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)

Introduction

- 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
[2]PF Van de Moortele et al.: MRM 47:888-895, 2002.

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[1], for Dynamic estimation

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

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

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

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

[1]C Hutton et al., NIMG 16:217-240, 2002
[2]PJ Reber et al., MRM 39:328-330, 1998

Dual Echo Time EPI

- 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

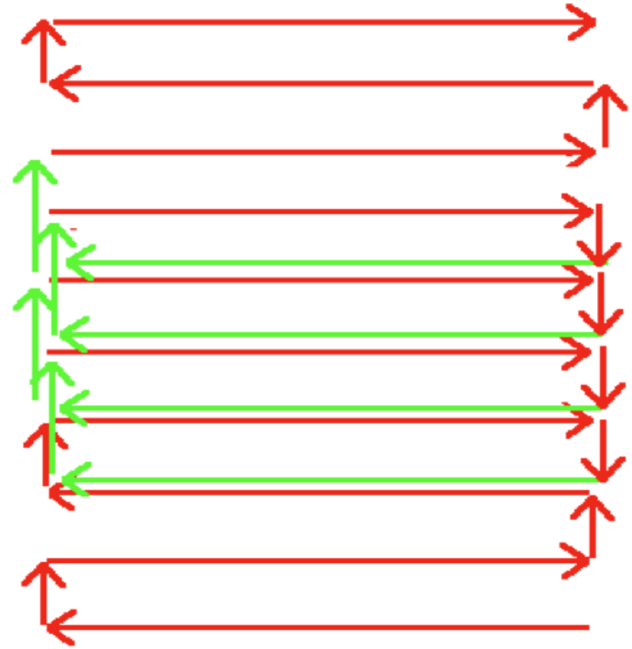
$$\Delta\hat{\omega}_t = \frac{\arg\left(e^{i\hat{\phi}_t} e^{-i\hat{\phi}_{t-1}}\right)}{TE_t - TE_{t-1}}$$

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

$$\Delta\hat{\omega}_t = \Delta\hat{\omega}_{t+1}$$

Moving Racetrack Trajectory

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



$$\Delta\hat{\omega}_t = \frac{\arg\left(e^{i\hat{\phi}_{t,pass\,2}} e^{-i\hat{\phi}_{t,pass\,1}}\right)}{n t_{esp}}$$

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

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

$t_{\mathrm{esp}} =$ echo spacing time

t=1,…,N-1

[1]V Roopchansingh et al., MRM 50:839-843, 2003

Expected Accuracy

- Image phase measurement includes $N(0,\sigma^2)$ noise, η_1, η_2
- ϕ_e represents all other phase errors
  - Change in ϕ_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 *TE*s is important as noise amplifies with decreasing difference

$$\Delta\hat{\omega} = \frac{\arg\left(e^{i(\phi_2+\eta_2)}e^{-i(\phi_1+\eta_1)}e^{i\phi_e}\right)}{TE_2 - TE_1}$$

