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# Managing Motion in MRI

M229 Advanced Topics in MRI  
2023.05.23

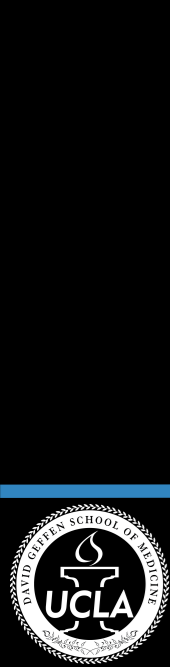
**Holden H. Wu, Ph.D.**

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Department of Radiological Sciences,  
University of California, Los Angeles, CA, USA



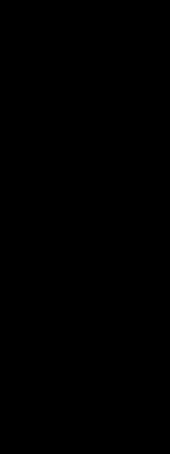
# Class Business

- Final project
- Office hours: this Friday 10 am - 11 am
- Next week: Guest lectures
- In 2 weeks: ISMRM



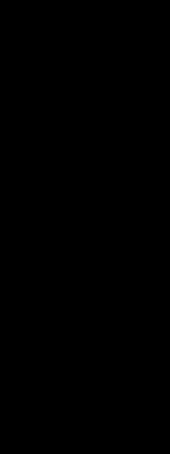
# Outline

- MRI and Motion
- Techniques to Manage Motion
- Managing Cardiac Motion
- Managing Respiratory Motion



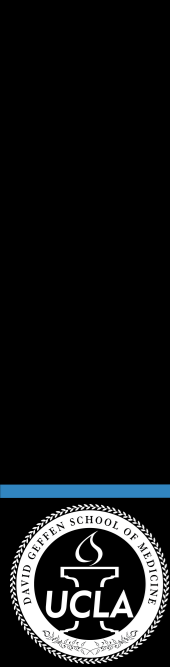
# MRI and Motion

- MRI is slow (vs. US, X-ray, CT)
- MRI time scales
  - TR: 1 - 1000 ms
  - image: 100 ms - 10 min



# MRI and Motion

- Motion Characteristics
  - voluntary vs. non-voluntary
  - periodic vs. aperiodic
  - rigid vs. non-rigid
    - e.g., *translation, rotation, shearing ...*
  - inter-voxel vs. intra-voxel
  - inter-view vs. intra-view



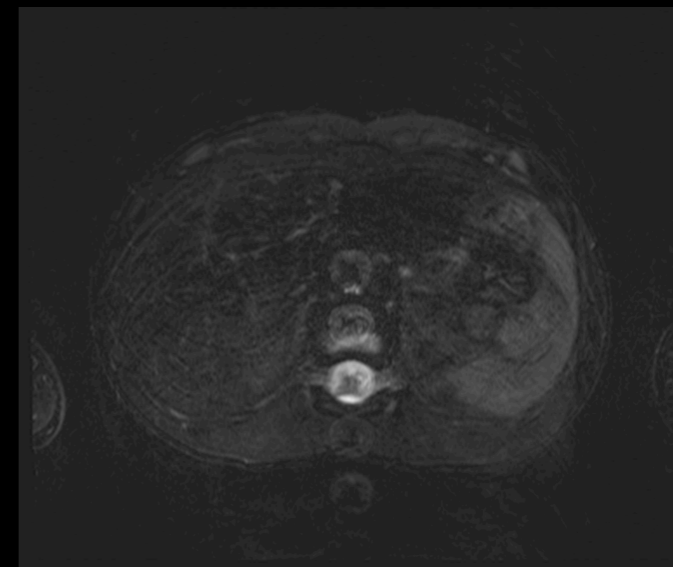
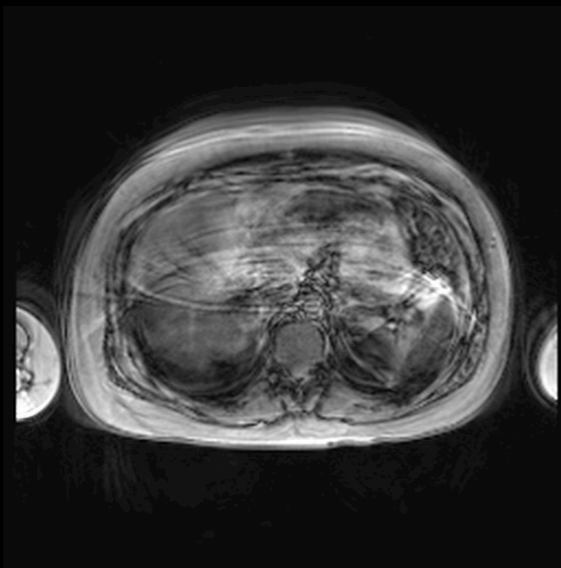
# MRI and Motion

- Motion Sources, Time Scales, Magnitudes
  - cardiac: ~60 bpm (1 Hz), mm
  - respiratory: ~5 sec/breath (0.2 Hz), mm - cm
  - bulk motion: mm - cm
  - vascular pulsation, CSF pulsation: mm
  - peristalsis: mm
  - swallowing, coughing, twitching: mm - cm
  - blood flow



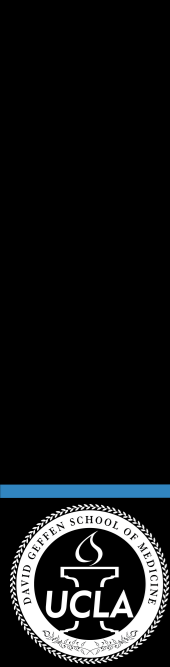
# MRI and Motion

- Effects of Motion on MRI Quality
  - inter-view vs intra-view motion
    - frequency encoding vs. phase encoding
  - k-space inconsistency
  - image blurring; aliasing artifacts; signal dropout; other artifacts



# Techniques to Manage Motion

- Subject Setup and Communication
- Acquisition Methods
- Reconstruction Methods





# Subject Setup and Communication

- Explain Scan Procedures
- Medication (if required)
  - reduce claustrophobia
  - reduce peristalsis
- Coaching (e.g., stay still, breath hold)
- Coil and placement
- ECG and bellows placement
- Reassurance and breaks



# Acquisition Methods

- Suppress Signal from Moving Tissues
  - e.g., flow suppression, spatial saturation
- Swap Frequency and Phase Encoding Directions
  - e.g., A/P vs R/L in axial acquisitions
- Multiple Averages
- *Disadvantages?*



# Acquisition Methods

- Accelerate the Acquisition
  - partial Fourier
  - parallel imaging
  - multi-slice imaging
  - single-shot EPI
  - single-shot HASTE
- Use Motion-Robust Acquisition
  - gradient moment nulling
  - PROPELLER / BLADE, radial, spiral, etc.
- *Disadvantages?*



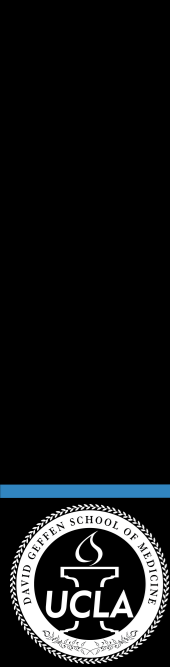
# Reconstruction Methods

- **Reconstruct Undersampled Data**
  - partial Fourier
  - parallel imaging
- **Motion Compensation**
  - may need some motion information
  - reject inconsistent data
  - use consistent data
  - correct motion-affected data
- *Disadvantages?*

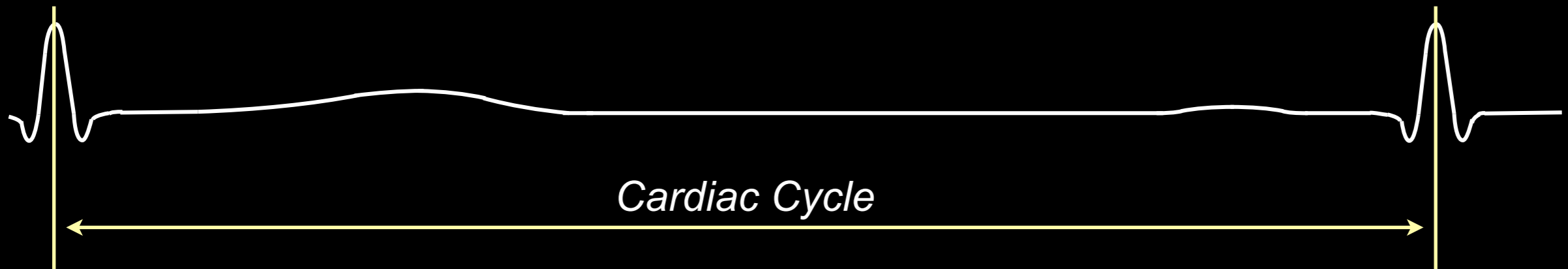


# Managing Cardiac Motion

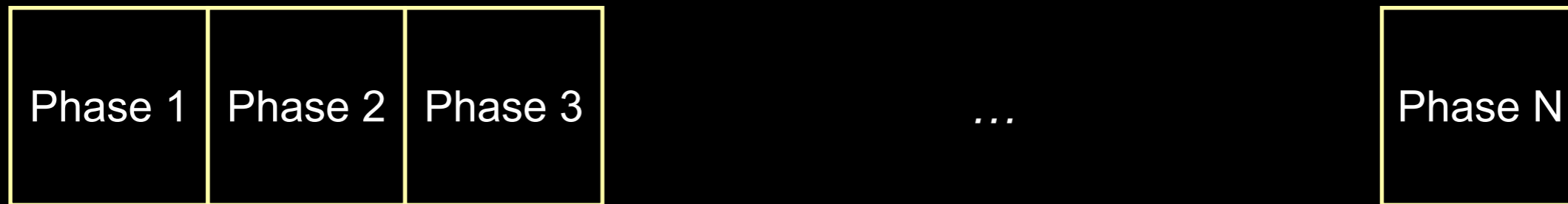
- Cardiac Motion
  - non-voluntary
  - non-rigid
  - quasi-periodic
  
  - ~60 bpm (1 Hz)
  - mm scale



# Managing Cardiac Motion



## Cardiac Phases



Temporal duration of the cardiac phases?

- <50 ms to resolve cardiac motion (i.e., >20 frames/sec)
- depends on sampling parameters (and trade-offs)

# Managing Cardiac Motion

- Real-Time MRI



# Managing Cardiac Motion

- Real-Time MRI





# Managing Cardiac Motion

- **Real-Time MRI: Challenges**
  - compromises in spatial resolution and/or temporal resolution (i.e., frame rate)
  - typical parameters
    - 2-3 mm in-plane resolution
    - 50-200 ms/frame (5-20 frame/sec)
  - may not have high enough spatial resolution and/or frame rate to resolve cardiac motion



# Managing Cardiac Motion

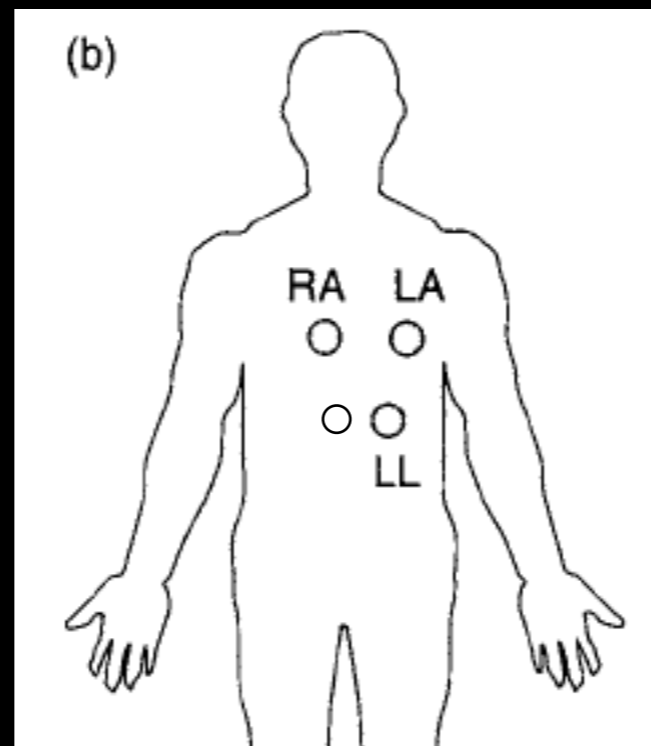
- Cardiac Triggering
  - ECG or pulse ox signal
  - sync scan to cardiac cycle
  - assume steady HR
  - segmented acquisition
    - acquire subset of data each HB
    - fully acquire data over multiple HBs
  - Need to manage respiratory motion as well
    - e.g., breath holding (BH)



# Managing Cardiac Motion

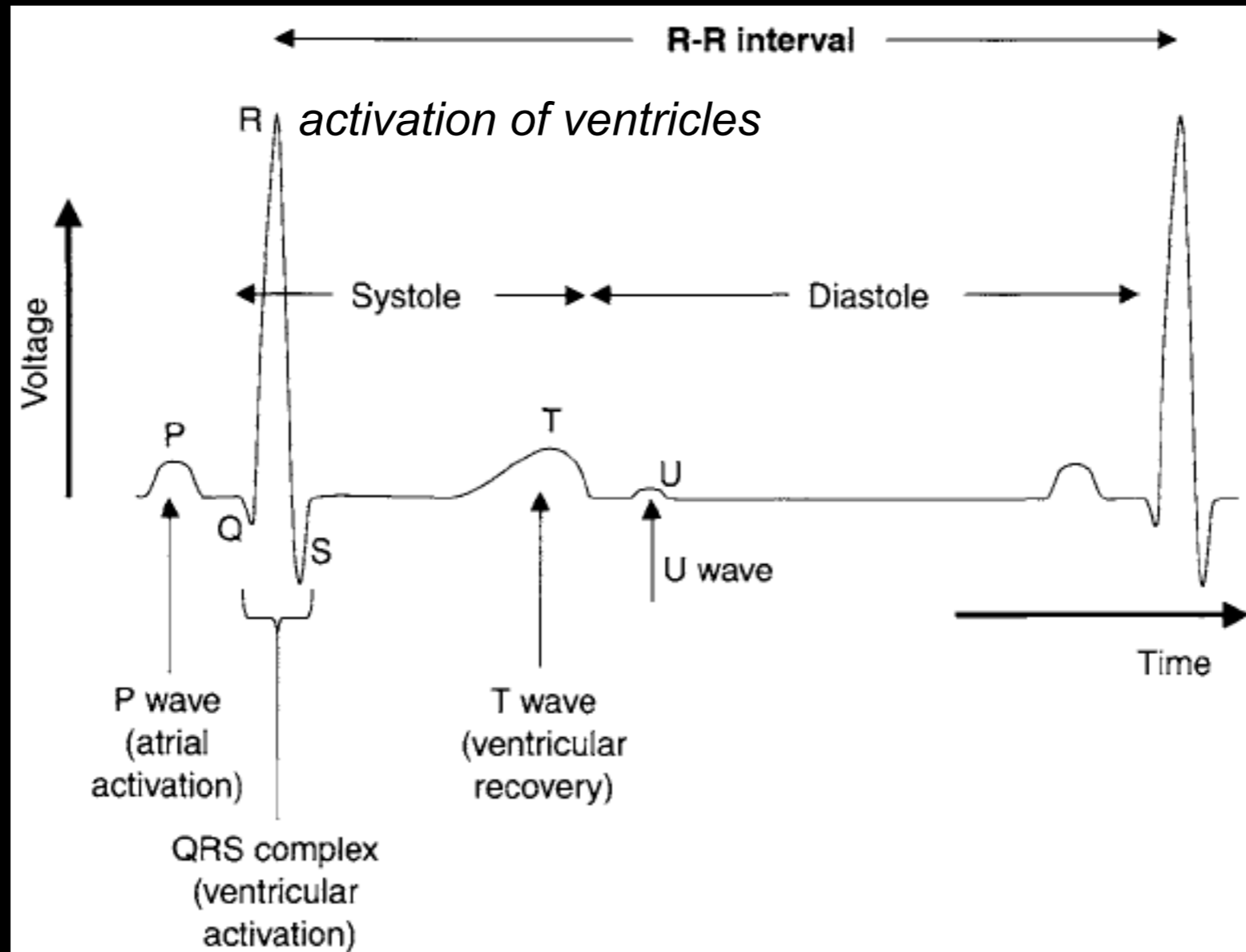
## *Cardiac Triggering*

### *ECG lead placement*



# Managing Cardiac Motion

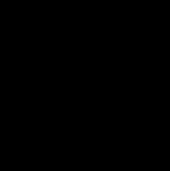
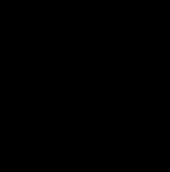
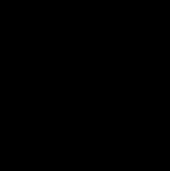
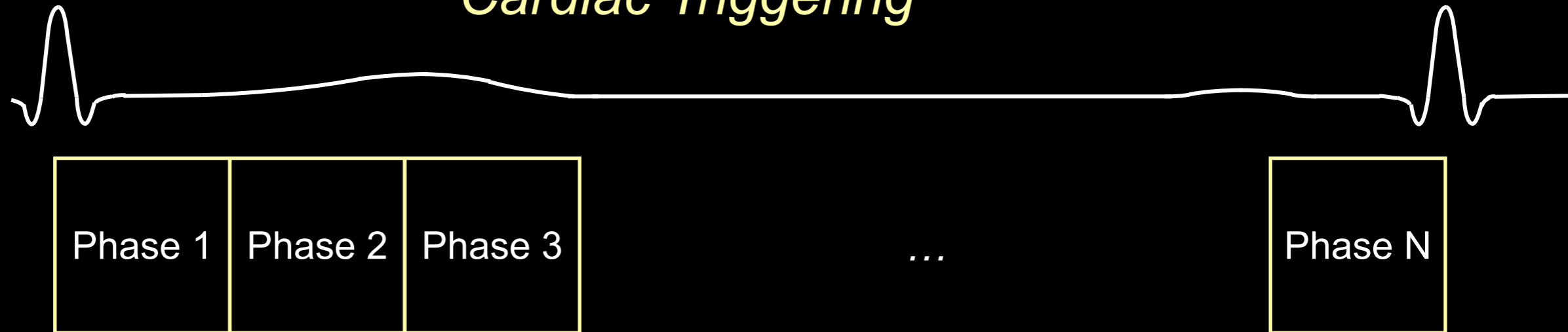
## Cardiac Triggering



$$\text{R-R interval [ms]} = 60,000 / \text{heart rate [bpm]}$$

# Managing Cardiac Motion

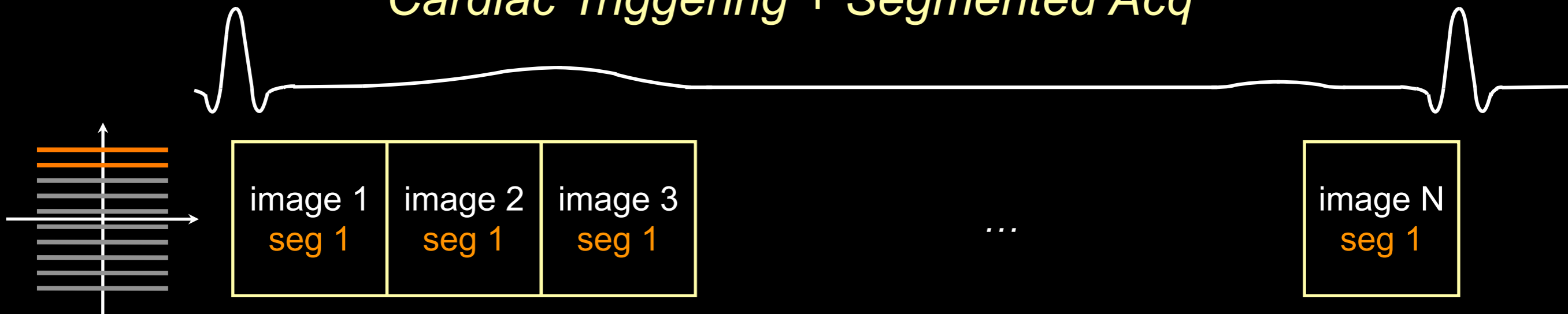
## *Cardiac Triggering*



# Managing Cardiac Motion

HB 1

*Cardiac Triggering + Segmented Acq*



How many lines per segment?

