UCLA David Geffen School of Medicine

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Motion in MRI

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M229
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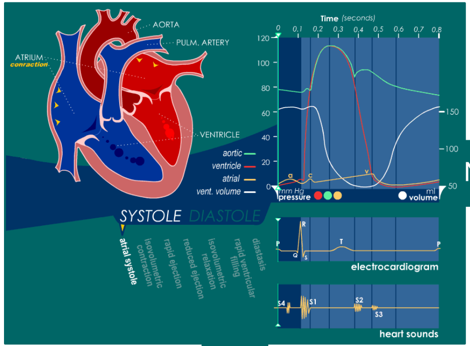
Why do we care about motion?

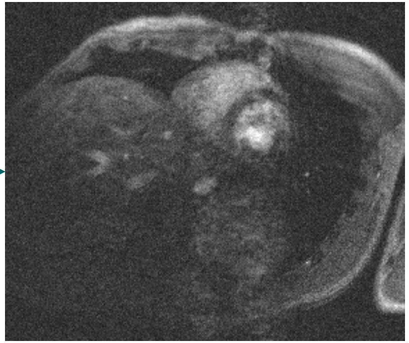
MRI is a slow image modality!

Motion during scans often violates our encoding assumptions

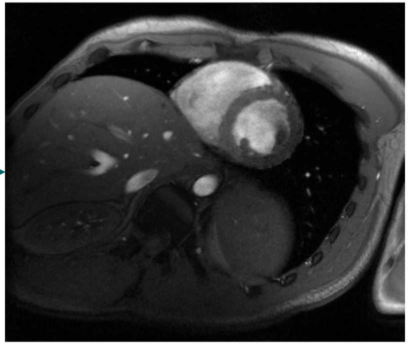
- Variously impacts:
  - Acquisition
  - Reconstruction
  - Analysis



No motion handling



Motion handling



Solutions depend on whether:

- We want the motion **out** of our images
- We want the motion **in** our images

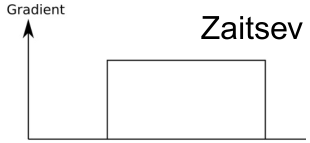
What types of motion are there?

Various sources, speeds, displacements, and patterns

Source	Speed	Displacement	Pattern
Cardiac	1–2 Hz	mm	~Periodic
Respiratory	0.2–0.5 Hz	mm–cm	~Periodic
Bulk motion	Varies	mm–cm	Often transient or instantaneous
Vascular pulsation	1–2 Hz	mm	~Periodic
Peristalsis	≤0.2 Hz	mm	Unpredictable
Swallowing/coughing	Varies	mm–cm	Transient

What happens when an object moves?

Motion *during* readouts: spin phase perspective



Zaitsev M et al., *JMRI* 2015

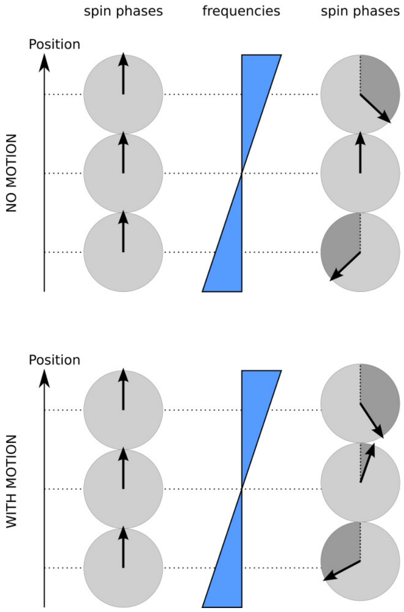
Gradients encode position as phase and frequency

Position changes during gradients

↳ inaccurate encoding

↳ inaccurate decoding

(spins in the wrong place)



What happens when an object moves?

Motion *during* readouts: spin phase perspective

Gradients encode position as phase and frequency

Position changes during gradients

↳ inaccurate encoding

↳ inaccurate decoding

(spins in the wrong place)

Position changes between gradients

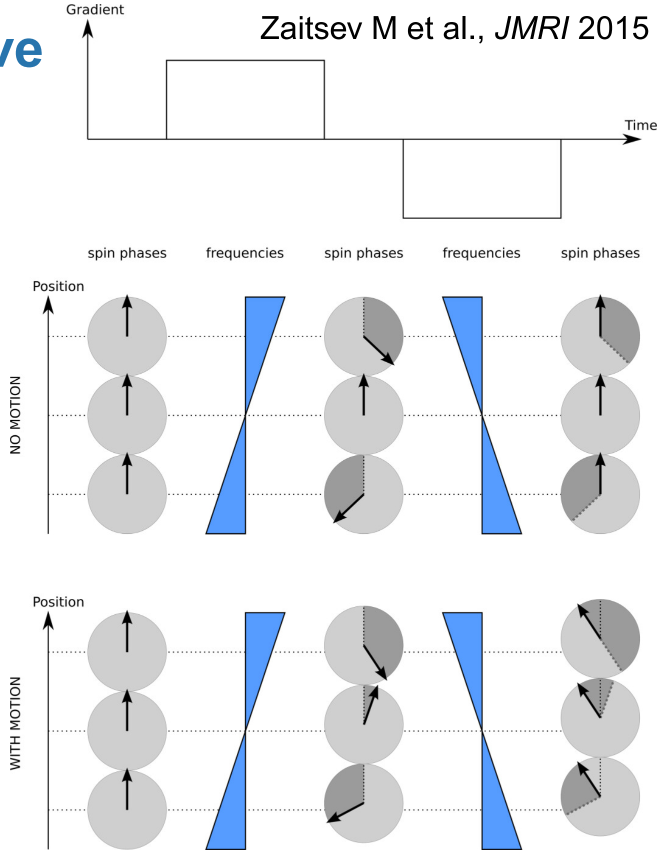
↳ incomplete echo/recall/rewinding

↳ phase accumulation

↳ signal loss

(similar principle to diffusion encoding)

Zaitsev M et al., *JMRI* 2015



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Position changes between gradients

↳ incomplete echo/recall/rewinding

↳ phase accumulation

↳ signal loss

(similar principle to diffusion encoding)

Le Bihan D et al., *JMRI* 2006

What happens when an object moves?

Motion *between* readouts: k-space perspective

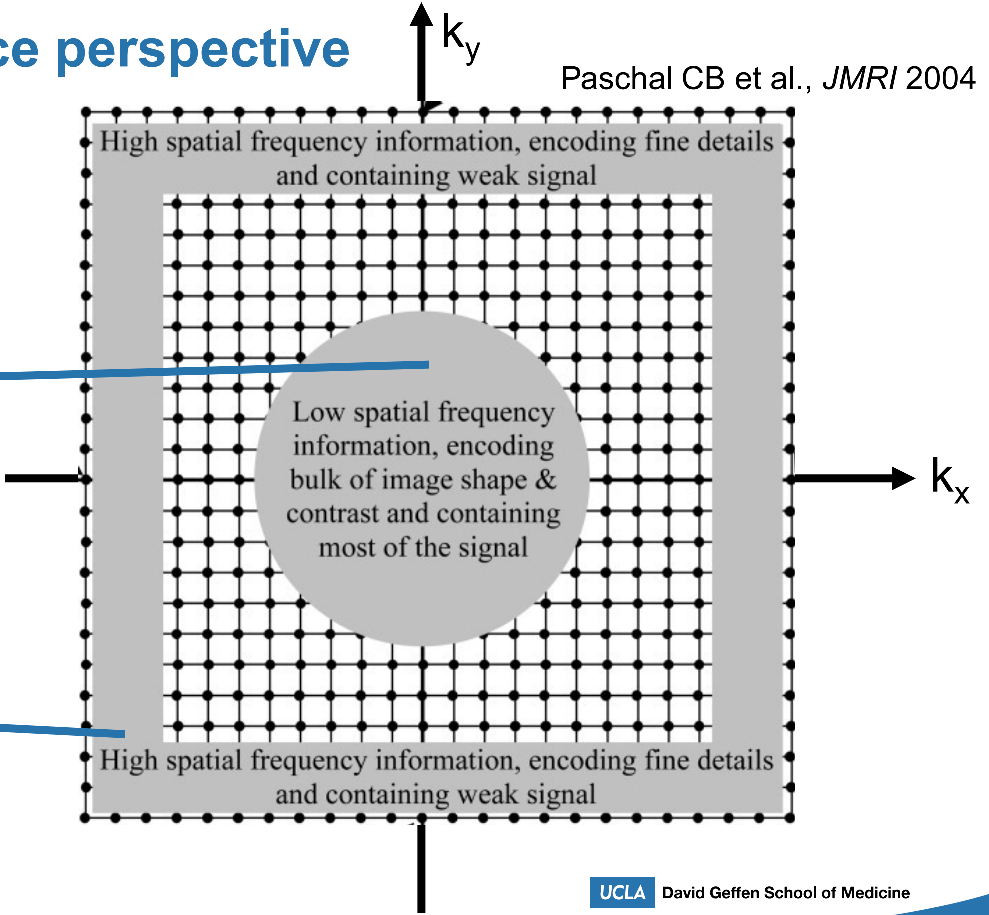
$$S(k) = \int I(x) e^{-j2\pi kx} dx$$

signal image

Low-freq. mismatches ~ blurring

High-freq. mismatches ~ ghosting

Paschal CB et al., *JMRI* 2004

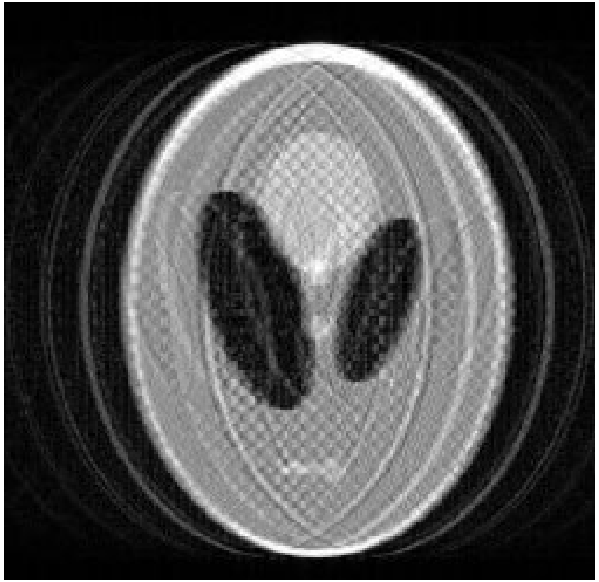


What happens when an object moves?

