Managing Motion for MRI

M229 Advanced Topics in MRI

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Class Business

- Guest lecture on 5/9 Thu
- Project Proposal due 5/10 Fri
- ISMRM week - no class

- Finish ORC from last lecture

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

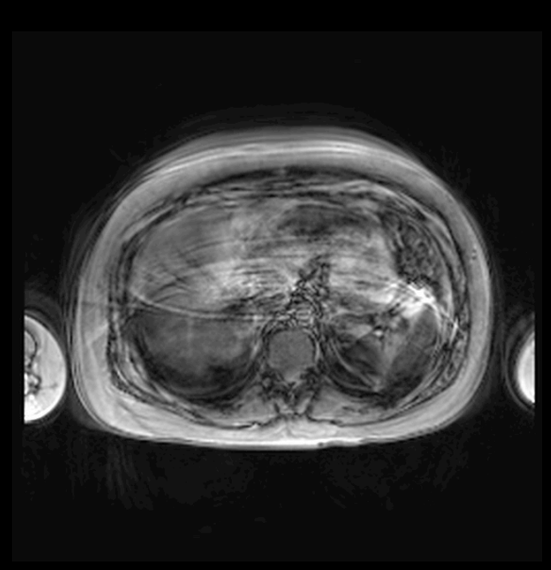
MRI and Motion

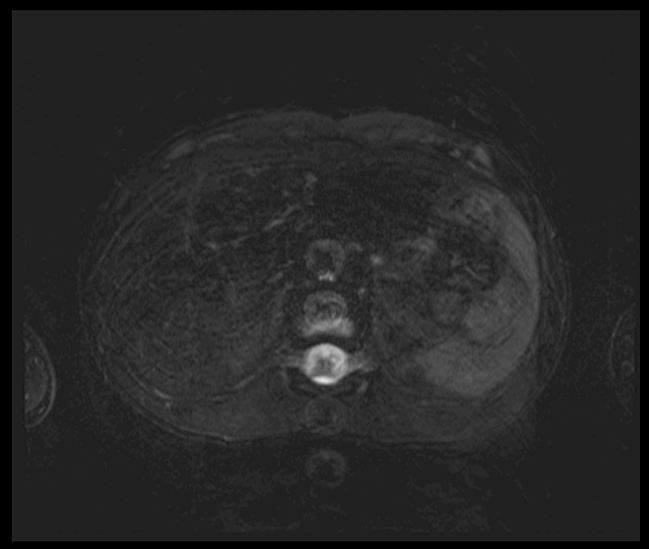
- Motion Sources, Time Scales, Magnitudes
  - cardiac: ~60 bpm (1 Hz), mm
  - respiratory: ~5 sec/breath (0.2 Hz), mm - cm
  - bulk motion: mm - cm
  - vascular pulsation, CSF pulsation: mm
  - peristalsis: mm
  - swallowing, coughing, twitching: mm - cm

  - 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

Phase 1	Phase 2	Phase 3	…	Phase N

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

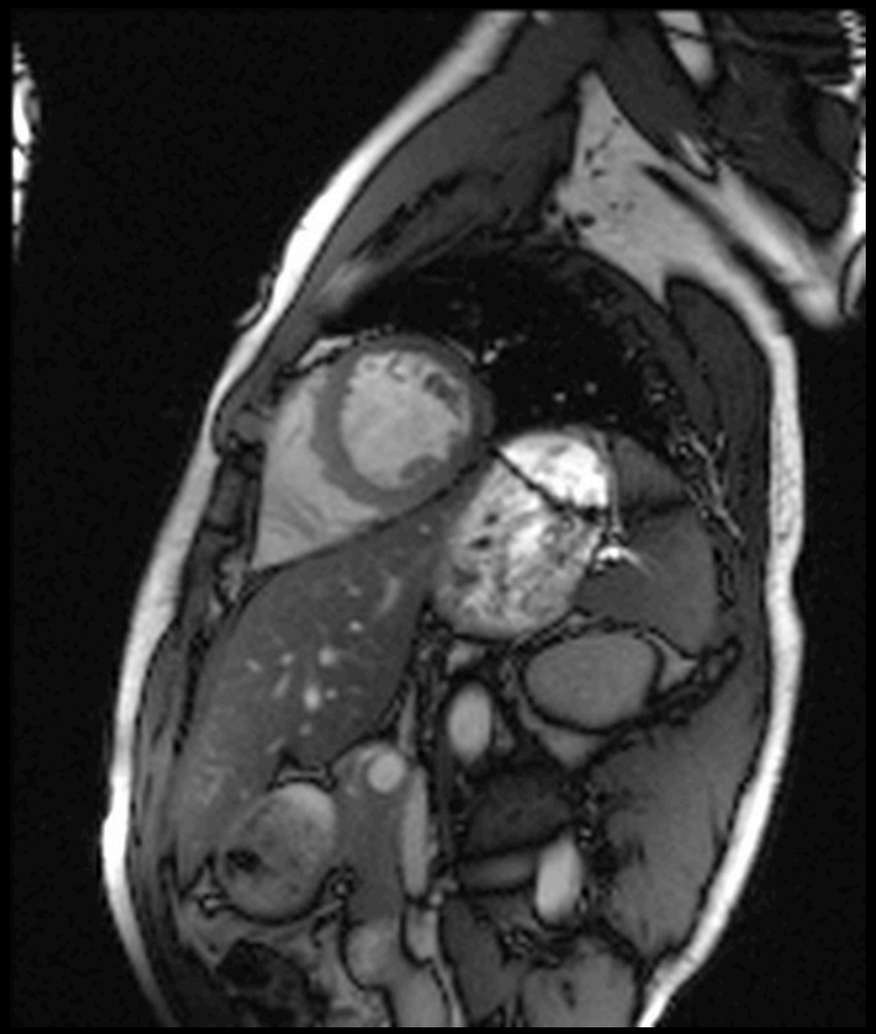
Managing Cardiac Motion

- Real-Time MRI

Phase 1	Phase 2	Phase 3	…	Phase N
MR image 1	MR image 2	MR image 3	…	MR image N

Managing Cardiac Motion

- Real-Time MRI



courtesy of Dr. Daniel Ennis

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

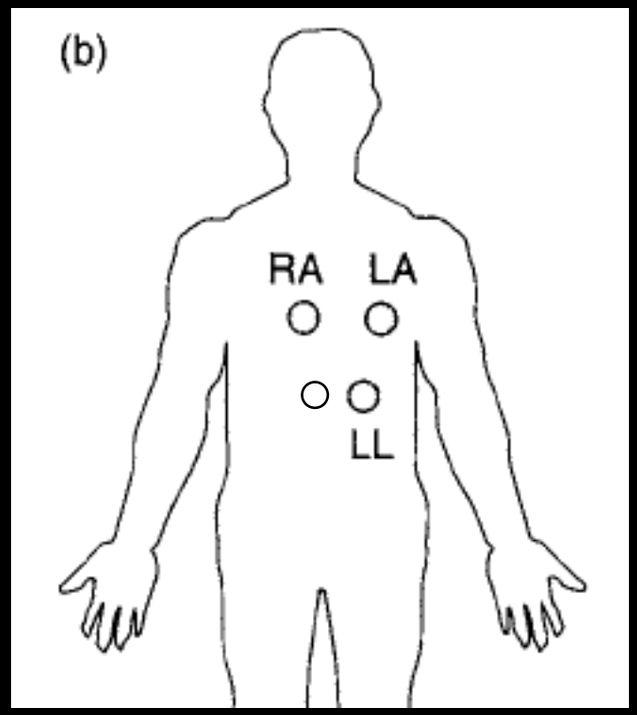
- Cardiac Triggering
  - ECG or pulse ox signal
  - sync scan to cardiac cycle
  - assume steady HR
  - segmented acquisition
    acquire subset of data each HB
    fully acquire data over multiple HBs

  - Need to manage respiratory motion as well
    e.g., breath holding (BH)

Managing Cardiac Motion

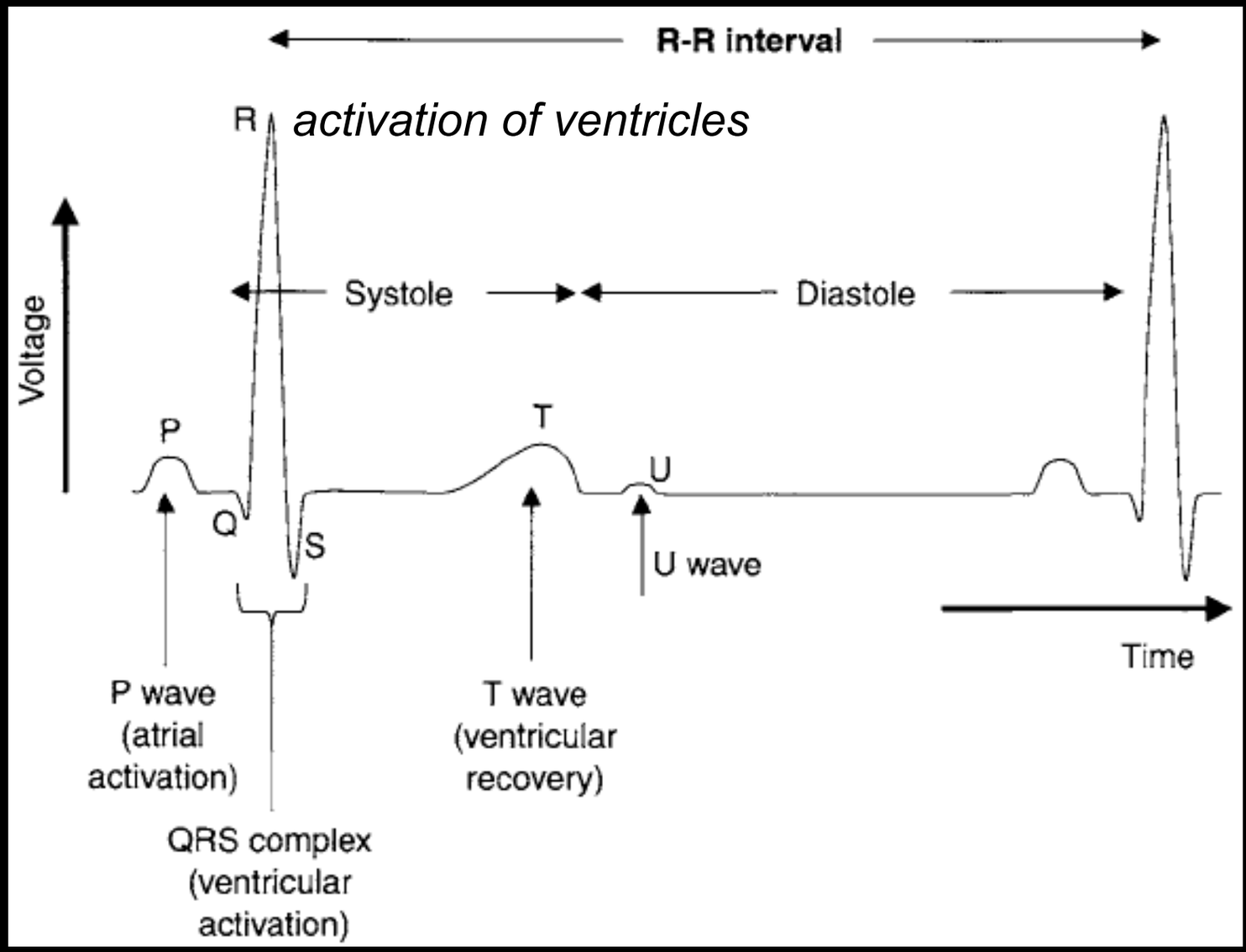
Cardiac Triggering

ECG lead placement



Managing Cardiac Motion

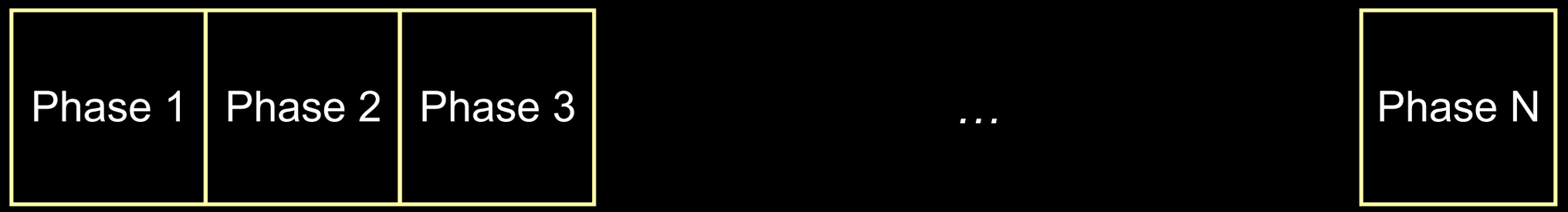
Cardiac Triggering



R-R interval [ms] = 60,000 / heart rate [bpm]