-  $\text{LinesPerSeg} * \text{TR} = \text{temporal duration of "cardiac phase"}$



# Managing Cardiac Motion

HB 1

*Cardiac Triggering + Segmented Acq*



...



HB 2



...



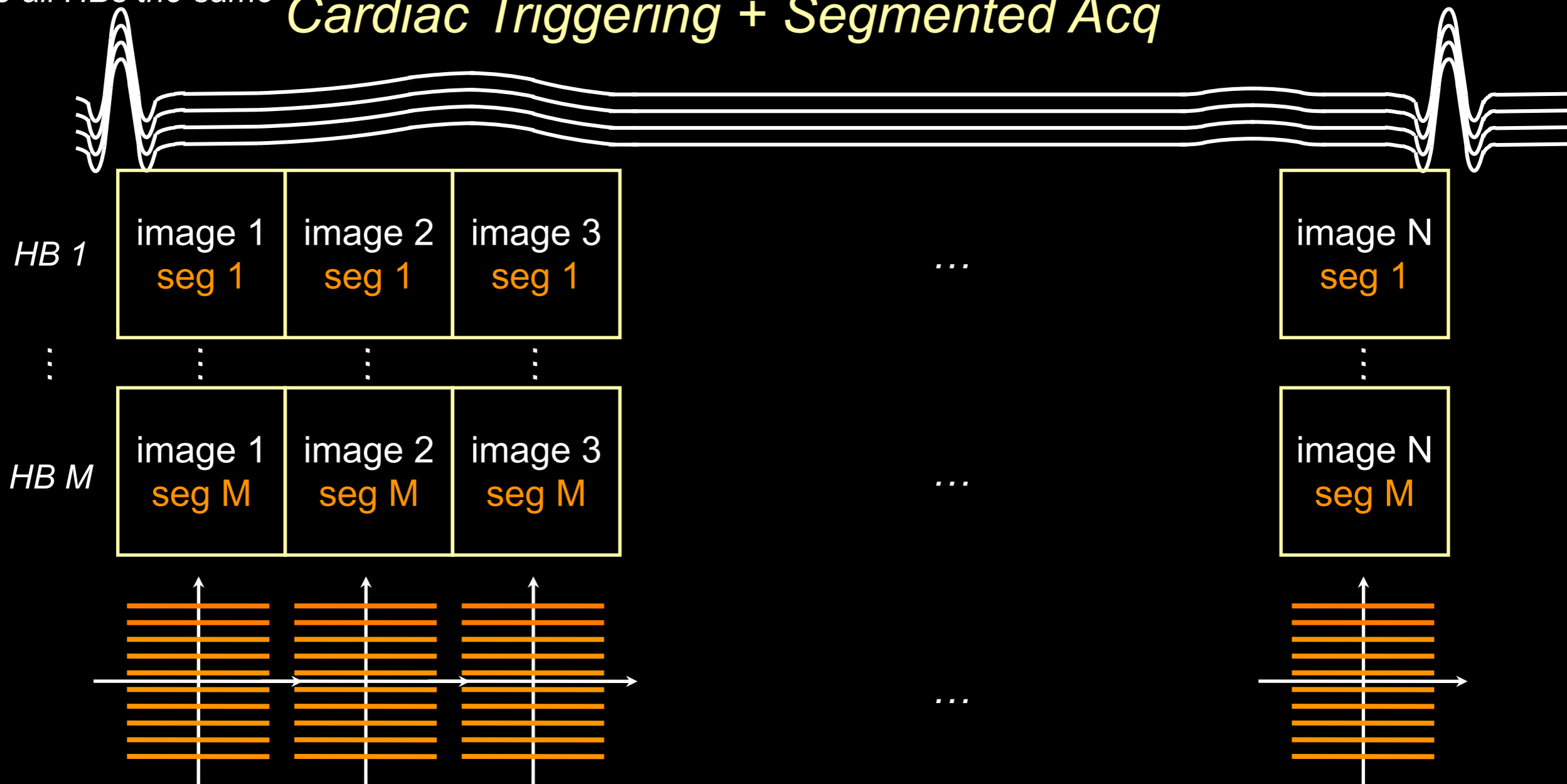
How many heartbeats (HB) needed?

- need  $M = \text{NumKspLines} / \text{LinesPerSeg}$  segments to cover k-space
- If we need M segments to cover k-space, need M heartbeats

# Managing Cardiac Motion

Assume all HBs the same

## Cardiac Triggering + Segmented Acq





# Managing Cardiac Motion

## Cardiac Triggering

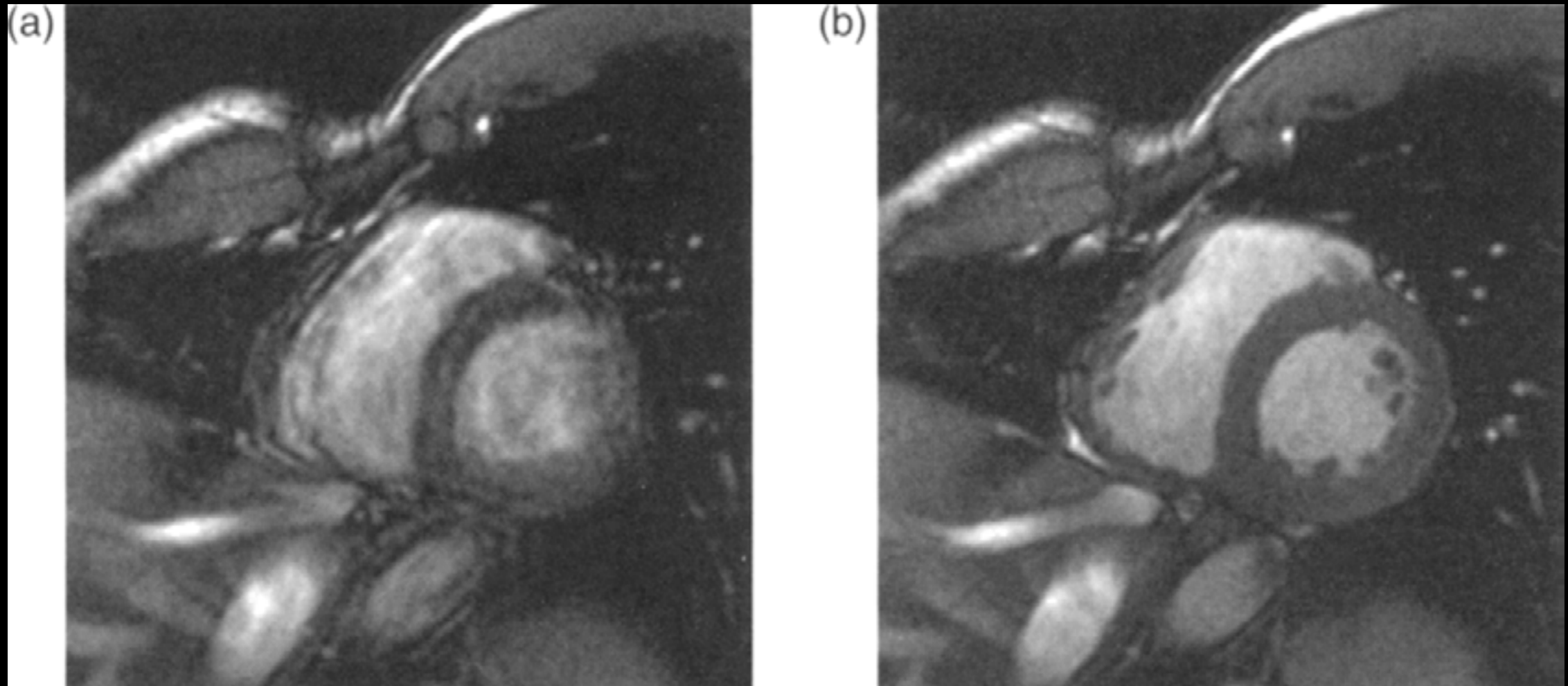


### Example

- NumKspLines = 128
- LinesPerSeg = 8; TR = 5 ms
- temporal duration of “cardiac phase” = 40 ms (i.e., 25 phases per sec)
- need  $M = 128/8 = 16$  segments
- need a 16-HB breath hold scan

# Managing Cardiac Motion

## *Cardiac Triggering*

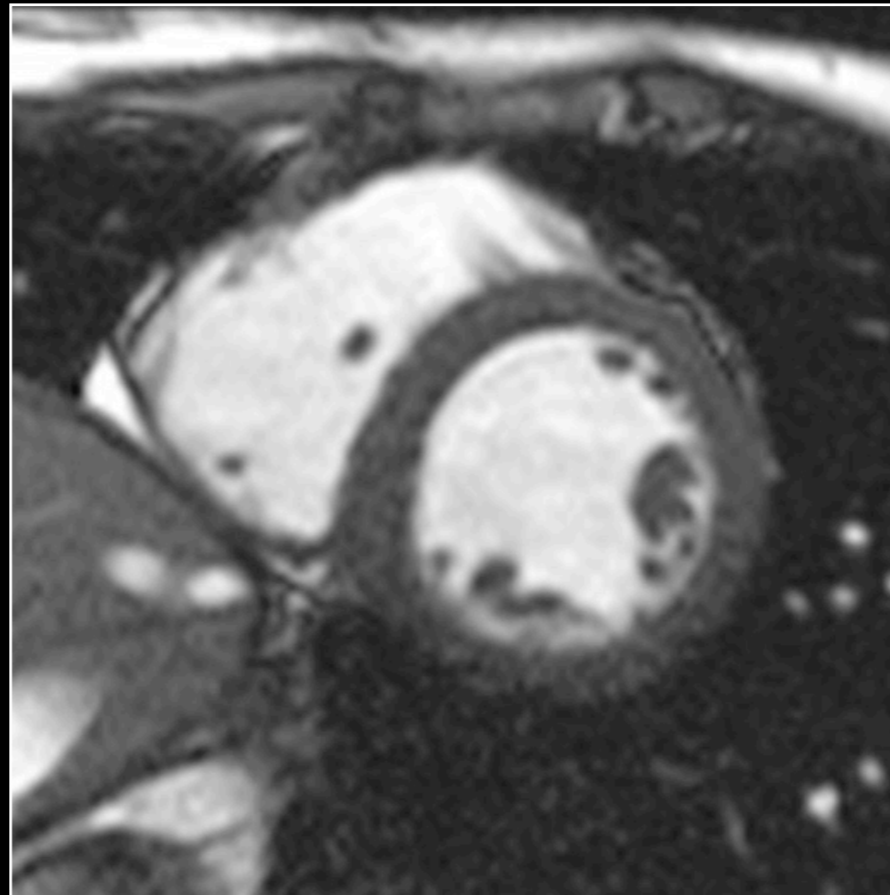


*No triggering*

*ECG triggering*

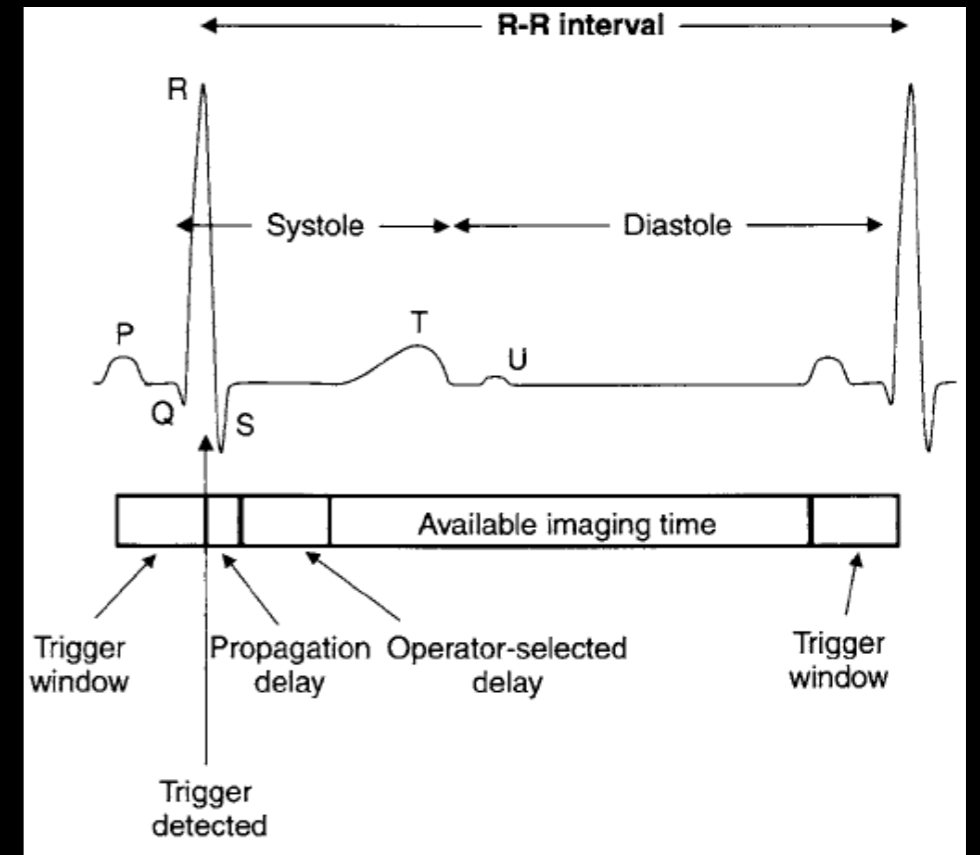
# Managing Cardiac Motion

## *Cardiac Triggering*



# Managing Cardiac Motion

- Prospective triggering
- Retrospective triggering
- *Advantages and Disadvantages?*



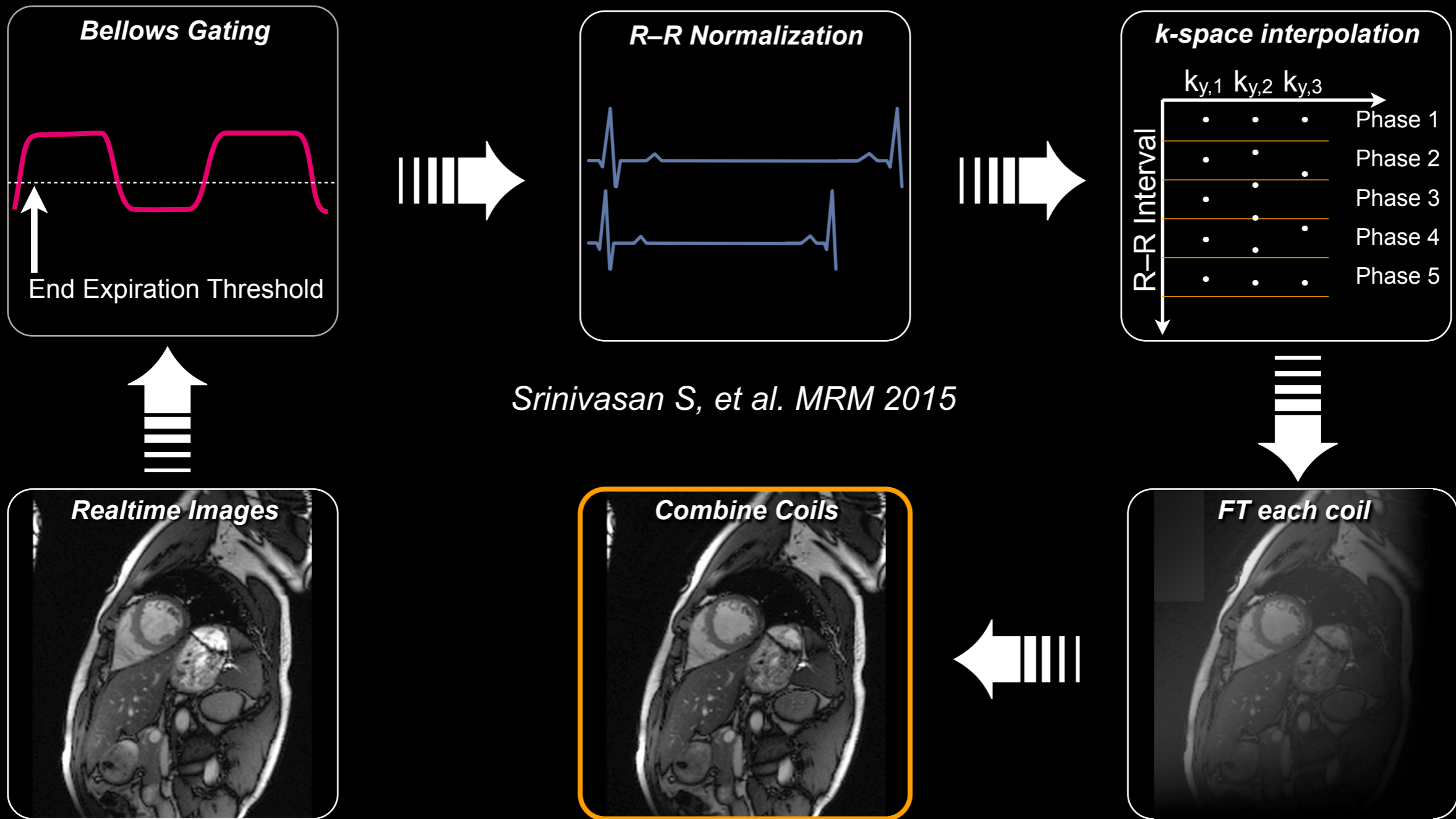
# Managing Cardiac Motion

- Cardiac Triggering: Challenges
  - unreliable ECG signal
    - especially at higher field ( $B_0 \geq 3T$ )
  - variations in each HB
  - fast HR; irregular HR
  - BH limits scan duration
    - limits # HBs
    - limits segmentation and # cardiac phases