Motion *between* readouts: k-space perspective

Original image

Blurring



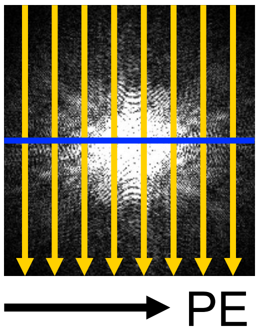
Ghosting

Zaitsev M et al., *JMRI* 2015

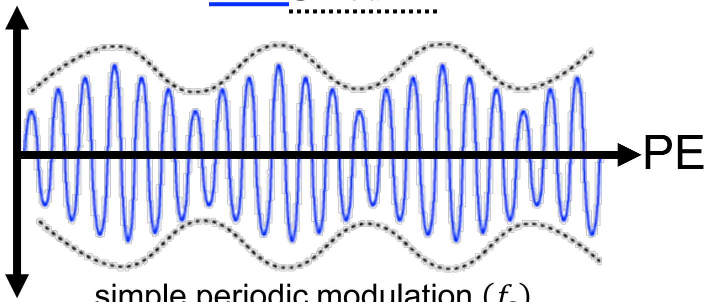
What happens when an object moves?

Motion *between* readouts: k-space perspective

$S(k)$

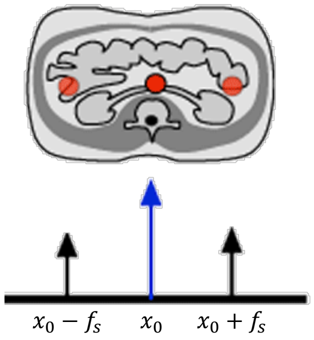


$S(k) g_{\text{mod}}(k)$



simple periodic modulation (f_s)

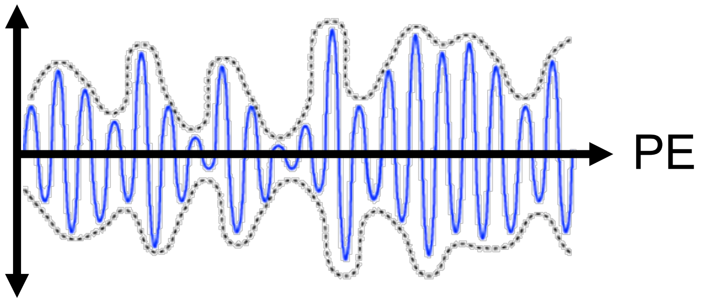
$I(x) * G_{\text{mod}}(x)$



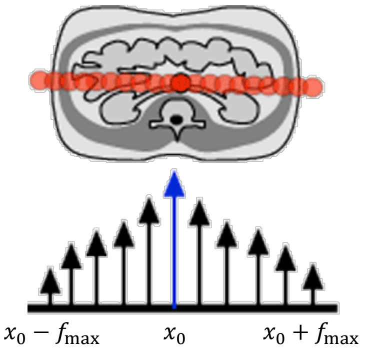
Coherent ghosting

Artifacts depend on:

1) Readout direction
2) Motion timing
3) Acquisition timing



complex modulation $\in (-f_{\max}, f_{\max})$

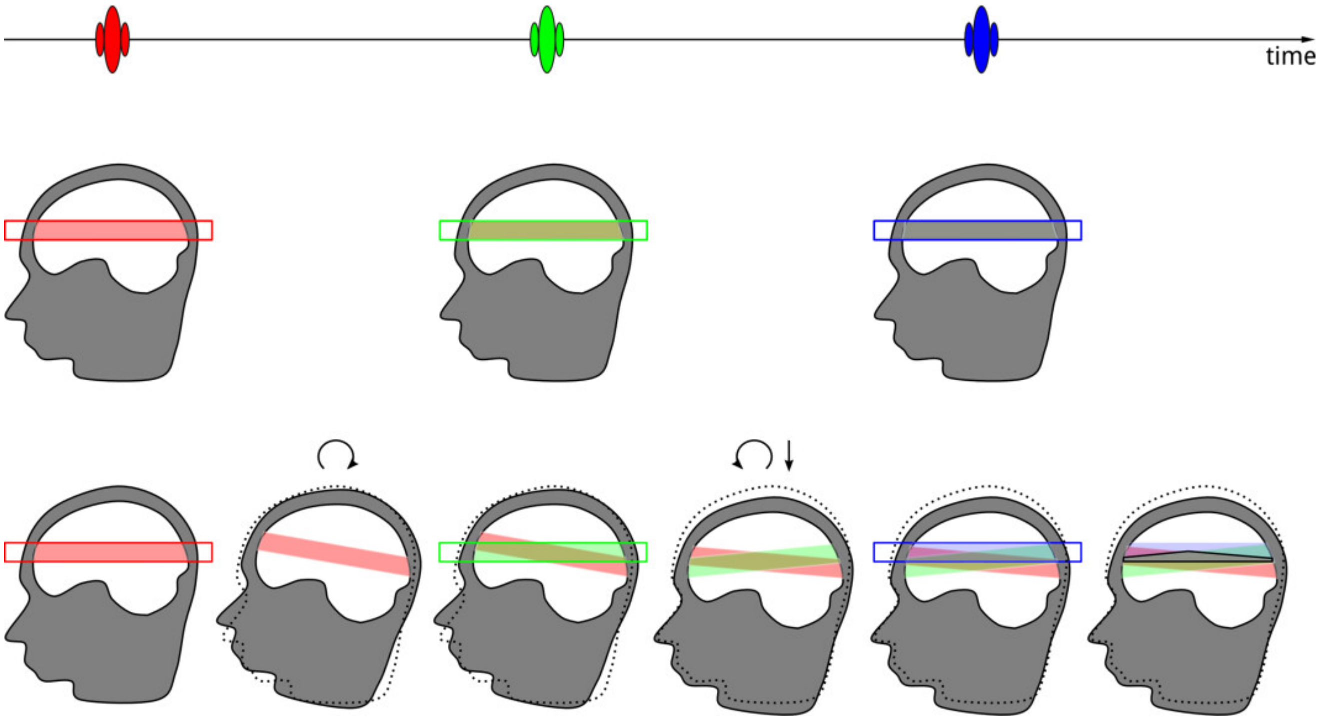


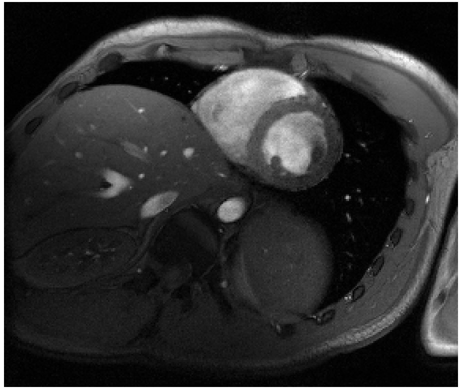
Incoherent ghosting

What happens when an object moves?

Motion *between* excitations: spin history perspective

We are not exciting the same spins every time → incomplete/incorrect steady-state contrast





This can sometimes be used to our advantage, e.g. bright-blood contrast from inflowing spins

Can’t we just image faster?

Real-time imaging

Yes, BUT

- Physiological limits on
  - how fast readouts can be
  - how often excitations can be
- Tradeoffs in spatial/temporal resolution
  - Several “fast imaging” reconstruction solutions
    - out of scope for today
- Does not solve analysis problems
  - motion considered “physiologic noise”

What is our menu of options?

⟵ **Prospectively OR Retrospectively** ⟶

IGNORE	AVOID	RESOLVE	COMPENSATE
• • •	• • •	• • •	• • •
		(make a video)	(adjust for motion)

These are not mutually exclusive

SOLUTIONS:

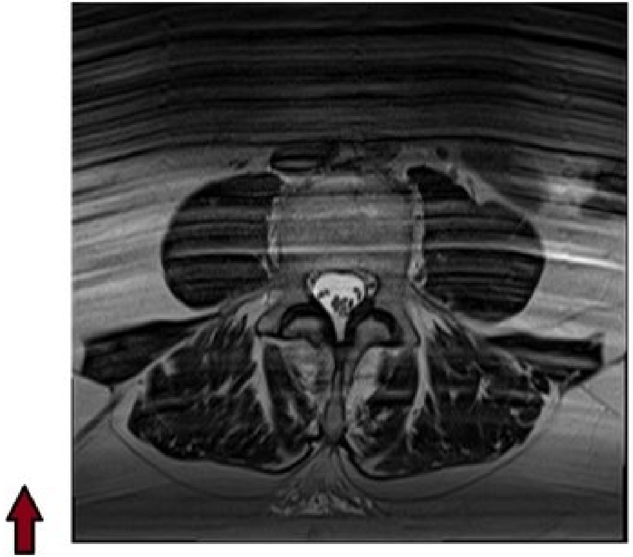
IGNORING MOTION

Motion-robust encoding

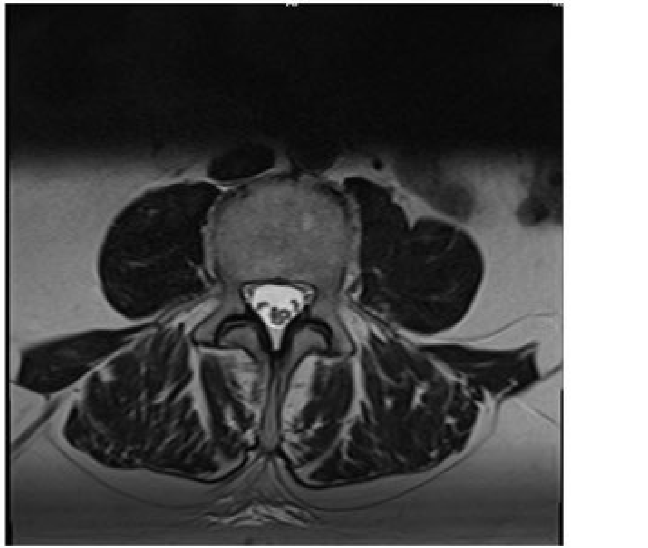
Can we adjust our trajectory and/or timing?

