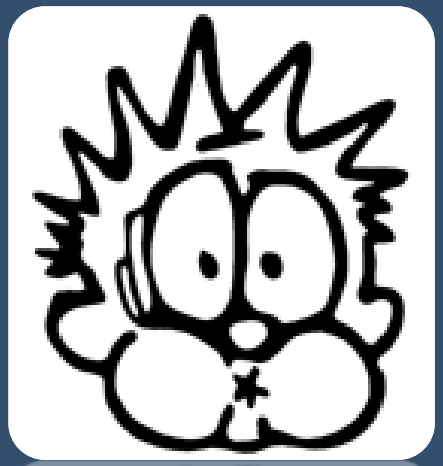
Respiratory Motion Compensation

1) Breath holding - *Disadvantages*



Respiratory Motion Compensation

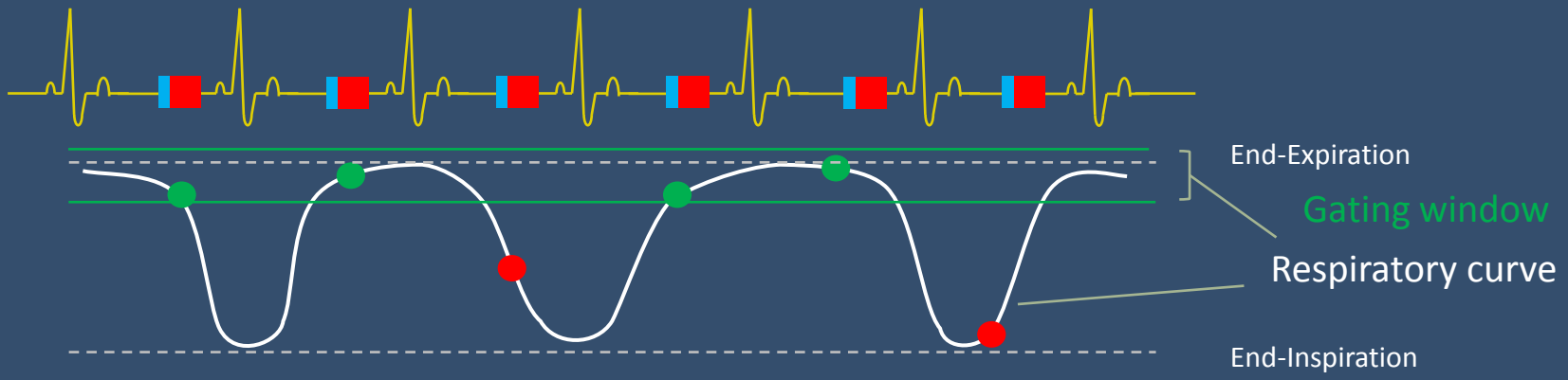
1) Breath holding - *Disadvantages*



- ✘ Patient's ability to hold his/her breath governs maximum spatial resolution
- ✘ Residual motion due to diaphragmatic drift
- ✘ Mis-registrations in serial breath-holds
- ✘ Major operator and patient involvement
- ✘ Heart rate variations

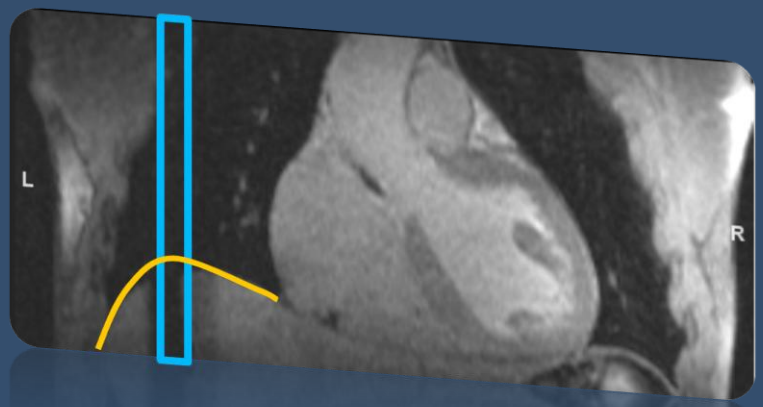
Respiratory Motion Compensation

2) Navigator Gating



- Data accepted
- Data rejected

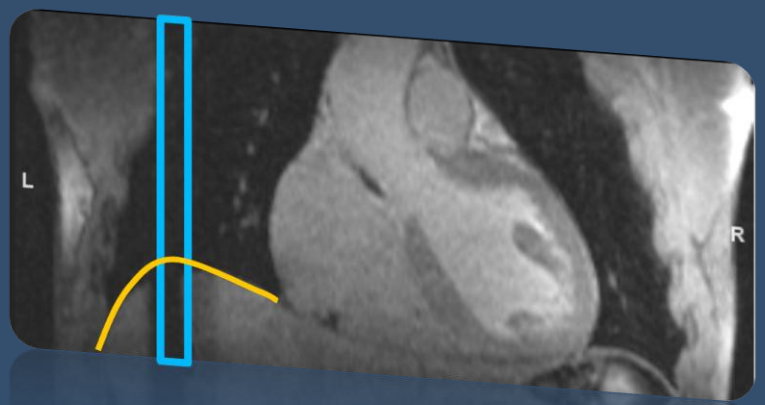
Scan efficiency = $\frac{\#\,\text{accepted}}{\#\,\text{accepted} + \#\,\text{rejected}}$