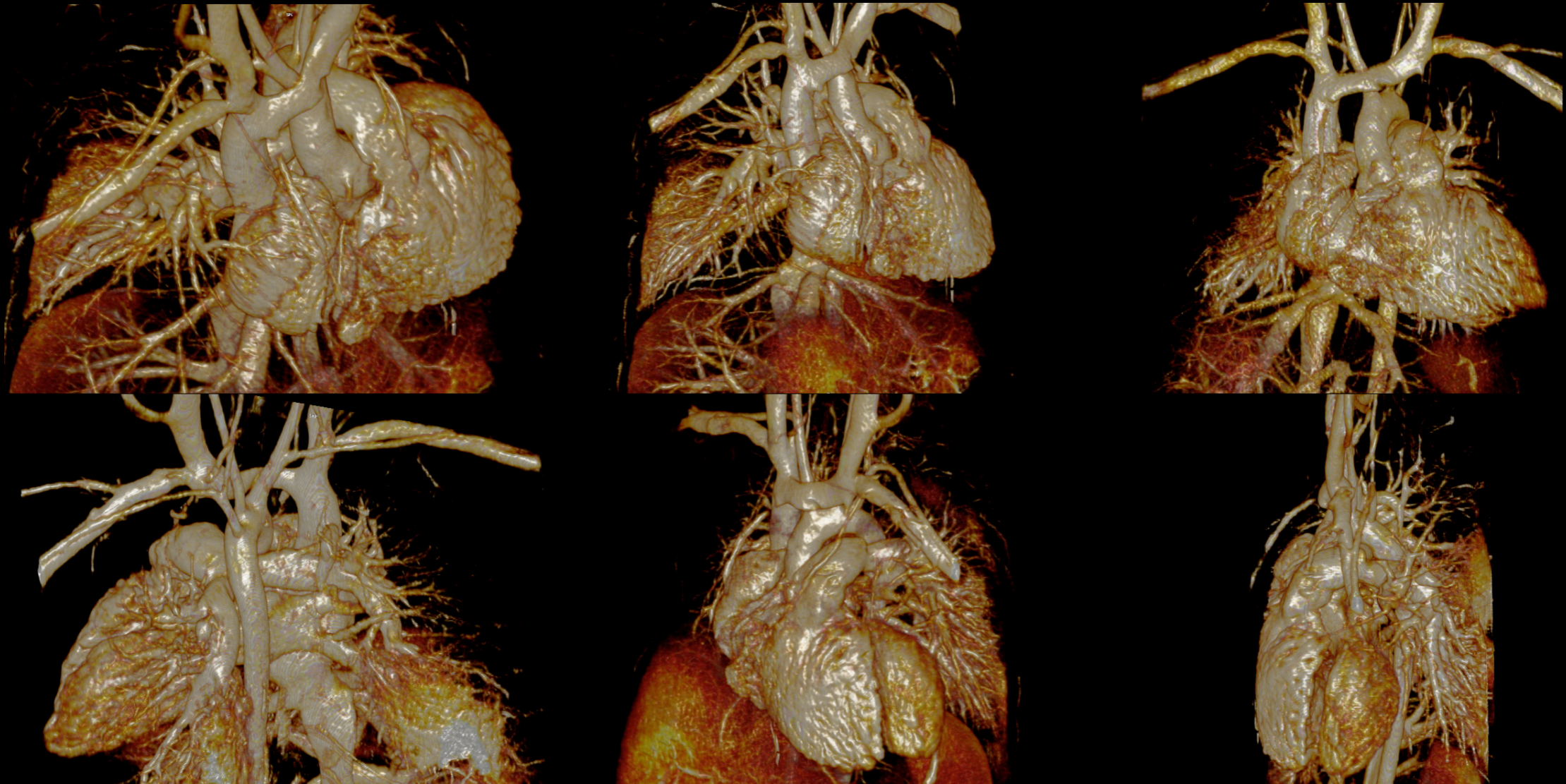
# Managing Cardiac Motion

## New Techniques: Free-Breathing Cardiac Cine MRI



# Managing Cardiac Motion

*New Techniques: Free-Breathing 4D Cardiovascular MRI*



*Han et al. MRM 2017; Zhou et al. NMR Biomed 2017; Han et al. MRM 2015; Nguyen et al JMRI 2017; Nguyen et al JCMR 2017; Finn et al. JMRI 2017*



# Managing Respiratory Motion

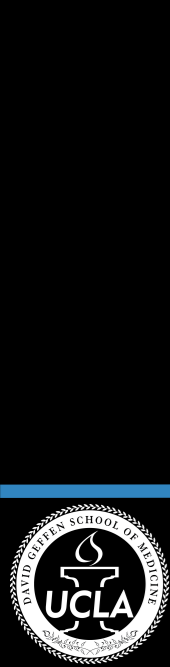
- Respiratory Motion
  - voluntary
  - non-rigid
    - mostly S/I
  - quasi-periodic
  - ~5 sec/breath (0.2 Hz)
  - mm - cm scale



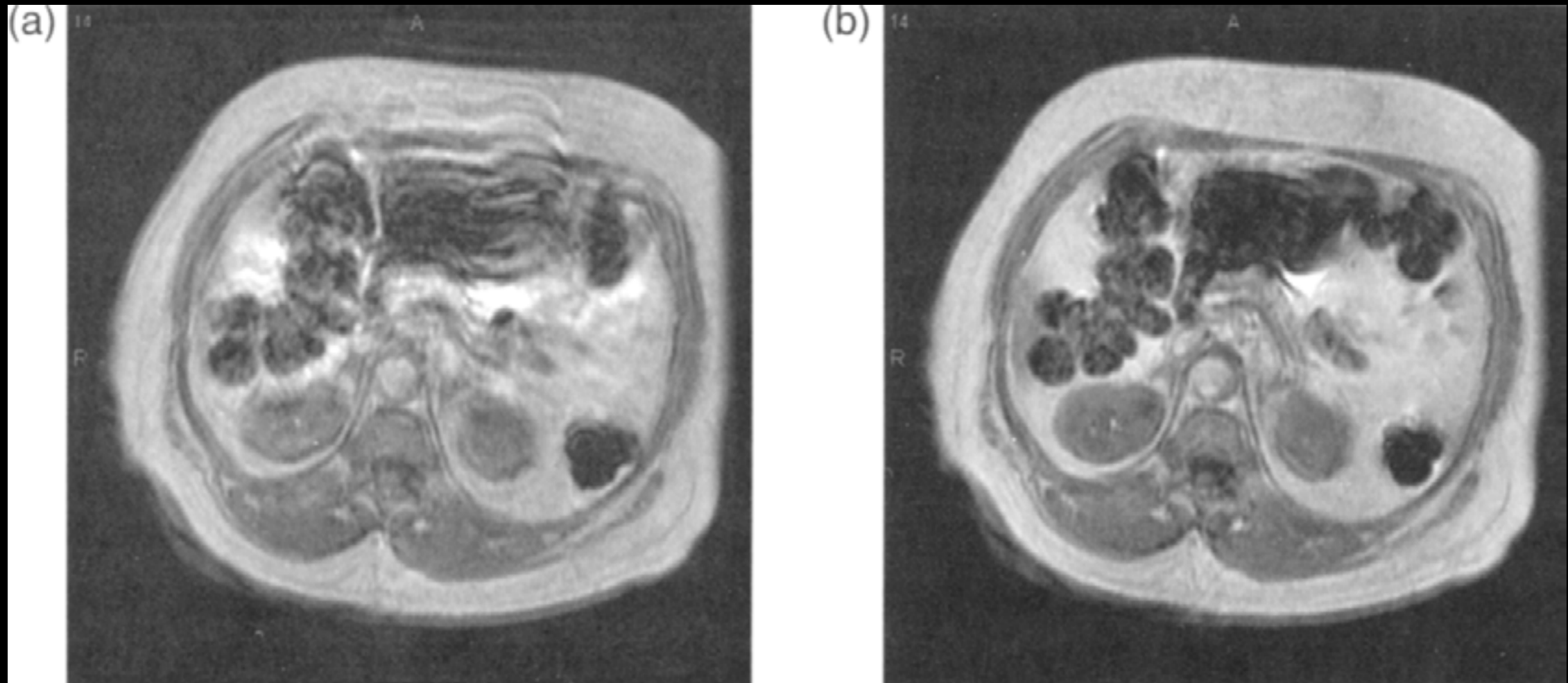


# Managing Respiratory Motion

- **Breath Holding (BH)**
  - temporarily suspend respiratory motion
  - usually end expiration or end inspiration
  - 10-20 sec in patients
  - may need multiple BH (sets of slices/slabs)



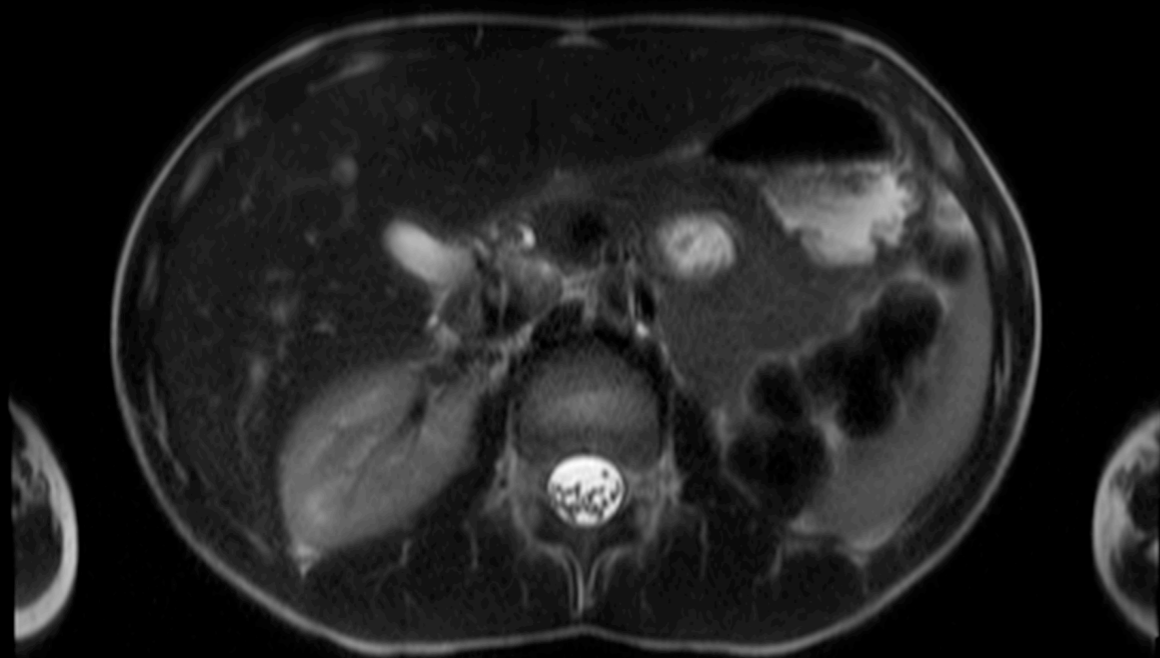
# Managing Respiratory Motion



*No breath-holding*

*With breath-holding*

# Managing Respiratory Motion

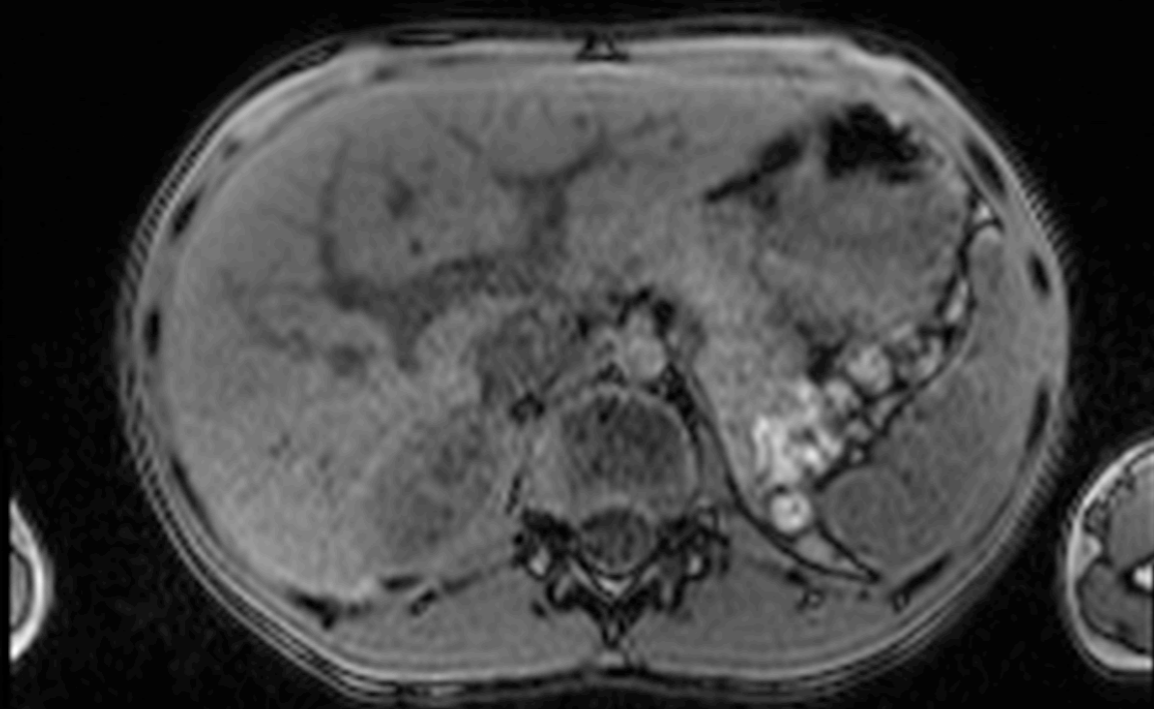


BH T2w HASTE AXL (2D)



BH T2w HASTE COR (2D)

# Managing Respiratory Motion



BH T1w VIBE AXL (3D)



BH T1w VIBE COR (3D)

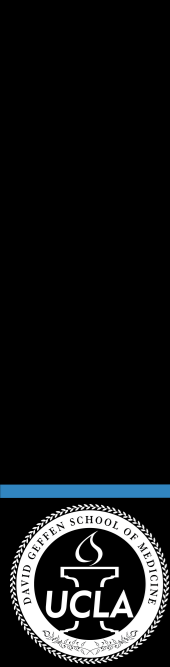
# Managing Respiratory Motion

- **BH MRI: Challenges**
  - short BH duration
    - compromises in scan parameters
  - imperfect BH
    - residual motion artifacts (e.g., aliasing)
  - multiple BH scans
    - wears subject down
    - inconsistent BH position
  - patient may be unable to BH