Example 1

Change the readout direction:



Anterior to posterior phase direction



Right to left phase direction

Motion-robust encoding

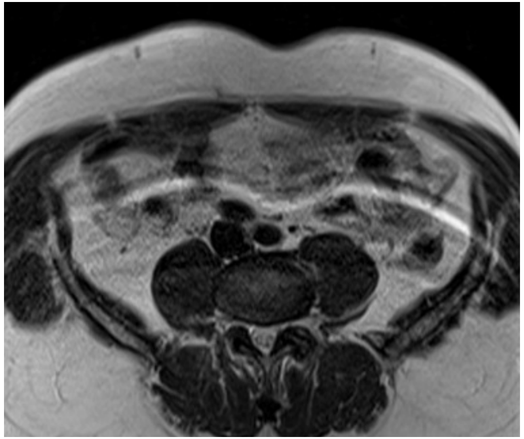
Can we adjust our trajectory and/or timing?

Example 2

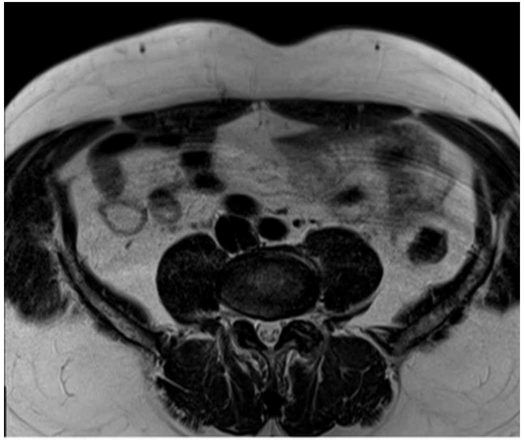
Center of k-space → shape → blurring
↳ Re-acquire → ~similar blurring

Periphery of k-space → edges → ghosting
↳ Re-acquire → ~different ghosting

Collect multiple signal averages:



1 average



5 averages

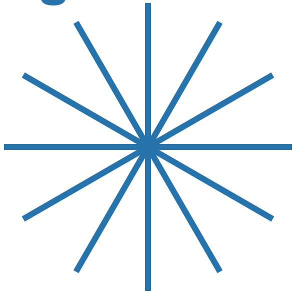
Motion-robust encoding

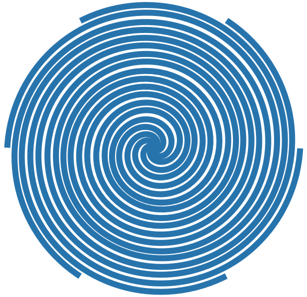
Can we adjust our trajectory and/or timing?

Example 3

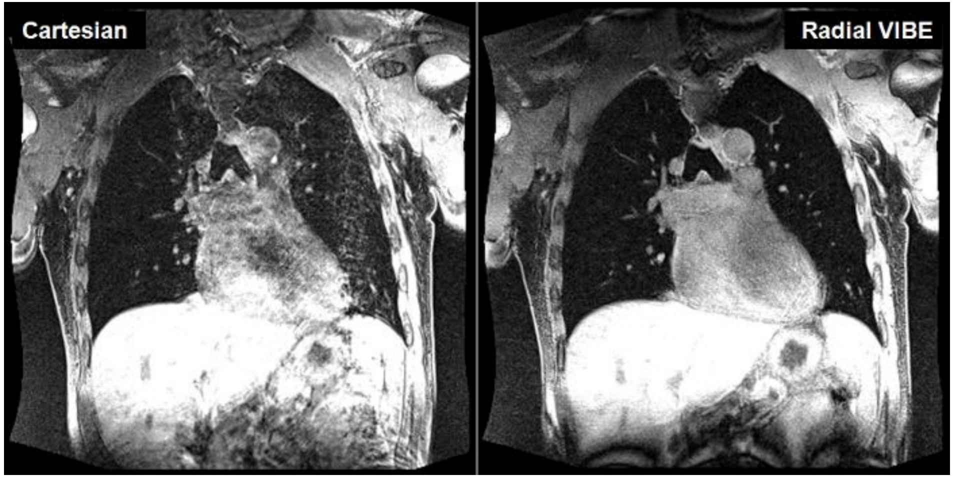
Do both at once:

- Continually change our readout direction
- Continually re-acquire the center of k-space





Use non-Cartesian trajectories:



Block KT et al., NYU CAI^{2}R

SOLUTIONS:

AVOIDING MOTION

Stopping bulk motion

Communication, immobilization, and/or medication

Communication
- Instructions
- Updates

Physical approaches
- Padding
- Restraints
- Bite bars

Pharmacological approaches
- Sedation
- Anesthesia
- Glucagon (for peristalsis)

Cambridge Research Systems

Menon V, et al. *BRM* 1997

Wikimedia, CC BY-SA 4.0, Whispyhistory

Stopping respiratory motion

Breath-holding

Bernstein MA et al., *Handbook of MRI Pulse Sequences*

Gives ~20 sec window for fast acquisition

Hard to repeat exact positioning in successive breath-holds

Doesn't work for patients who can't cooperate

Free-breathing

Breath-held

Avoiding respiratory motion

Terminology: triggering vs. gating

Terms are sometimes used interchangeably, but for the purposes of this lecture:

Triggering

- An event initiates acquisition after pauses
- Must be prospective

Gating

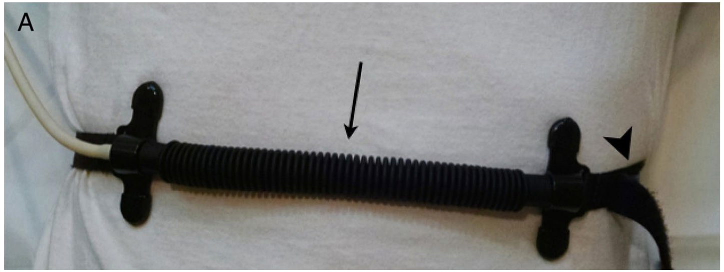
- Acquisition is continuous
- Data are:
  - selectively accepted (if avoiding motion)
  - **or** binned/sorted by motion state (if resolving motion)
- *Prospective* gating only keeps accepted/binned data
- *Retrospective* gating keeps all data for acceptance/binned at the end of the scan

Avoiding respiratory motion

Prospective triggering

External monitoring

- Respiratory bellows
- RF monitoring



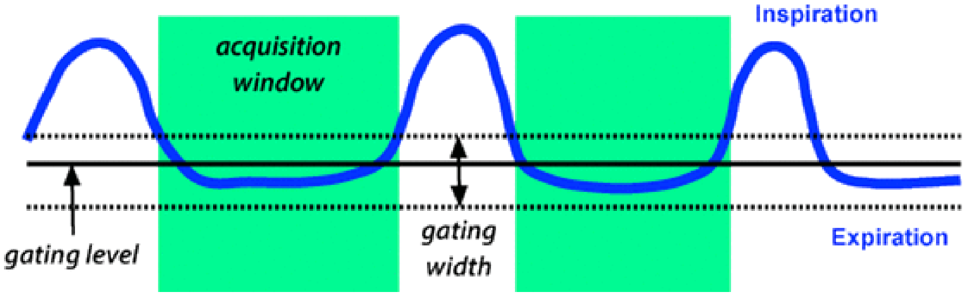
Hope TA et al., *EJNMMI Physics* 2015

Respiratory navigation

- Diaphragmatic navigators

Pre-defined acceptance window

- Tradeoff: precision vs. scan time
- Scan time is unpredictable



https://www.mriquestions.com/respiratory-comp.html

Avoiding respiratory motion

Prospective gating (acceptance)

External monitoring

- Respiratory bellows
- RF monitoring

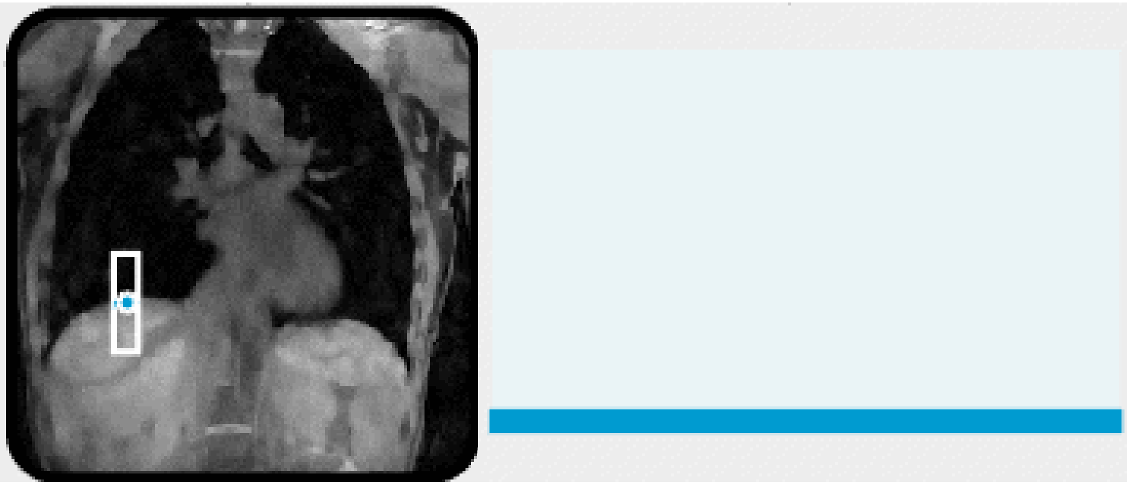
Respiratory navigation

- Diaphragmatic navigators

Pre-defined acceptance window

- Tradeoff: precision vs. scan time
- Scan time is unpredictable

navigator k-space



PTB (Germany)