Managing Cardiac Motion

Cardiac Triggering



Managing Cardiac Motion

HB 1

Cardiac Triggering + Segmented Acq

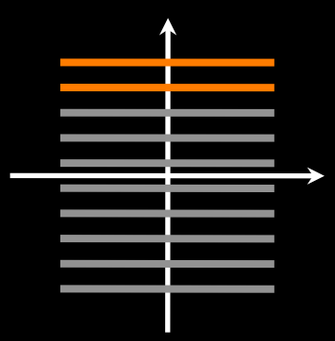


image 1 seg 1	image 2 seg 1	image 3 seg 1	…	image N seg 1

How many lines per segment?
- LinesPerSeg * TR = temporal duration of “cardiac phase”

Managing Cardiac Motion

HB 1

Cardiac Triggering + Segmented Acq

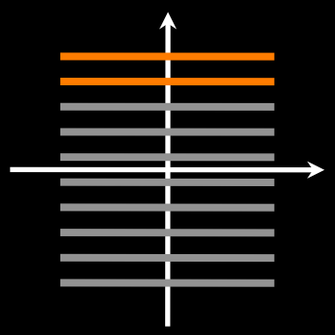


image 1 seg 1	image 2 seg 1	image 3 seg 1	…	image N seg 1

HB 2

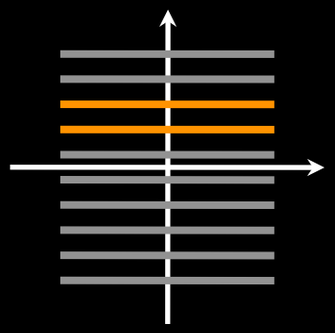


image 1 seg 2	image 2 seg 2	image 3 seg 2	…	image N seg 2

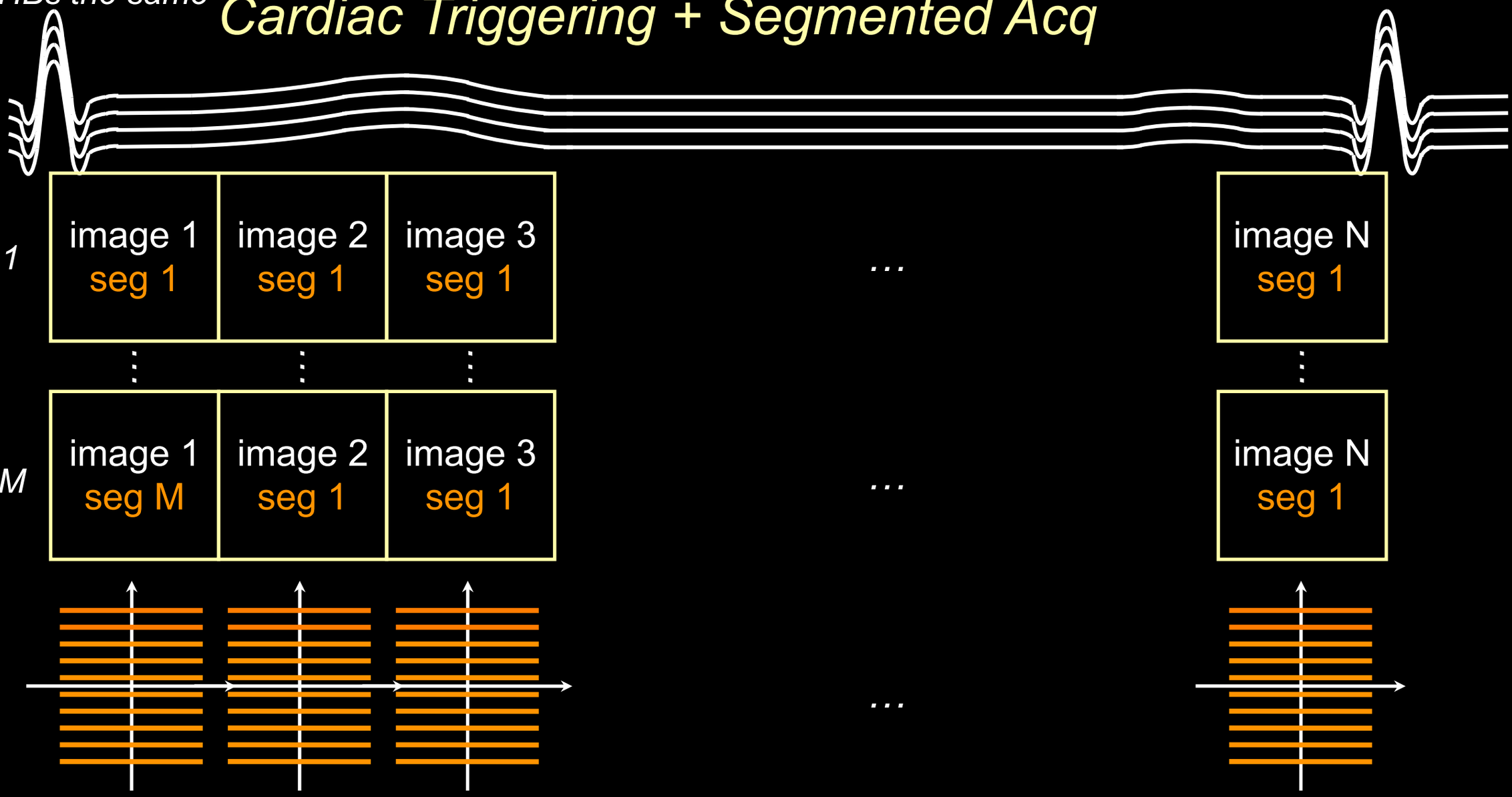
How many heartbeats (HB) needed?