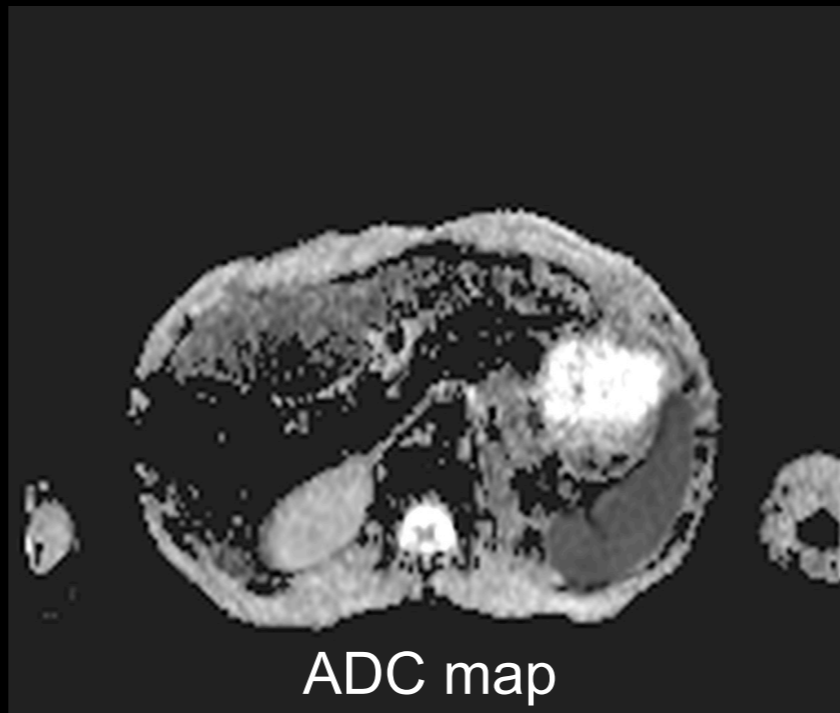
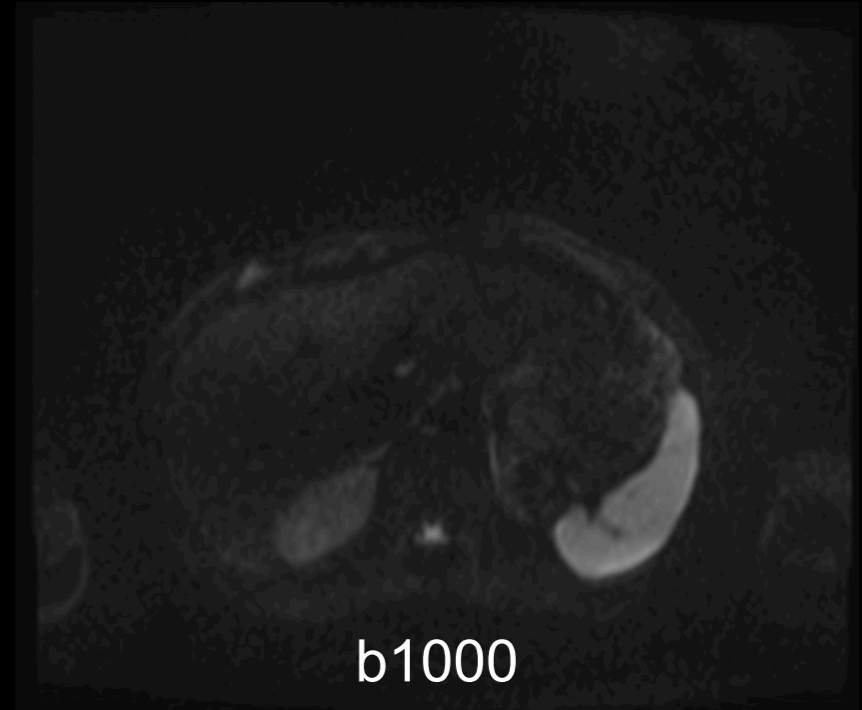
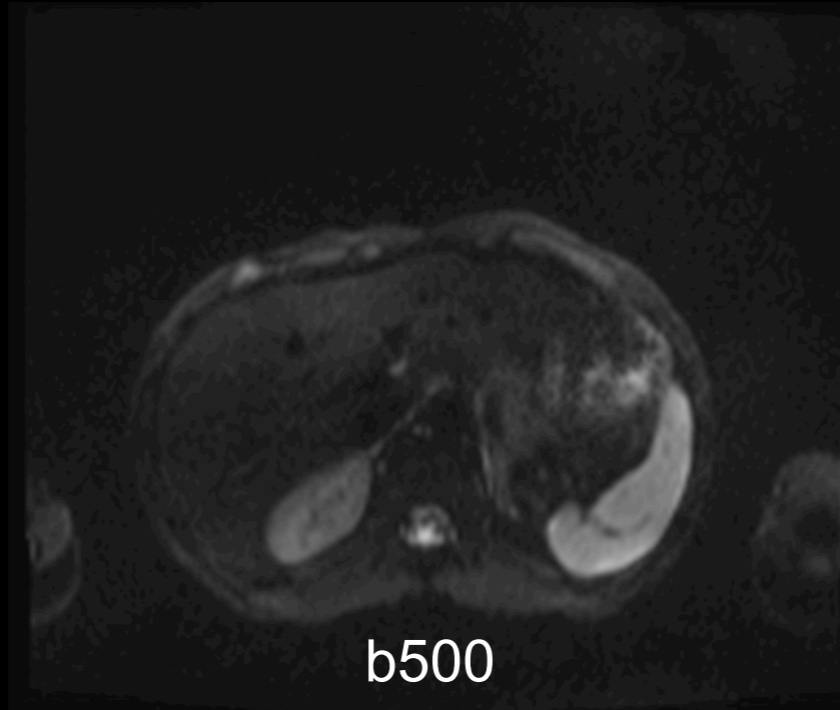
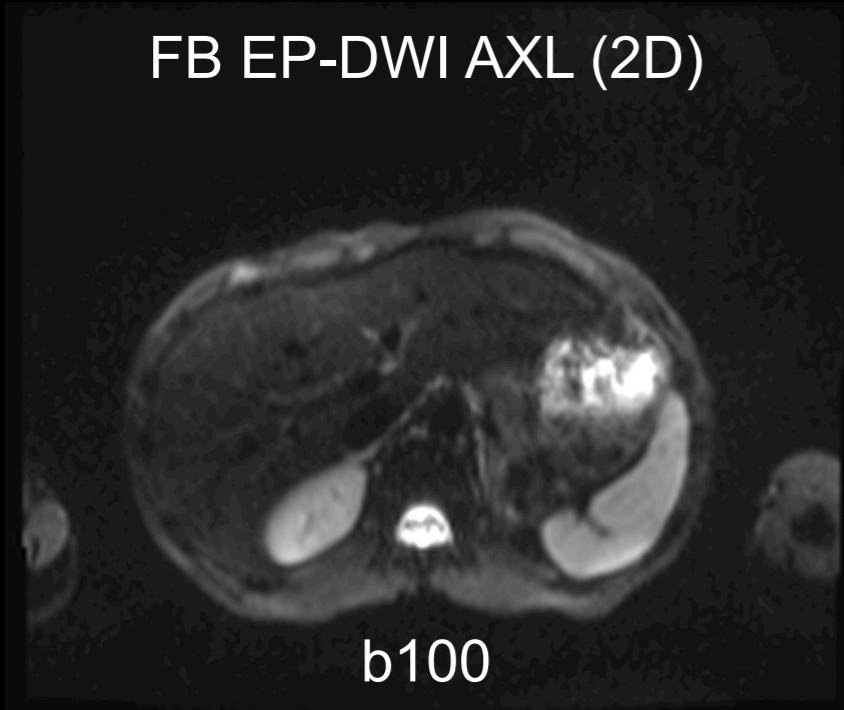
# Managing Respiratory Motion

- Free Breathing (FB) + Multiple Averages
  - average out the motion
  - e.g., 3-8 averages
  - can be used for different types of motion



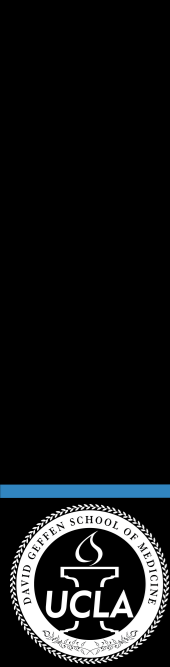
# Managing Respiratory Motion

FB EP-DWI AXL (2D)



# Managing Respiratory Motion

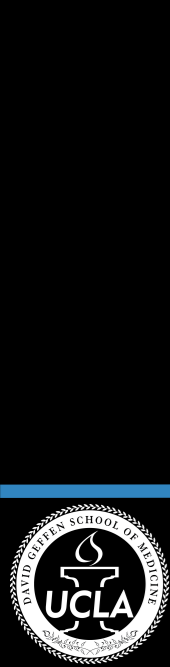
- **FB + Multiple Averages: Challenges**
  - variations in respiratory pattern
  - image blurring
  - residual artifacts (e.g., aliasing)
  - long scan





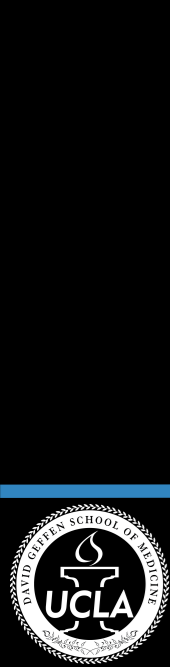
# Managing Respiratory Motion

- **FB + Respiratory Gating**
  - measure respiratory status / position  
e.g., bellows, MR navigator signal
  - acquire data when in consistent resp. state
  - fully acquire data over multiple resp. cycles



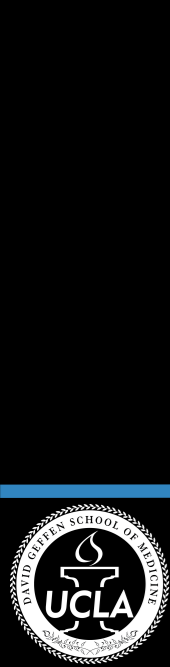
# Managing Respiratory Motion

- MR Navigators
  - MR data to track motion
  - Assumes negligible motion between navigator and imaging data
  - Use navigator info to prospectively or retrospectively compensate for motion



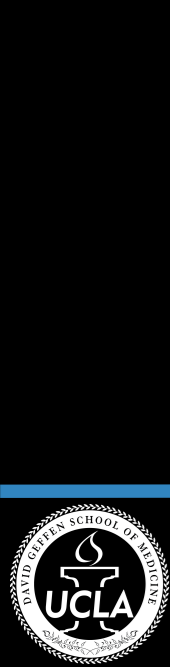
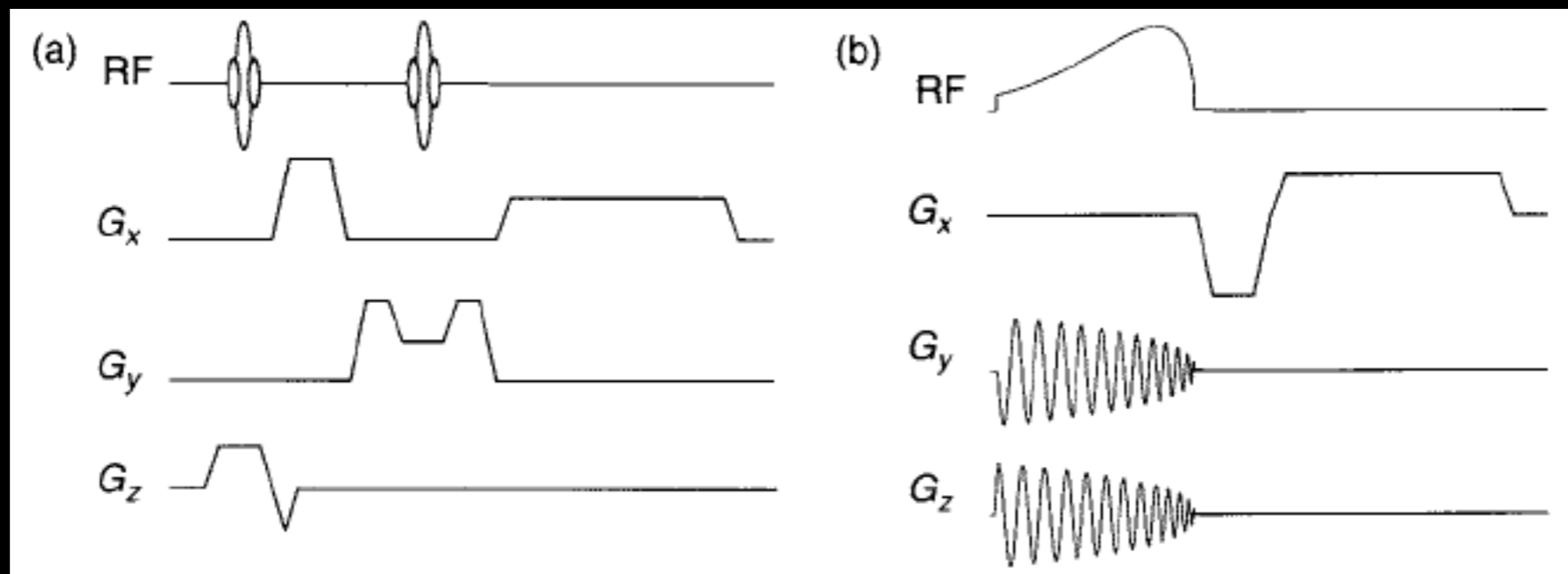
# Managing Respiratory Motion

*MRI with Navigators*



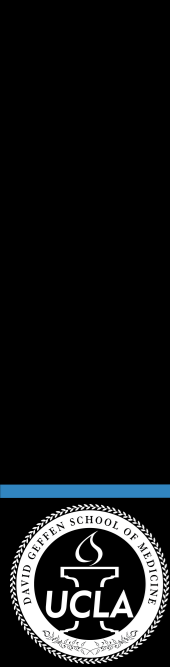
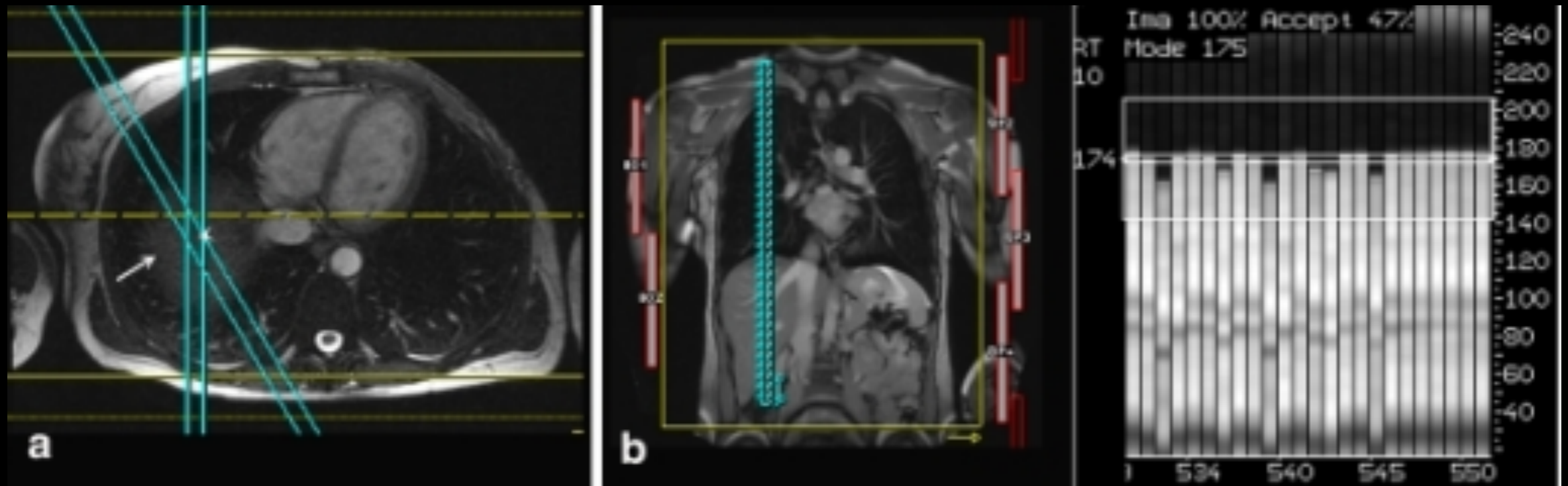
# Managing Respiratory Motion