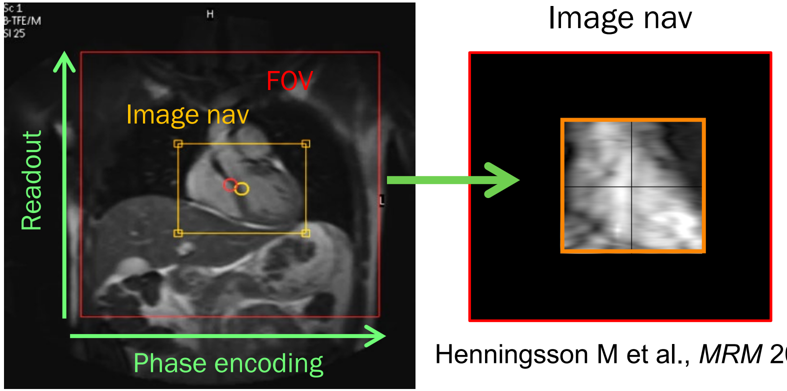
Avoiding respiratory motion

Retrospective gating (acceptance)

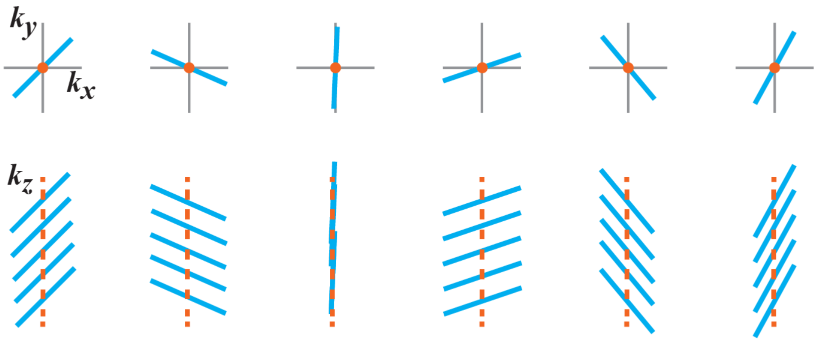
External monitoring
- Respiratory bellows
- RF monitoring

Respiratory navigation
- Diaphragmatic navigators
- Image navigators
- Acquired k-space data (self-navigation)
  - DC (center k-space point)
  - Projection lines (actual or extracted)

More flexible acceptance window
- Tradeoff: precision vs. scan time
- Scan time may be predetermined



Henningsson M et al., *MRM* 2012



Courtesy Holden Wu

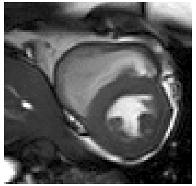
Avoiding cardiac motion

Prospective triggering

Cardiac monitoring:

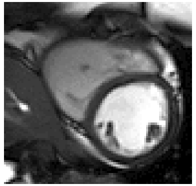
- ECG (most common)
- Pulse oximetry (less common)

Two quiescent periods:



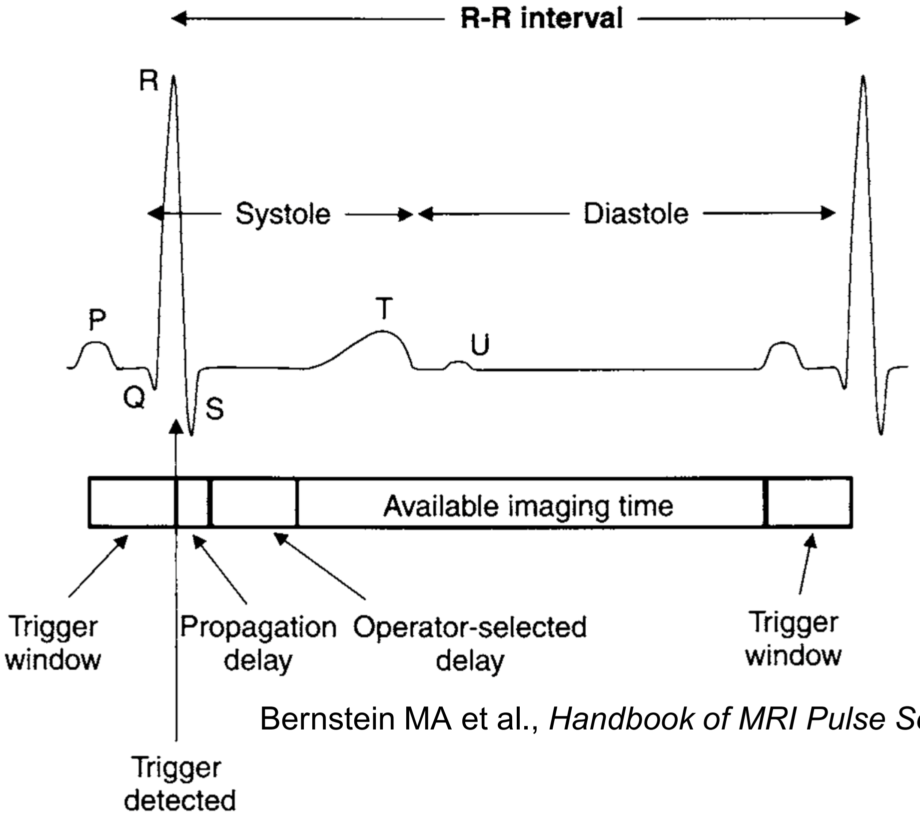
Systolic

- Shorter (~120 ms)
- Timing is reliable



Diastolic

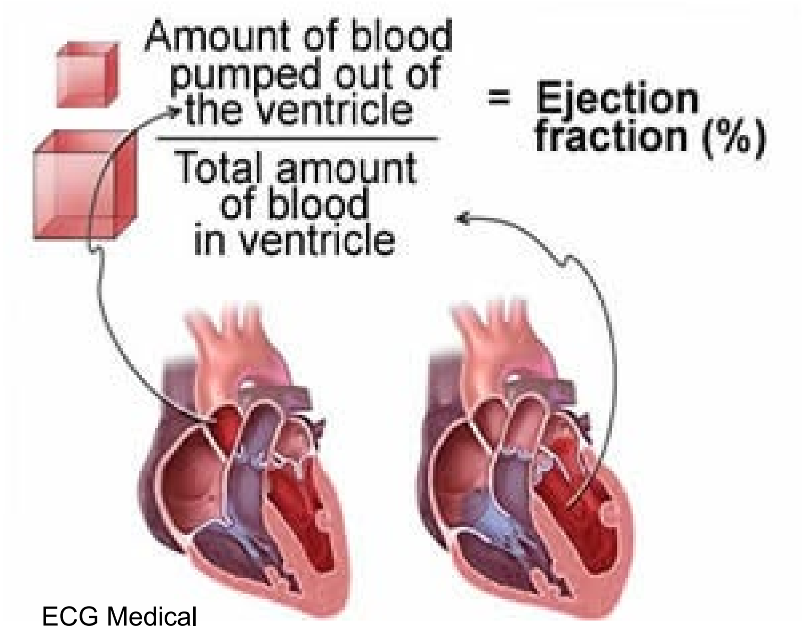
- Typically longer (~180 ms)
- Timing is variable



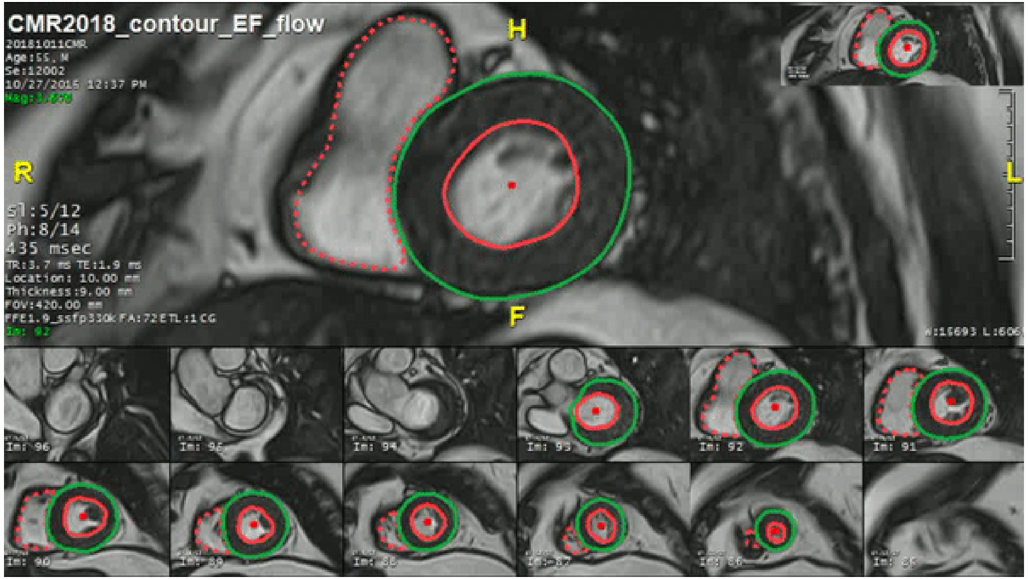
Bernstein MA et al., *Handbook of MRI Pulse Sequences*

SHOULD we avoid motion?

What if the motion is what we specifically want to image?