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

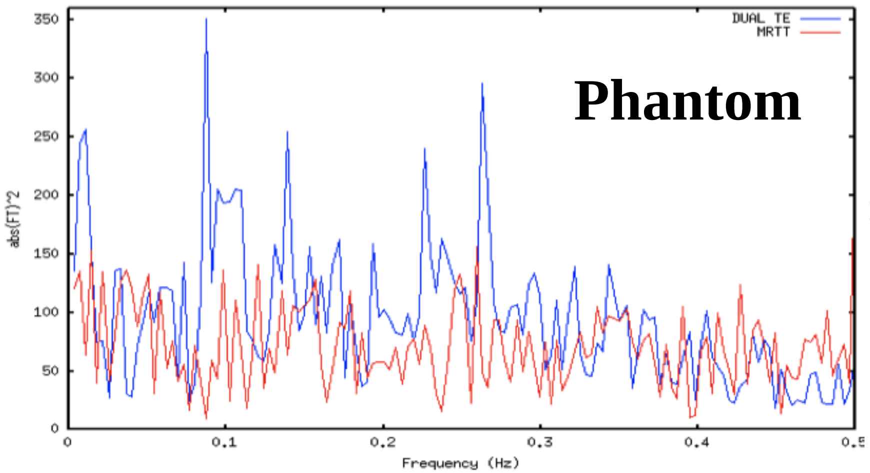
Methods

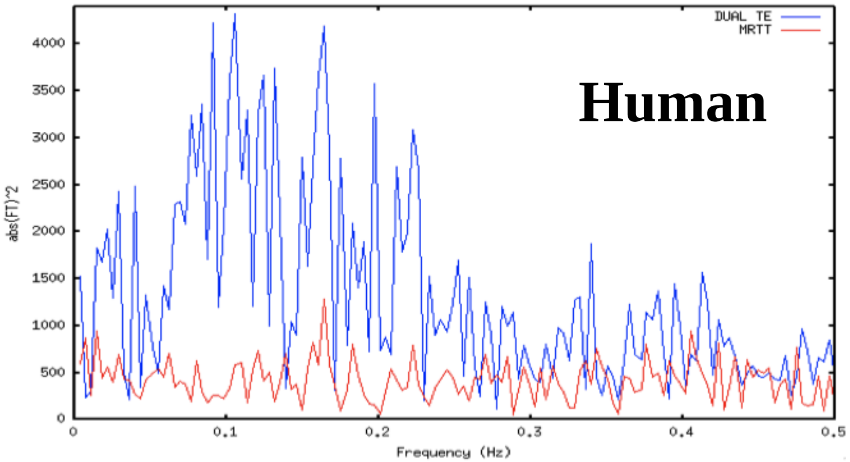
- Scan parameters
  - 64×64
  - 24cm FOV
  - Sl. Thickness = 3.8cm
  - TE = 44.3
  - TR = 1
  - Flip angle = 45 degrees
  - Reps = 276;

*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 7^{th} order polynomial to reduce noise

Results



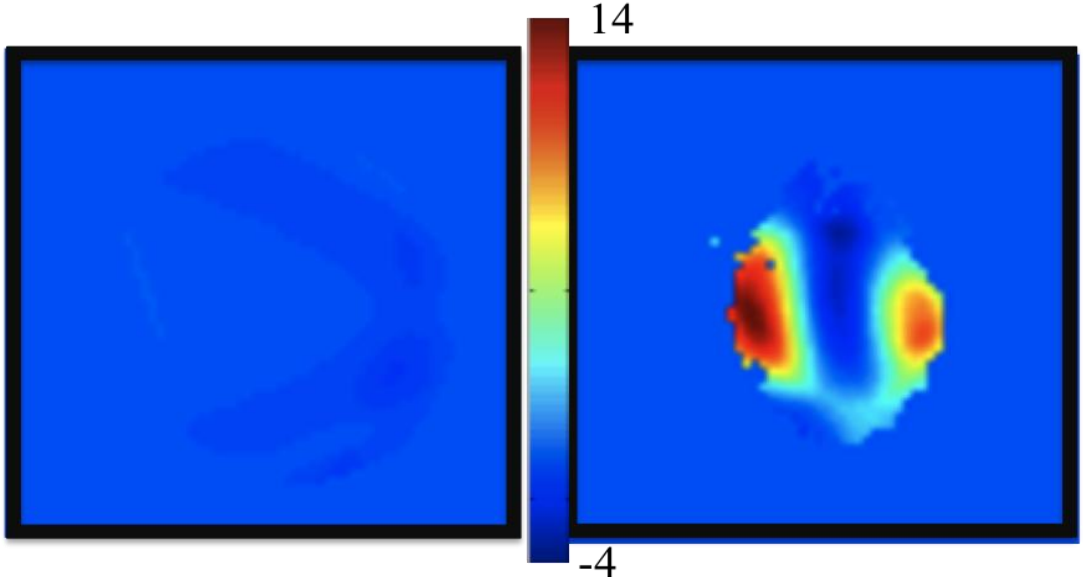


Average power spectrum of voxel time series in a 5×5 voxel region for phantom (left) and human (right). Results of Dual Echo Time EPI data shown in blue and MRTT in red.

- 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

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:

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