- need M = NumKspLines / 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

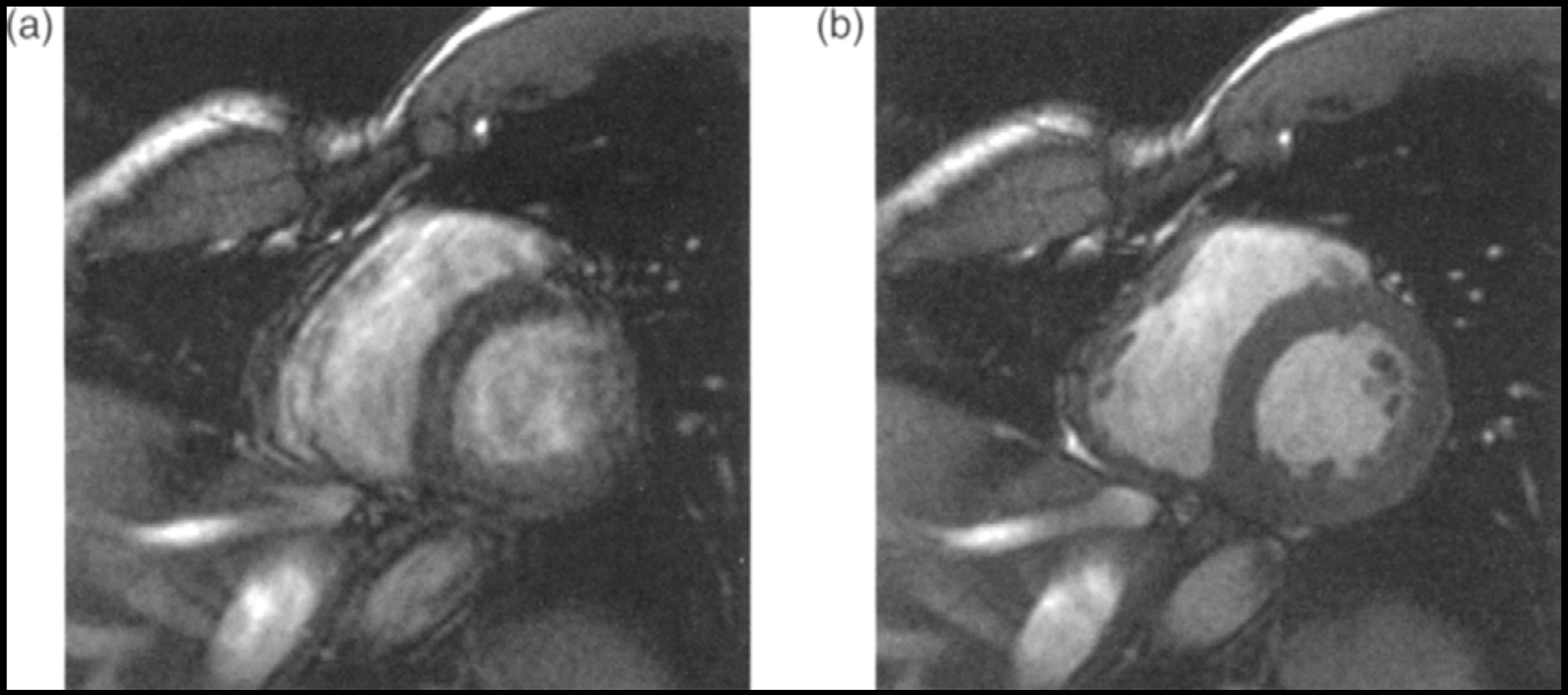
image 1	image 2	image 3	…	image N

Phase 1	Phase 2	Phase 3	…	Phase N

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

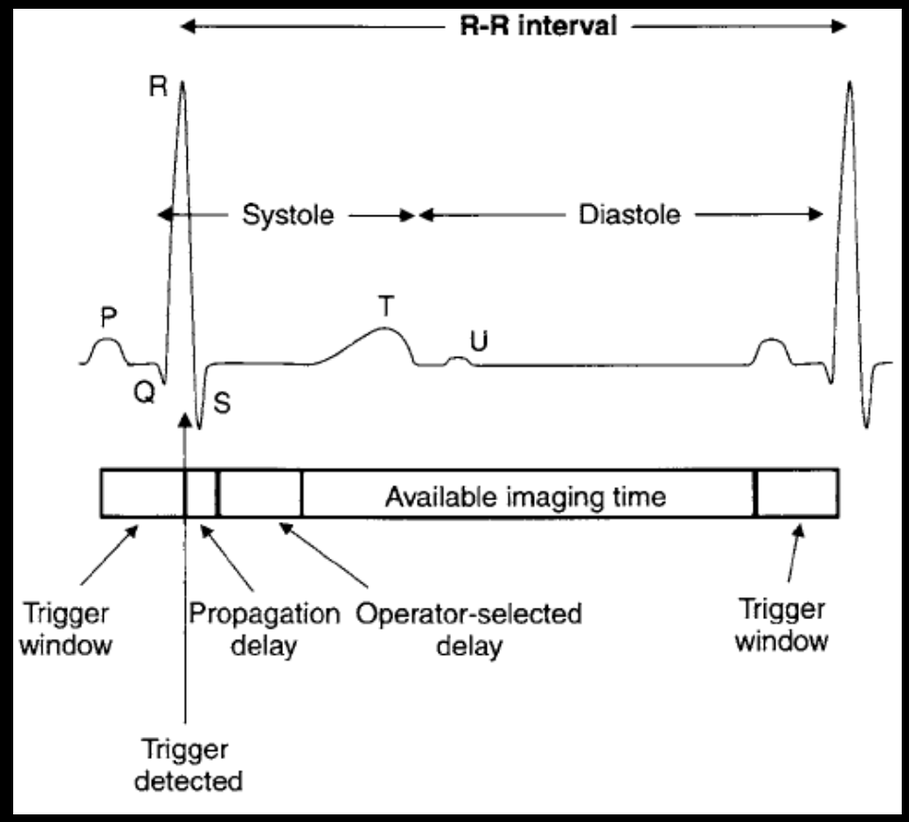
Managing Cardiac Motion

Cardiac Triggering

Managing Cardiac Motion

- Prospective triggering

- Retrospective triggering



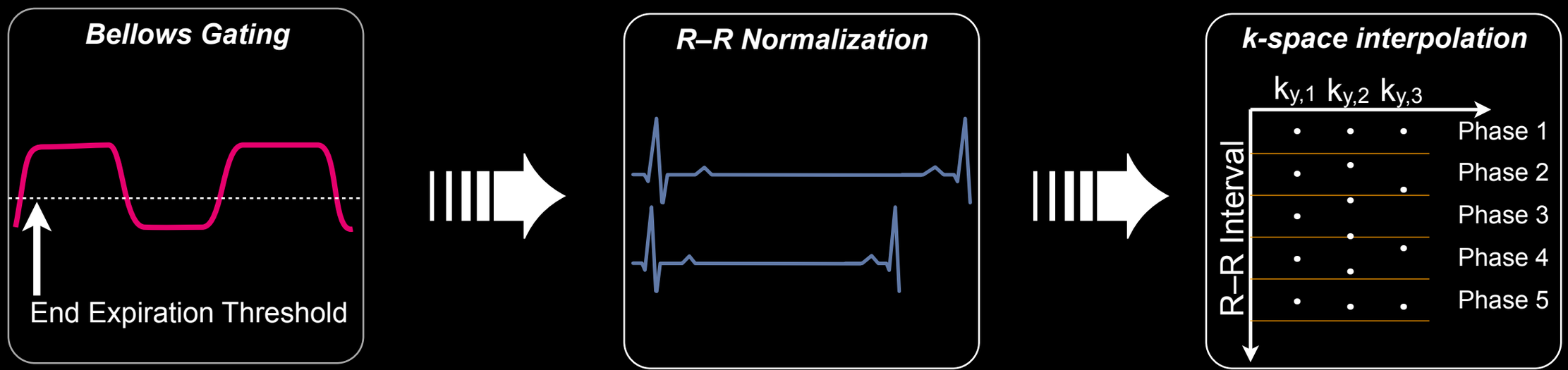
- *Advantages and Disadvantages?*

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



Srinivasan S, et al. MRM 2015

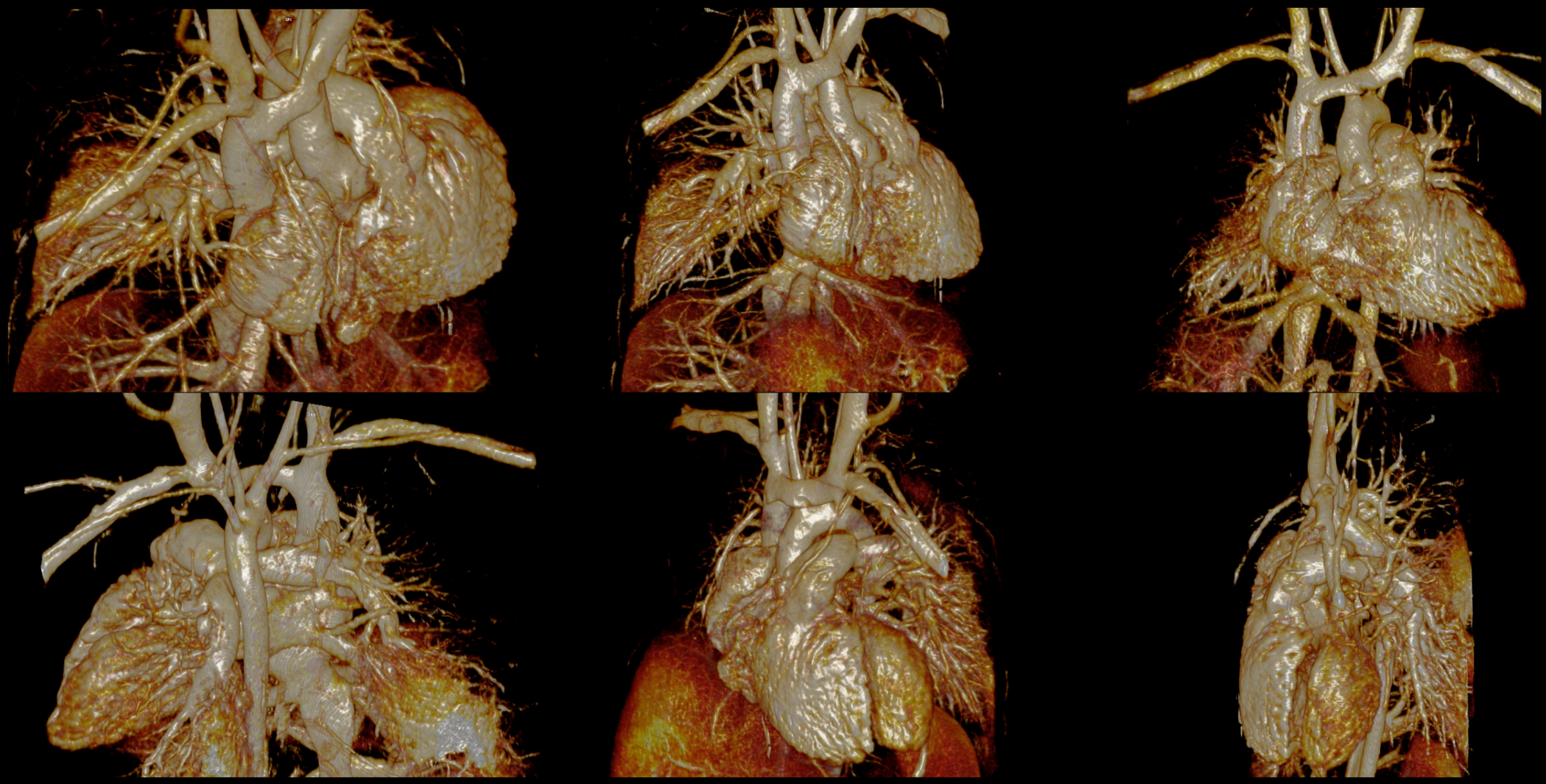
courtesy of Dr. Daniel Ennis

David Geffen School of Medicine

UCLA Radiology

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

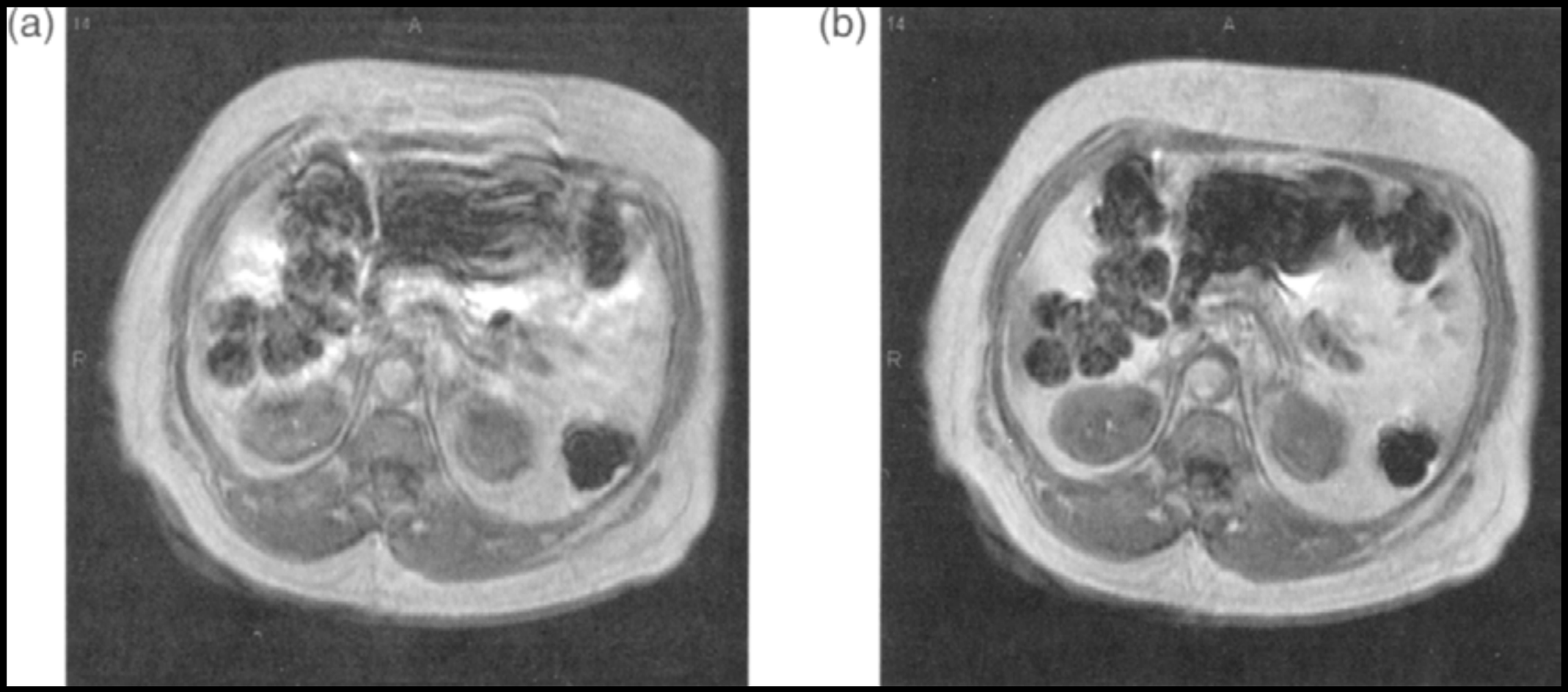
- Respiratory Motion
  - voluntary
  - non-rigid
    mostly S/I
  - quasi-periodic

  - ~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

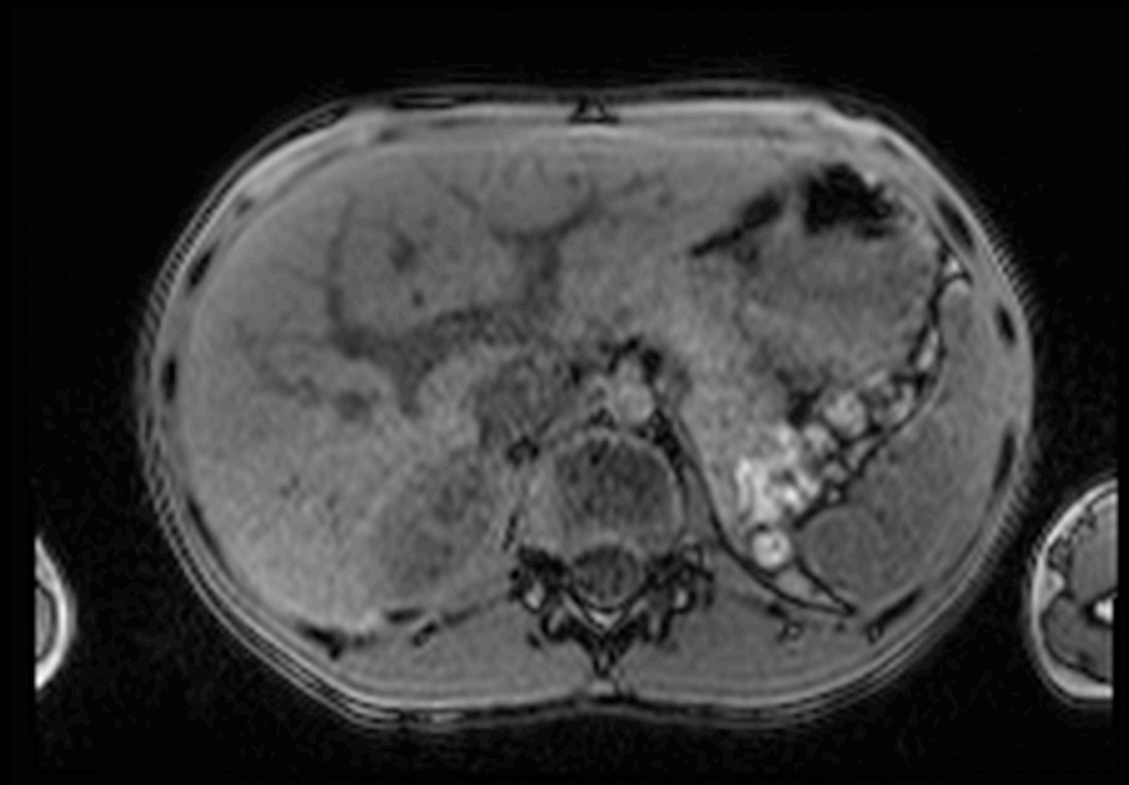
With breath-holding

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

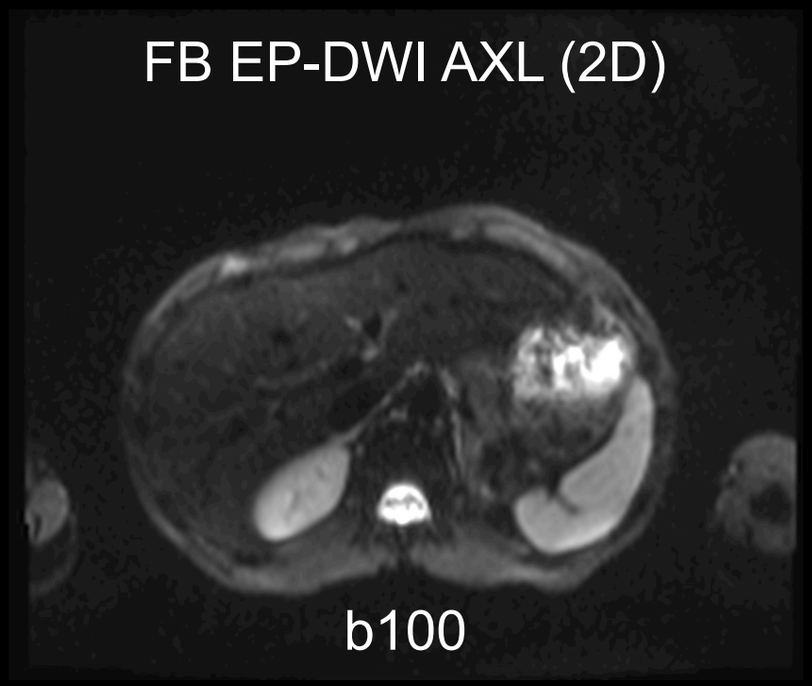
- BH MRI: Challenges
  - short BH duration
    compromises in scan parameters
  - imperfect BH
    residual motion artifacts (e.g., aliasing)
  - multiple BH scans
    wears subject down
    inconsistent BH position
  - patient may be unable to BH