## MR Navigator: 1D Example



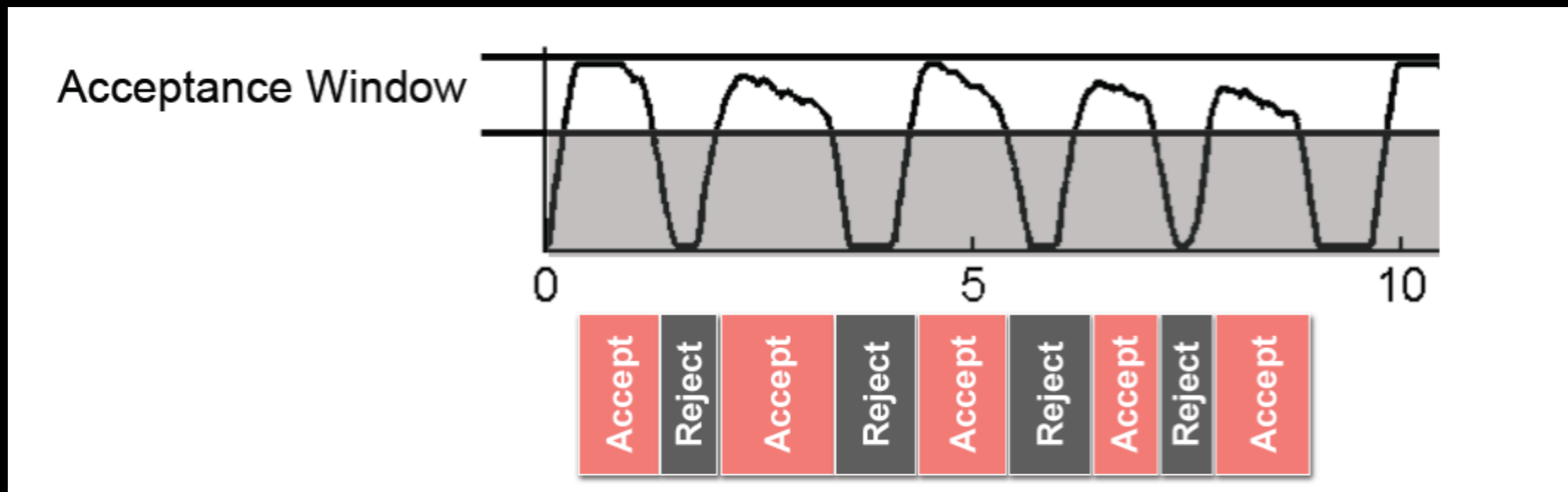
# Managing Respiratory Motion

## MR Navigator: 1D Example



# Managing Respiratory Motion

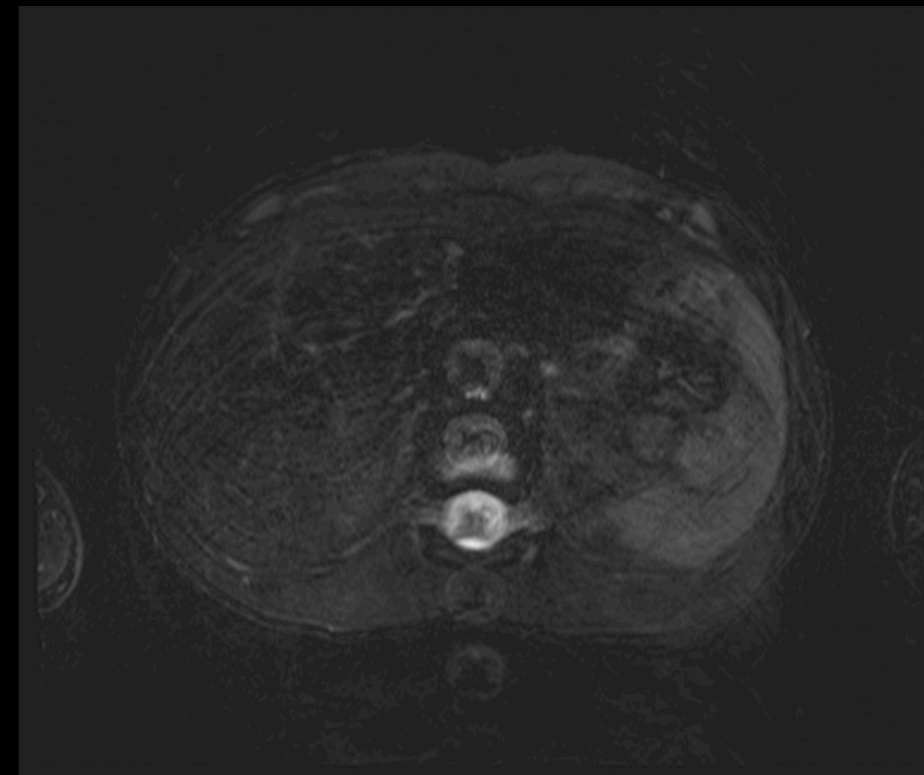
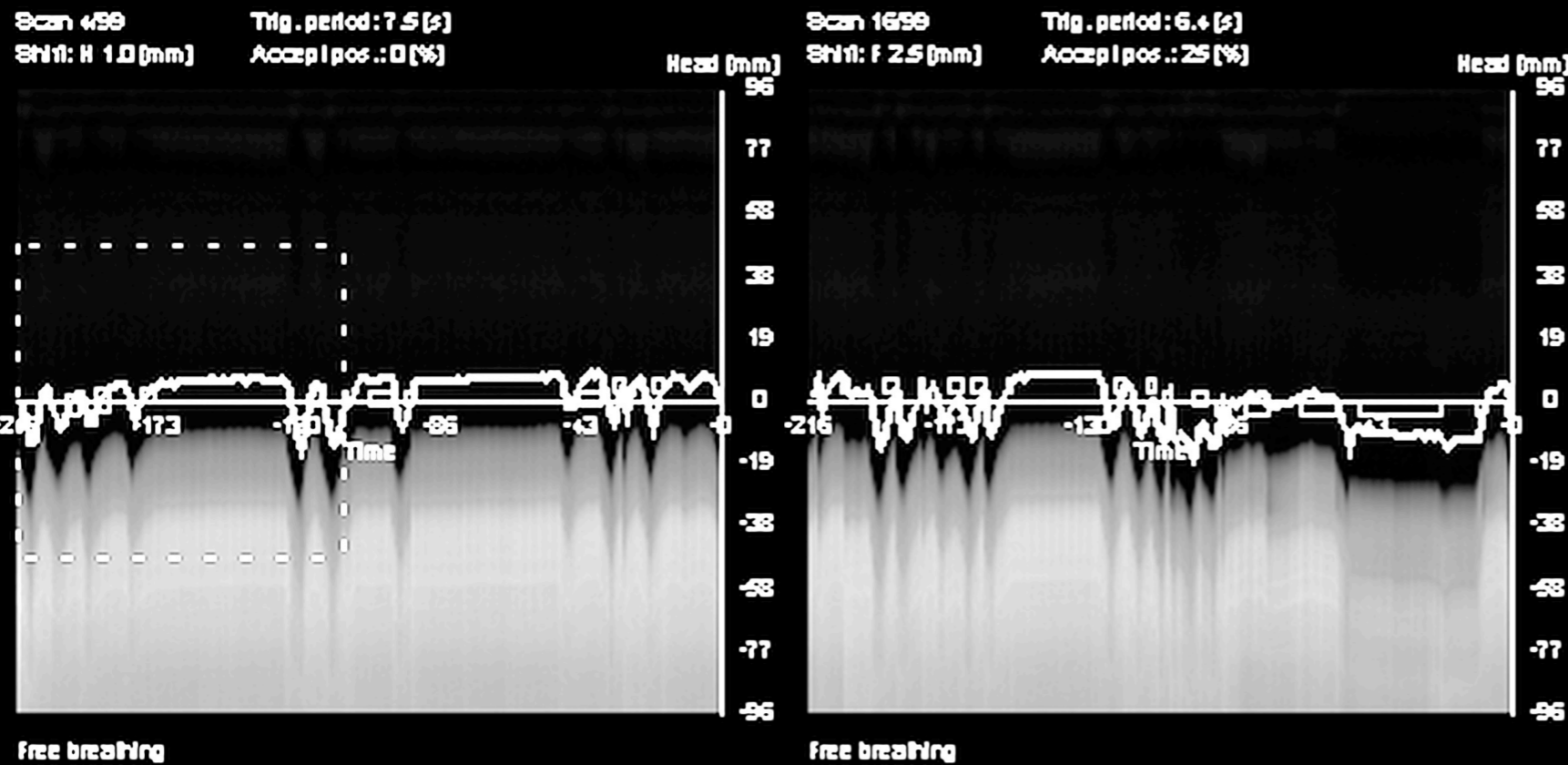
## Respiratory Gating



Prospective vs. Retrospective

# Managing Respiratory Motion

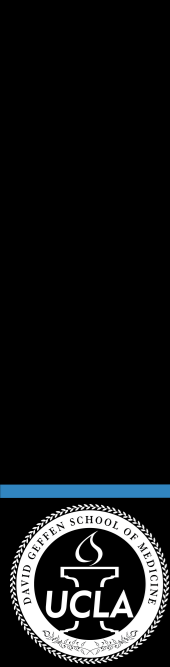
## Respiratory Gating



FB T2w TSE AXL (2D)

# Managing Respiratory Motion

- **FB + Respiratory Gating: Challenges**
  - inconsistent respiratory pattern
  - residual motion artifacts (e.g., aliasing)
  - can be long scans with unknown duration





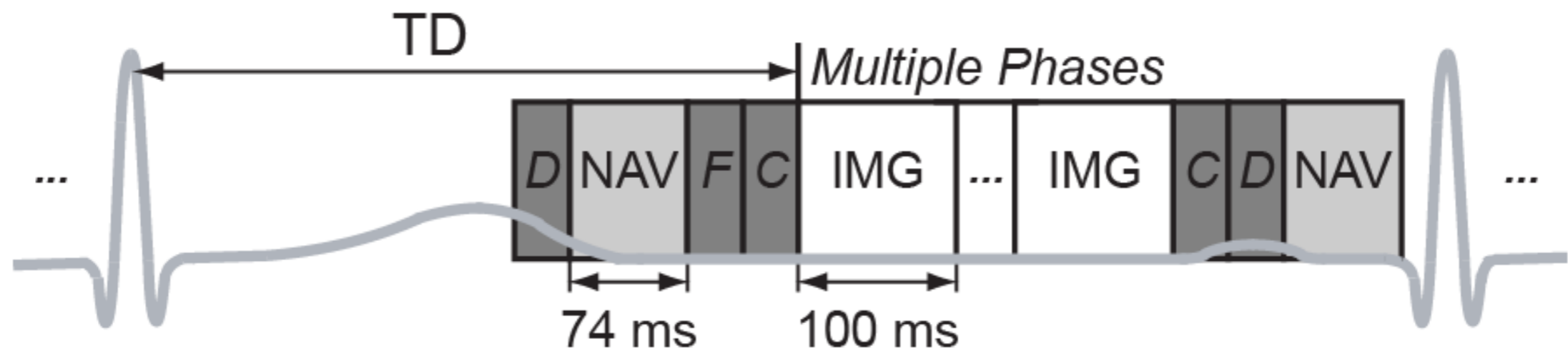
# Managing Respiratory Motion

- **FB + Retrospective Compensation**
  - measure respiratory status / position  
e.g., bellows, MR navigator signal
  - determine the most consistent respiratory position (can also bin data into motion states)
  - reject or compensate data outside of consistent respiratory position
  - reconstruct data (may be undersampled)



# Managing Respiratory Motion

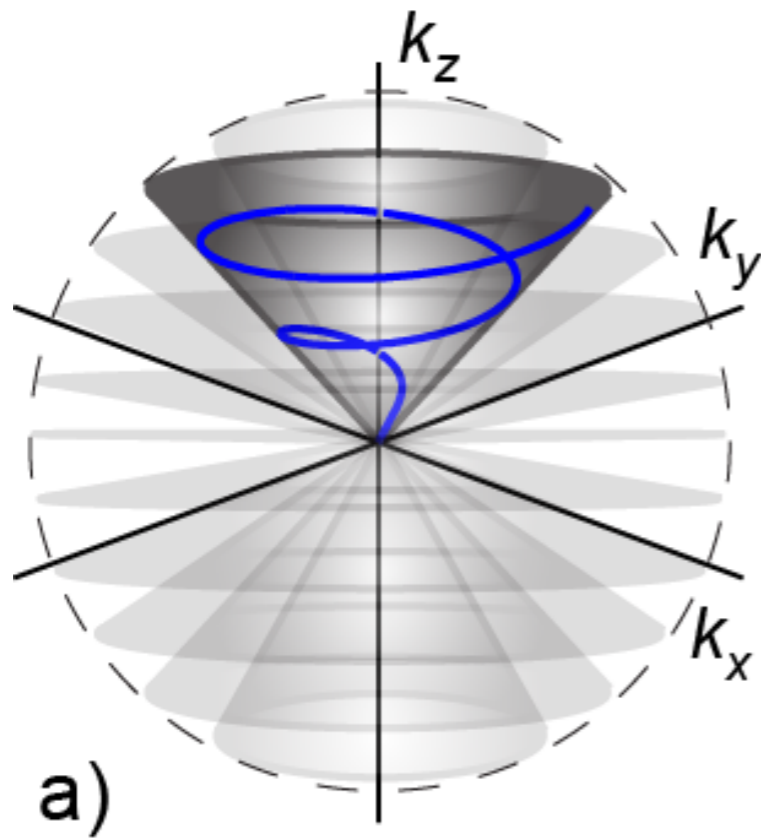
*FB + Cardiac Triggering + Navigators*



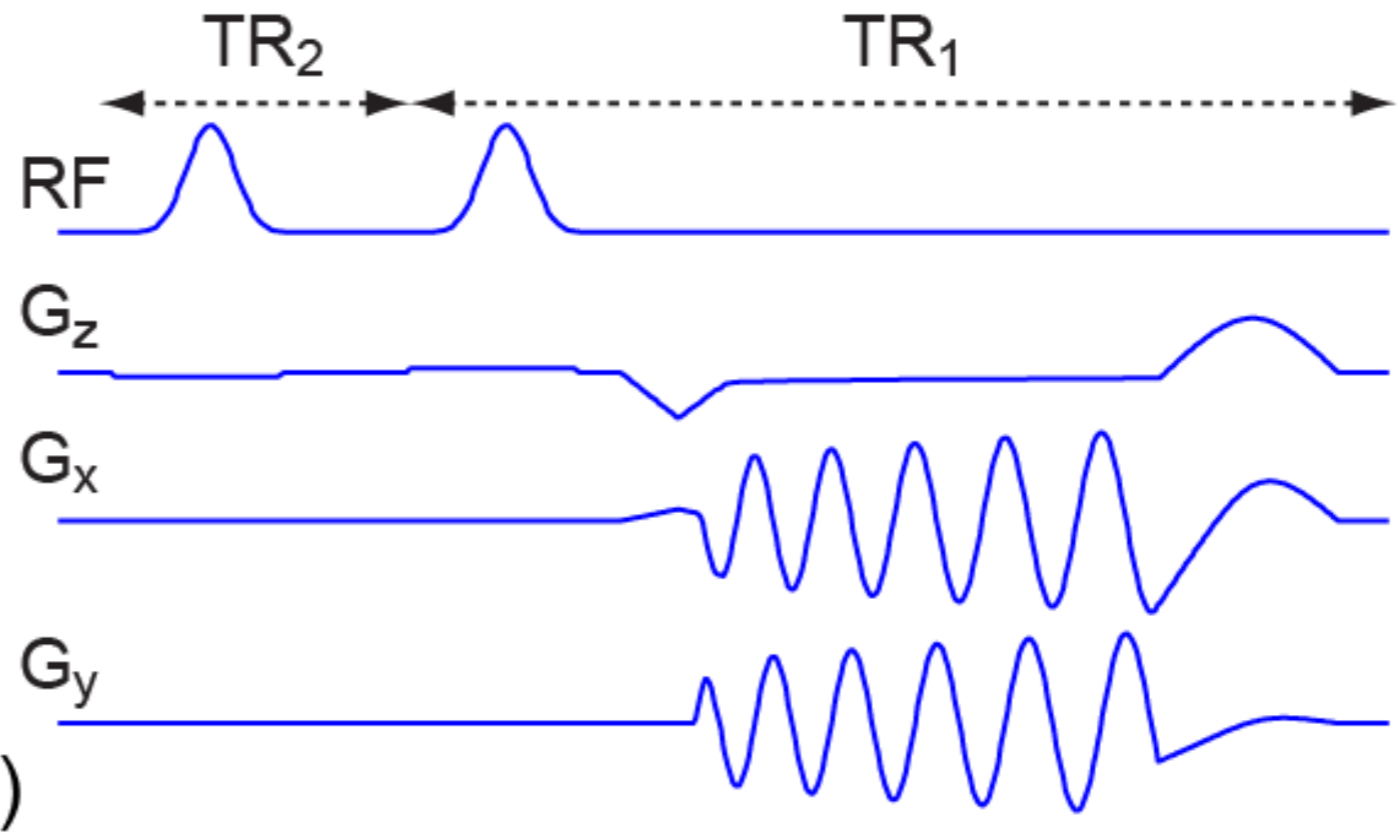
**TD:** trigger delay, **D:** dummy cycles, **NAV:** 2D navigator image, **F:** fat saturation, **C:** SSFP catalyzation cycles, **IMG:** 3D cones acquisition

# Managing Respiratory Motion

## 3D Cones Acquisition



3D Cones



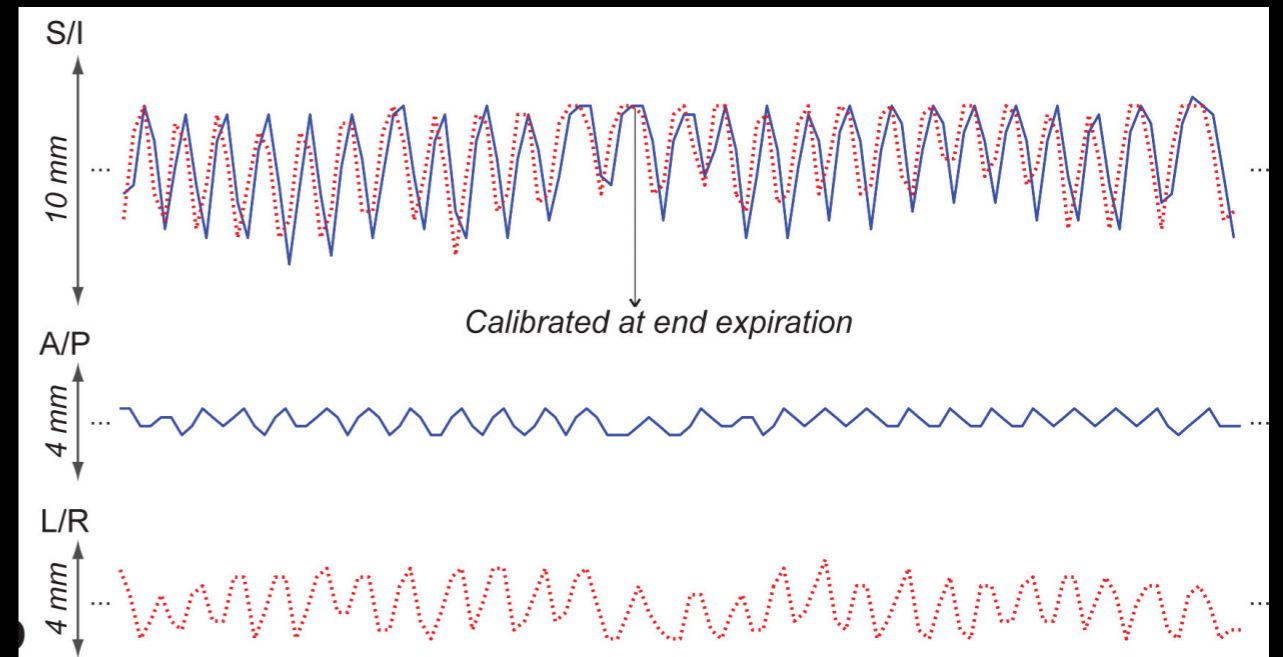
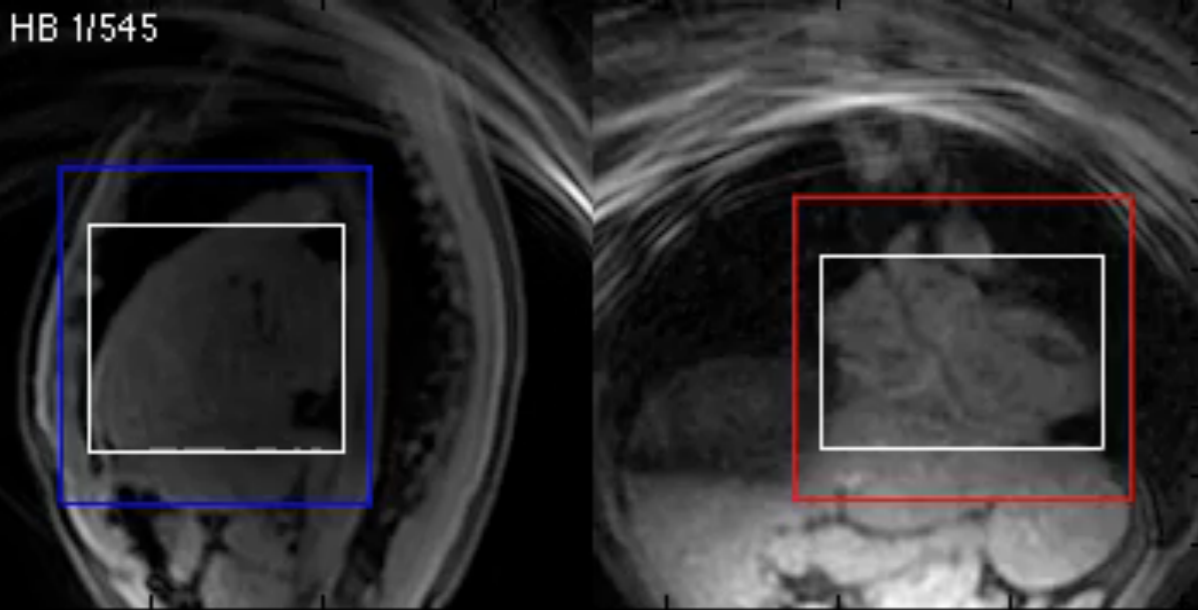
Alternating-TR SSFP Sequence

