Methodology for Robust Motion Correction of Complex-Valued MRI Time Series

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Introduction

In functional MRI (fMRI), the presence of subject motion during the acquisition of an image series can confound results. In general practice, only the magnitude portion of each image is used in the functional MRI analysis [1], and thus correction for subject motion is required in only the magnitude images. However, statistical models for performing complex-valued fMRI analysis are readily available [2] which can provide benefits beyond the standard magnitude-only technique, and the investigation of a signal resulting from direct neuronal current involves complex-valued analysis [3]. Furthermore, it has been demonstrated that signal of potential functional interest can be found in the phase portion of the signal [4]. In order to maximize the utility of these investigative techniques, motion correction of the phase as well as the magnitude is required. Unfortunately, this complex-valued correction is not as straightforward as magnitude correction alone.

The image phase can be considered to consist of three separate parts, resulting from:

1) Local tissue susceptibility differences

2) More spatially global bulk magnetic field inhomogeneity

3) Inhomogeneity of the RF pulse phase

Motion correction would be appropriately applied on the first part of this phase only. The second portion, while variable through time, does not behave like bulk motion. Bulk field inhomogeneity changes as the head moves, but these changes are unpredictable and cannot be accounted for using bulk motion correction techniques [5]. The phase from the RF pulse is considered to be constant through time for the amount of motion generally present during acquisition. Therefore, correction of this phase would also be invalid. The goal of this work is to demonstrate the ability to isolate the phase due to local tissue susceptibility and how doing so improves the performance of motion correction of the phase signal.

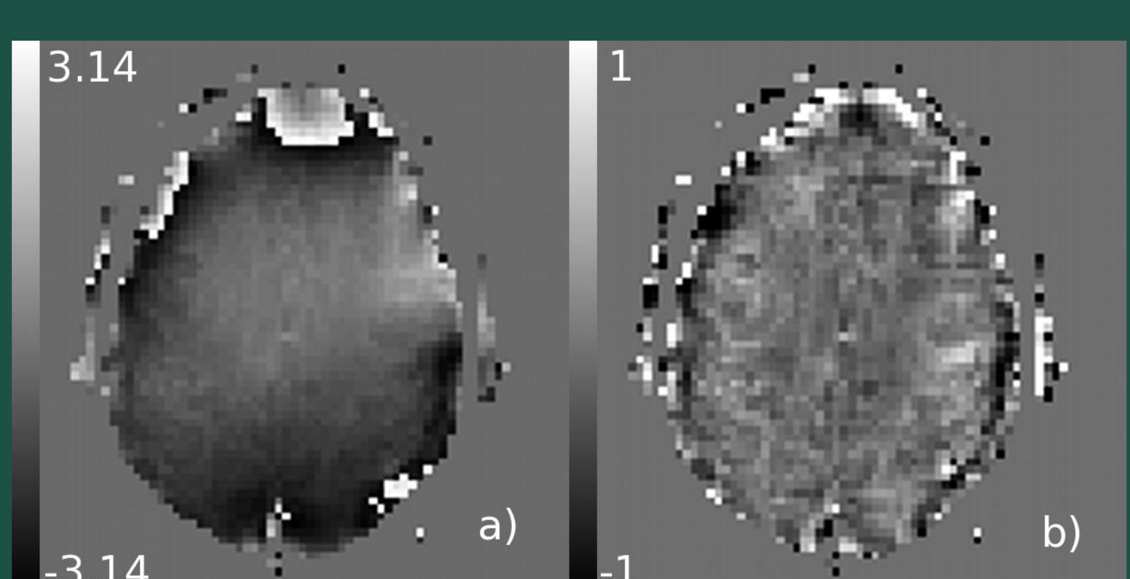

Figure 1. Phase image of a single slice from the acquired image time series after TOAST correction only (a) and after TOAST correction and RF phase removal (b). The left image shows the low spatial frequency phase attributed to RF phase, while the right image shows phase which appears mainly anatomical in nature. Note the difference in scale. Images are masked above 10% of the maximum magnitude.

Methods

An MRI time series was acquired for a single subject on a 3T MRI scanner (General Electric, Milwaukee, WI) using an echo planar imaging (EPI) pulse sequence (TE=42.7 ms, BW=125 Hz, matrix= 96×96, FOV=24 cm, slice thickness=2.5 mm, #slices=9, TR=1 s, repetitions=296). During the first 20 repetitions, even repetitions had their echo time increased to 47.7 ms to facilitate magnetic field off-resonance estimation. Dynamic magnetic field offset correction was applied using the Temporal Off-resonance Alignment of Single-echo Timeseries (TOAST) method as described by Hahn et al. [6]. After this correction, the complex-valued mean over all images was computed and smoothed with a 12.5 mm FWHM Gaussian kernel. The phase of this smoothed image, representing the phase of the RF pulse, was then subtracted out of every image in the series. Finally, 2-dimensional motion parameters were computed from the magnitude portion of the TOAST corrected images and applied to the real and imaginary portions of the same images using the AFNI plugin 2dImReg [7].