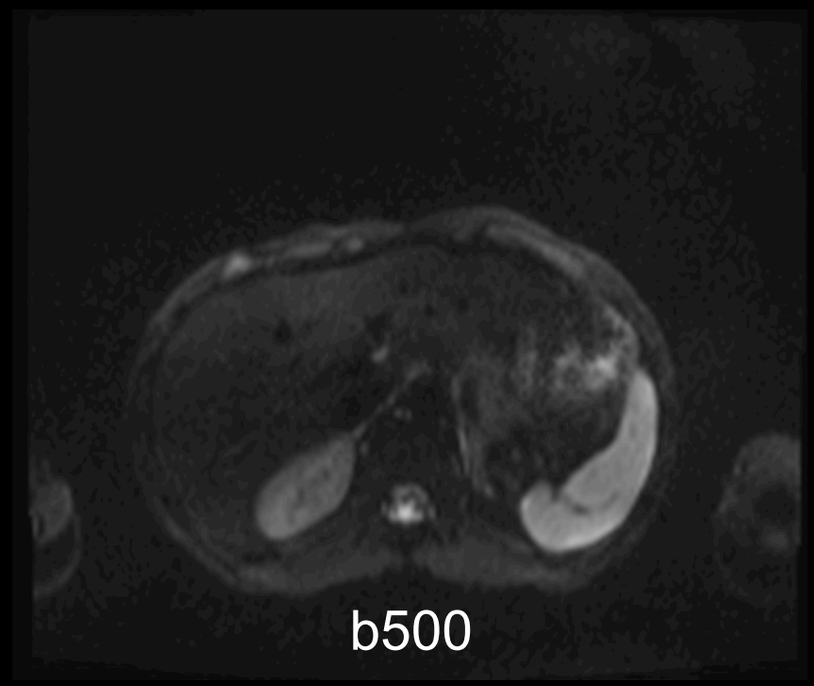
Managing Respiratory Motion

- 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)


b100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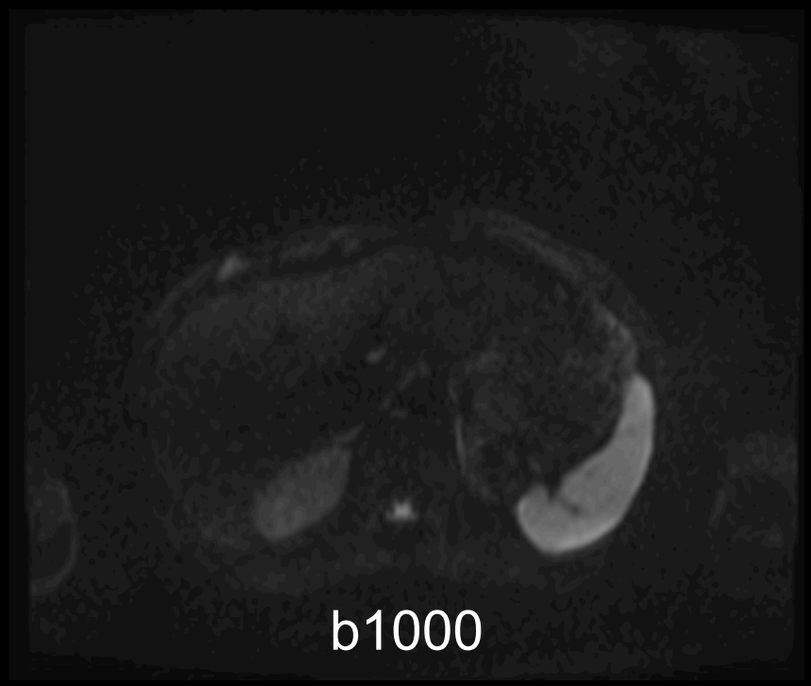
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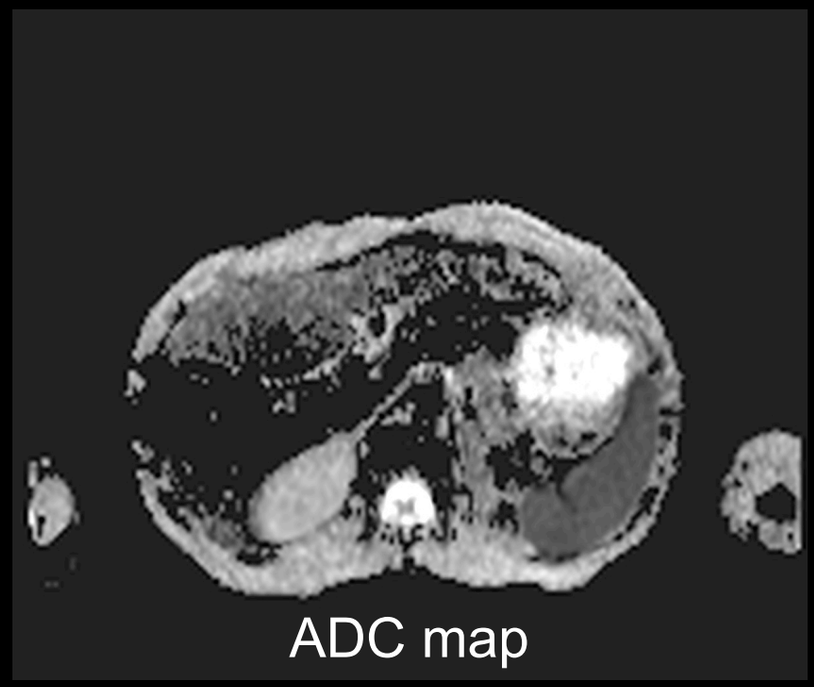

ADC map

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

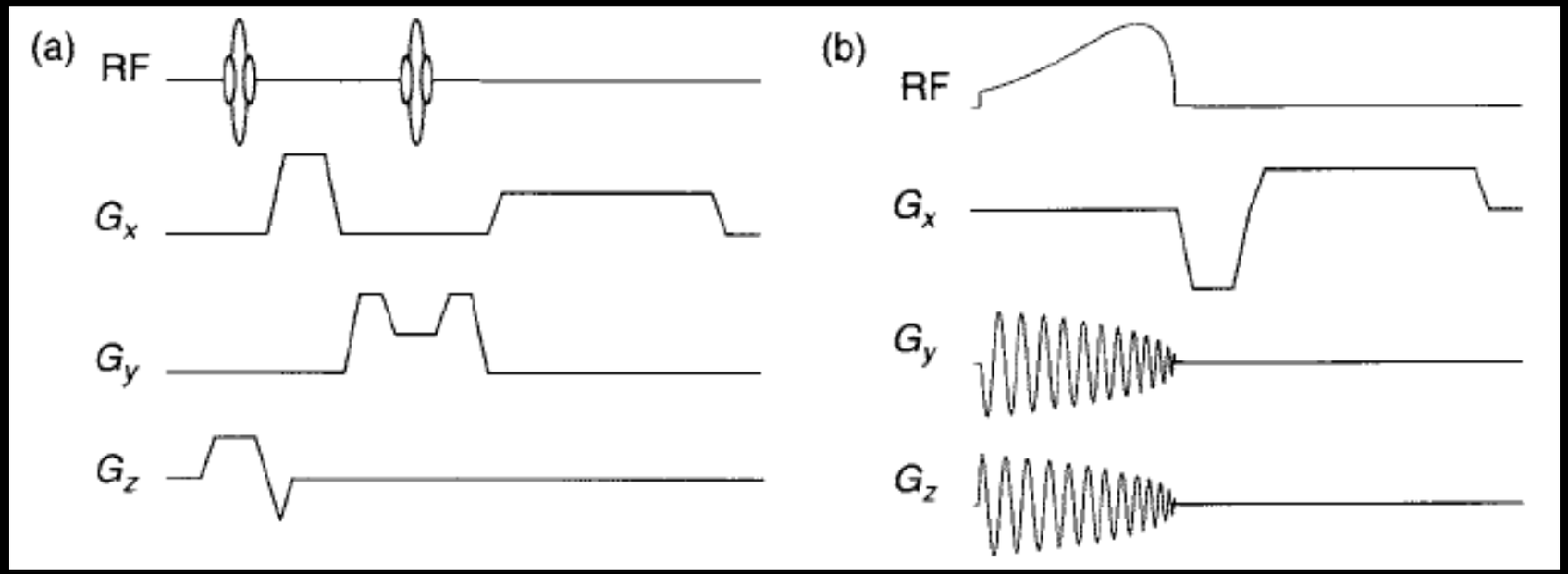
- MR Navigators
  - MR data to track motion
  - Assumes negligible motion between navigator and imaging data
  - Use navigator info to prospectively or retrospectively compensate for motion