Respiratory Motion Compensation

2) Navigator Gating - *Advantages*

- ✓ Quality of breath-hold does not govern image resolution
- ✓ No major patient involvement
- ✓ Offers flexibility for high resolution, 3D acquisition, signal averaging
- ✓ Has demonstrated to be effective (Multicenter experience*)

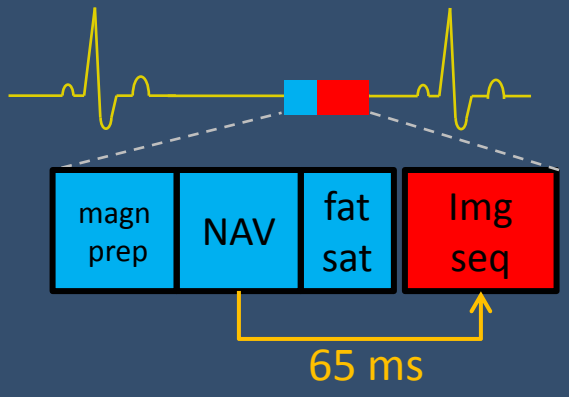


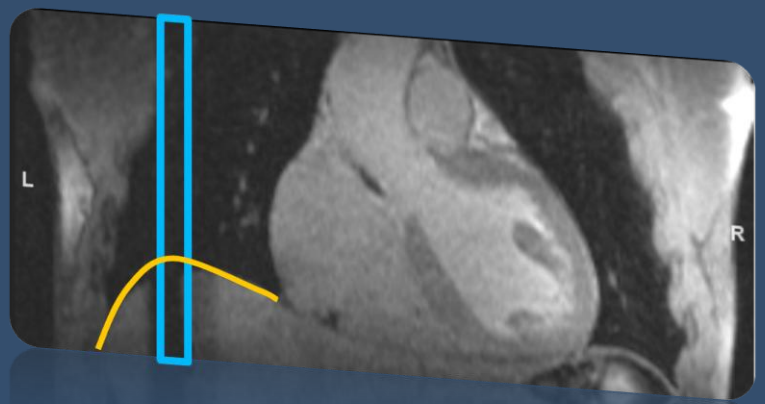
* Kim WY et al.: N Engl J Med;345(26):1863-1869 (2001).

Respiratory Motion Compensation

2) Navigator Gating - *Disadvantages*

- **indirect measure of the cardiac motion**
- temporal delay between NAV and data acquisition
- efficiency = 30 - 40% → scan time!!
- additional planning



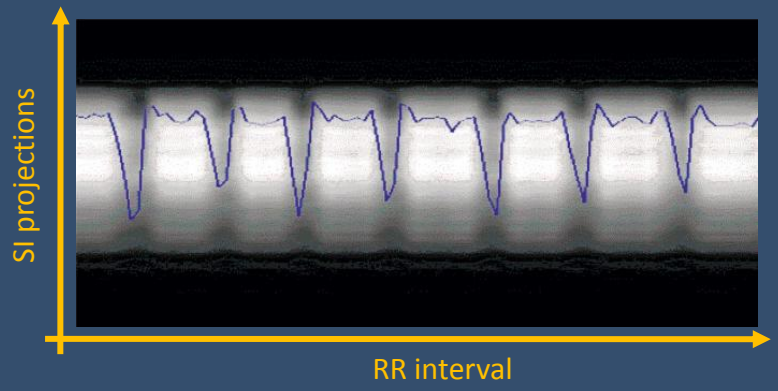


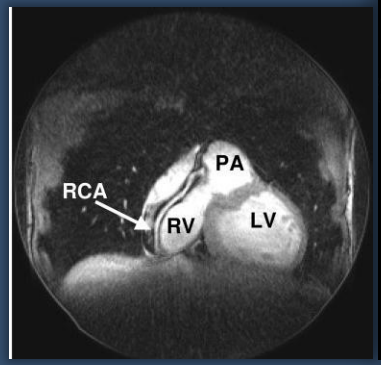
Retrospective Self-Navigation: *what has been done …*