Results

The spatially global phase variations remaining after removing the effects of bulk magnetic field inhomogeneities using TOAST can be seen in Figure 1a, and can be attributed to the phase of the RF excitation pulse. After removing this low spatial frequency phase as described in Methods, the remaining phase depicted in Figure 1b appears to have mainly anatomically related structure, which is the desired result.

Temporal phase variance was used to investigate the benefit of the motion correction. Specifically, the ratio of the phase variance following complex-value motion correction was computed between time series with and without the phase isolation applied. Images of the results of this analysis are shown for the case where the RF phase is not removed, and for the case where it is removed in Figures 2a and 2b, respectively. In these images, part 1 has been subtracted from the ratio, so that larger (more positive) values indicate a greater reduction in variance, while negative values indicate that motion correction increased the phase variance. It should be noted that no data is presented without the TOAST correction, due to the fact that the phase variance due to motion is negligible compared to that resulting from temporal bulk field variation. The results in Figure 2 show that

1) Variance is improved over most of the brain (more grey/white than dark grey/black) in both a) and b).

2) In at least one area (outlined in red in Figure 2) indicates an area where removal of the RF phase significantly improves the performance of the motion correction.

3) Various other areas (some outlined in blue) indicate where it appears the RF phase removal improves performance as well, although less so.

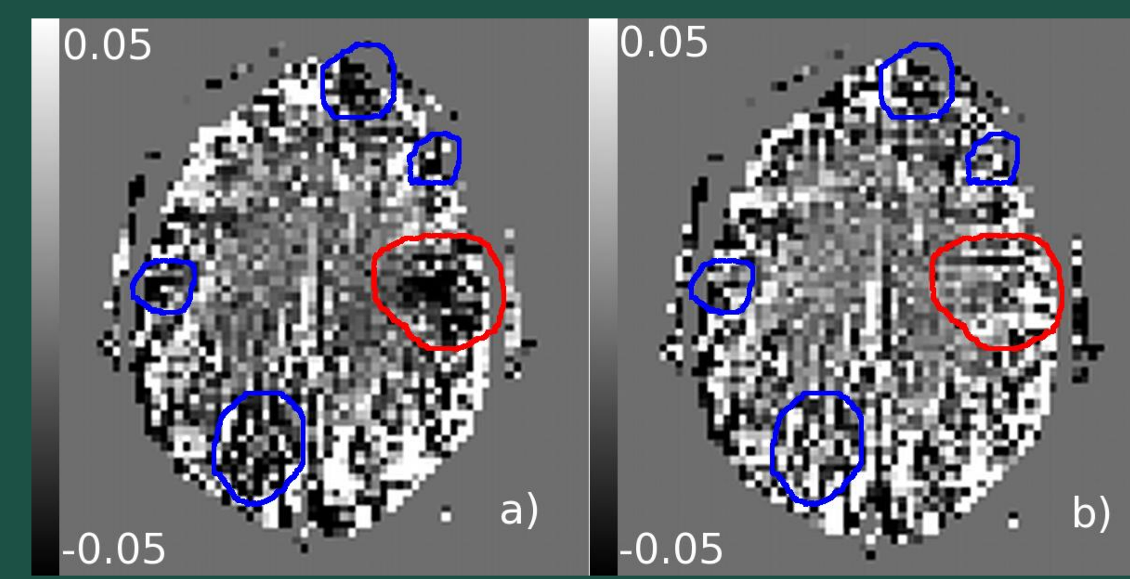

Figure 2. Image of the voxel-wise ratio of the phase variance after TOAST correction without motion correction to the phase variance with motion correction following only TOAST correction (a) and both TOAST correction and RF phase removal (b). The ratio is then subtracted by 1 so positive values indicate reduced variance and vice versa. The area indicated in red shows where the RF phase removal greatly improves motion correction performance and the areas indicated in blue show where the removal noticeably improves motion correction performance. Images are masked above 10% of the maximum magnitude.

Discussion

The results seem to show that areas are affected locally by the presence of the RF phase, while others are not, which is not unexpected. Areas where the RF phase appears detrimental seem to coincide with locations where the RF phase has more spatial variation (see Figure 1a), which is logical. If main magnetic field inhomogeneity is not corrected for using TOAST, similar results can be seen, and the phase induced by this inhomogeneity tends to have more rapid spatial variation (data not shown). Although the motion correction applied here was only in 2 dimensions, applying a 3 dimensional correction using this technique should be equally useful. It is not done here because of the limited data in 3 dimensions (only 9 slices) to determine appropriate motion parameters. Finally, it is worth noting that the motion correction is applied to the real and imaginary channels of the data rather than the phase channel directly in order to avoid the need to unwrap the image phase. If a 2 dimensional phase unwrap is applied to every image, the motion correction could be applied to the phase directly.

References

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