ECG Medical



TeraRecon

SOLUTIONS:

RESOLVING MOTION

Resolving respiratory motion

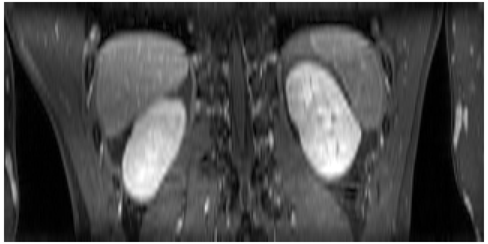
Retrospective gating (binning)

External monitoring

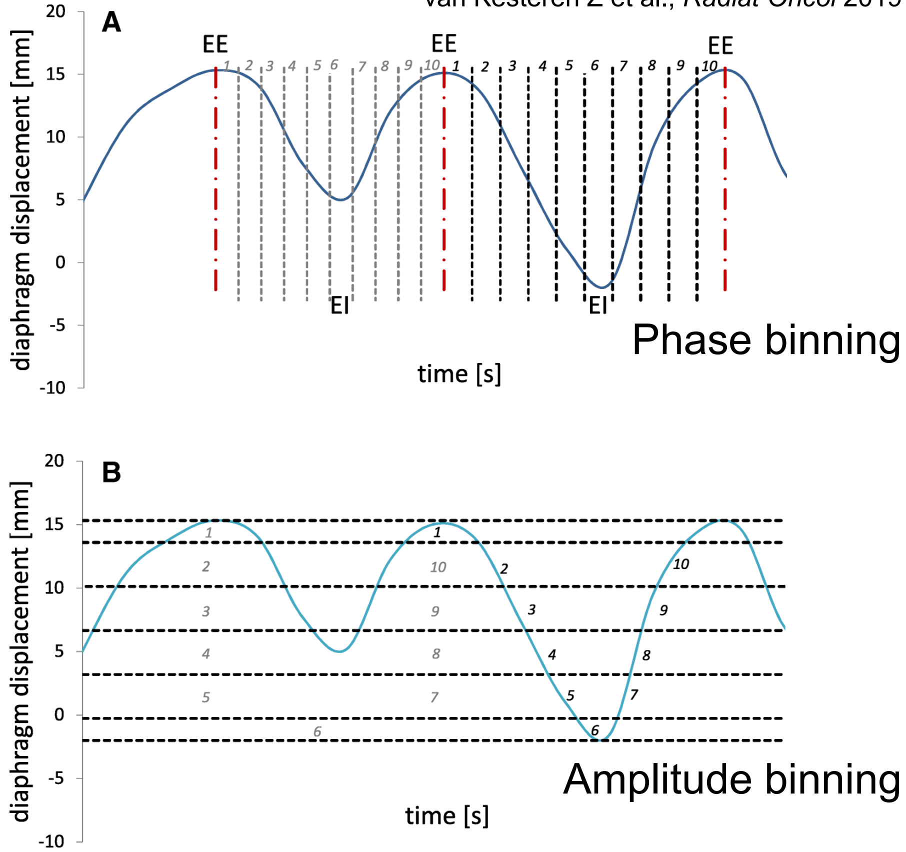
- Respiratory bellows
- RF monitoring

Respiratory navigation

- Diaphragmatic navigators
- Image navigators
- Acquired k-space data (self-navigation)
  - DC (center k-space point)
  - Projection lines (actual or extracted)



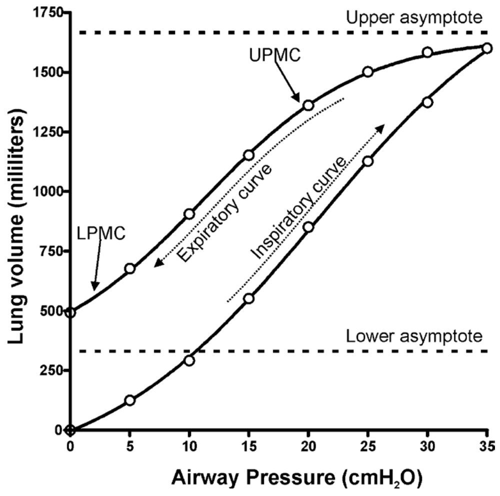
van Kesteren Z et al., *Radiat Oncol* 2019



Resolving respiratory motion

Phase or amplitude binning?

Hysteresis: Expiration does not just retrace inspiration



Albaiceta GM et al., *Biomed Eng Online* 2007

Amplitude binning:

- Ignores hysteresis
- Groups together inspiratory/expiratory data

Phase binning:

- Preserves hysteresis
- Potentially halves the data per bin

The “right” method depends on what information we want to preserve:

- e.g., inspiration/expiration *processes* vs. inspiration/expiration *endpoints*

Resolving cardiac motion

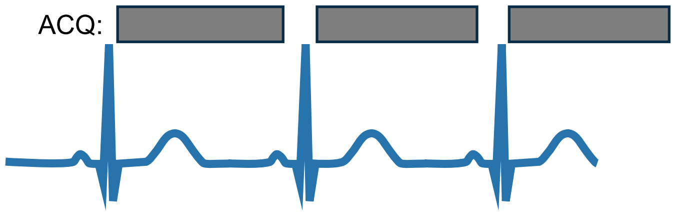
Prospective gating (binning)

Cardiac monitoring:

- ECG (most common)
- Pulse oximetry (less common)

Gradients can interfere with ECG signal, complicating R-wave detection during acquisition

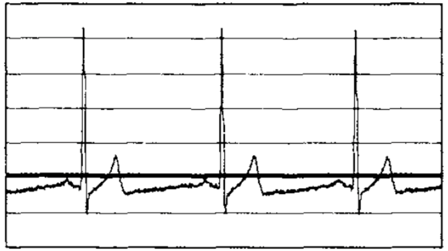
Prospective gating momentarily pauses acquisition



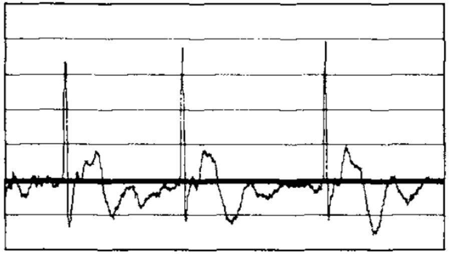
- Misses end-diastole (key phase in ejection fraction)
- Causes “flash” artifact (T1 recovery during gaps)

Bernstein MA et al., *Handbook of MRI Pulse Sequences*

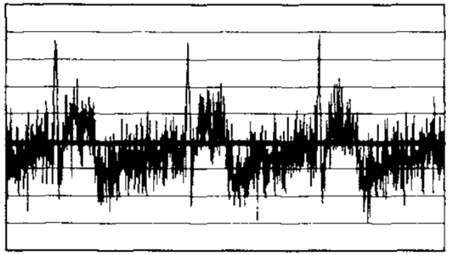
Outside magnet



Inside magnet



Inside magnet, gradients on

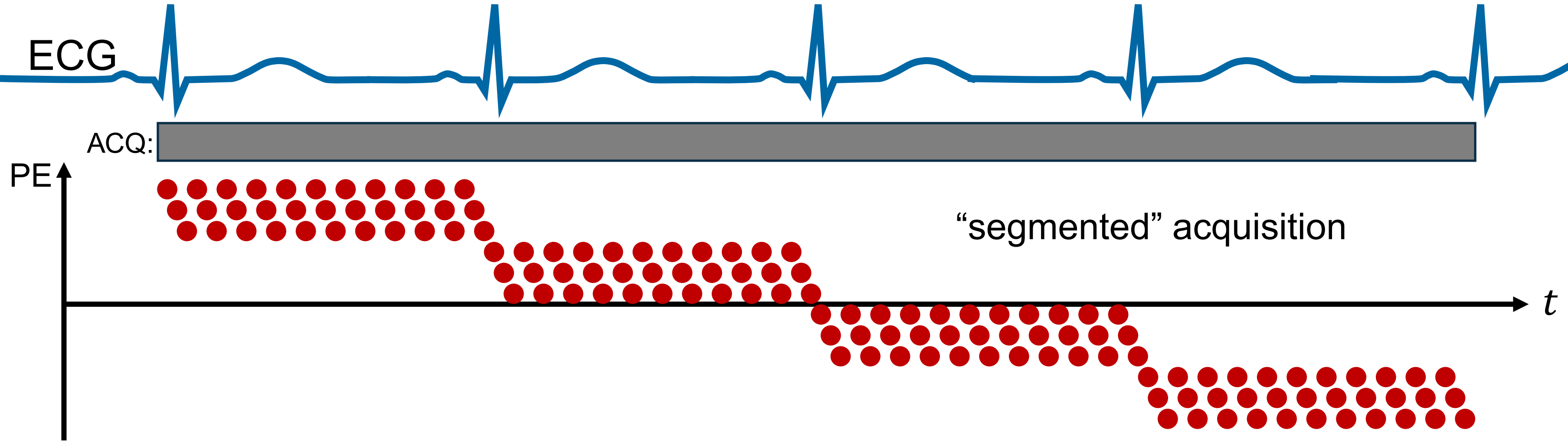


Resolving cardiac motion

Retrospective gating (binning)

Cardiac monitoring:

- ECG (most common)
- Pulse oximetry (less common)



Resolving cardiac motion

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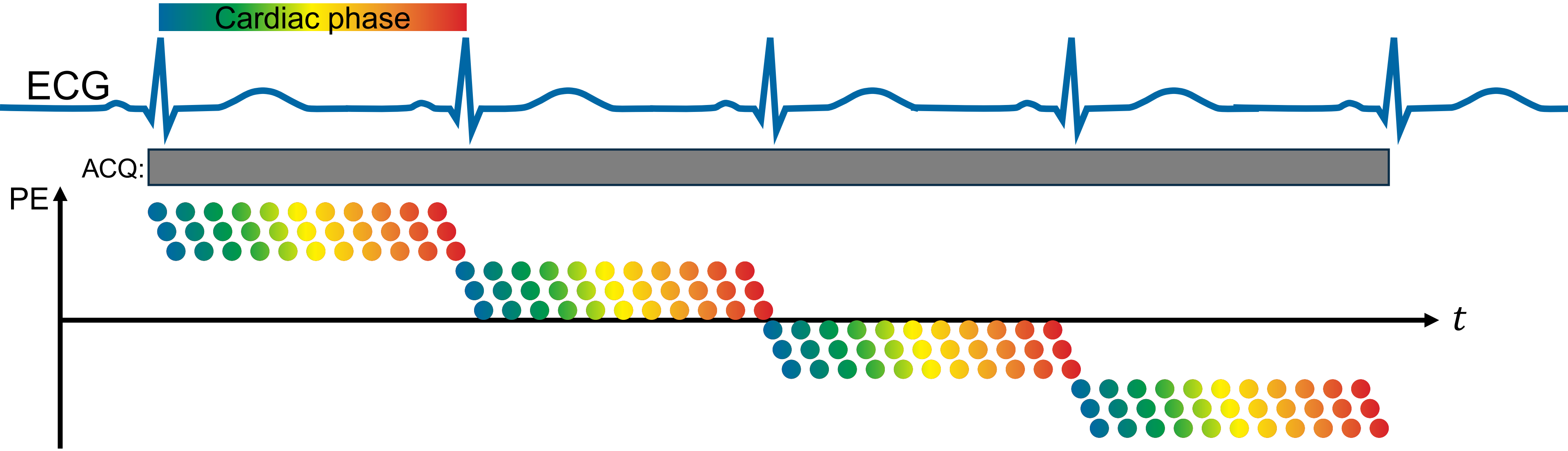