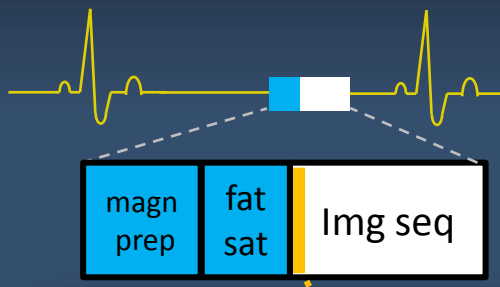
➢ Stehning et al. 2005

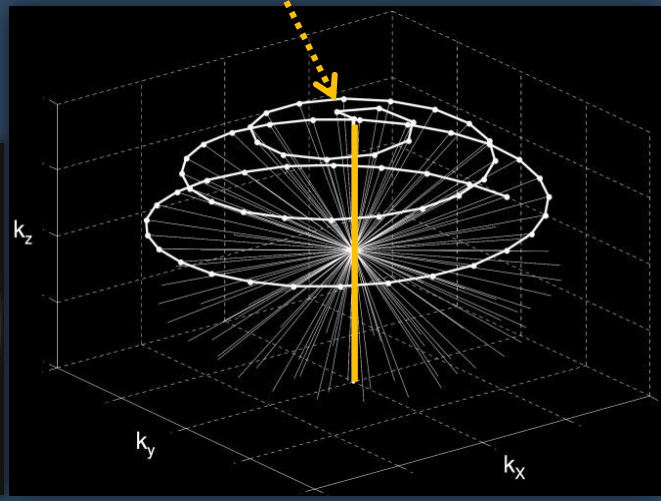
Beat-to-beat respiratory SI motion estimated by *k-space* center line repeatedly acquired during each segment data acquisition.

Center of mass evaluation for motion extraction









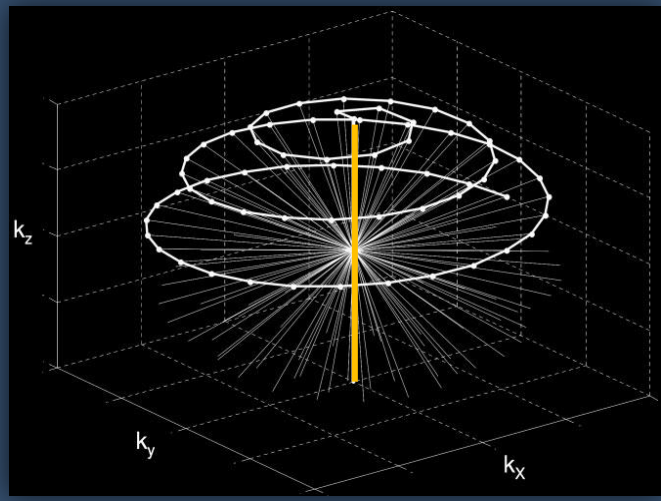
Stehning et al. MRM 54:476–480 (2005)

- Lai et al. 2008: used Least Square for SI extraction
- Bhat et al. 2011: multi-dimensional Self-Nav with binning of respiratory states for affine motion correction
- Henningsson et al. 2011: modified bSSFP for2D Self-Nav
- …

Retrospective Self-Navigation: *what has been done …*

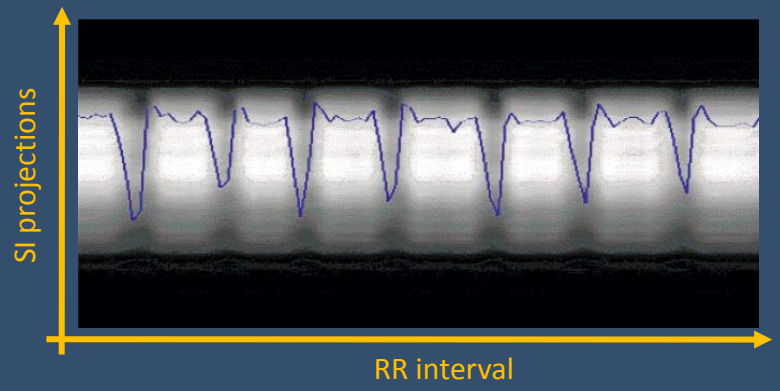
➢Stehning et al. 2005

✓ ***Heart motion is directly extracted from the MR data.***
✓ 100% efficiency
✓ no additional planning



Stehning et al. MRM 54:476–480 (2005)

Foot-head projections of the heart!



