Phase Correction of a Bipolar Gradient-Echo Acquisition for Quantitative Susceptibility Mapping

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Synopsis

A method to remove phase offsets in bipolar gradient-echo readouts is proposed. Their effects on Quantitative Susceptibility Mapping (QSM) reconstruction are demonstrated by comparing QSM before and after phase offsets removal.

Purpose

To demonstrate a method that removes phase offsets from a multi-echo bipolar gradient-echo acquisition, and investigate the effect of the phase offset correction on quantitative susceptibility map (QSM) reconstruction.

Methods

In a gradient-echo sequence, phase accumulates linearly with echo time in addition to an initial phase offset: $\phi = -\gamma \cdot \Delta B \cdot TE + \phi_0$, where ϕ is the measured phase at TE and ϕ_0 is the initial phase offset. However, in multi-echo bipolar gradient-echo readouts, the phase offsets in odd and even echoes are different, and simple linear regression with non-zero intercept introduces errors for QSM [1,2]. Here we propose a method to remove phase offsets in both odd and even echo readouts completely, and then perform a linear regression with zero intercept.

Consider all the odd echo readouts first: a phase difference map between the first two odd echoes was generated through the division of the raw complex images (S):

$$\Delta\phi = \angle(S_2 \cdot S_1^*) = -\gamma \cdot \Delta B \cdot \Delta TE.$$

After unwrapping the phase difference map $\Delta\phi$ and obtaining $\Delta\Phi$, using a path-based method such as PRELUDE of FSL package, the phase evolution at TE_1 without offset can be estimated as:

$$\Phi_1 = \Delta\Phi / \Delta TE \cdot TE_1.$$

The phase offset can then be calculated by complex division of estimated phase at TE_1 from the measured complex image at TE_1:

$$\phi_0 = \angle(S_1 \cdot \exp(j\Phi_1)^*).$$

Finally, offset corrected phase can be computed by removing estimated offset from the complex image:

$$\phi_{corr} = \angle(S \cdot \exp(j\phi_0)^*).$$

Figures

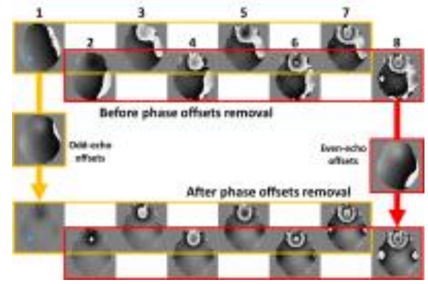

Fig. 1: Raw phase images from 8 bipolar echoes are shown at the top, the phase offsets corrected phase images are shown at the bottom. The calculated phase offsets from odd and even echoes are displayed on the sides.

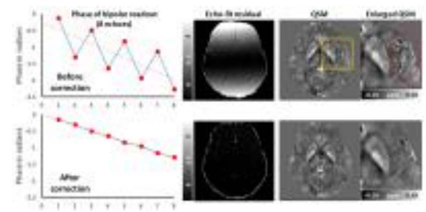

Fig. 2: Phase evolutions with echo times in bipolar readouts, the linear fitting residuals and the resulting QSM images are demonstrated for both before (top row) and after phase offsets correction (bottom).

Phase offset in the even echoes was removed following the same process.

After phase offsets correction, QSM can be reconstructed following the pipeline of (1) spatial phase unwrapping of each echo using PRELUDE, (2) magnitude-weighted least-square fitting of the unwrapped phase with zero intercept, (3) background field removal using RESHARP, and (4) dipole inversion using total variation regularization.

Ten healthy subjects were scanned using a three-dimensional bipolar gradient-echo acquisition at 3 T (GE Healthcare). The parameters were: 25.6 x 25.6 x 12.8 cm^3 FOV, 1 mm isotropic spatial resolution, 8 bipolar echoes with a first TE of 2 ms and a 2.4 ms echo spacing thereafter, 22 ms TR, 488 Hz/pixel bandwidth, ASSET = 2 parallel imaging, and a total scan time of 3 mins 50 secs. QSM reconstructions with and without the correction procedure outlined above were performed.

Results

The effect and removal of phase offsets in odd and even echo readouts is demonstrated in Fig. 1. In the top two rows, odd and even echo readouts display asymmetric phase wrap patterns. After removing the odd and even echo offsets from the respective echoes, the corrected phase images display symmetric wraps that evolve with echo times, as shown at the bottom rows. Average phase values in the blue circle region-of-interest in Fig. 1 were measured across the 8 echoes and are plotted in Fig. 2, both before and after offset correction. The raw phase from the bipolar readout shows large jumps between odd and even echoes, as opposed to the linear phase evolution after correction. The residuals of fitting the unwrapped phase with echo time are also shown in Fig. 2. The voxel-based fitting residuals are substantially reduced after phase offset correction. QSM images derived from phase uncorrected and corrected data are superficially similar, however, if examined carefully it is clear that the phase corrected QSM images have improved image quality and significantly reduced artifacts around vessels (Fig. 2 right column).

Discussion

Bipolar gradient phase correction has been proposed in a previous paper [2], using the first three echoes to remove the offset difference between odd and even echoes. Here we propose to directly remove the odd and even echo offsets from all the respective echoes. We then linearly fit the unwrapped phase with a zero intercept. We implement our method in a complex manner that reduces the need for a phase unwrapping process for the offset correction. For example, in the previous method, phase maps from each of the first three echoes need to be unwrapped, while in our method only the phase difference is unwrapped once. QSM failures have been reported if reconstructed without bipolar phase offset correction [2]. Interestingly, we did not observe any failed QSM's reconstructed without offsets correction, though the QSM image quality was degraded. This may be due to the symmetry of the phase offsets between the uncorrected odd and even echoes, as observed in Fig. 2, and the robustness of our QSM pipeline. However, with the phase offsets correction proposed here, we observed a significant reduction in artifacts around some vessels in all the ten subjects.

Acknowledgements

Funding supports from Campus Alberta Innovates Program (CAIP) and Canadian Institutes for Health Research (CIHR).

References

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