A rapid calibration scan for estimating temporally-varying eddy currents in diffusion MRI

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Objective

Diffusion imaging is well known to suffer from eddy-currents, manifesting as distortions in EPI images[1]. Many methods for correcting such distortion effects have been proposed[2,3], with commonly applied techniques relying on estimating a static eddy-current field from a series of distorted images across diffusion-directions. As an alternative, field-probes have shown excellent promise for direct eddy-current field measurements, with capability to capture both spatial and temporal variations[4], but this requires expensive specialized hardware and is not yet widely accessible.

Recently, time-resolved EPI techniques have been developed[4,5], including the PEPTIDE method for application to diffusion imaging[6]. These avoid the typical image-distortion artifacts from B_0 and eddy-current fields, with the phase evolution effects from these fields instead captured in the reconstructed time-series images.

In this work, the phase evolution information in the PEPTIDE images was exploited to create a rapid (<30s) eddy-current calibration scan, to enable accurate eddy field correction without specialized hardware. Realistic simulations were performed to demonstrate the capability of such an approach to accurately capture both spatial and temporal eddy-current field variations, even in the presence of strong eddy-currents. This was then further validated through phantom and in-vivo experiments.

Methods

Eddy-field estimation:

Estimations can be performed using data from a single low-resolution PEPTIDE shot across three principal diffusion directions, with estimates of eddy-fields across other diffusion-directions calculated through a linear model. Estimation for each principal diffusion-direction is performed using the time-series images from that direction and the b=0 reference, which contain the following phase components (Fig 1):

$$\phi_{DWI}(t) = \phi_{Background,DWI} + \phi_{B_0}(t) + \phi_{EC}(t)$$
$$\phi_{b=0}(t) = \phi_{Background,b=0} + \phi_{B_0}(t)$$

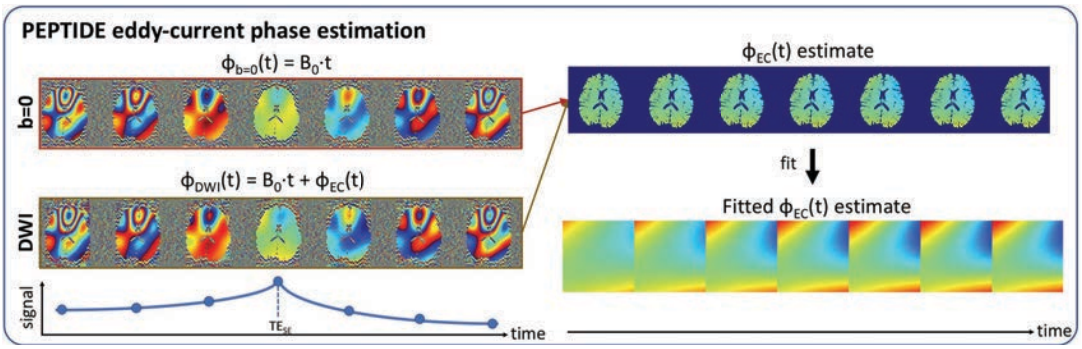

Fig 1 – time-varying eddy current estimation method utilizing single-shot time-resolved PEPTIDE for fast acquisition

Across the time-series, the background phase is removed from both datasets and the difference between the two resultant image phases found, to yield the eddy current induced phase. A weighted quadratic fit is then applied per time-point to determine the spatial components of the time-varying phase. For the case where ϕ_{EC} is assumed to vary linearly with time, a temporal-fit to a constant eddy-field is performed. Assuming a TR of 3.5s, the proposed 3-direction, single-shot PEPTIDE acquisition requires 3.5s x 4 = 13.5s (including a reference b=0s/mm^2 acquisition), with an additional PEPTIDE reconstruction reference scan of ~15s, resulting in a total eddy-current calibration acquisition time of <30s. More shots/directions can be added as needed to improve eddy-field estimation.

Simulation validation:

Simulated PEPTIDE-data for the proposed calibration scan were generated using previously-acquired fully-sampled in-vivo k-t dataset, as previously described. Here, realistic eddy-current phase changes were also added to the data, using eddy-current fields estimated with FSL eddy from EPI-acquisitions with matched parameters at b=1000s/mm^2 and b=5000s/mm. Two cases were simulated: a static eddy-field and an eddy-field with an exponential temporal decay.

Phantom & in-vivo validation:

Phantom and in-vivo datasets were acquired on a Siemens Prisma 3T with a 32-channel coil. A high-SNR diffusion phantom was used for optimal eddy-current estimation and in-vivo data were acquired in a healthy subject. Diffusion-PEPTIDE and diffusion-EPI were both acquired with ESP/TE/TR=1.1ms/128ms/3.5s, 1.5x1.5x3.0mm, 18-slices, 64 diffusion-directions, b=5000s/mm^2. The EPI acquisitions were repeated with reverse phase-encode directions to enable accurate eddy-field estimation with FSL eddy for use as comparison.