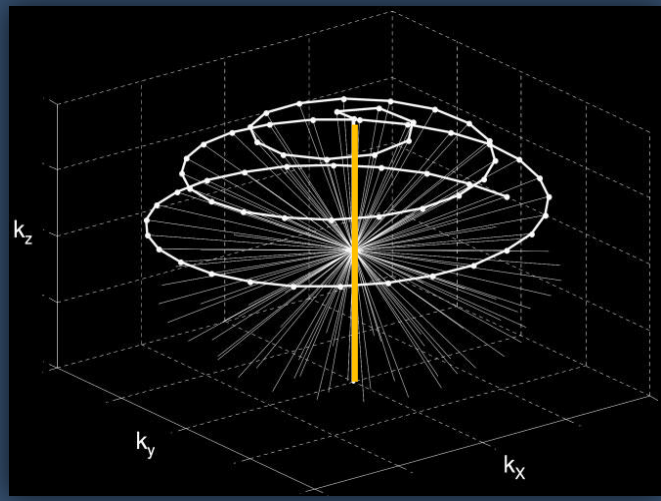
Retrospective Self-Navigation: *what has been done …*

- Stehning et al. 2005

  - ✘ 1D motion correction
  - ✘ No advanced reconstruction strategies

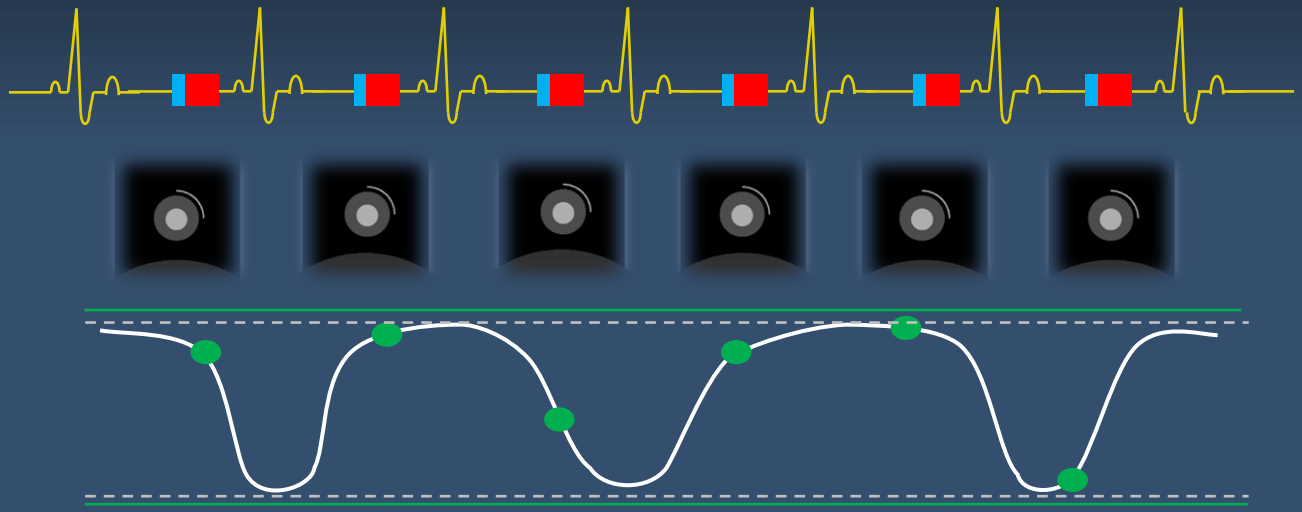
→ Multi-dimensional motion correction

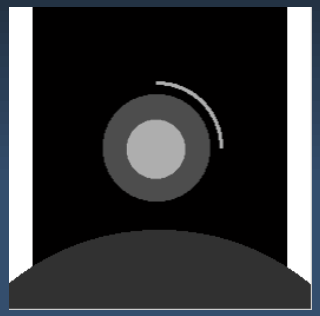
→ Non-linear reconstruction



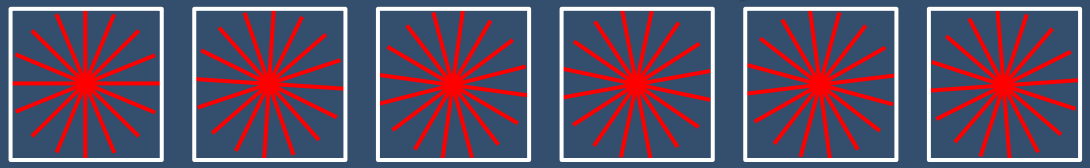
Stehning et al. MRM 54:476–480 (2005)