Resolving cardiac motion

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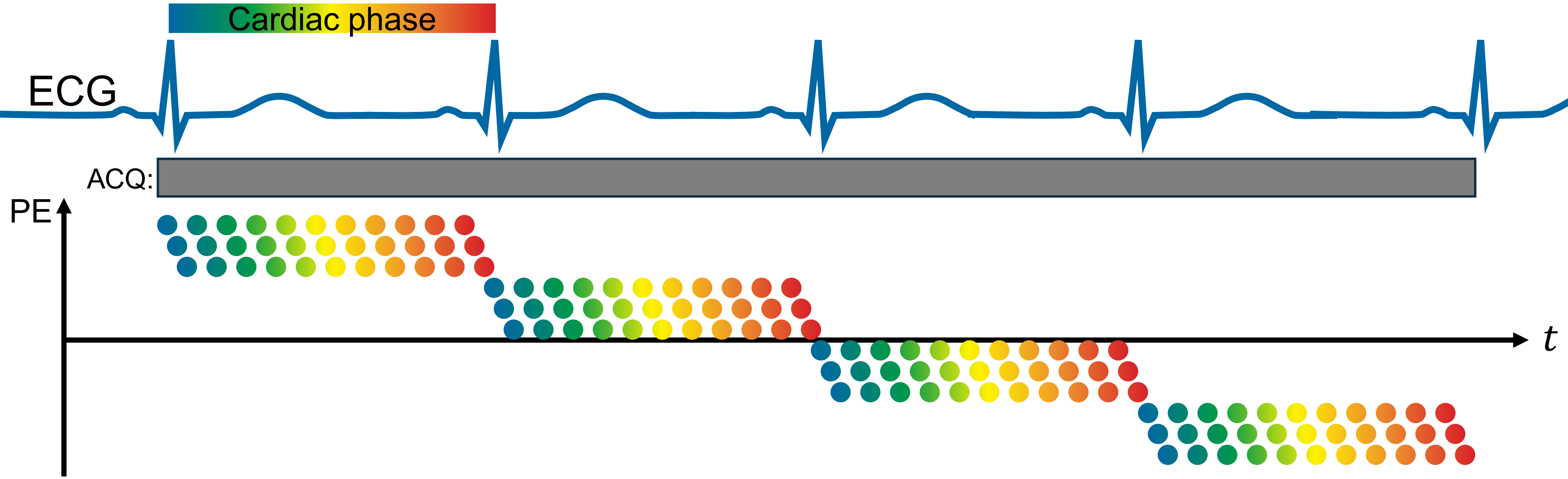

Resolving cardiac motion

Retrospective gating (binning)

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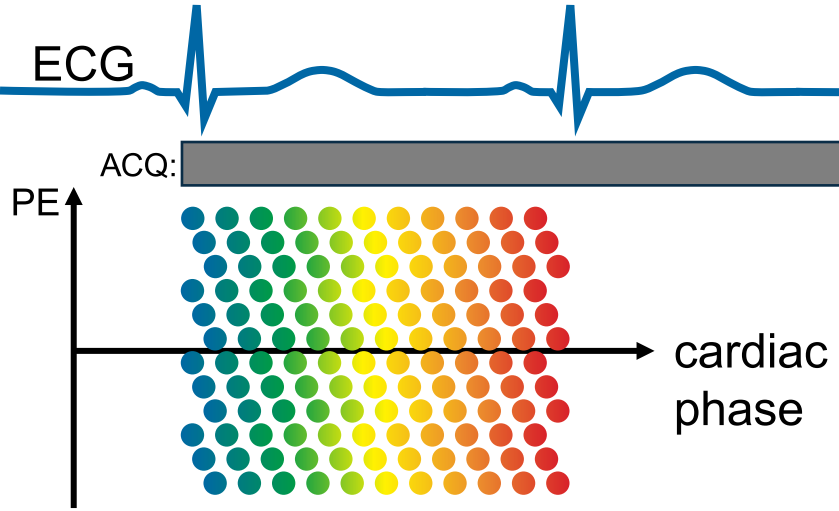
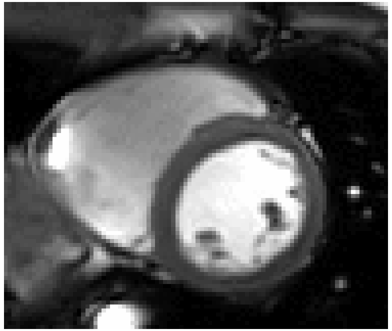




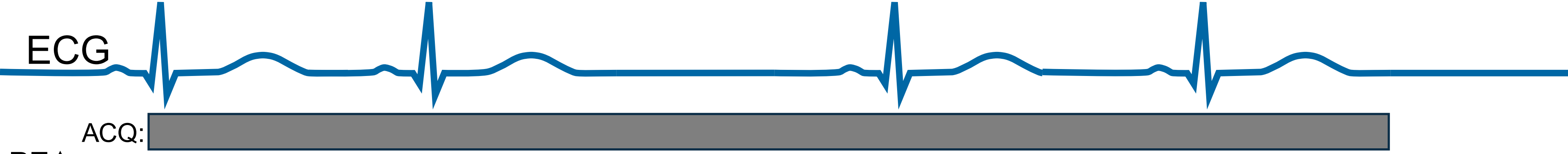
Segmented techniques produce one “typical” cardiac cycle

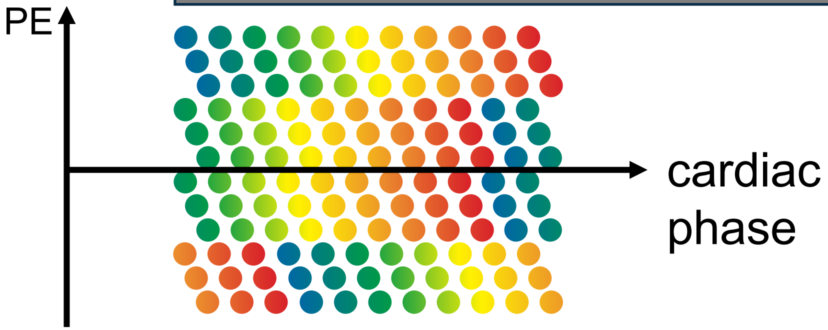
Resolving cardiac motion

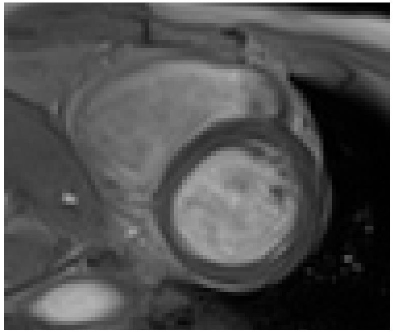
Retrospective gating (binning) in arrhythmia

Cardiac monitoring:

- ECG (most common)
- Pulse oximetry (less common)







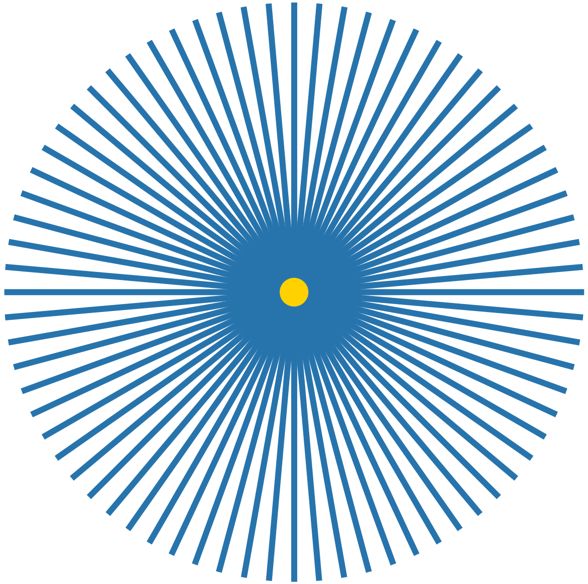
Failed gating → motion artifacts

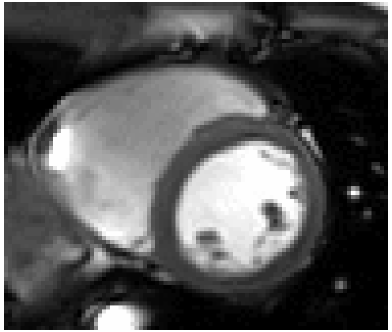
Resolving cardiac motion

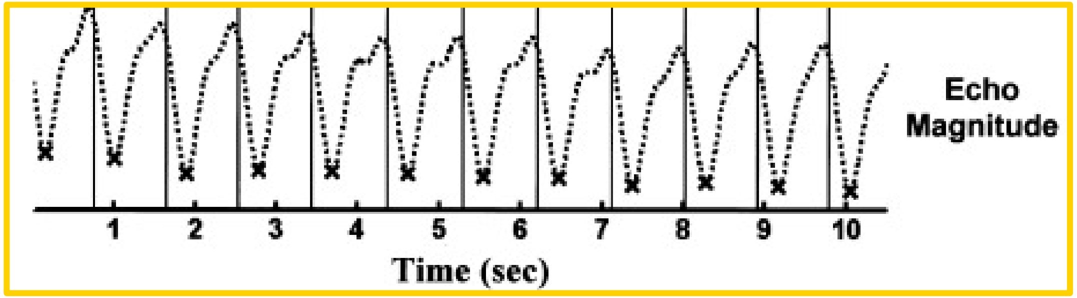
Retrospective gating (binning)

Self-gating:

- DC (center k-space point)
- Projection lines







Larson AC et al., *MRM* 2004

SOLUTIONS:

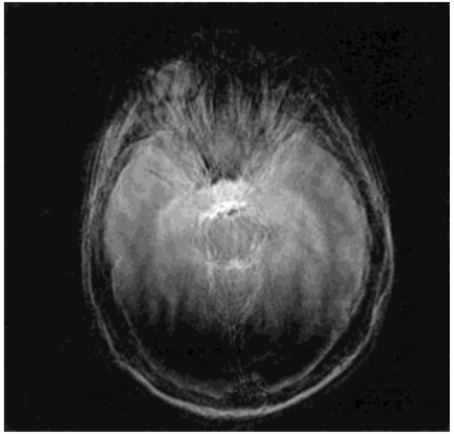
COMPENSATING MOTION

What is motion compensation?