# Managing Respiratory Motion

## MR Image-Based Navigators

multi-resolution algorithm  
template matching  
3D rigid body motion

HB 1/545



# Managing Respiratory Motion

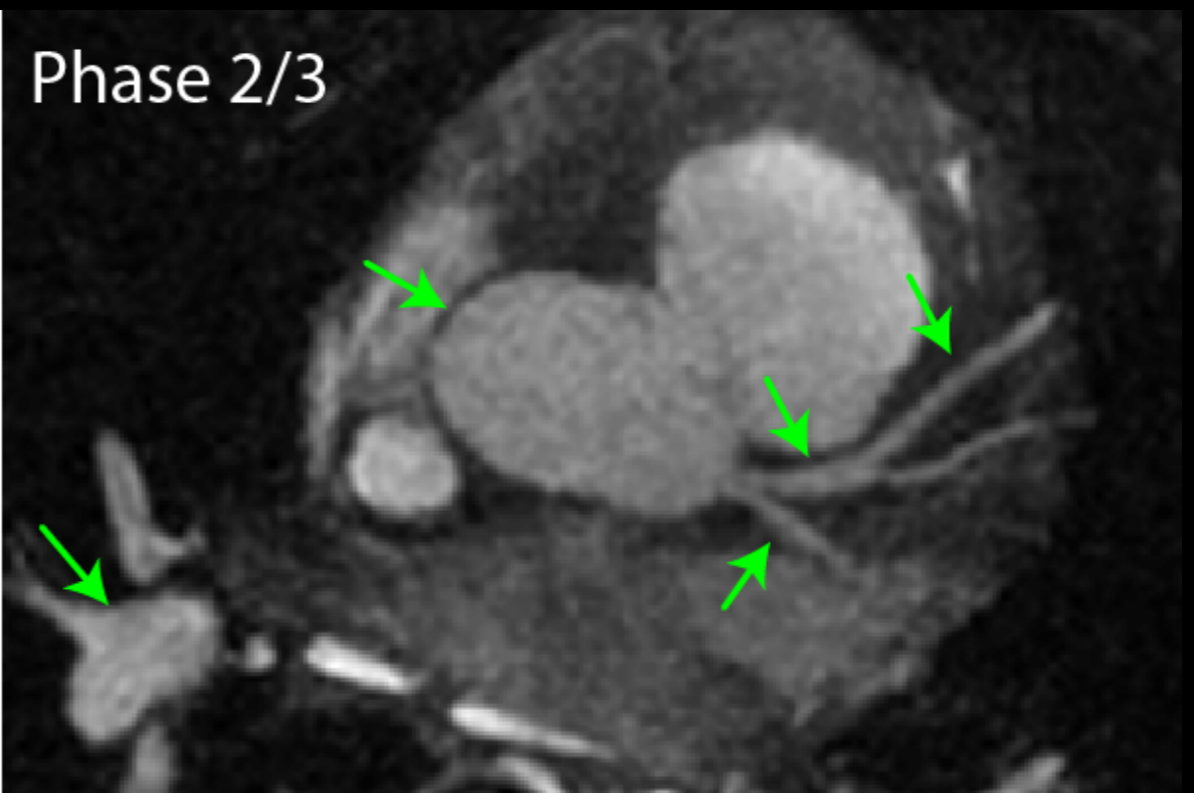
## *Retrospective Motion Compensation*

*No Motion Correction*



Already recognize vessels

After Motion Correction

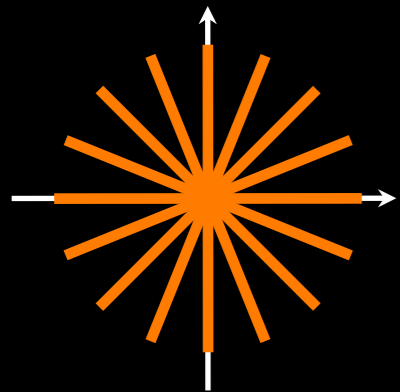


Sharpening of features (arrows)

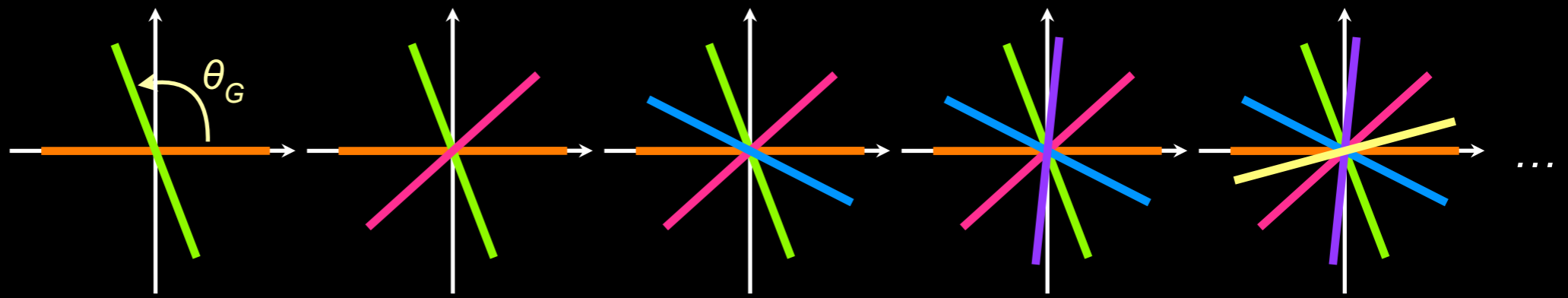
1.5 T; 508 HBs @ 67 bpm ~7:37 scan

# Managing Respiratory Motion

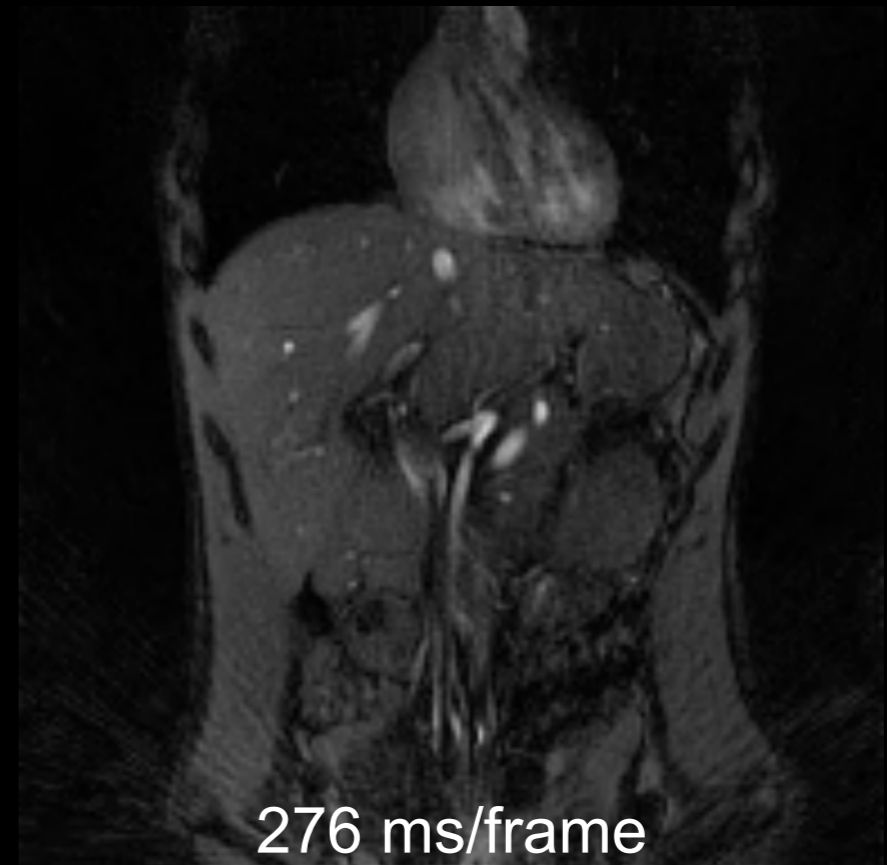
*New Techniques: Real-Time Non-Cartesian 2D MRI*



2D Radial



Golden angle ordering



276 ms/frame

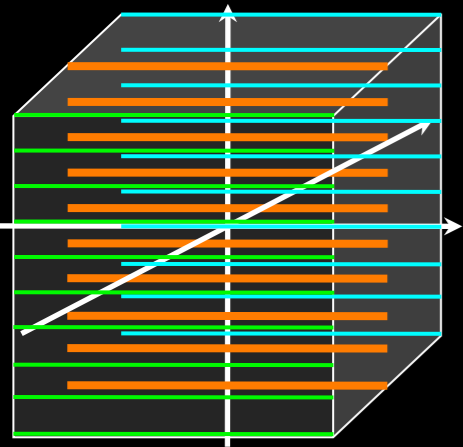


# Managing Respiratory Motion

*New Techniques: FB Non-Cartesian 3D MRI*

BH 3D Cartesian MRI

FB 3D Stack-of-Radial MRI

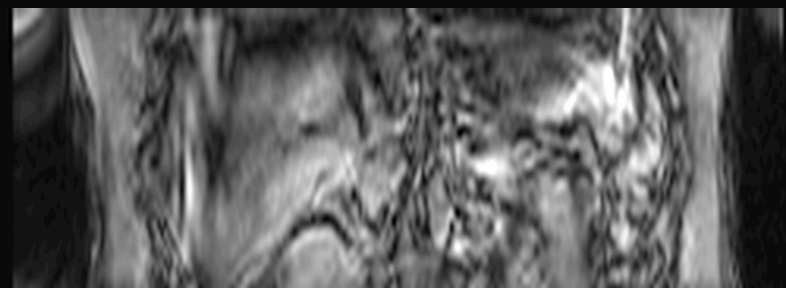


3D Cartesian

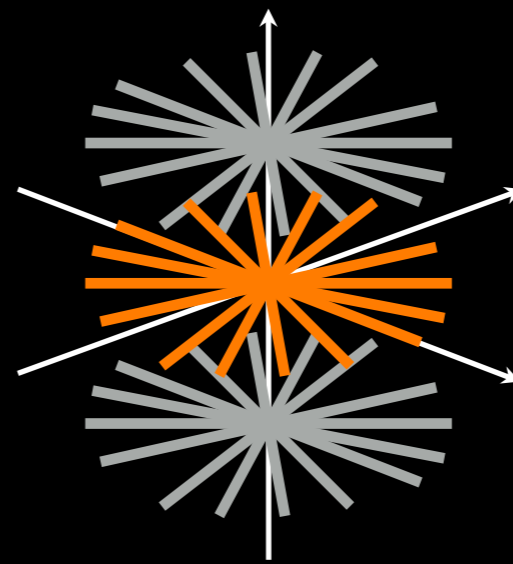


*imperfect BH*

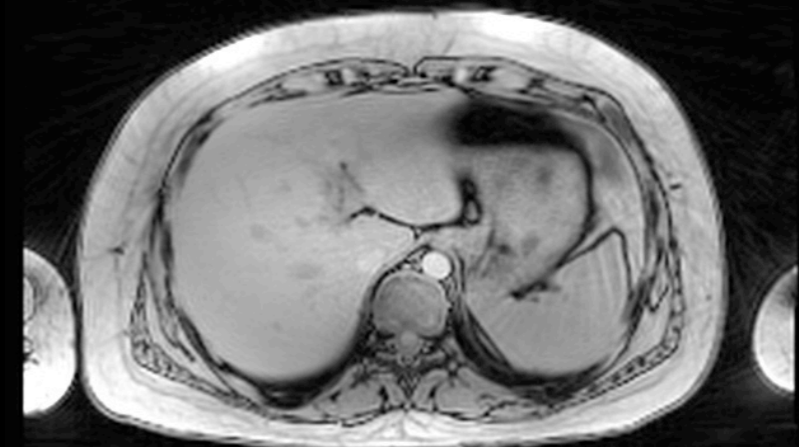
AXL



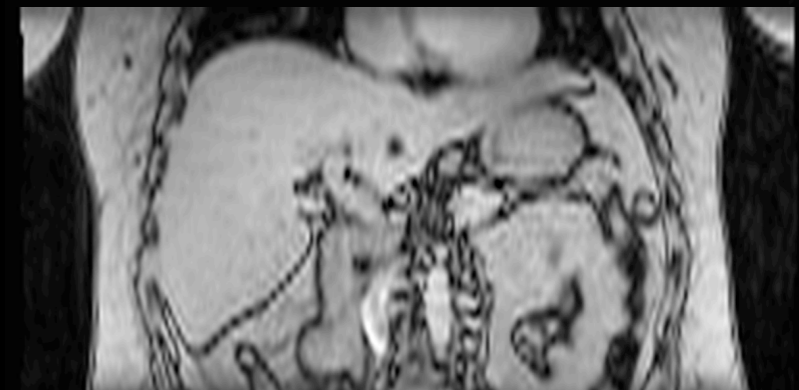
COR reformat



3D Stack of Radial



AXL



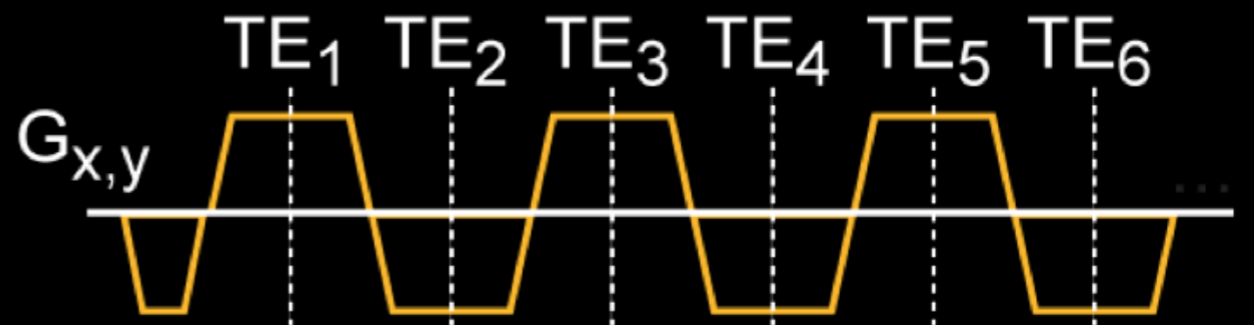
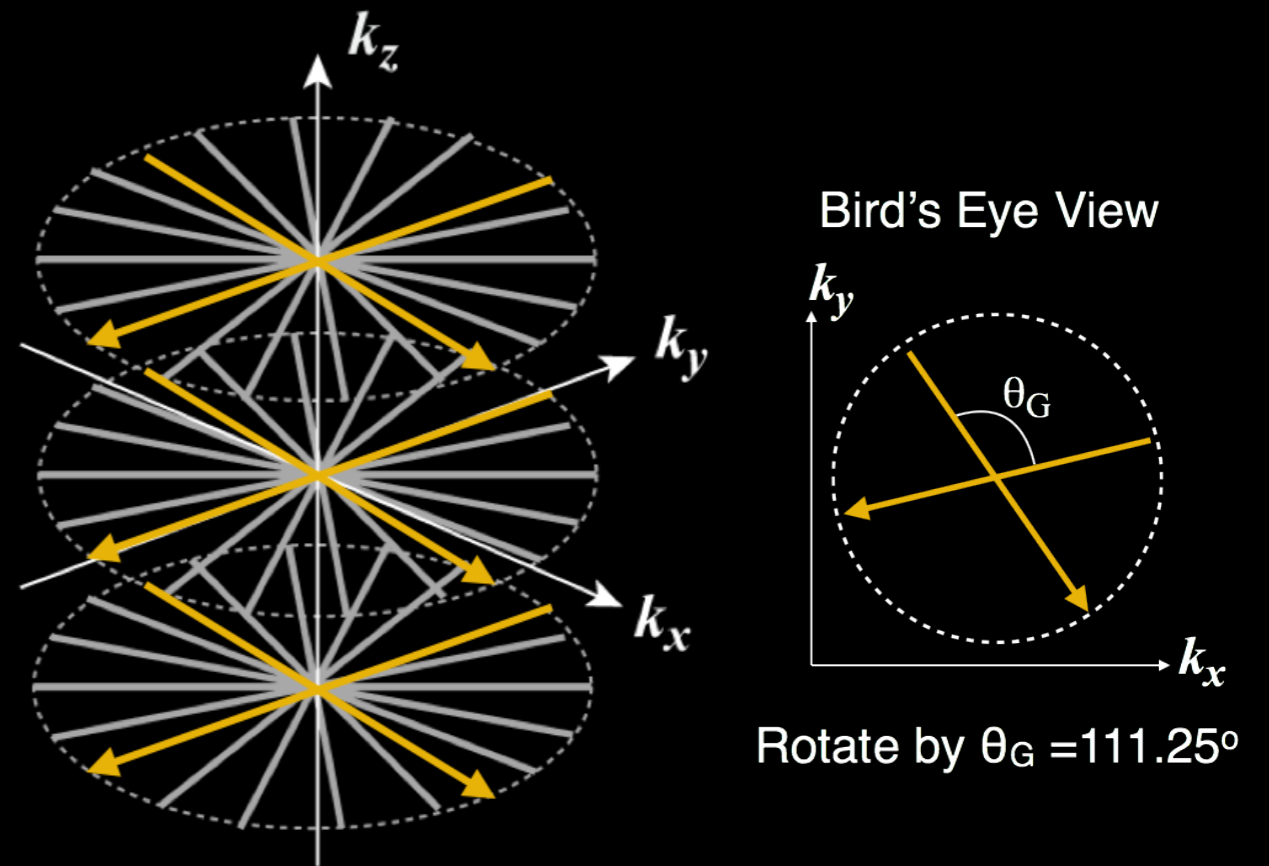
COR reformat

# Managing Respiratory Motion

*New Techniques: FB Non-Cartesian 3D MRI*

## 3D Stack-of-Radial MRI

- golden angle ordering
- bipolar multi-echo
- gradient calibration
- multi-peak F/W and  $R_2^*$
- proton density fat fraction (PDFFF)