Managing Respiratory Motion

MRI with Navigators

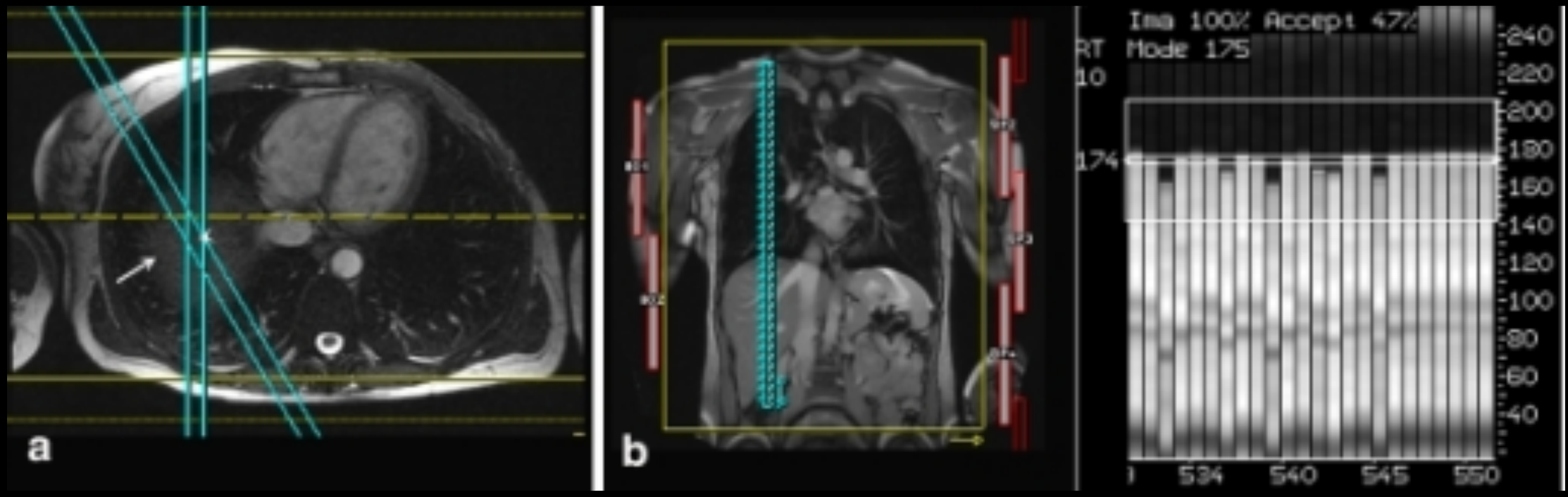
Managing Respiratory Motion

MR Navigator: 1D Example



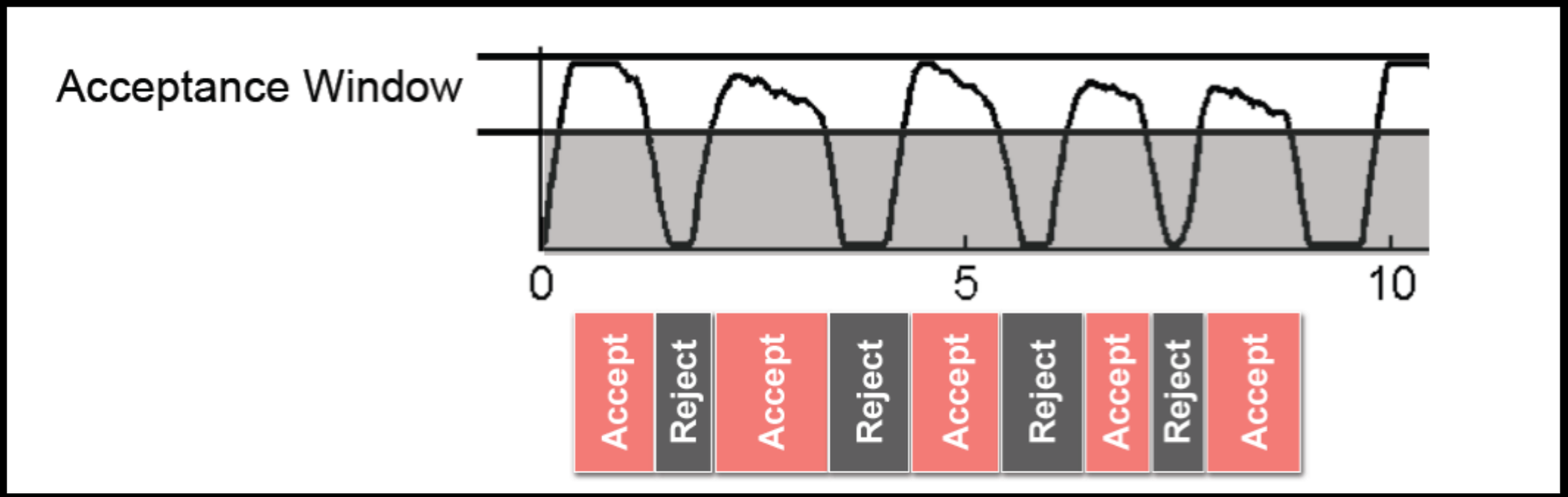
Managing Respiratory Motion

MR Navigator: 1D Example



Managing Respiratory Motion

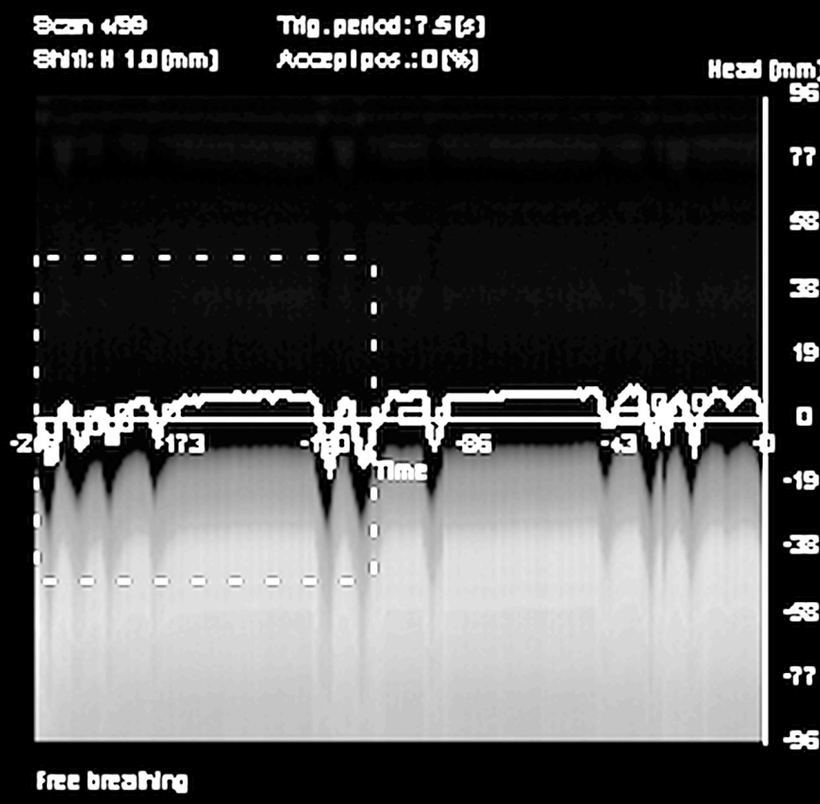
Respiratory Gating

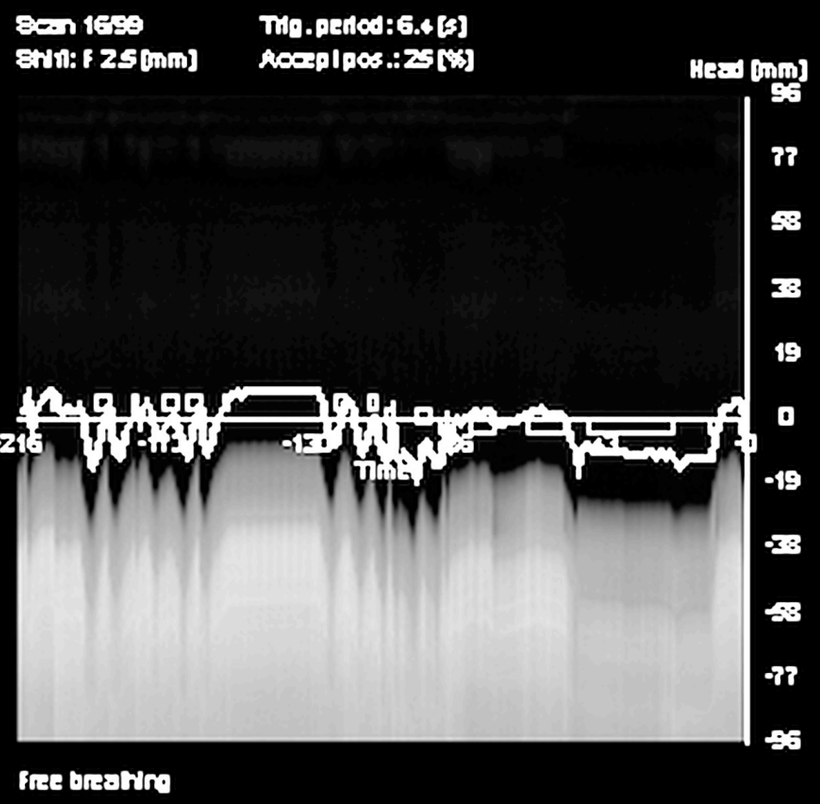


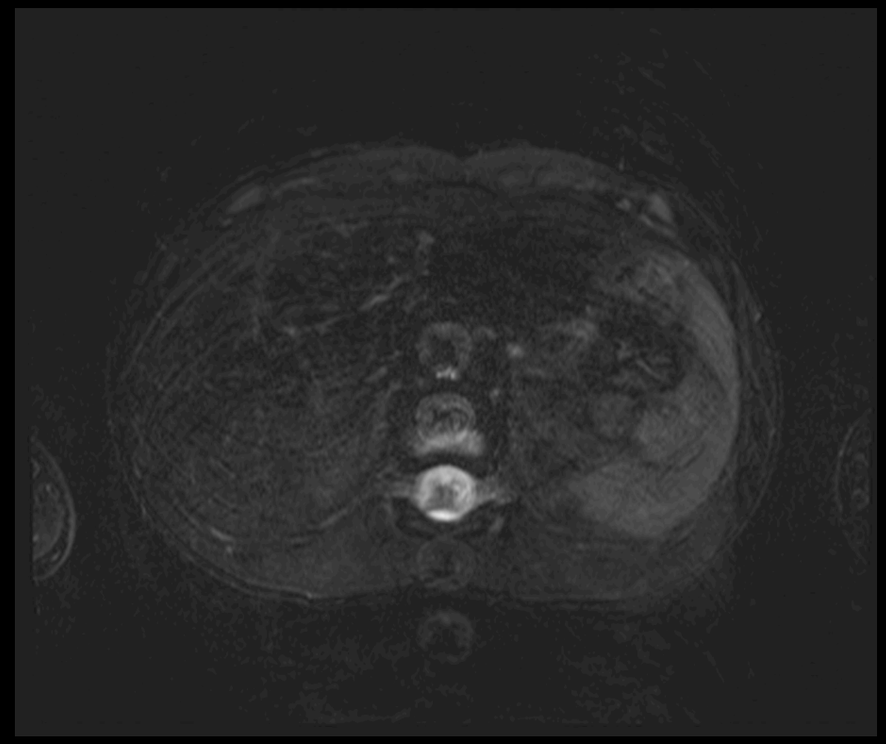
Prospective vs. Retrospective

Managing Respiratory Motion

Respiratory Gating







FB T2w TSE AXL (2D)

Managing Respiratory Motion

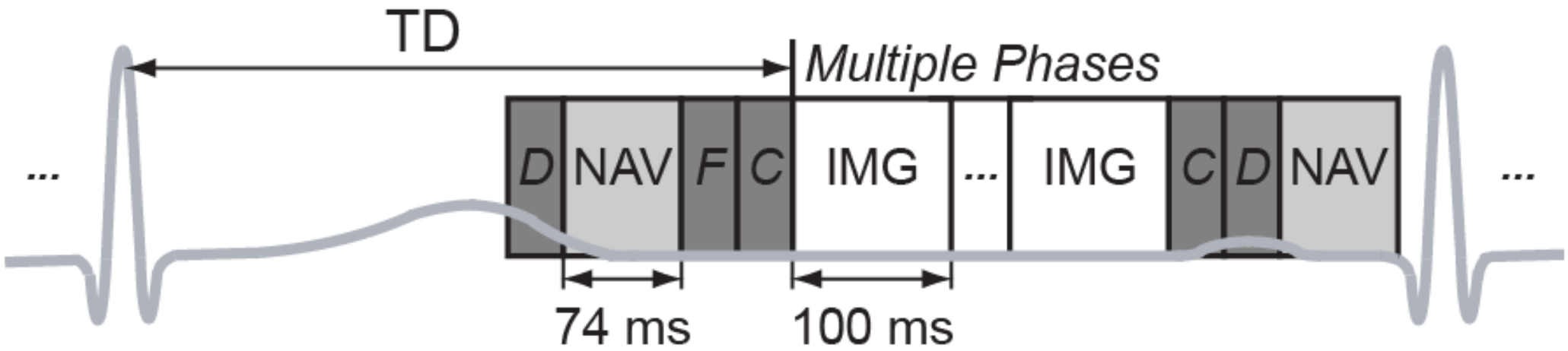
- FB + Respiratory Gating: Challenges
  - inconsistent respiratory pattern
  - residual motion artifacts (e.g., aliasing)
  - can be long scans with unknown duration