Retrospective Self-Navigation:
the concept



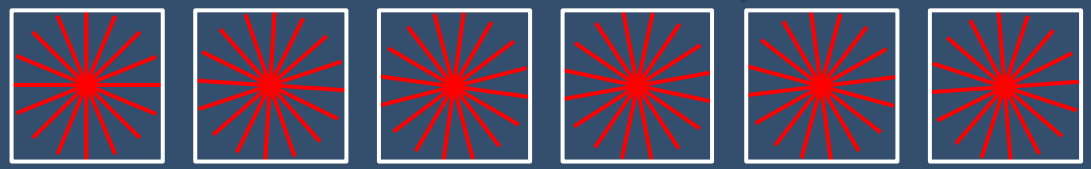


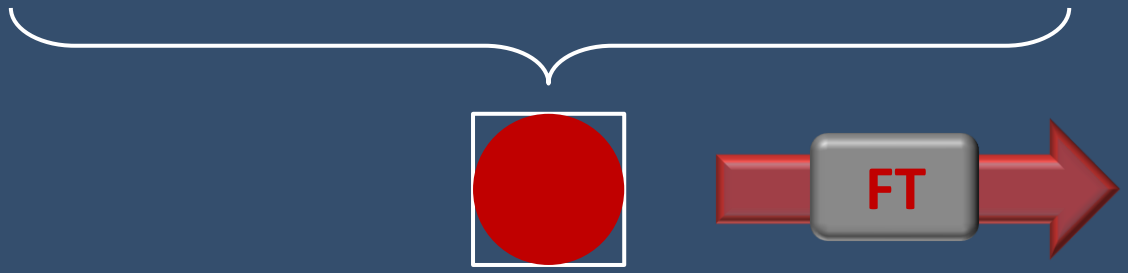
interleaved 2D radial acquisition



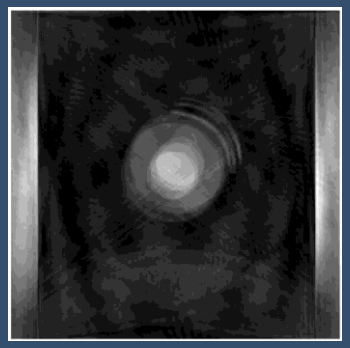
Retrospective Self-Navigation:
the concept

interleaved 2D radial acquisition



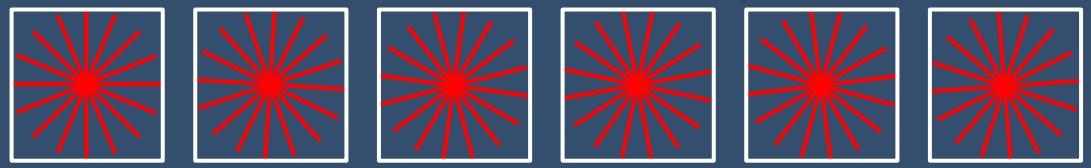


Motion corrupted



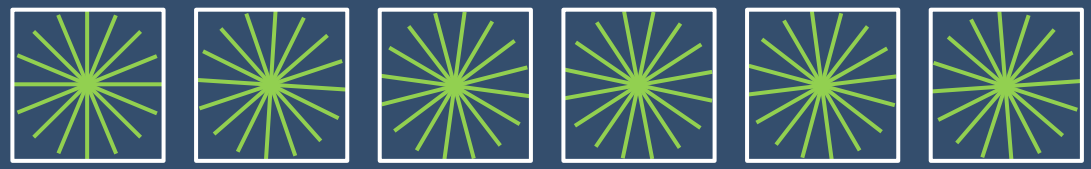
Retrospective Self-Navigation:
the concept