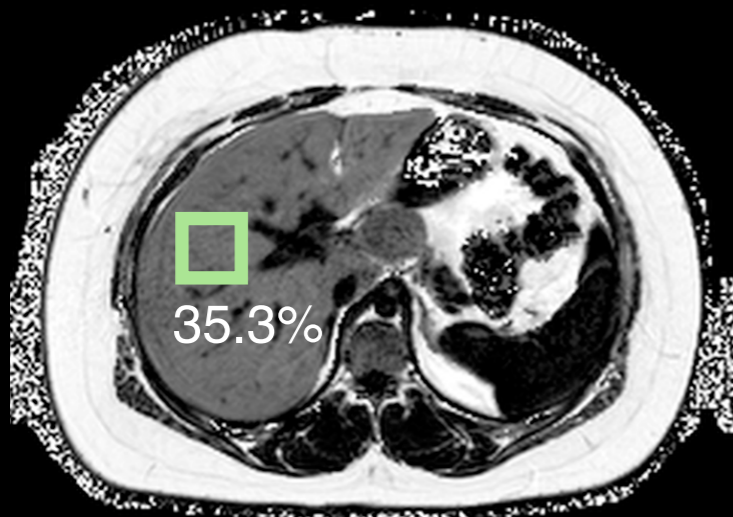




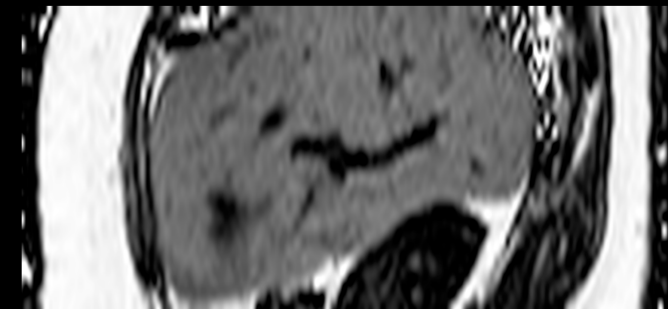
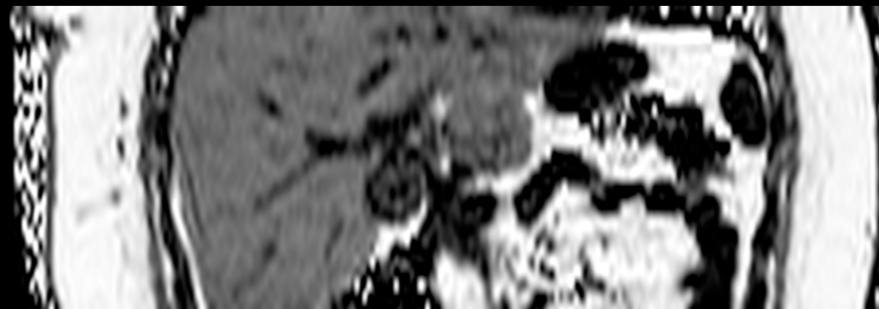
# Managing Respiratory Motion

*New Techniques: FB Non-Cartesian 3D MRI*  
NAFLD Pediatric Subject

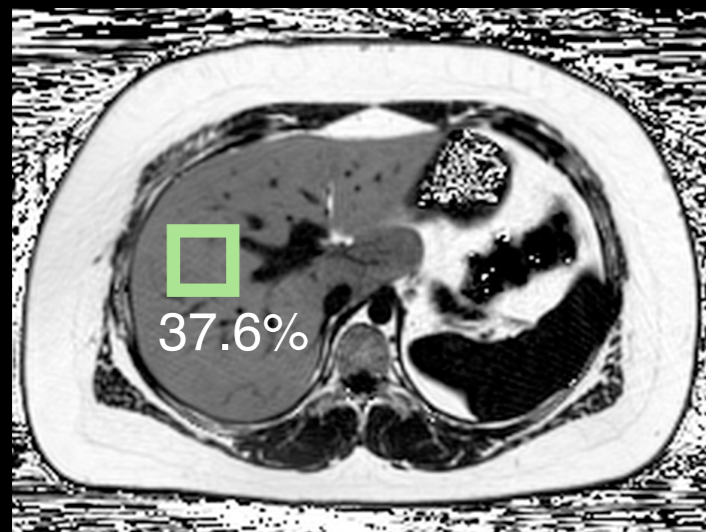
BH Cartesian (0:20)



Liver Slice Coverage = 68%



FB Radial (3:42)



Liver Slice Coverage = 100%



Axial

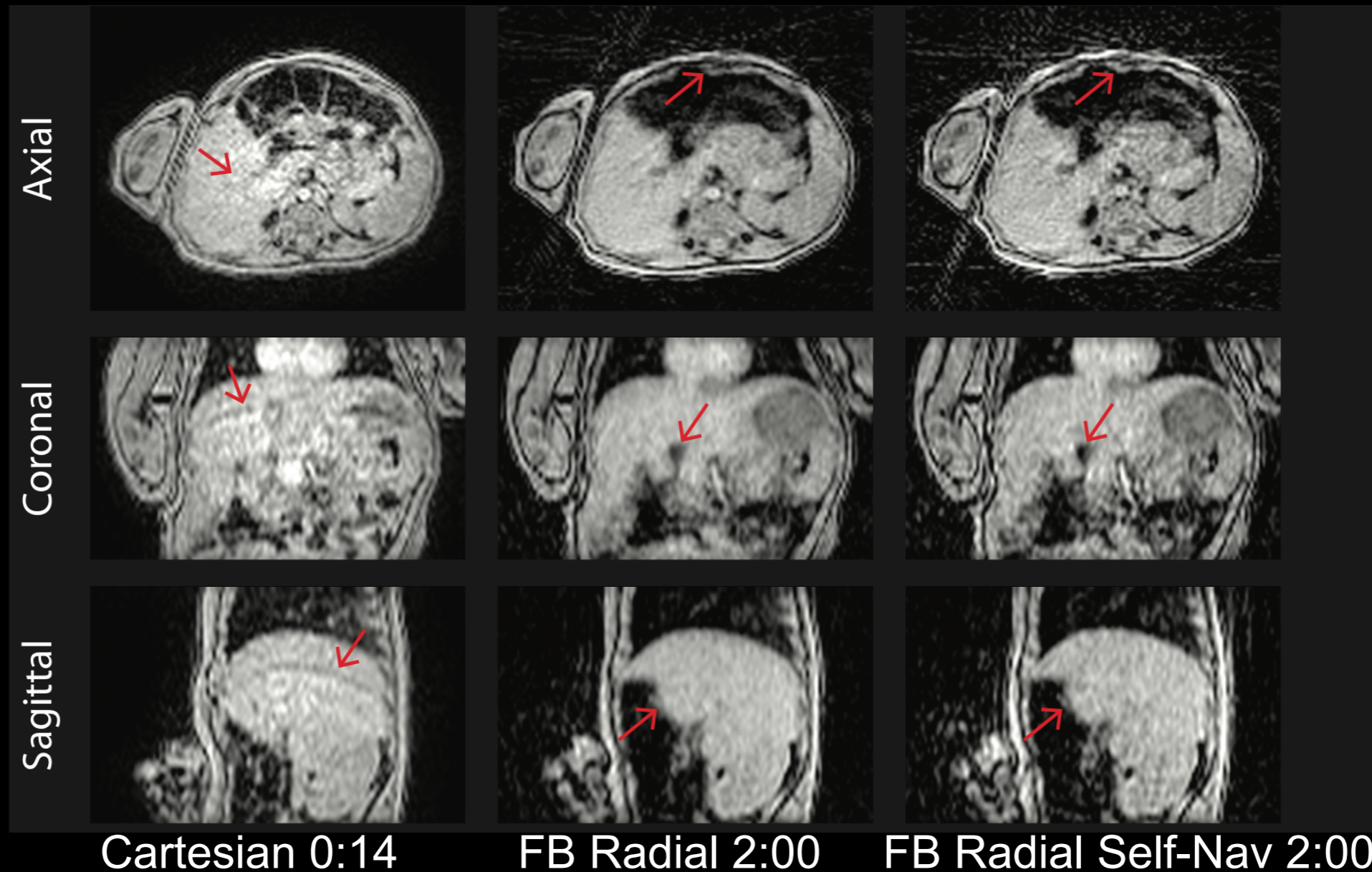
Coronal Reformat

Sagittal Reformat



# Managing Respiratory Motion

*New Techniques: FB Non-Cartesian 3D MRI*  
Infant Subject

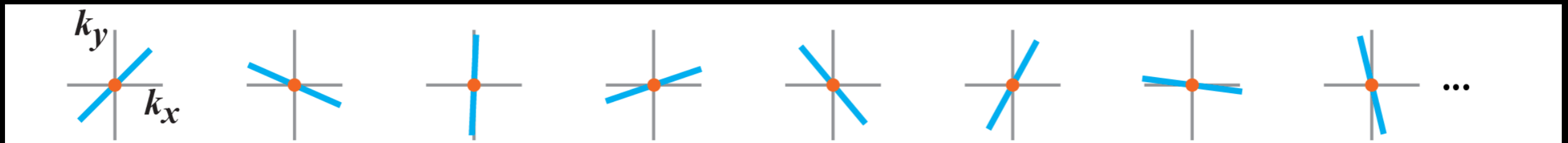


# Managing Respiratory Motion

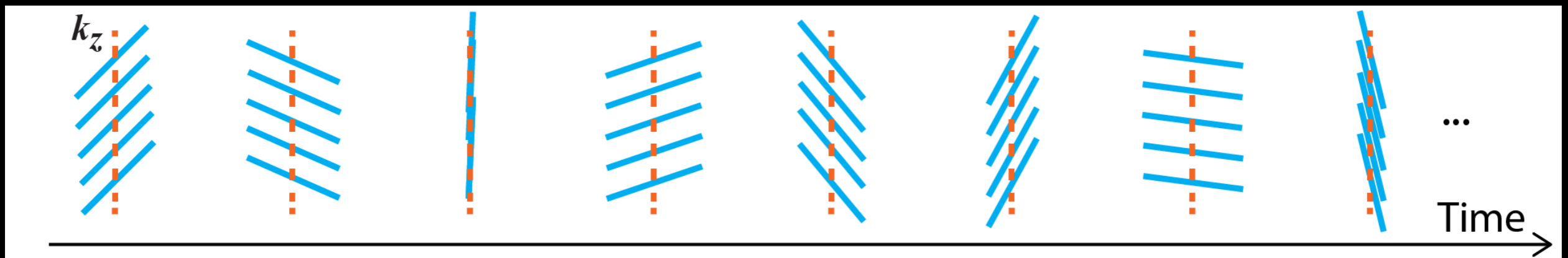
*New Techniques: FB Non-Cartesian 3D MRI*