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

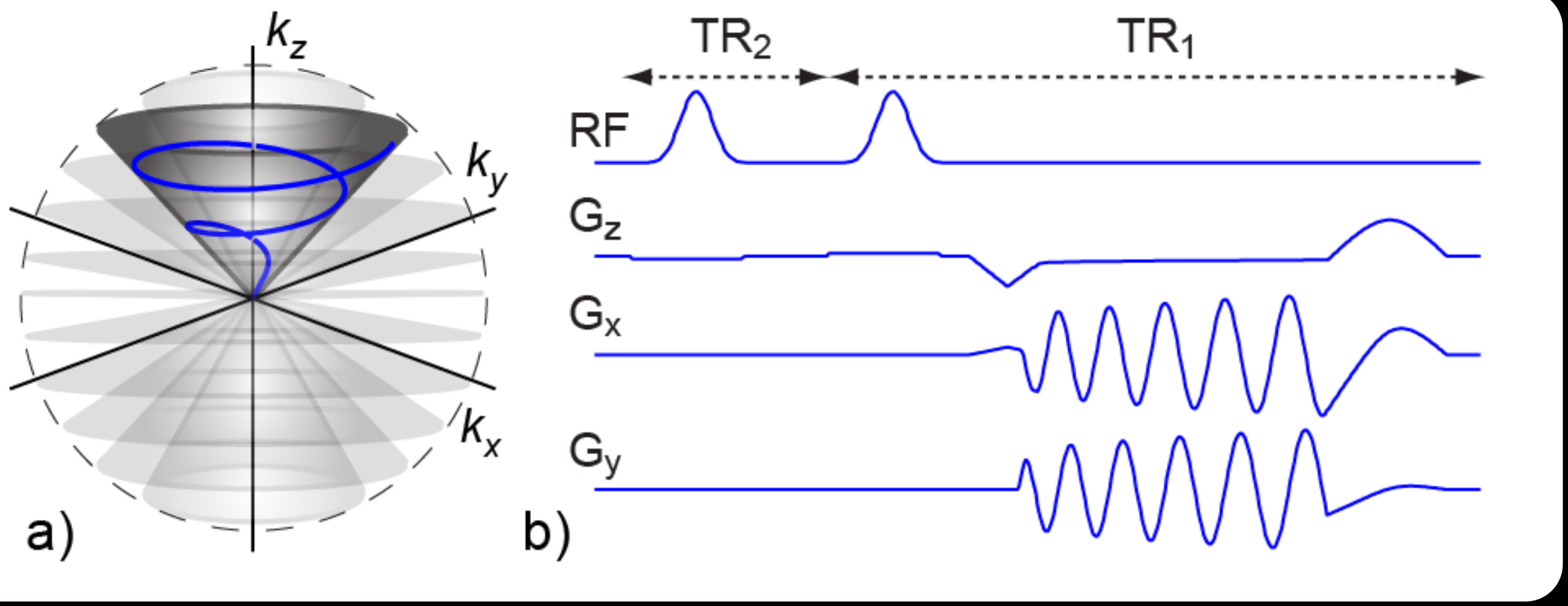
FB + Cardiac Triggering + Navigators



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



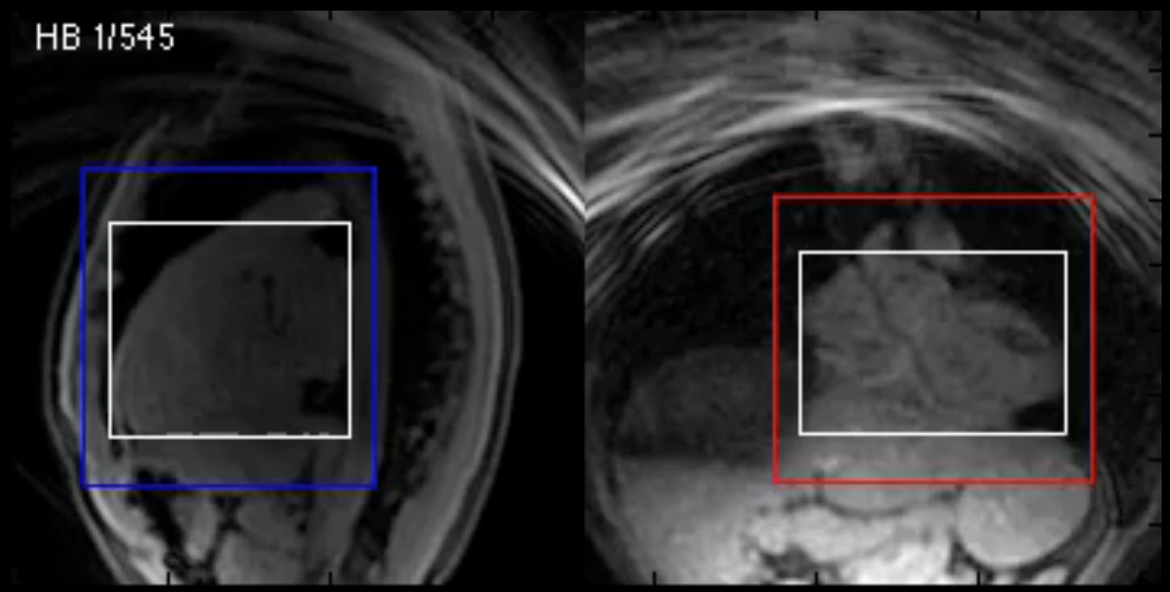
3D Cones

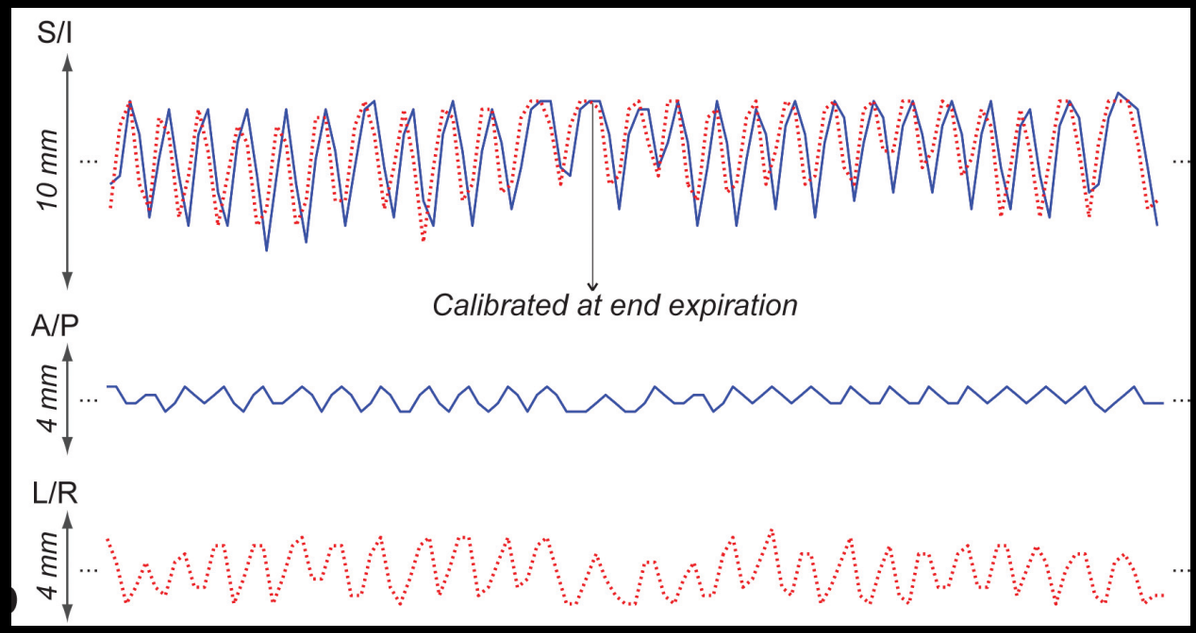
Alternating-TR SSFP Sequence

Managing Respiratory Motion

MR Image-Based Navigators

multi-resolution algorithm
template matching
3D rigid body motion

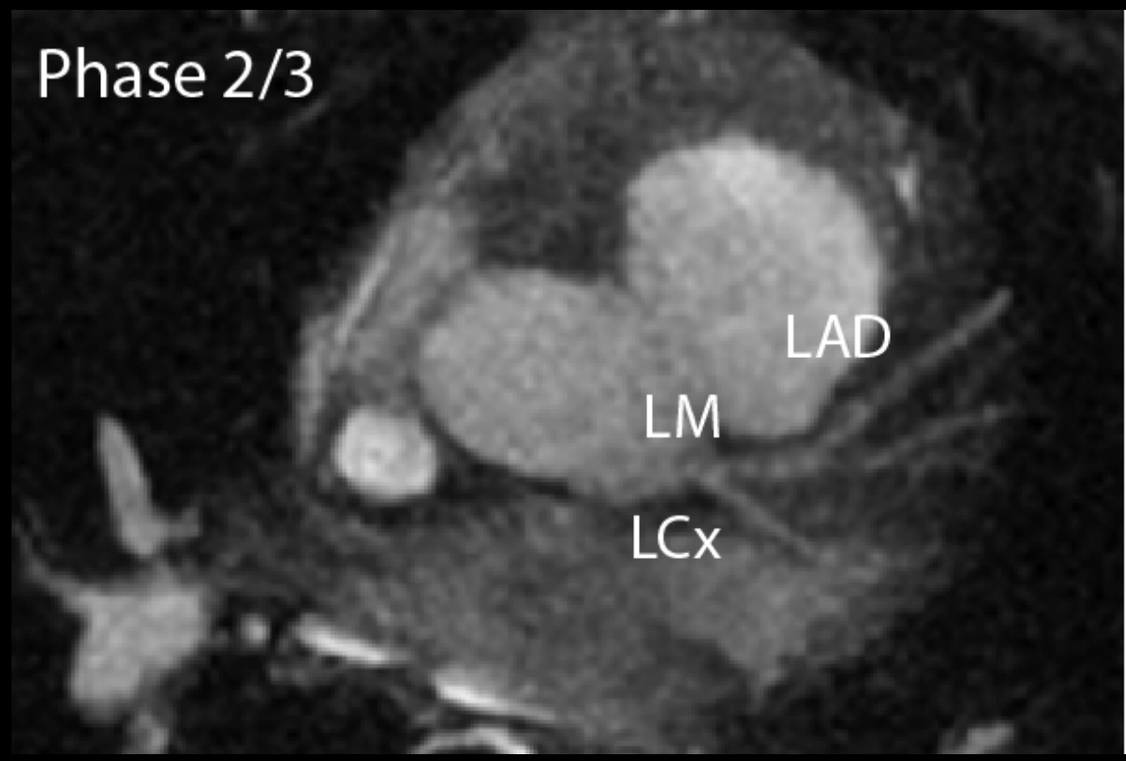




Managing Respiratory Motion

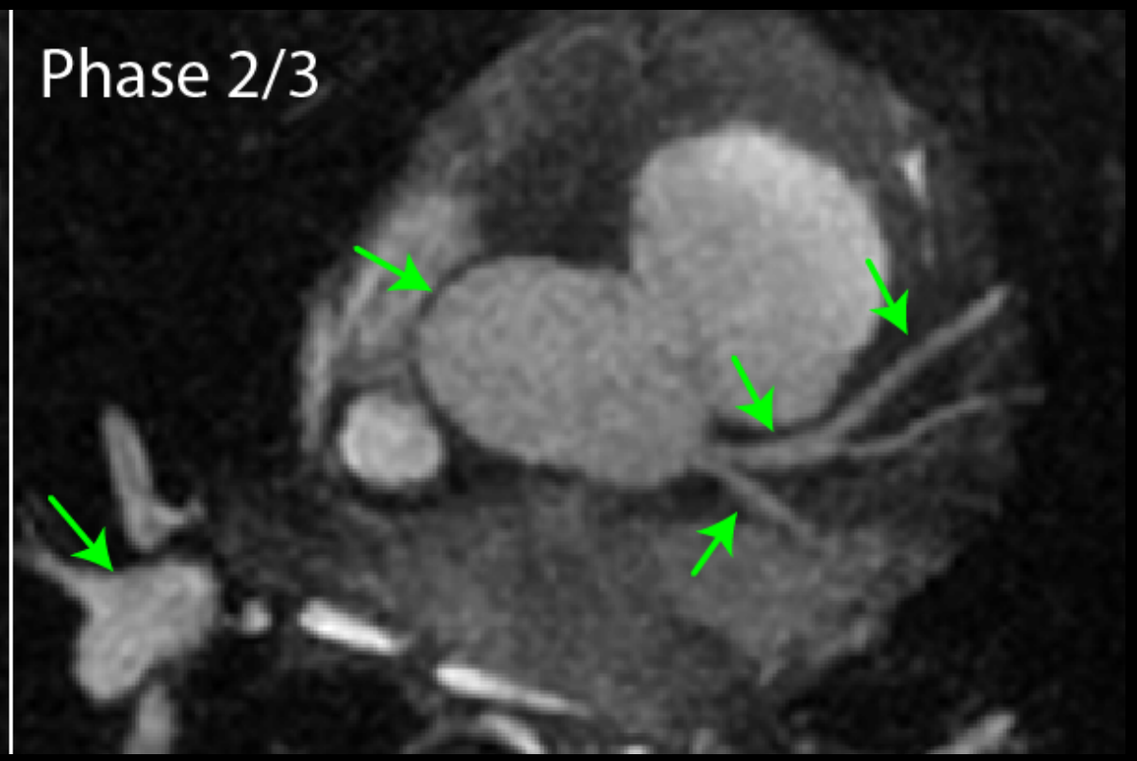
Retrospective Motion Compensation

No Motion Correction



Already recognize vessels

<u>After</u> Motion Correction

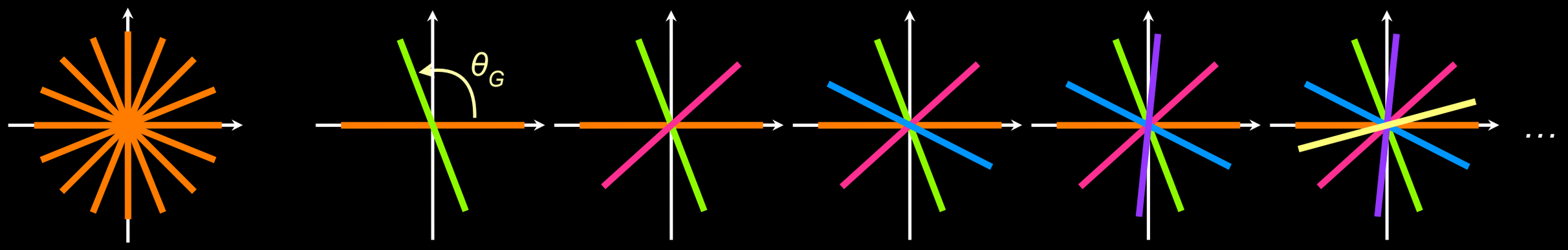


Sharpening of features (arrows)