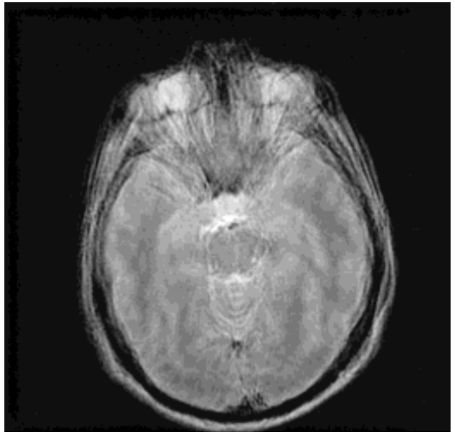
Undoing or attempting to “correct” the effects of motion

Can be minor (phase adjustments) to major (image deformation)

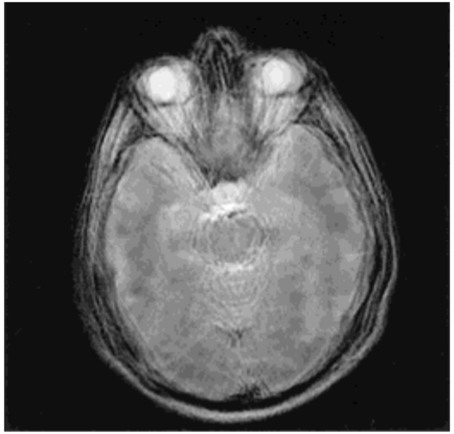
Can be prospective (slice following) to retrospective (image registration)



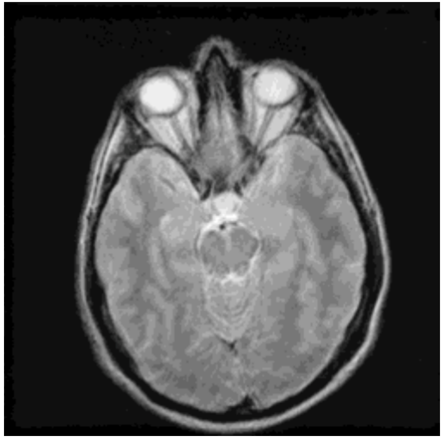
No compensation



Phase compensation



Rotation compensation



Shift compensation

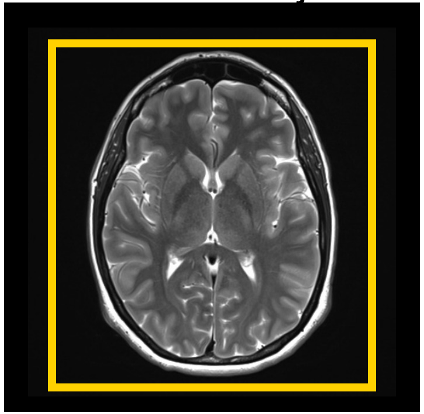
Pipe JG et al., *MRM* 1999

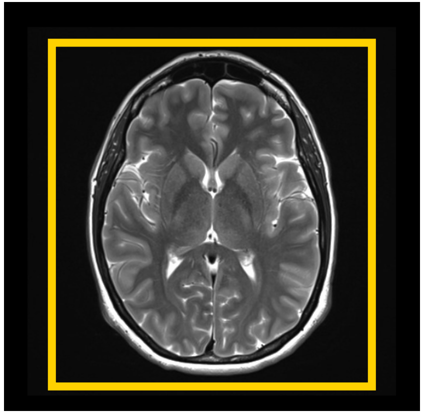
Prospective motion compensation

Monitor and act

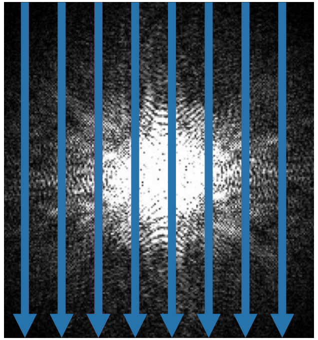
Slice following/FOV adjustment to “move with” the subject

- Primarily for rigid body motion





Data rejection and re-acquisition

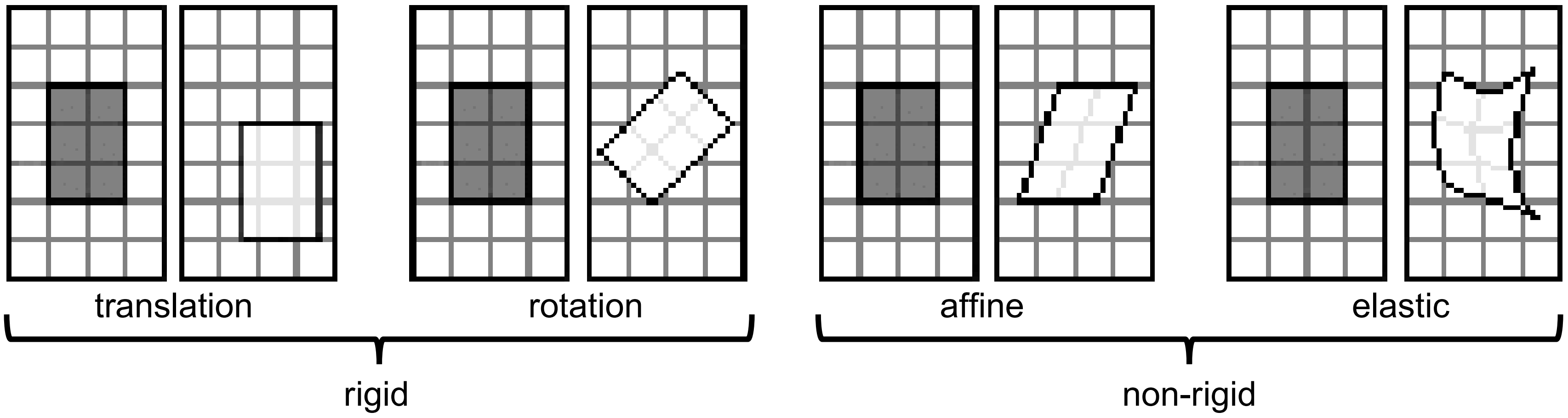


Retrospective motion compensation

Image registration to “undo” motion

Varying complexities of image registration models

Boucher A et al., *IEEE-ICPR 2010*



Complexity dictates when/where you can impose them

None can retrospectively compensate for through-plane motion in 2D imaging

Retrospective motion compensation

Retrospective…but before image reconstruction

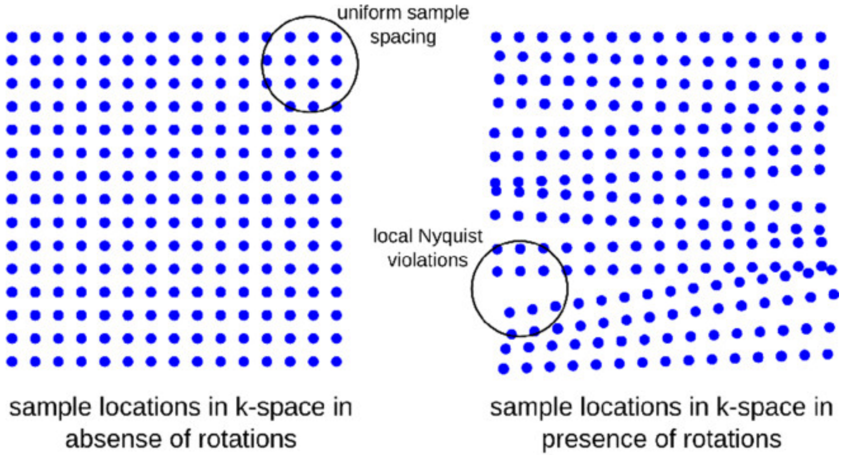
Translation → compensate the data

- Translation in image domain
  ↳ phase modulation in k-space
- No reconstruction time penalty
  aside from translation detection

Rotation/affine → compensate k-space locations

- No reconstruction time penalty
  if already doing non-Cartesian reconstruction
- Moderate reconstruction time penalty
  if switching from Cartesian to non-Cartesian