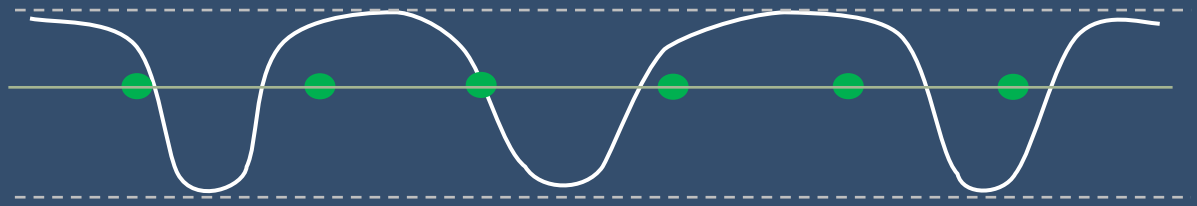
interleaved 2D radial acquisition



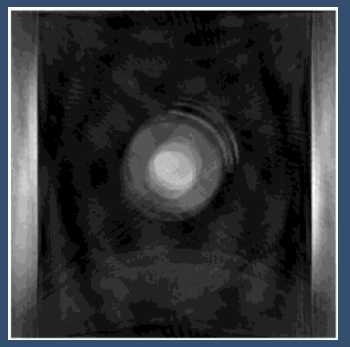
$[\Delta x, \Delta y]_i$

Beat-to-beat Motion Correction



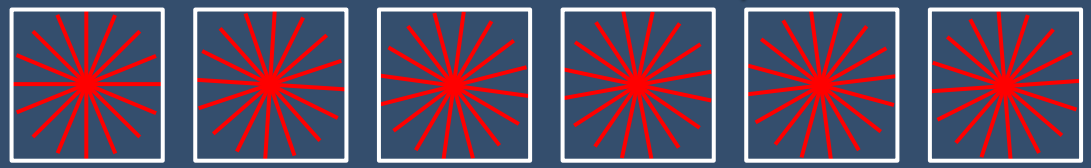


Motion corrupted



Retrospective Self-Navigation:
the concept

interleaved 2D radial acquisition



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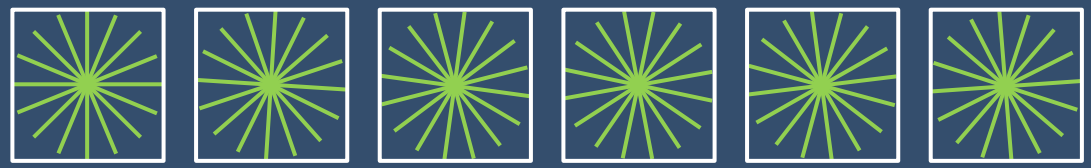
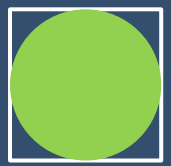
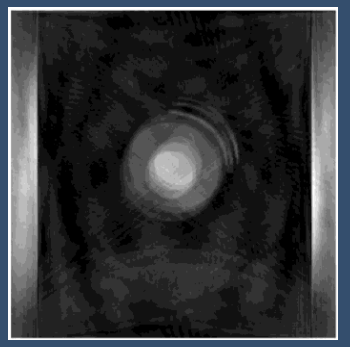
Beat-to-beat Motion Correction



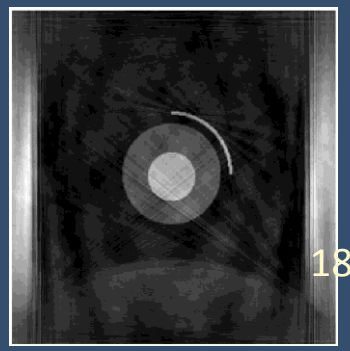


FT

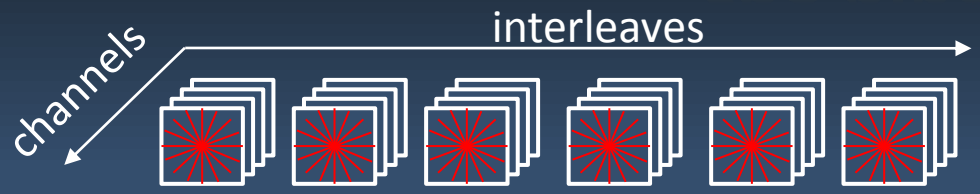
Motion corrupted



Motion corrected



Retrospective Self-Navigation:
the pipeline



Channels Selection

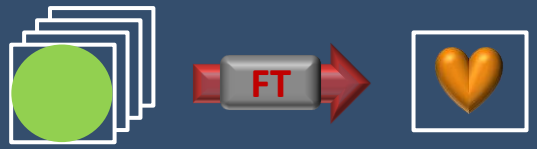
***Sub-images* Recon**

$\Delta x,y_1$ $\Delta x,y_2$ $\Delta x,y_3$ $\Delta x,y_4$ $\Delta x,y_5$ $\Delta x,y_6$

Coregistration

$\bullet\ e^{-2\pi j(k \bullet \Delta_i)}$

Motion Correction



Final Recon

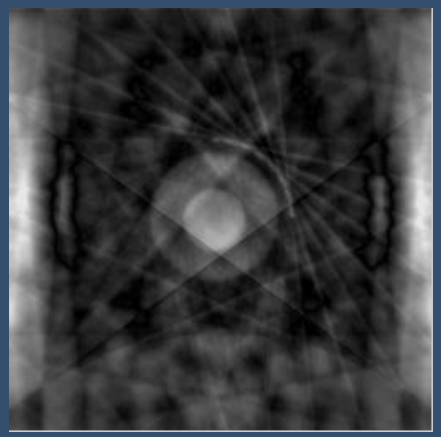
Retrospective Self-Navigation:
Sub-images Recon

Sub-images from a 2D radial acquisition:

- *Schäffter et al. 1999* – first application for knee imaging
- *McLeish et al. 2004* – cardiac imaging of *ex vivo* data

Sub-images from a numerical simulation with 5% of the data:

Standard of Reference: convolution-based gridding [1]



Non-Linear Reconstruction with a Total Variation prior [2,3]

1) Jackson et al.,IEEE-TMI 10:473-478 (1991)