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

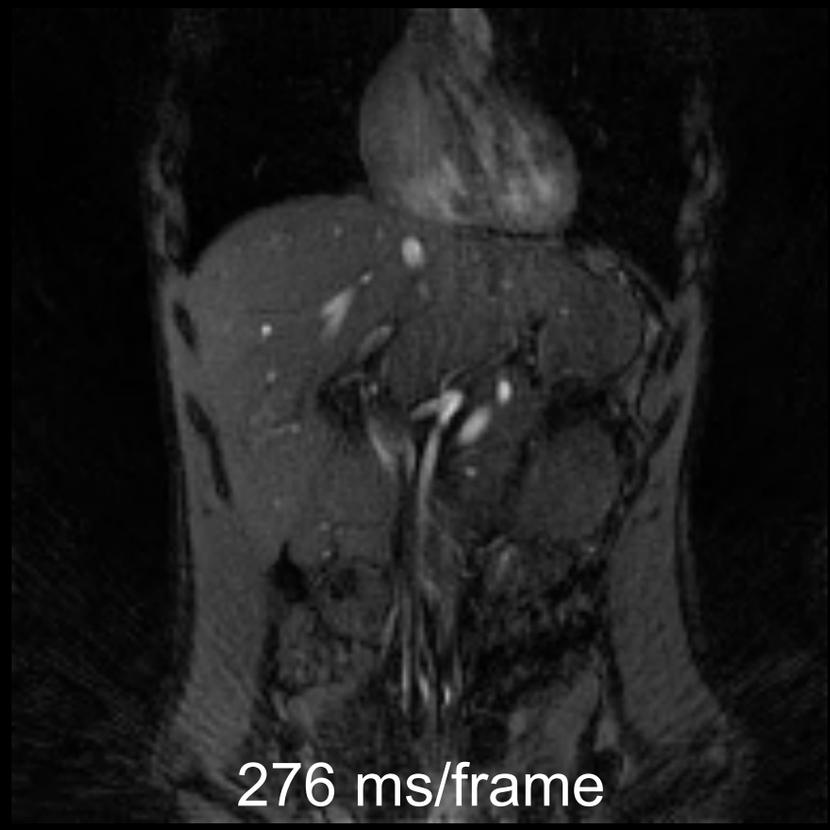
Managing Respiratory Motion

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



2D Radial

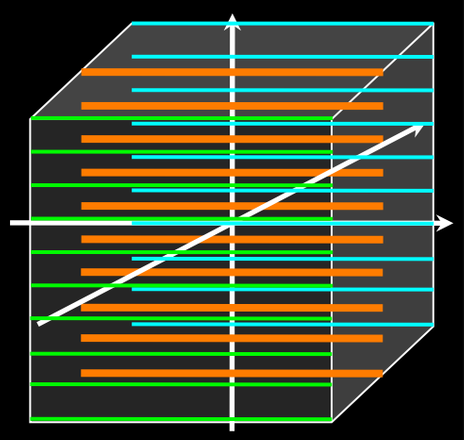
Golden angle ordering



Managing Respiratory Motion

New Techniques: FB Non-Cartesian 3D MRI

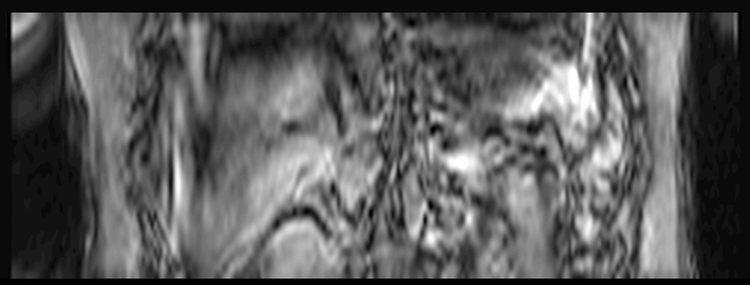
BH 3D Cartesian MRI



3D Cartesian

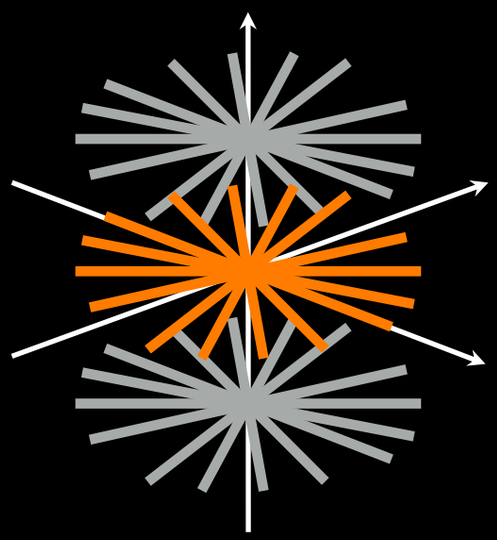
imperfect BH

AXL



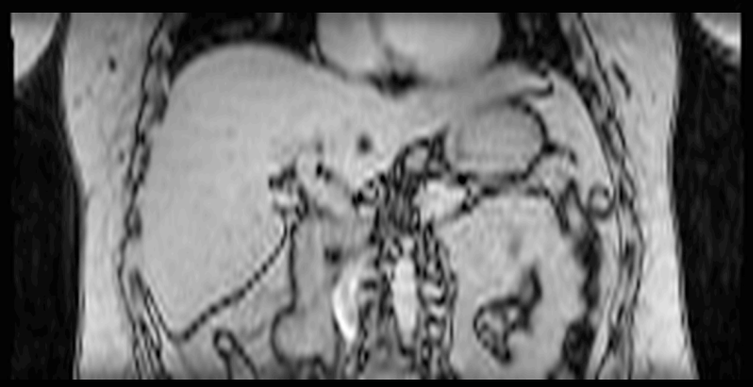
COR reformat

FB 3D Stack-of-Radial MRI



3D Stack of Radial

AXL

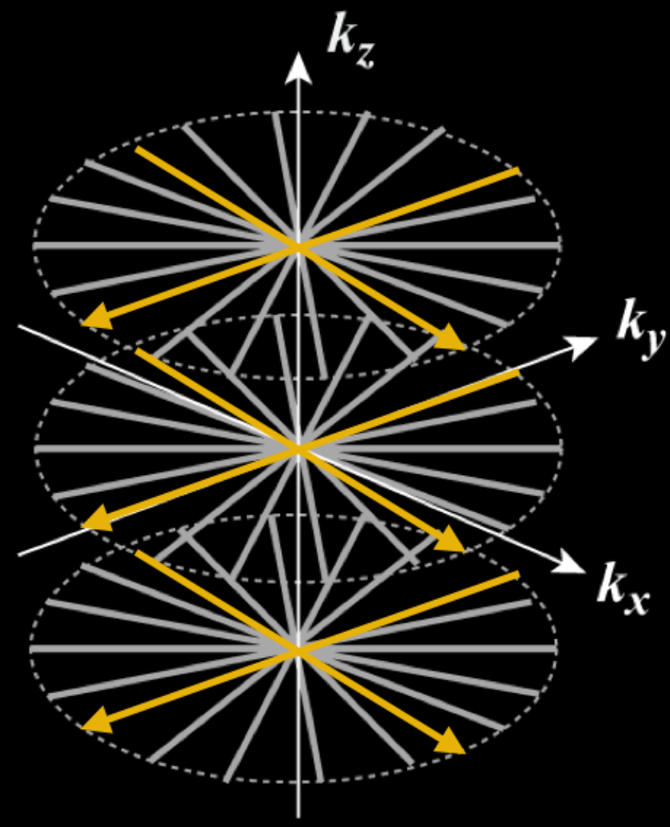


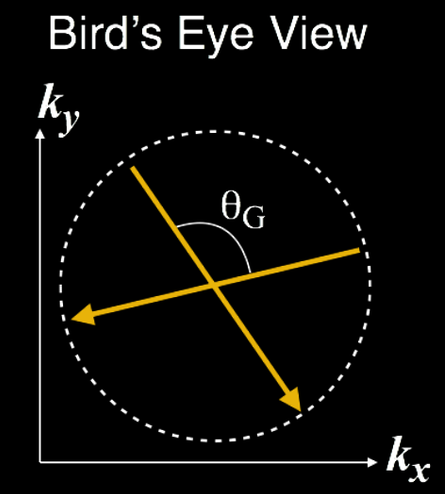
COR reformat

Managing Respiratory Motion

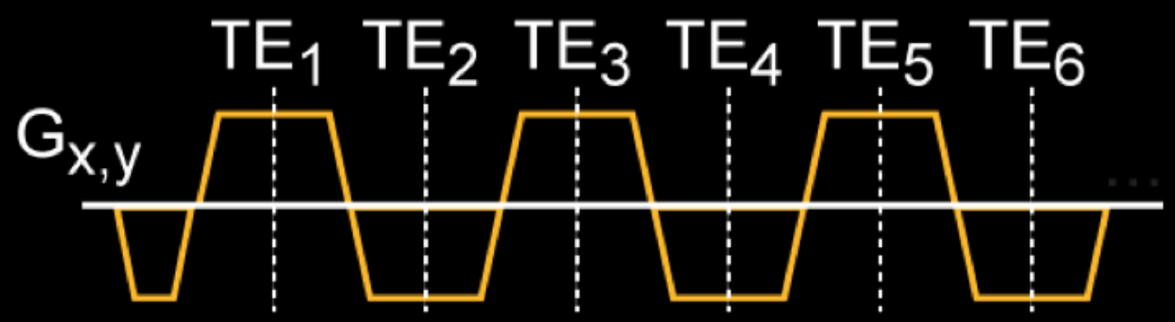
New Techniques: FB Non-Cartesian 3D MRI

3D Stack-of-Radial MRI
- golden angle ordering
- bipolar multi-echo
- gradient calibration
- multi-peak F/W and R_2*
- proton density fat fraction (PDFF)