## Self-Navigation

DC (center of k-space) signal



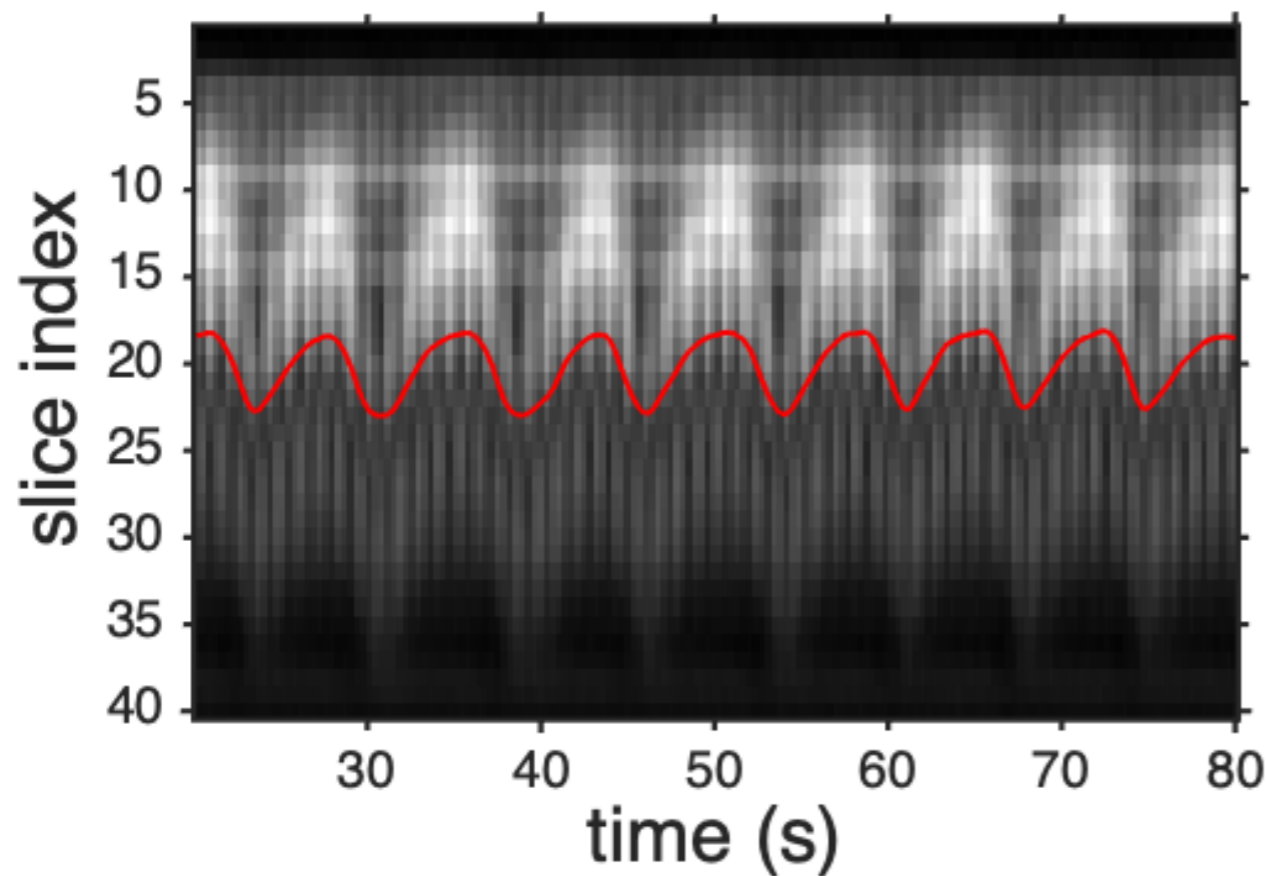
1D projections along z



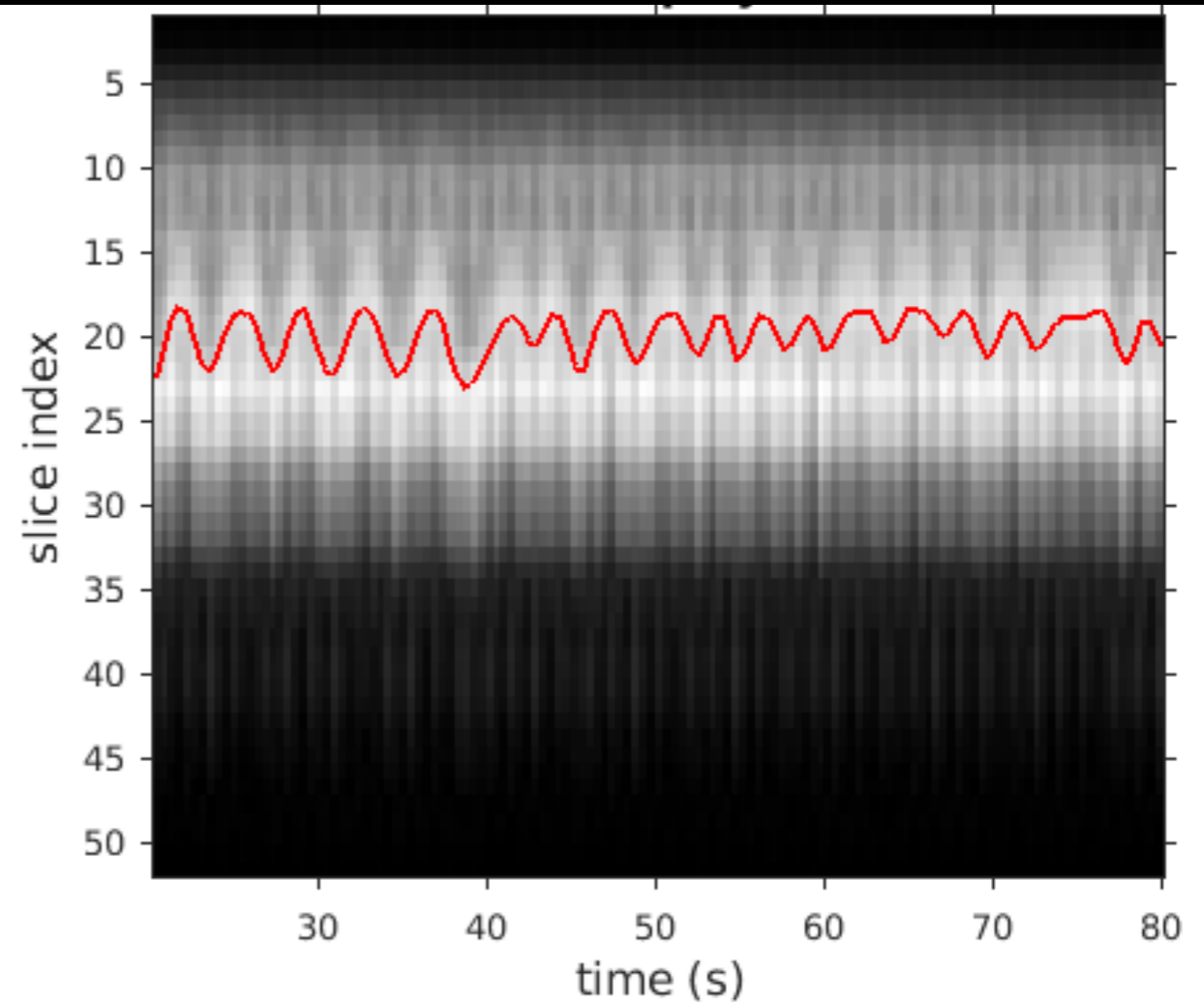
# Managing Respiratory Motion

*New Techniques: FB Non-Cartesian 3D MRI*

Projection-Based Self-Navigation



Example from an adult

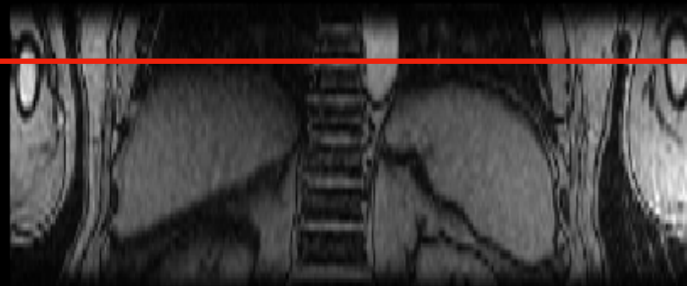


Example from a child

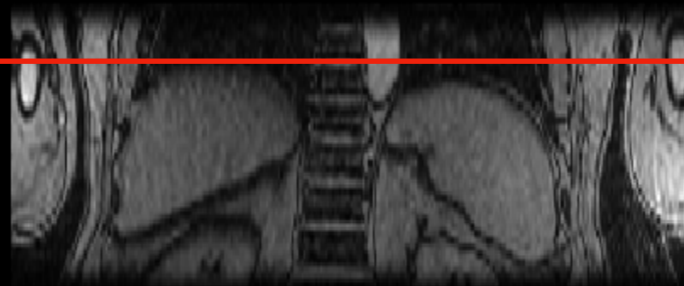
# Managing Respiratory Motion

*New Techniques: FB Non-Cartesian 3D MRI*

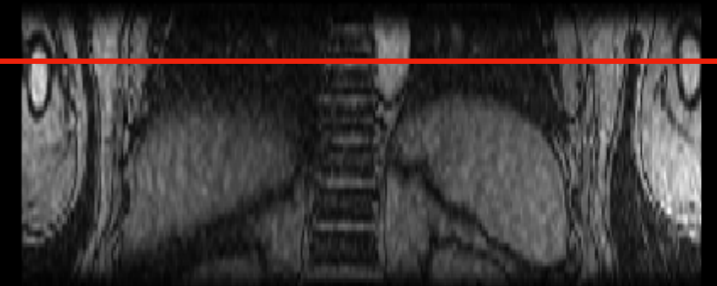
Motion-Resolved Reconstruction



**fully sampled  
(motion averaged)**



**Soft-gated  
Expiration**



**Soft-gated  
Inspiration**



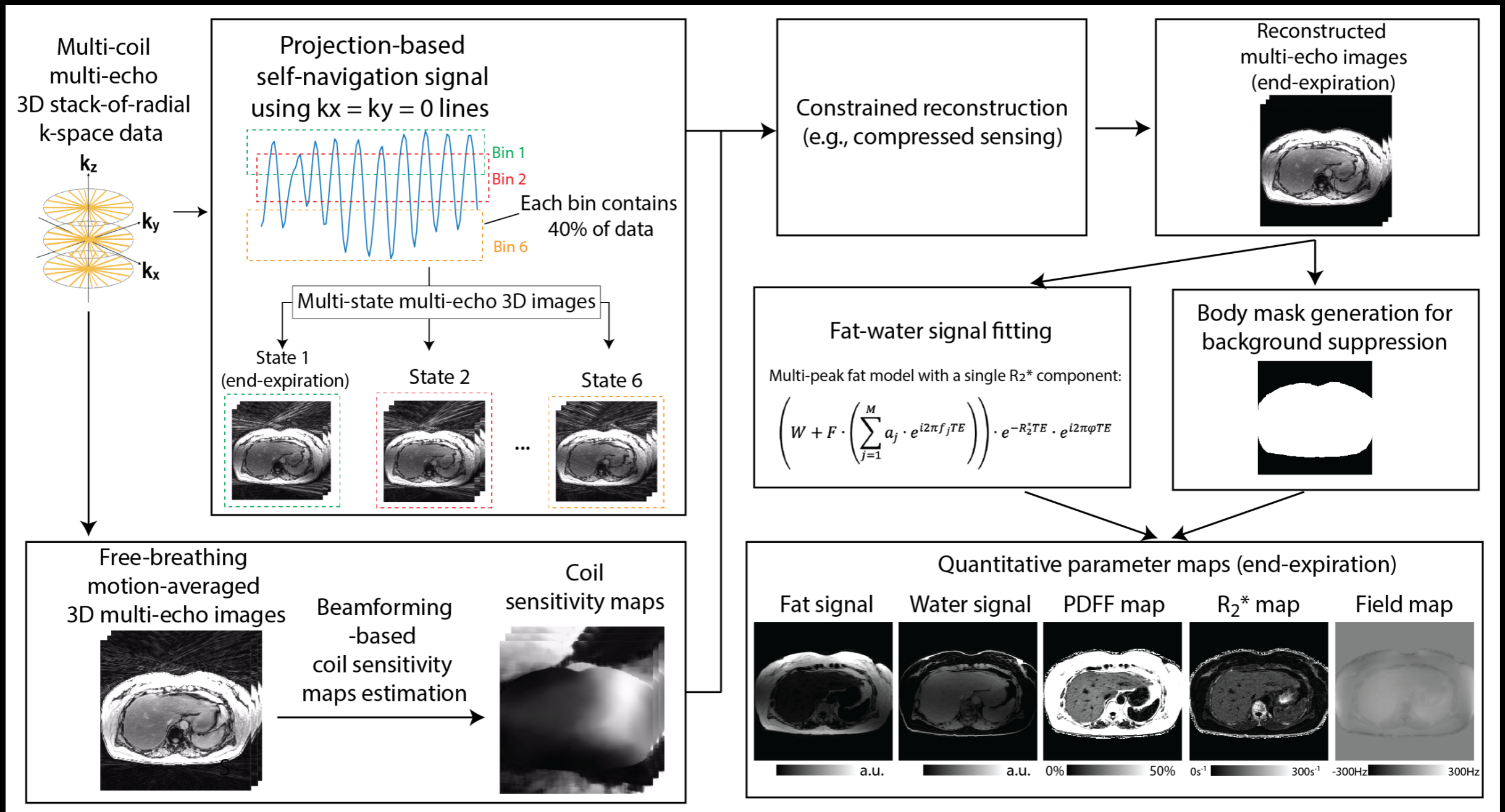
# Managing Respiratory Motion

- FB + Retrospective Compensation
  - Non-Cartesian acquisition
  - Self-navigation signal
  - determine the most consistent respiratory position (can also bin data into motion states)
  - reject or compensate data outside of consistent respiratory position
  - reconstruct data (may be undersampled) using prior information and constraints



# Managing Respiratory Motion

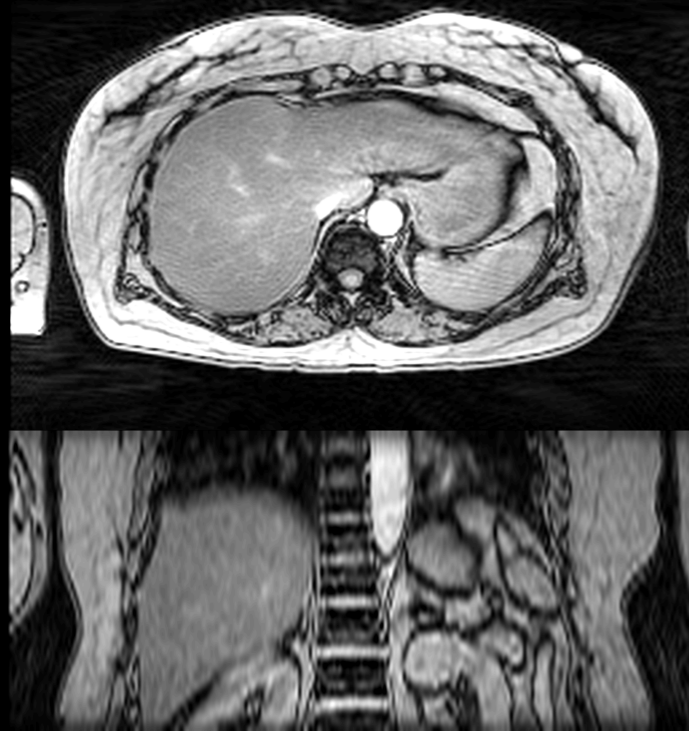
*New Techniques: FB Non-Cartesian 3D MRI + Motion-Resolved Recon*



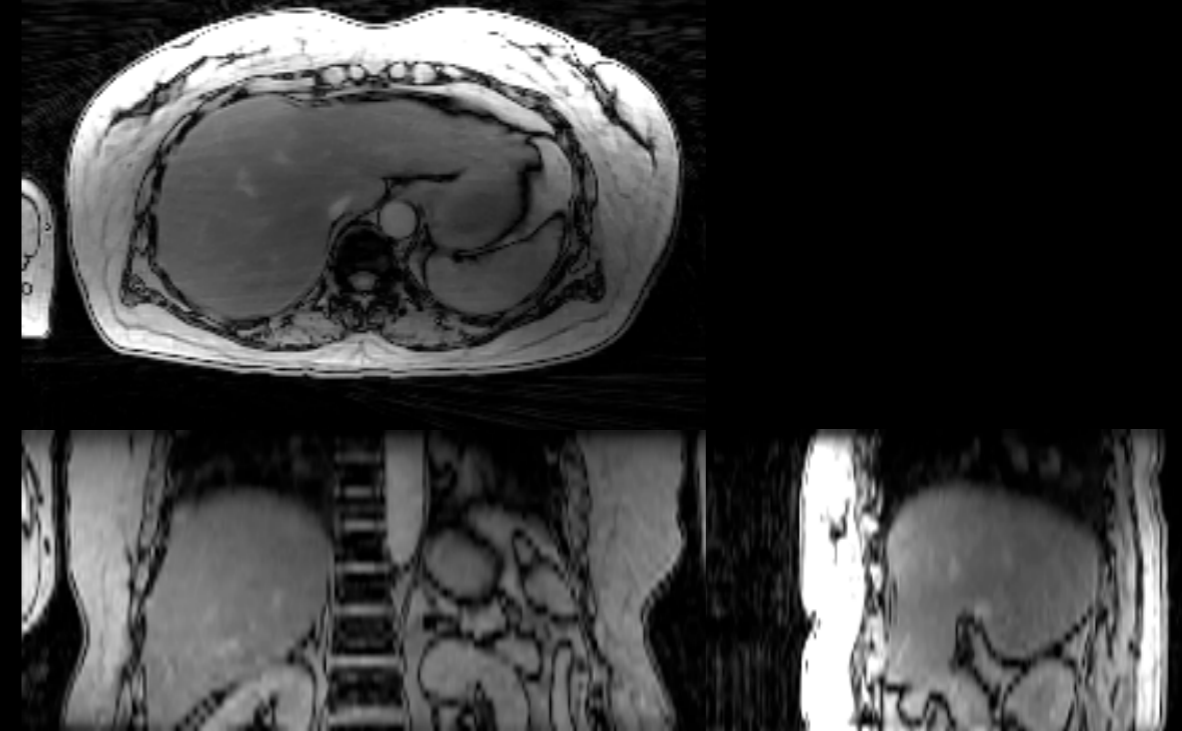
# Managing Respiratory Motion

*New Techniques: FB Non-Cartesian 3D MRI + Motion-Resolved Recon*

Motion averaged Echo 1 images (from scanner)



Self-gated CS-reconstructed Echo 1 images

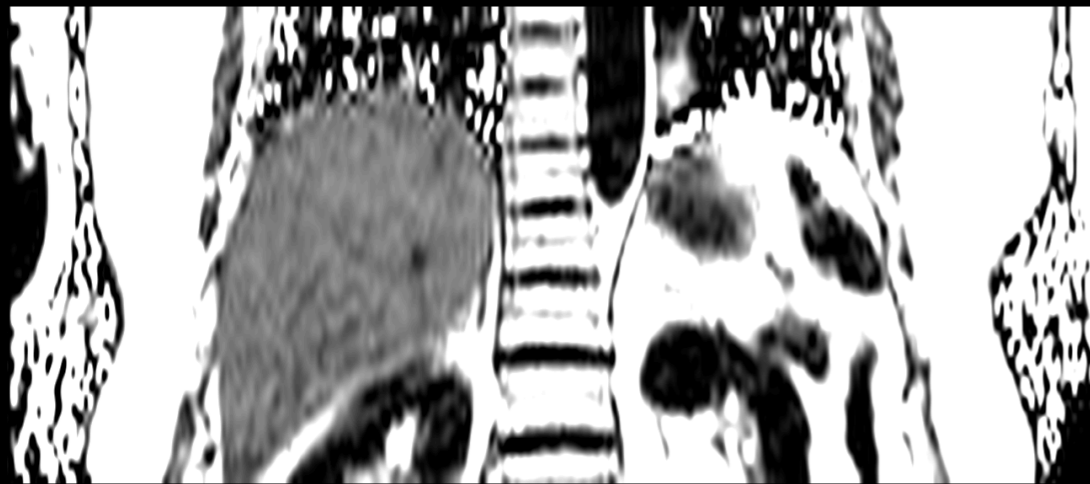




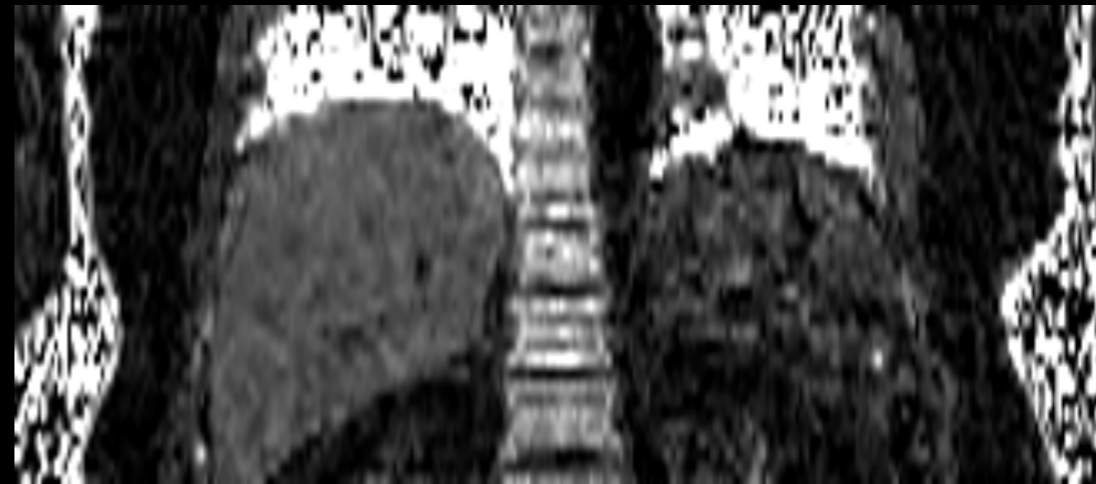
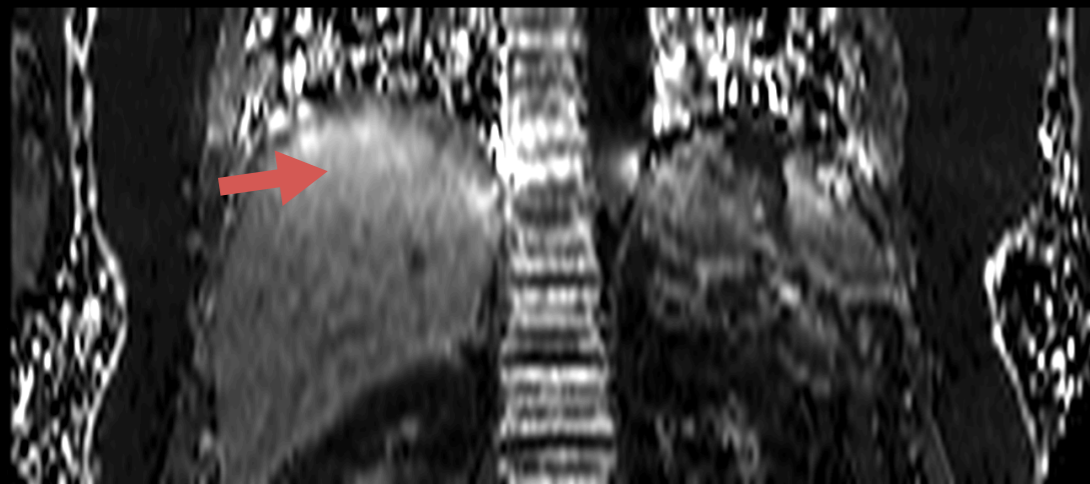
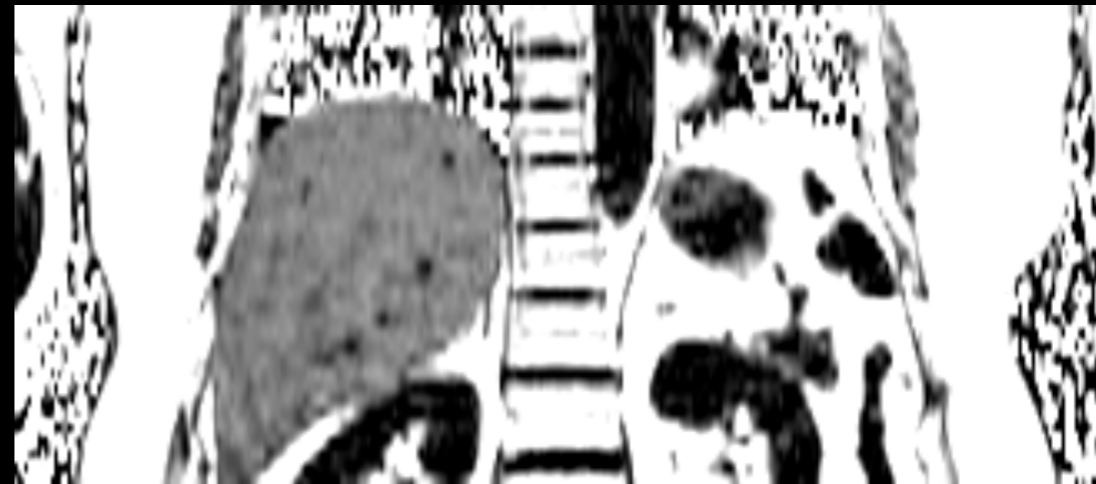
# Managing Respiratory Motion

*New Techniques: FB Non-Cartesian 3D MRI + Motion-Resolved Recon*

Motion averaged  
Quantitative PDFF and R2\* map



Self-gated CS-reconstructed  
Quantitative PDFF and R2\* map



50%

0%

300s<sup>-1</sup>

0s<sup>-1</sup>

# Summary

- MRI and Motion
- Techniques to Manage Motion
- Managing Cardiac Motion
- Managing Respiratory Motion
  
- Resolving motion
  - Important source of information



# References and Information

- Handbook of MRI Pulse Sequences, Ch 11.5 & Ch 12
- References on each slide

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