Lecture-06B — Imperfections II
Motion Compensation

Daniel Ennis
dbe@stanford.edu
Learning Objectives

• List several methods for managing patient motion.
• Explain how synchronization between imaging and physiology can limit imaging errors.
• Appreciate that MRI signals are complex valued.
• List several sources of phase in MRI signals.
• Describe the relationship between motion, phase, and gradients.
• Understand how flow-compensated gradient waveforms eliminate motion-induced signal phase for moving spins.
Motion Management

- Patient
- Acquisition
- Reconstruction
Motion Management - Patient

- Breath-holding
  - (-) Requires fast sequences
- Respiratory gating / ECG gating
  - (-) \(\uparrow\) scan time; constrains TR
- Patient coaching, physical restraint, sedation
  - (-) Patients acceptance and discomfort
The MRI scanner is synchronized to the EKG during data acquisition.
A single segment of k-space is acquired repeatedly during a heart beat.
Motion Management – Cardiac

A different k-space segment is acquired in a subsequent heart beat.
By compositing \( k \)-space from several heart beats a dynamic and high resolution image series is obtained.
Motion Management - Reconstruction

- **Undersampled Data**
  - partial Fourier, parallel imaging
  - Realtime imaging
- **Motion Compensation**
  - 1D-3D motion from “navigators”
  - reject inconsistent data
  - correct motion-affected data
Motion Management - Acquisition

- Swap frequency and phase encoding
  - e.g., A/P vs R/L in axial acquisitions
- Multiple averages
  - Distribute motion artifacts incoherently
- Suppress signal from moving tissues
  - e.g., flow suppression, spatial saturation
- Accelerate the acquisition
  - partial Fourier, parallel imaging, single-shot
- Motion-robust acquisitions
  - gradient moment nulling
  - radial, spiral, etc.
- Flow compensated gradient waveforms
Managing Motion Artifacts

• Which of the following is NOT associated with reducing motion artifacts?

A. Segmented $k$-space imaging.
B. Transient suspension of respiration.
C. Swapping the phase and frequency directions.
D. Lowering the imaging flip angle.
MRI Signals are Complex Valued

\[ M_{xy}(\vec{r}, \rho, T_1, T_2) = |M_{xy}(\vec{r}, \rho, T_1, T_2)| e^{i\phi} \]

- Transverse Magnetization
- Magnitude Image
- Phase

\[ I(\vec{r}, \rho, T_1, T_2) = |I(\vec{r}, \rho, T_1, T_2)| e^{i\phi} \]

- Complex Image
- Magnitude Image
- Phase Image

Fourier Sampling and Signal Equation
Phase from many things...

\[ \phi = \phi_{off} + \phi_{motion} \]

- \( \phi_{CS} \): Chemical Shift [1] Can be minimized.
- \( \phi_{Sus} \): Susceptibility [2] Can be corrected.
- \( \phi_{\delta B_0} \): Inhomogeneity [2] Can be corrected.
- \( \phi_{Maxwell} \): Maxwell terms [3] Can be corrected.
- \( \phi_{Eddy} \): Eddy currents [4] Can be minimized.
- \( \phi_{motion} \): Applied gradients [5] Motion artifacts OR encode motion!

Motion, Phase, and Gradients

- Phase arises from a gradient according to:
  \[ \phi \vec{G}(\vec{r}, t) = \gamma \int \vec{G}(t) \cdot \vec{r}(t) dt \]
  - Stronger and longer gradients produce more phase

- Spin’s position history (Taylor Series)
  \[ \vec{r}'(t) = \vec{r}_0 + \vec{v}_0 t + \frac{1}{2} \vec{a}_0 t^2 + \ldots \]
  
  *Initial Position*  *Initial Velocity*  *Initial Acceleration*
Motion, Phase, and Gradients

\[ \phi_G(\vec{r}, t) = \gamma \int \vec{G}(t) \cdot [\vec{r}_0 + \vec{v}_0 t + \frac{1}{2} \vec{a}_0 t^2] \, dt \]

- For 2D through-plane (z) velocity sensitivity:
  \[ \phi = \phi_{off} + \gamma M_{0,z} \cdot r_{0,z} + \gamma M_{1,z} \cdot v_{0,z} \]
  \( M_{0,z} = \int_0^T G_z(t) \, dt \) \hspace{1cm} \( M_{1,z} = \int_0^T G_z(t) t \, dt \)

Design \( M_0 \) to be zero.
Design \( M_1 \) to be ZERO.
Flow Compensation

\[ \phi_{FC} = \phi_{off} \]

Spin phase (\(\phi_{FC}\)) only accumulates from off resonance.
Spoiled GRE Sequence

How do you flow compensate the GRE sequence?
The TR in flow compensated spoiled GRE is 5-15% longer.
Spoiled GRE Sequence – Flow Compensated

\[ M_0 = 0 \at TE \]
\[ M_1 = 0 \at TE \]
Flow Compensation – CSF Flow

- The combination of flow and *uncompensated* gradients leads to intravoxel dephasing.

For gradient echo imaging use flow compensation to mitigate flow artifacts (longer TE/TR).

Figure 1 (A-F): Sagittal T2-weighted images showing syrinx in cervical (A) and thoracic (B) cord; faint flow voids (arrows) are seen within the syrinx. (C, D): Axial T2-weighted images of cervical cord with (C) and without (D) flow compensation; flow voids (arrows) are more obvious in D (without flow compensation). (E, F): Axial T2-weighted images of thoracic cord with (E) and without (F) flow compensation; flow voids (arrows) are more obvious in F (without flow compensation).

http://www.ijri.org/viewimage.asp?img=IndianJRadiolImaging_2013_23_1_97_113626_f1.jpg
In flow-compensated images the phase is nearly zero even in areas of continuous flow. What is happening in the fat?
Flow Compensation

- Flow compensating a gradient waveform:
  A. Means it is designed for $M_1=0$.
  B. Extends its duration by $\sim 10\%$.
  C. Limits flow artifacts in images.
  D. Ignores acceleration effects.
  E. All of the above.
Summary

- Discussed several methods to manage patient motion.
- We learned about synchronizing imaging the physiological signals.
- We know that MRI signals are complex valued and that several factors contribute to the MRI signal phase.
- Described the connection between motion, phase, and gradients.
- Learned that flow-compensated gradient waveforms eliminate motion-induced signal phase for moving spins.
If we can manage motion can we measure it too?
Further Learning…

- *Principles of Magnetic Resonance Imaging: A Signal Processing Perspective* by Zhi-Pei Liang and Paul C. Lauterbur
- *Handbook of MRI Pulse Sequences* edited by Matt A. Bernstein, Kevin K. King, and Xiaohong J. Zhou