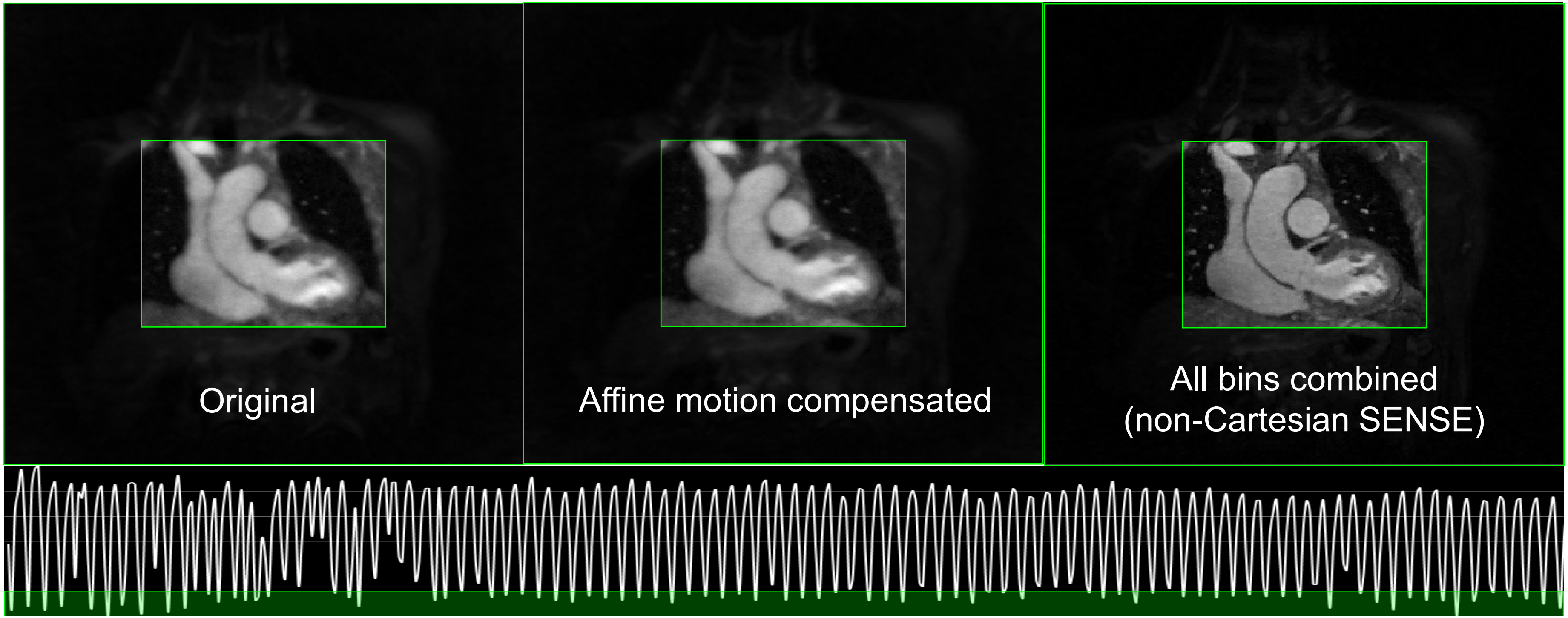
Non-rigid elastic motion is more complicated



Zaitsev M et al., *JMRI* 2015

Retrospective motion compensation

Retrospective…but before image reconstruction

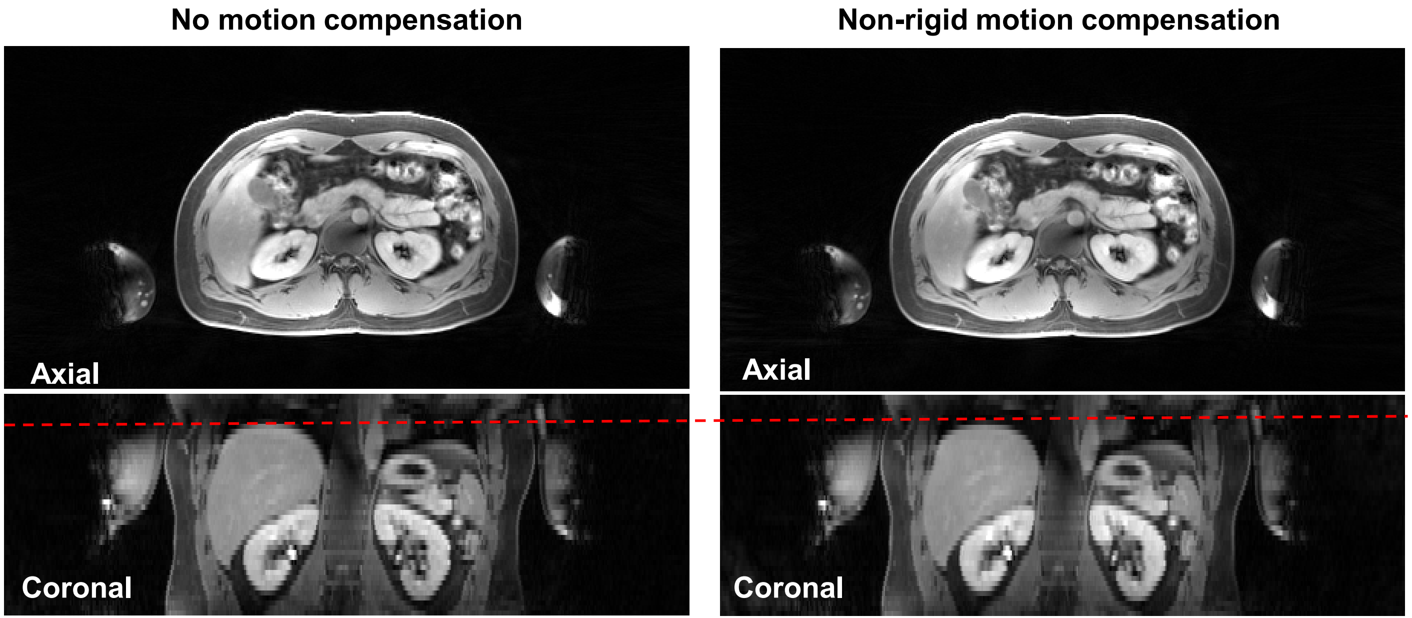


Retrospective motion compensation

Retrospective, during image reconstruction

Non-rigid elastic motion can be built into the forward model & inverted (explicitly/implicitly)

$$S(k,t) = \int M[I(x),t]e^{-j2\pi kx}dx \rightarrow I(x) = M^{-1}\left[\int S(k,t)e^{j2\pi kx}dk, t\right]$$

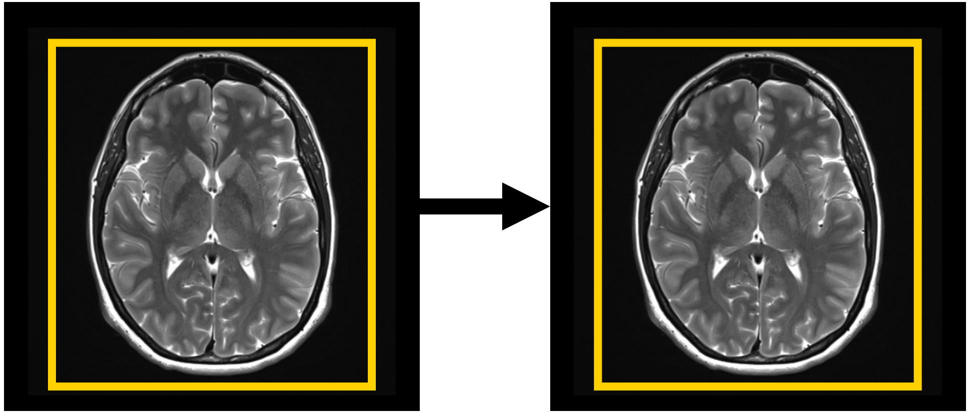


Retrospective motion compensation

Retrospective, after image reconstruction

If there are no artifacts, but motion would confound analysis (physiologic noise)

Essentially a pure image analysis problem (registration)



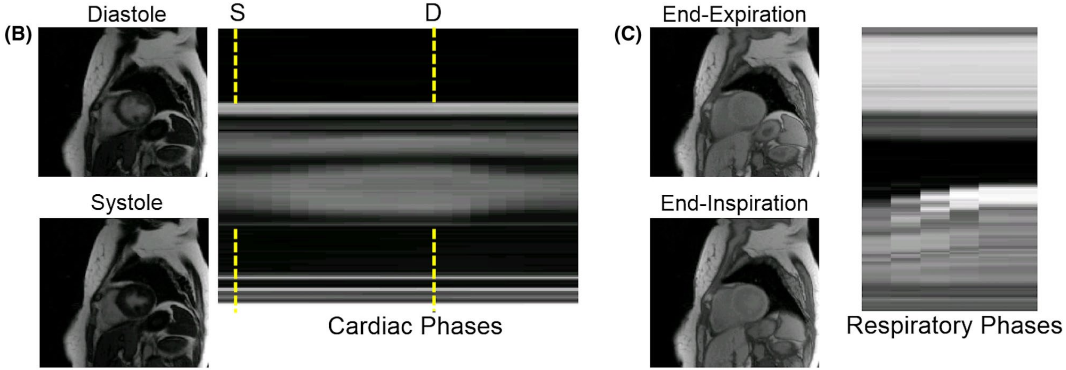
Motion strategies can be combined

There are so many options

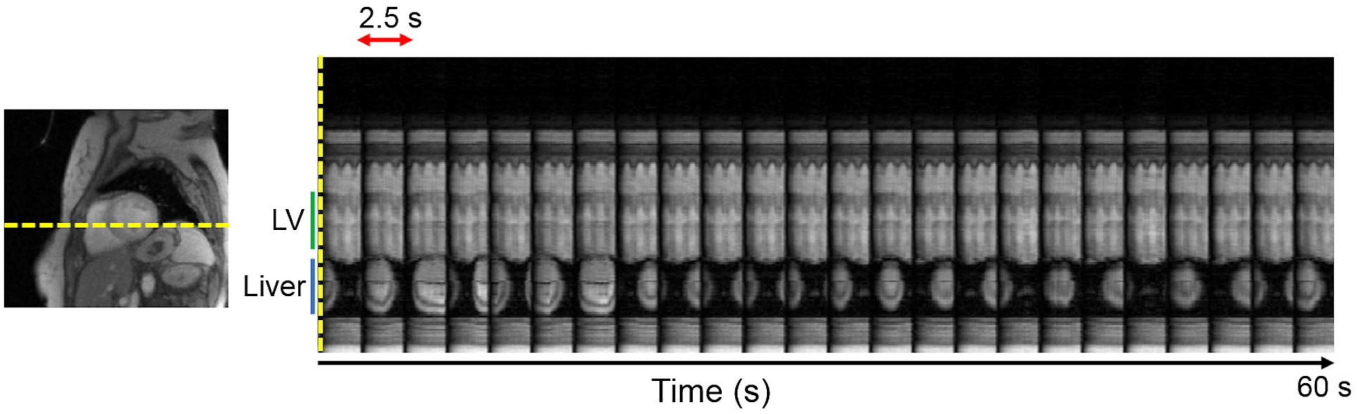
Can resolve *and* compensate if desired

Can mix/match based on source, eg:

- Avoid bulk motion
- Use breath-holding
- Use retrospective cardiac gating



Or just resolve them all!



Shaw JL et al., *MRM* 2019