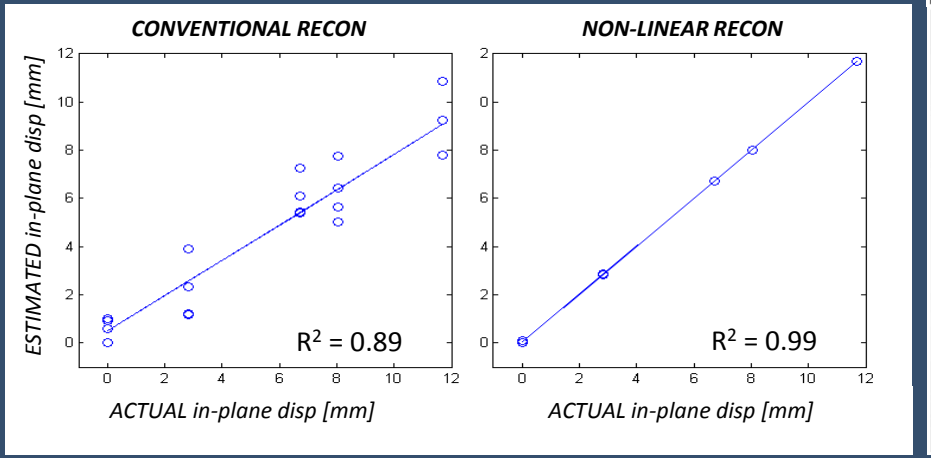
2) Beck et al. IEEE-TIP 18:2419-34 (2009)
3) Combettes et al. IEEE-JSTSP 14:564-574 (2007)

Retrospective Self-Navigation: *numerical simulations*

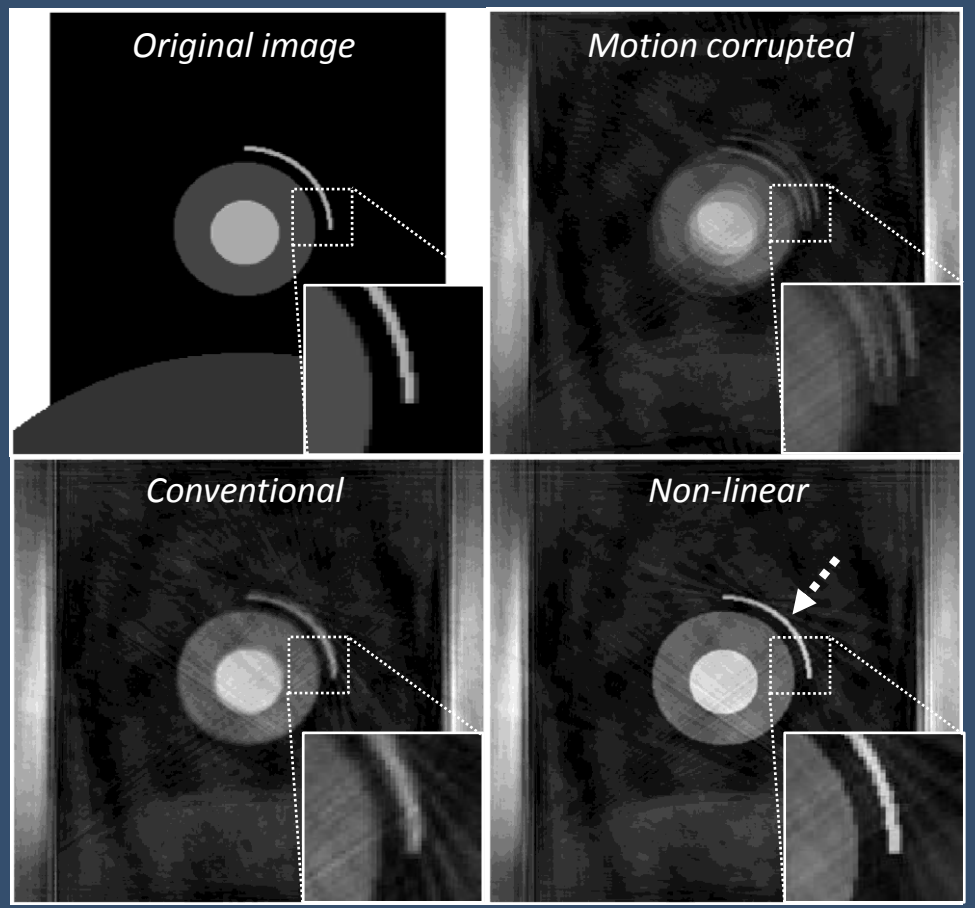
Numerical simulations were used to develop and rigorously test the method in a controlled environment:

- motion patterns and contrast values from *in vivo* MRI
- 20 shots
- 300 total projections in *k*-space
- 15 projections/shot (5% of the data)
- 256 matrix

Linear Regression analysis of in-plane displacements



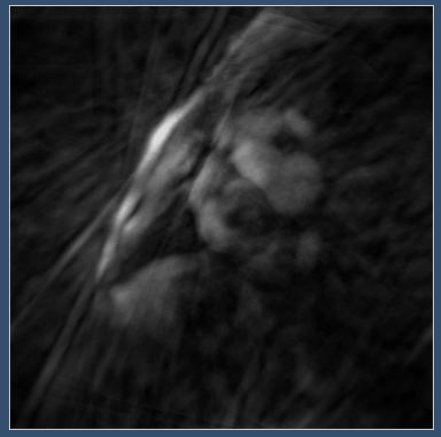
Reconstruction results



Retrospective Self-Navigation:
Sub-images Recon

Sub-images from a 2D high resolution scan @3T with 4% of the data:

Standard of Reference: convolution-based gridding [1]



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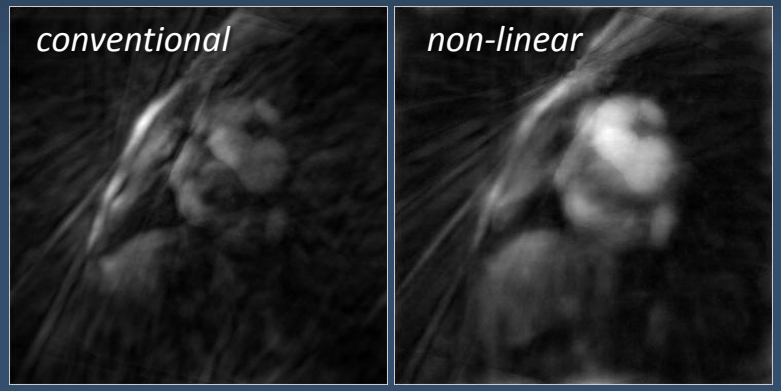
Retrospective Self-Navigation: *in vivo results @3T*

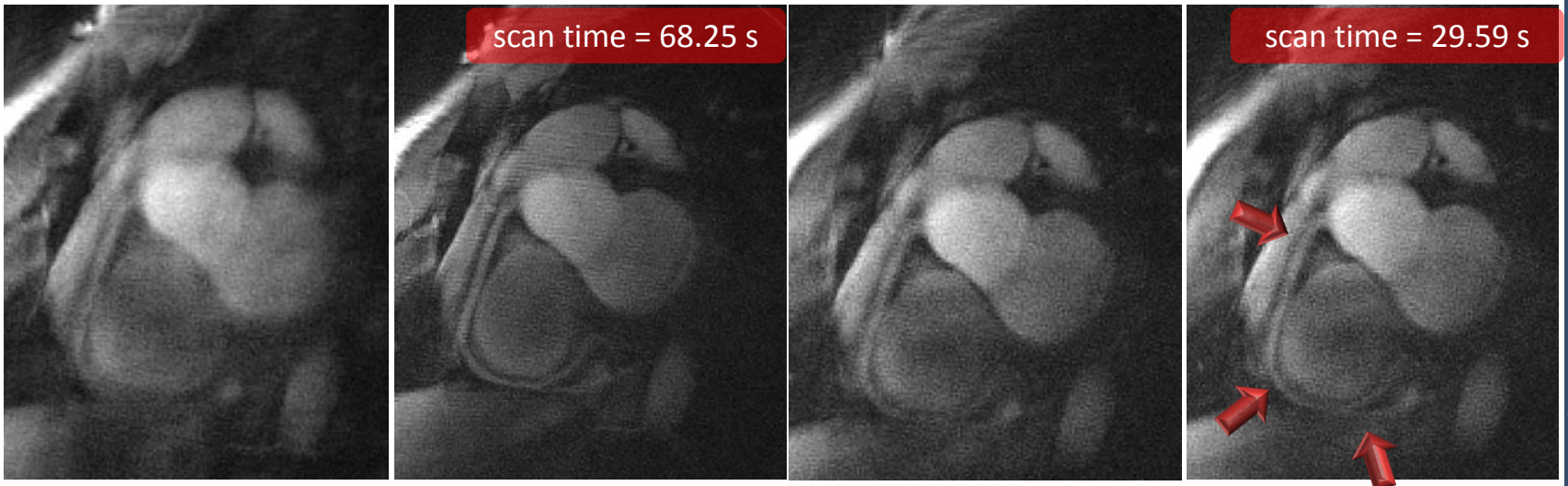
High Resolution 2D scan of a Right Coronary Artery:

26 shots, 364 total projections in *k*-space
14 projections/interleave(4% of the data)
368 matrix, 32 ch
0.8x0.8mm resolution, 5mm slice thickness,
300x300mm FOV, TE=3.26ms, TR=7.2ms, T2prep=50ms,
α=15deg, BW=234Hz/pixel

Sub-images



Motion corrupted	*NAV*	*Self-NAV with conventional recon*	*Self-NAV with non-linear recon*



Conclusions

- Beat-to-beat 2D image-based Self-Navigation for free-breathing coronary MRI has successfully been implemented
- Non-Linear reconstruction for sub-image extraction has shown to provide improved accuracy of motion estimation in numerical simulations and preliminarily *in vivo*
- No motion model or additional data acquisition are needed
- Improved time-efficiency and ease-of-use

What's next …

- Quantitatively validate and characterize the limits of the technique against to conventional NAV gating
- Image coregistration with affine transformation
- 3D motion correction

Acknowledgements

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- Ruud B. van Heeswijk, PhD
- Matthias Stuber, PhD

Thank you for your attention!