Results

With the simulated PEPTIDE-data, eddy-current phases were accurately estimated for both static and temporally-varying eddy-current fields cases (Fig 2). The relatively low errors seen at both b=1000s/mm^2 and b=5000s/mm^2, support the resilience of the technique.

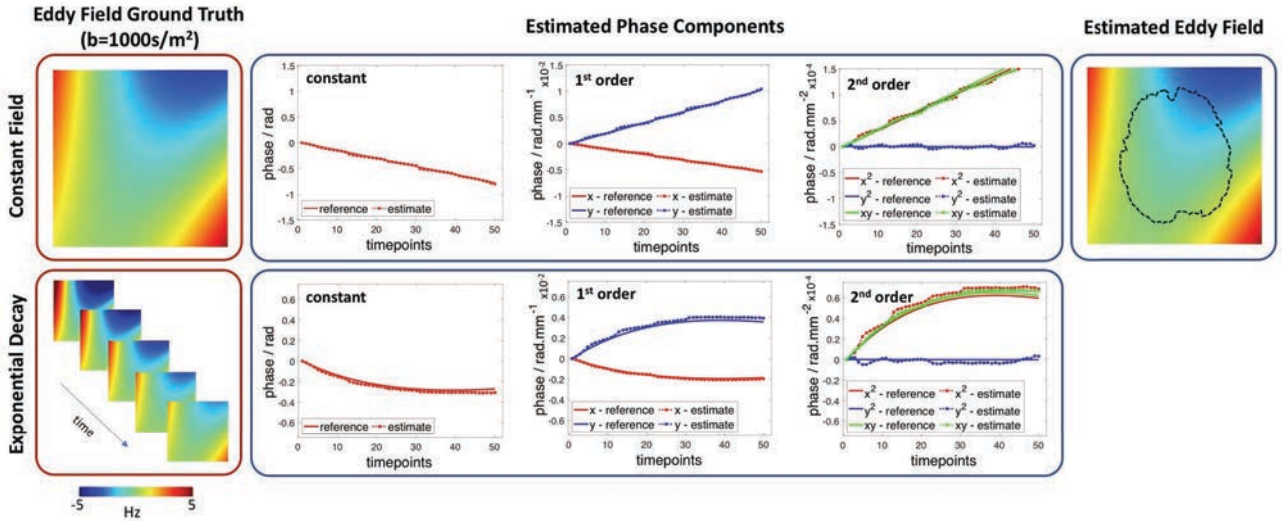

Fig 2 – demonstration of the estimation of constant and time-varying eddy currents using a PEPTIDE calibration scan

Even at b=5000s/mm^2, artifacts in the uncorrected PEPTIDE acquisitions are subtle, with some small signal variations mitigated through the second-iteration reconstruction, suggesting successful estimation and correction of the eddy-currents. The estimated associated field agrees closely with the FSL-EPI estimate obtained from 64 pairs of blipped-up and -down acquisitions.

While in-vivo data at b=5000s/mm^2 has substantially lower-SNR than the phantom, by using image phase in PEPTIDE rather than relying on small distortions in the magnitude images as in FSL-EPI, accurate eddy-field estimate is still feasible. Phantom and in-vivo PEPTIDE field estimates show good agreement with each other as well as with the FSL-EPI phantom estimates, while the in-vivo-FSL estimates contain significant deviation for this low-SNR, high-b-value acquisition.

Conclusions

The time-resolved PEPTIDE technique has been demonstrated capable of accurately detecting eddy-current induced phase changes. Agreement is seen with the well-established FSL eddy technique in a high-SNR phantom, with PEPTIDE able to determine eddy-fields for arbitrary directions from as little as 3 diffusion-directions in-vivo at b=5000s/mm^2. The technique is capable of detecting higher-order temporal components, as well as higher-order spatial components, as needed. Future work could involve confirmation of the temporal field variations against field-probe measurements.

Acknowledgements

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References:

1. Le Bihan, D., et al. Artifacts and pitfalls in diffusion MRI. JMRI. 2006. **2.** Haselgrove, J.C., Moore, J.R. Correction for distortion of echo-planar images used to calculate the apparent diffusion coefficient. MRM. 1996. **3.** Andersson JLR and Sotiropoulos SN. An integrated approach to correction for off-resonance effects and subject movement in diffusion MR imaging. NeuroImage. 2016. **4.** De Zanche, et al. NMR probes for measuring magnetic fields and field dynamics in MR systems. MRM. 2008. **5.** Wang, F., et al. Echo planar time-resolved imaging (EPTI). MRM. 2019. **6.** Fair, et al. Propeller echo-planar time-resolved imaging with dynamic encoding (PEPTIDE). MRM. 2020. **7.** Fair, M.J., et al. Diffusion-PEPTIDE: Distortion- and blurring-free diffusion imaging with self-navigated motion-correction and relaxometry capabilities. MRM. 2021.