In fMRI a Dual Echo Time EPI Pulse Sequence Can Induce Sources of Error in Dynamic Magnetic Field Maps

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Introduction

• Fast imaging sequences such as Echo Planar Imaging (EPI) expose imperfections in the magnetic environment
  – Long exposure, often 50, 60, 70+ milliseconds of near-continuous readout
  – Long delay between adjacent k-space points;

• Results of EPI acquisitions are generally the target for optimization due to
  – Low SNR
  – Artifact prone
  – Common target for statistical analysis (fMRI)
• $B_0$ field off-resonance
  (resonance frequency offset)
  – Caused by spatially varying magnetic susceptibility
  – Phase accrues over the readout time, leading to warping in the transformed image
  – Difficult to register functional data to anatomical volumes
  – Usually considered temporally invariant
Dynamic Implications

• In reality, variation occurs during a series of EPI data, such as in fMRI\(^1,2\)
  – Leads to variable warping, potentially confounding motion correction
  – variable phase accrual, thus increased temporal phase variance
  – Serious confound to complex-valued statistical analysis\(^1\)

\(^1\)AD Hahn et al., NIMG 44:742-52, 2009
Dual Echo Time EPI

• Resonance offset estimated from phase difference between images with different $TE^2$

• Alternate $TE$ over an entire series, as in Hutton, et al\textsuperscript{1}, for Dynamic estimation

$$\Delta \hat{\omega}_t = \frac{\text{arg} \left( e^{i\hat{\phi}} e^{-i\hat{\phi}_{t-1}} \right)}{TE_t - TE_{t-1}}$$

$\Delta \hat{\omega}_t$ = estimated frequency offset at time $t$

$\hat{\phi}$ = estimated phase at time $t$

$t = 1, ..., N - 1$

\textsuperscript{1}C Hutton et al., NIMG 16:217-240, 2002
\textsuperscript{2}PJ Reber et al., MRM 39:328-330, 1998
Suffers from logical flaw as a dynamic method

- Formula for field offset operates assuming this offset is equal during acquisition of each
- If assumption holds, field can never change
- Otherwise the estimated field will be erroneous

\[
\Delta \hat{\omega}_t = \frac{\text{arg}(e^{i\hat{\phi}_t} e^{-i\hat{\phi}_{t-1}})}{TE_t - TE_{t-1}} \\
\Delta \hat{\omega}_{t+1} = \frac{\text{arg}(e^{i\hat{\phi}_{t+1}} e^{-i\hat{\phi}_t})}{TE_{t+1} - TE_t}
\]

\[
\Delta \hat{\omega}_t = \Delta \hat{\omega}_{t+1}
\]
**Moving Racetrack Trajectory**

- Modified EPI retracing multiple k-space lines at a constant $\Delta TE$ within a single RF shot
- Red paths indicate the first pass and green the second acquisitions of the line
- Generally low resolution

\[
\Delta \hat{\omega}_t = \text{arg} \left( e^{i \hat{\phi}_{,pass_2}} e^{-i \hat{\phi}_{,pass_1}} \right) \frac{nt_{esp}}{\Delta t}
\]

$\Delta \hat{\omega}_t$ = estimated frequency offset at time $t$

$\hat{\phi}_{,pass N}$ = estimated phase at time $t$ for pass $N$

$t_{esp}$ = echo spacing time

$t=1,\ldots,N-1$

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1V Roopchansingh et al., MRM 50:839-843, 2003
Expected Accuracy

- Image phase measurement includes $N(0,\sigma^2)$ noise, $\eta_1$, $\eta_2$
- $\phi_e$ represents all other phase errors
  - Change in $\phi_0$ between images
  - Any response to variable accumulation, such as intra-acquisition motion
  - Any difference in the field during acquisition of both images

- Difference between TEs is important as noise amplifies with decreasing difference
  \[ \Delta \hat{\omega} = \arg\left( e^{i(\phi_2 + \eta_2)} e^{-i(\phi_1 + \eta_1)} e^{i\phi_e} \right) / (TE_2 - TE_1) \]
Methods

• Test performance of dual echo time EPI against MRTT, which is not susceptible to the same errors

• Two scans performed, one with phantom and the other human
  – MRTT acquired at full resolution
    (all k-space acquired twice)
  – $TE$ also increased by 1.872ms on every other image
Methods

- **Scan parameters**
  - $64 \times 64$
  - 24cm FOV
  - Sl. Thickness = 3.8cm
  - TE = 44.3
  - TR = 1
  - Flip angle = 45 degrees
  - Reps = 276;

*ΔTE* was equal in both scans to preserve equal SNR

- **Phantom scanning** (spherical agar phantom) involved no involvement beyond scanner operation

- A single time series in a single human subject was acquired. Subject was told only to lay still and rest

- After estimation of raw field maps, each was fit using a 7th order polynomial to reduce noise

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Results

Average power spectrum of voxel time series in a 5×5 voxel region for phantom (left) and human (right). Results of Dual Echo Time EPI data shown in blue and MRTT in red.

- Both plots show elevated power in the dual $TE$ case, even at specific frequencies in the phantom.
  - Likely scanner instability or variable RF pulse phase.
- Human results are elevated across the whole spectrum, with the greatest difference at lower frequencies where expected physiologic response is likely being amplified.
Results

• Shows disparity between MRTT and dual $TE$ maps

• Disparities more apparent & significant in human data
  – Suggests that violating the assumption of field equality has severe consequences

Maps of t-statistics from a paired-difference test between field maps estimated using MRTT and the dual echo time methods. Statistics for phantom maps shown left and human maps right

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Discussion

• The dual echo technique produces different results than the MRTT, but correctness of either is uncertain

• Appropriateness of dynamic field correction
  – If correction may be error prone, must weigh cost to benefit
  – Most valuable for complex analysis
  – Newer, more robust techniques
Final Thought

- The dual echo EPI method should still be robust for creating static estimations, especially when averaging
  - Probably the easiest technique to implement

- Acknowledgements:
  - This work was supported in part by NIH EB00215 and EB007827