Hadamard Encoded Time-Dependent Phase Constraint Parallel Image Reconstruction

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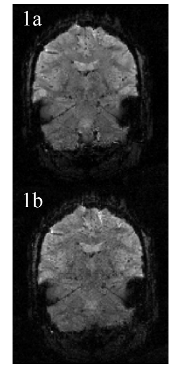
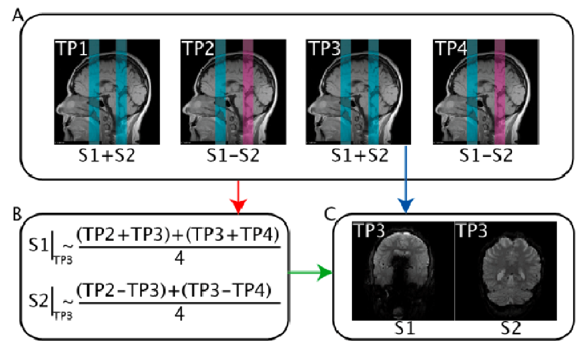
Introduction

The use of the multi-band parallel imaging along the slice-select direction in fMRI can increase the throughput (Larkman et al., JMRI 2001: 13(2) p.313) without signal reduction resulting from k-space undersampling as in conventional parallel acceleration along the phase-encoding direction. However, the multi-band parallel imaging is still susceptible to noise amplification due to non-ideal sensitivity profiles (i.e., g-factor). Even though several approaches have been developed to improve the signal-to-noise ratio (SNR) in multi-band parallel imaging, such as CAIPIRINHA (Breuer et al., MRM 2005: 53(3) p.684), the existing methods may not improve the SNR when the simultaneously excited bands are not spatially far apart. The purpose of this work is to present a novel method that integrates Hadamard slice encoding and time-domain phase constrained reconstruction, to significantly eliminate the noise amplification of multi-band parallel reconstruction even for simultaneously excited neighboring slices.

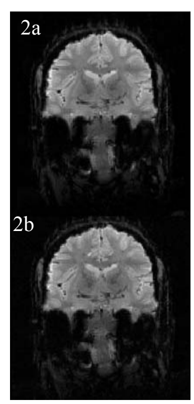


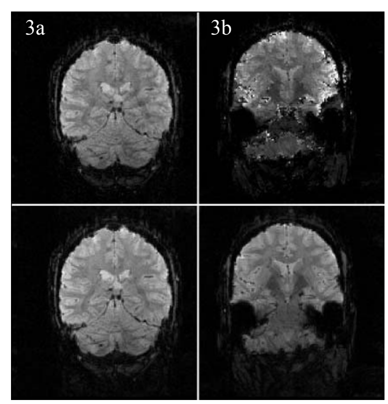
Theory and methods

Multi-band parallel imaging contains overlying information from two simultaneously excited (but spatially separate) slices. This information can be decomposed using a multi-channel array of coils and a known sensitivity profile through SENSE algorithm (Pruessmann et al., MRM 1999: 42 p.952), with noise amplification quantified by the g-factor. In contrast to the original SENSE implementation, phase constrained SENSE (Lew et al., MRM 2007: 50 p. 910-921) uses a known phase along with the real and imaginary equations associated with the complex data to extract the magnitude information of the original images, to reduce the g-factor. For example, Figure 1a shows image reconstruction with (1a) and without (1b) phase constraint. While it is better, the phase constraint extraction relies on accurate prior knowledge of phase information, which may not be easily obtainable particularly for dynamic scans (e.g., fMRI) where the B0 and thus phase values drift over time. What our new method attempts is to create a time-dependent phase constraint from modified fMRI acquisition strategies, based on alternative Hadamard encoding, as described below.



<u>*Alternative Hadamard Slice Encoding*</u>: When obtaining multi-slice images, we design an RF pulse introducing a 180-degree phase shift into one of the slices, but not the other, for every other time points of fMRI scans. A simple Hadamard reconstruction can be applied to reconstruct temporally-smoothed signals from each of the simultaneously excited slices. Diagram A shows that at every other time point, the second slice recieves a phase shift of π and the resulting image combinations can be expressed as S1+S2 or S1-S2 for odd and even time points, respectively. The red arrow indicates the slice extraction (B) by averaging either the sum or difference of neighboring time points. For invariance over time the extraction (green arrow) outputs the original images (blue arrow). However, because variance over time does exist, these Hadamard-created images are time-smoothed and are not accurate enough to be considered usable data. They can be used, though, to generate a time-dependent sensitivity profile and, more importantly, gain the phase information with which to produce accurate phase-constrained images from the original multi-band data.





Results and Discussion

Using images which were attained as single slices we were able to simulate the Hadamard encoded time-dependent phase constraint model while having knowledge of the original to use as a comparison. Figure 2 shows the extraction of overlain images using the method discussed above (2a) in comparison to the original images used (2b). Figure 3 is a comparison of SENSE extraction (top) with our method (bottom) for two cases. 3a shows that both methods behave similarly for original slices which were chosen far apart. 3b, however, shows the robustness of our method when choosing slices much closer together. All of these figures show that this method can dependably extract slices from parallel imaging. This allows for a variety of methods to increase speed of measurements, not the least of which to image one slice per coil reliably in a multi-channel system.

Conclusion

The Hadamard encoded time-dependent phase constraint model is a very robust and accurate method for extracting images from parallel imaging data. And like phase constraint SENSE, this method is applicable to both single-channel and multi-channel systems. However, this method may yield more uses such as reconstruction for undersampled k-space data and slice per coil imaging in multi-channel systems.