Lecture-10B — Pulse Sequences III

Echo Planar Imaging (EPI) Artifacts

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Learning Objectives

• Appreciate the challenges associated with EPI
• Describe the appearance of four principal EPI artifacts.
• Discuss the origin of each of these four artifacts
• Recall a solution for each EPI artifact.
Main Challenges with EPI

- Signal modulation over $k$-space
  - $T_2^*$ effects during long echo trains
- Geometric distortion
  - Off-resonance and eddy currents
- Ghosting artifacts
  - Mismatch between even and odd echoes
- Chemical shift artifacts
  - Low bandwidth in phase encode direction
Signal Modulation in EPI

• **Problem** – Object blurring that is $T_2^*$ dependent.

• **Origin** – $T_2^*$ causes signal decay, which is especially large for long single-shot readouts.

• **Solution** – Shorten the readout as much as possible.
  
  – High receiver bandwidth, use maximum gradient performance, under sample $k$-space.
Signal Modulation in EPI

Phase Encoding

- "Blip" direction is slow.
- Low effect PE bandwidth
- FE much smaller

T₂* Decay

Modulates k-space amplitude.

Off-Resonance

Modulates k-space phase.
Signal Modulation in EPI

Perfect Object

EPI Top-Down

EPI Center-Out

- $T_2^*$ Image contrast
- $T_2^*$ dependent blurring
- $T_2^*$ top-down $k$-space shading

- PD image contrast
- $T_2^*$ dependent blurring
- $T_2^*$ center-out $k$-space blurring

Example generated with Lecture_10B_EPI_T2star.m
Geometric Distortion in EPI

- **Problem** – Large object distortions and signal pile-up or dispersion.
- **Origin** – Field inhomogeneity ($\Delta B_0$) during readout.
  - Imperfect $B_0$ (bad shim, susceptibility)
  - Eddy currents
- **Solution** – Careful field shimming, mitigate eddy currents, under sample $k$-space.
Geometric Distortion in EPI

- Fast Spin Echo (FSE)
  - Slow ~3 minutes

- Echo Planar Imaging (EPI)
  - Faster ~10 seconds

$T_2$-weighted image. Full brain coverage. Same target resolution.
Geometric Distortion in EPI

Spatially inhomogeneous off-resonance (Hz) imparts image distortion during long EPI readouts. Try, Lecture_10B_EPI_OffRes_Distortion.m

\[ d_{pe}(\vec{r}) = \frac{\gamma}{2\pi} \Delta B_0(\vec{r}) t_{esp} FOV_{pe} \]

EPI displacement due to off-resonance.
EPI Distortion Solution – Better Shimming

The MRI scanner has shim coils that can be tuned to even out the $B_0$-field for a specific patient.

Images courtesy Brian Hargreaves
EPI Distortion Solution – Parallel Imaging

T2-weighted image. Same target resolution. Scan time matched.
EPI – Nyquist Ghosting

- **Problem** – EPI is prone to FOV/2 ghosting.

- **Origin** – Constant or linear phase offsets accumulate between echoes, but oppositely impact odd and even echoes.
  
  - $B_0$ eddy currents, center frequency offsets, gradient delays, gradient amplifier hysteresis.

- **Solution** – Limit center frequency shifts, minimize echo spacing, limit k-space coverage.
Constant (spatially independent) phase offsets cause even/odd echo phase shifts and FOV/2 ghosts.
Spatially linear phase offsets cause even/odd echo phase shifts, FOV/2 ghosts, and signal cancellation.
EPI – Chemical Shift

- **Problem** – Fat-specific ghosting artifacts.

- **Origin** – Fat is chemical shifted relative to water, especially in the low bandwidth phase encode direction.

- **Solution** – Decrease echo spacing as much as possible, under sample $k$-space, fat saturation.
Chemical shift displacement artifacts are generally apparent in the FE direction for single echo methods:

\[ \Delta x_{c.s.} = \frac{\Delta f_{c.s.}}{2\Delta f_{rbw}} \cdot FOV_x \]

- \( \Delta f_{c.s.} = 421 \text{Hz} \) @3T
- \( \Delta_{rbw} = \pm 32000 \text{Hz} \)
- \( FOV_x = 320 \text{mm} \)
- \( \Delta x_{c.s.} = 2.1 \text{mm} \)

Chemical shift is not a problem in the PE direction for single echo methods because the CS phase does not accumulate.
EPI – Chemical Shift

- EPI typically uses very high RBW, but the PE BW is much lower and dependent on the echo spacing.

\[ \Delta y_{c.s.} = \frac{\Delta f_{c.s.}}{2\Delta f_{pe}} \cdot FOV_{pe} = \frac{t_{esp}\Delta f_{c.s.}}{N_{shot}} \cdot FOV_{pe} \]

- \( \Delta f_{c.s.} = 421 \text{ Hz}, \ t_{esp} = 1 \text{ ms}, \ N_{shot} = 1 \)
  - \( \Delta f_{p.e.} = 1000 \text{ Hz} \) (Low bandwidth in PE direction!)

- \( \Delta y_{c.s.} = 134.7 \text{ mm} \) (Large displacement!)

Chemical shift is a problem in the PE direction for EPI because the CS phase accumulates between echoes.
Fat is chemical shifted from water (-3.3ppm) and accumulates significant phase during long EPI readouts. 

Try, Lecture_10B_EPI_ChemicalShift.m
Summary - EPI Artifacts

• EPI is a very fast, but challenging pulse sequence.

• Prone to artifacts from:
  – Off-resonance, $T_2^*$, $B_0$ and gradient imperfections, chemical shift and more!

• Mitigating field effects and limiting the EPI readout duration generally help, but come at a cost…
Further Learning...

- Principles of Magnetic Resonance Imaging
  A Signal Processing Perspective
  Zhi-Pei Liang
  Paul C. Lauterbur

- Handbook of MRI Pulse Sequences
  Matt A. Bernstein
  Kevin F. King
  Xiaohong Joe Zhou
What alternatives are there to single-shot EPI?