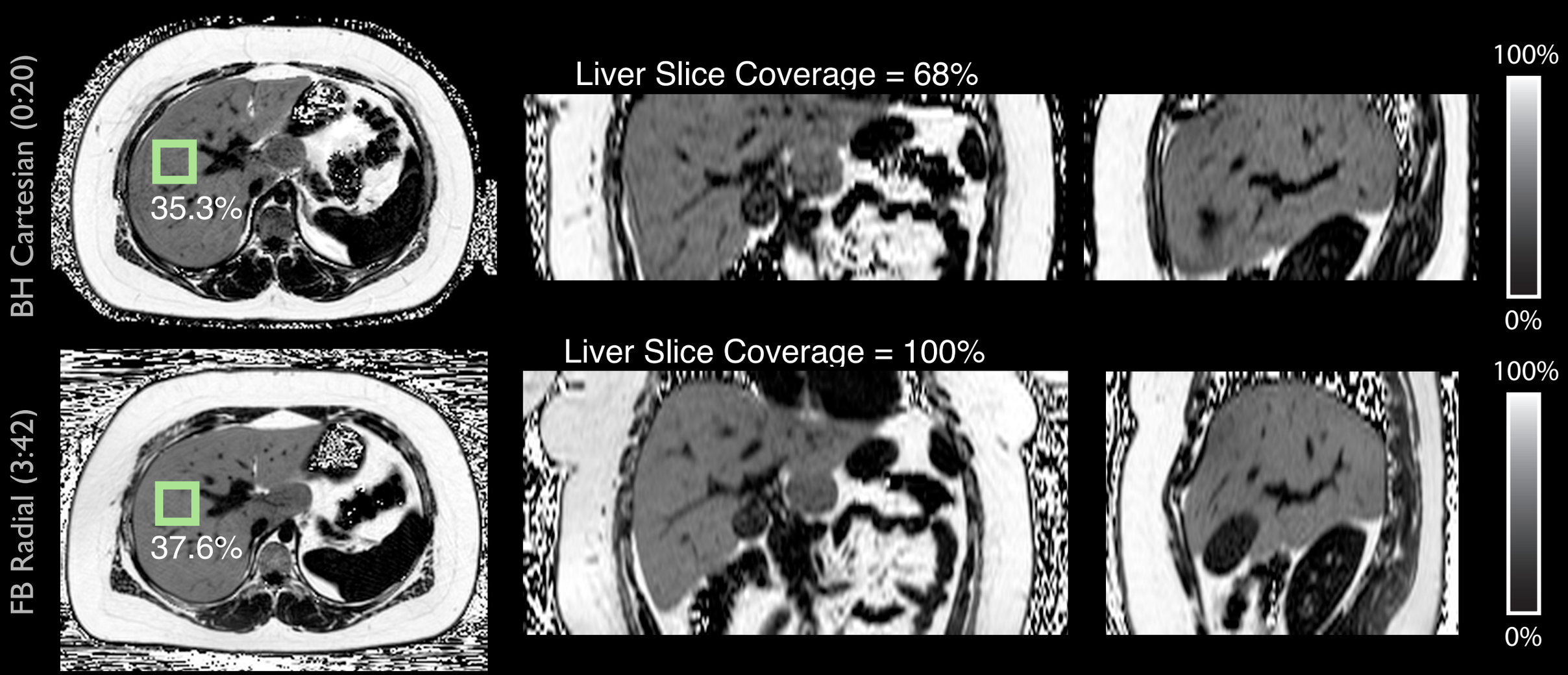
Rotate by θ_G =111.25°



Managing Respiratory Motion

New Techniques: FB Non-Cartesian 3D MRI

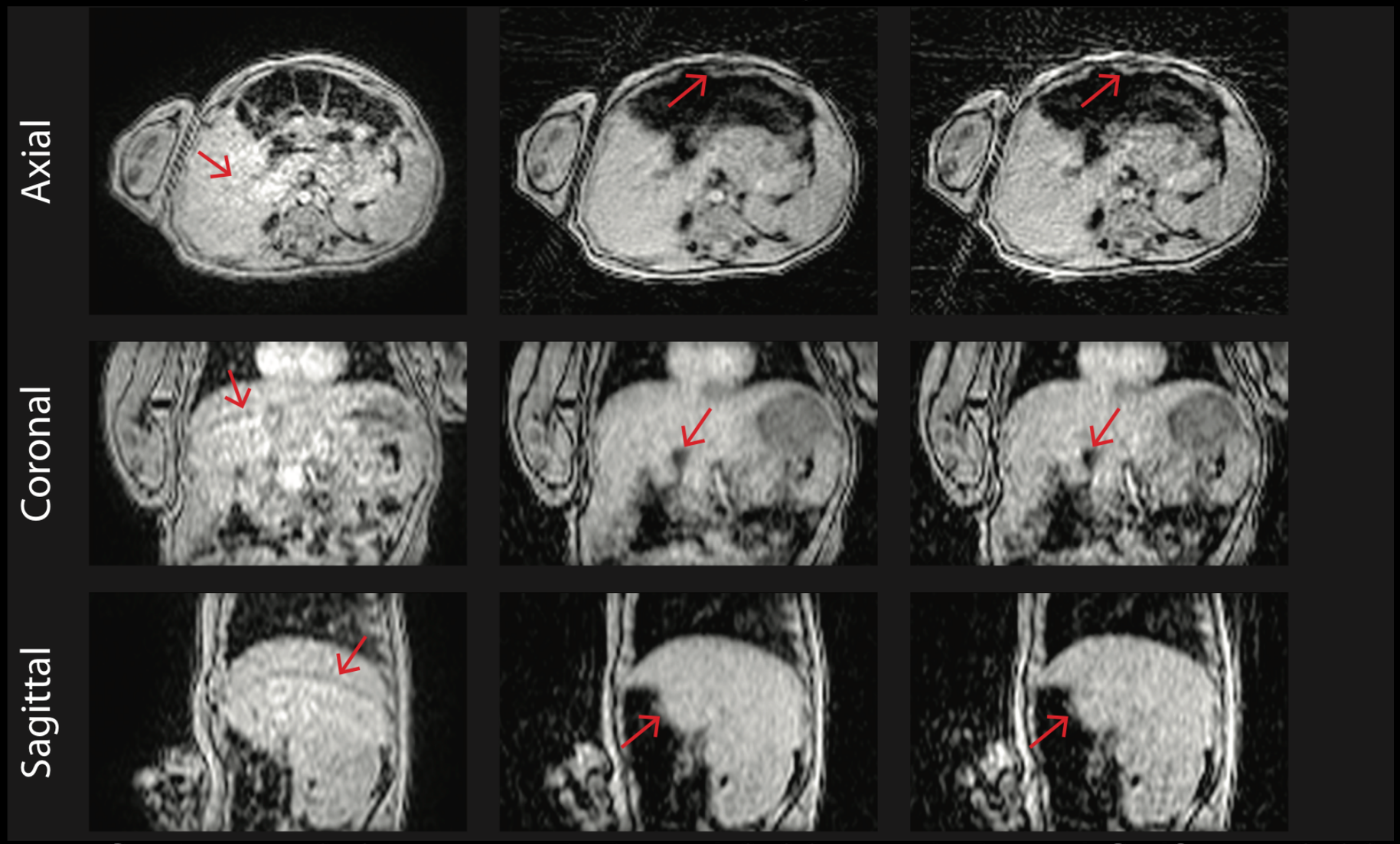
NAFLD Pediatric Subject



Managing Respiratory Motion

New Techniques: FB Non-Cartesian 3D MRI

Infant Subject

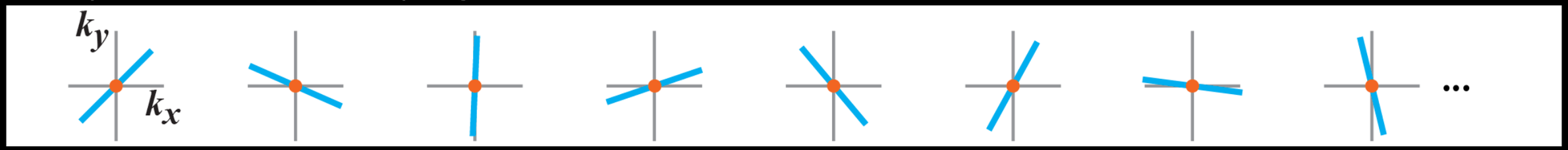


Managing Respiratory Motion

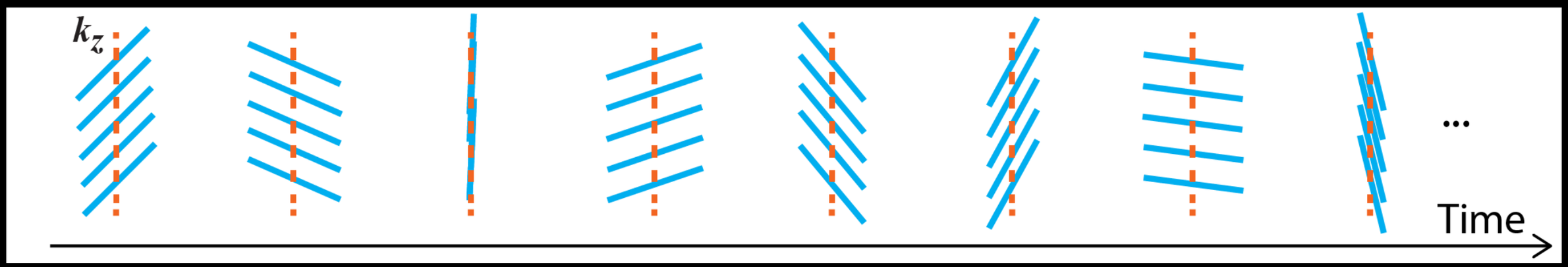
New Techniques: FB Non-Cartesian 3D MRI

Self-Navigation

DC (center of k-space) signal



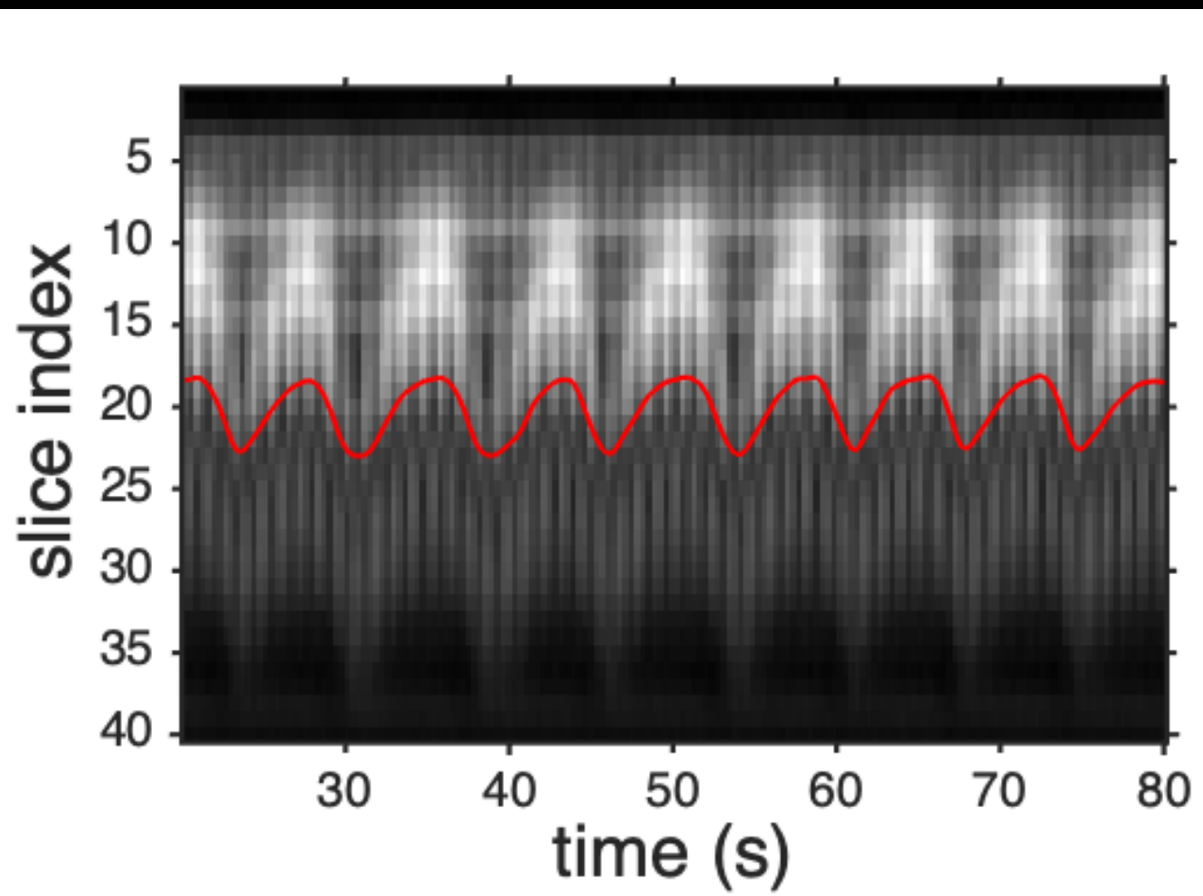
1D projections along *z*



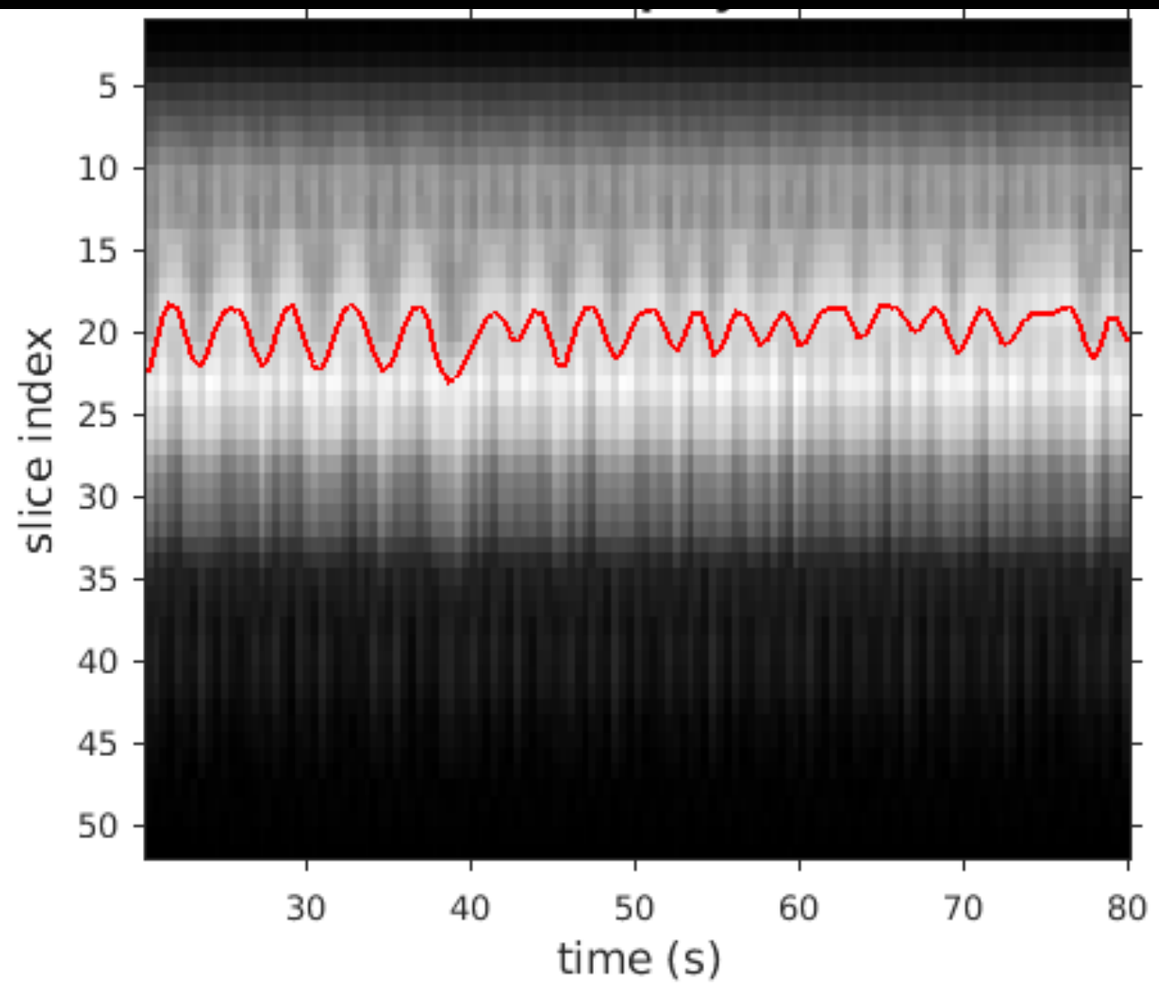
Managing Respiratory Motion

New Techniques: FB Non-Cartesian 3D MRI

Projection-Based Self-Navigation



Example from an adult

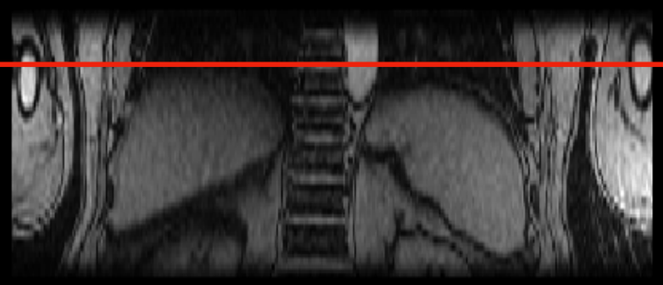


Example from a child

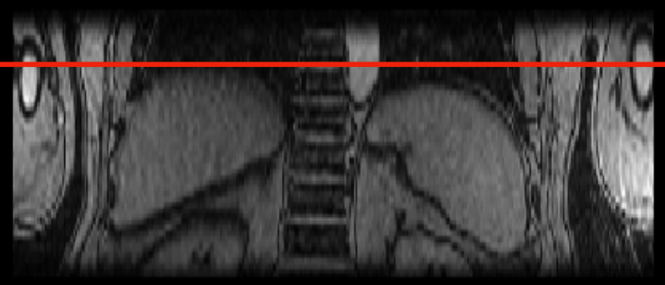
Managing Respiratory Motion

New Techniques: FB Non-Cartesian 3D MRI

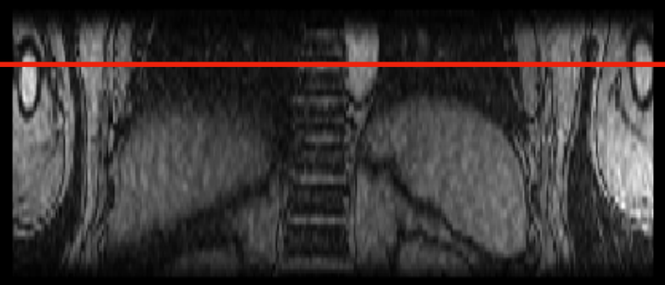
Motion-Resolved Reconstruction



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

Summary

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

References and Information

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