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Comparison of coil combination technique performance for phase preservation

Krithika Balaji[1], Peter J Lally[2,3], Zimu Huo[4], Michael Mendoza[4], Michael N Hoff[5], and Neal K Bangerter[4]
[1]Bioengineering, Imperial College London, London, United Kingdom, [2]Department of Brain Sciences, Imperial College London, London, United Kingdom, [3]UK Dementia Research Institute Centre for Care Research and Technology, London, United Kingdom, [4]Department of Bioengineering, Imperial College London, London, United Kingdom, [5]Department of Radiology and Biomedical Imaging, University of California, San Francisco, San Francisco, CA, United States

Synopsis

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MRI images are typically acquired using multiple receive coils, which introduce spatially varying phase offsets to each coil image. Many techniques have been developed to combine these coil images. For a variety of reconstruction techniques, phase preservation is necessary post-combination but it is unclear which method best achieves this. This work compared ESPIRiT, Simple Phase RCC, Full Phase RCC, 3T Siemens' Adaptive Combine and IMPA using phase-cycled bSSFP images. Phase preservation was evaluated using the elliptical signal model theory and characteristic bSSFP phase plots. ESPIRiT consistently produced combined images with phase characteristics most similar to those from a single coil.

Introduction

MRI images are typically acquired using a phased array of receive coils, with each coil element introducing spatially varying phase offsets to the data. This data is combined using a variety of techniques to generate a single MRI image. For phase-sensitive reconstructions (including quantitative imaging techniques such as elliptical T2 mapping with phase-cycled bSSFP), the reconstruction could either be conducted separately on the individual coil images and then combined, or on the coil combined image. While the former uses the uncorrupted phase data, it is often desirable to perform coil combination before performing the reconstruction or calculating the desired quantitative parameter, since fewer reconstructions are needed on higher SNR data.

For certain types of imaging, like phase contrast imaging[1], susceptibility weighted imaging[2], and phase-cycled balanced Steady State Free Precession (bSSFP)[3], it is crucial to preserve phase while performing coil combination. However, to our knowledge, a careful comparison of phase preservation across the range of techniques has not been performed. Hence, this comparative study aims to identify the coil combination technique that best preserves the original phase information.

Methods

To identify the coil combination techniques that best preserve phase, this comparative study used phase-cycled bSSFP as the test case given its unique phase characteristics. The bSSFP signals at a single location from different phase cycled acquisitions theoretically form an ellipse in the complex plane[3].

Five different techniques were tested: ESPIRiT[4], Simple Phase Robust Coil Combination (RCC), Full Phase RCC[5], Siemens Adaptive Combine (implemented on a 3T Verio, software version VB17A), and Intrinsic Multichannel Phase Alignment (IMPA)[6]. ESPIRiT and Adaptive Combine are general coil combination techniques that can be employed on images generated using any pulse sequence. The other techniques, however, are specific to phase-cycled bSSFP data. Both general and specific methods were chosen to see which one best preserves phase.

The methods were tested on 4 healthy volunteers. Axial knee slices were acquired on a 3T Siemens Verio (Erlangen, Germany) using a 2D phase-cycled bSSFP pulse sequence (flip angle: 22 degrees; TR/TE: 8.6/4.3 ms; voxel size: 0.4x0.4x5.0 mm; matrix size: 320x320; number of phase cycles: 12, evenly spaced; single slice) with an 8-channel knee coil. Once the raw data were acquired, coil combination was performed using the different techniques. The coil-combined images were compared with a single coil image sensitive to patellar cartilage under the assumption that its phase would largely be uncorrupted, except for the noise and a DC offset term. Phase preservation was tested for both voxel-wise and region-of-interest (ROI) averaged signals.

Results and Discussion

Figure 1 shows the normalized magnitude and DC-offset-removed phase images of the reconstructed complex and single coil data. The magnitude images look similar. The phase images differ depending on the combination technique.

The top panels in Figure 2 show the phase-cycled bSSFP signals acquired from one location in patellar cartilage across the multiple acquisitions plotted on the complex plane for the various reconstruction methods, along with an ellipse fitted using the phase-cycled points. The bottom panels show the corresponding characteristic phase plots for phase-cycled bSSFP across 48 different voxels.

Figure 3 plots the ROI-averaged signals in the complex plane (top panels) and the corresponding characteristic phase plots (bottom panels). One ROI containing 24 voxels was analyzed in patellar cartilage.

Figure 4 plots the average Root-Mean-Square-Error (RMSE) and standard deviation of the characteristic phase plots for each coil combination technique and the corresponding reference single coil phase plots over 4 healthy volunteers. The mean RMSE for each reconstruction method relative to the single-coil reconstruction was calculated using: the individual voxel-wise phase plots generated from 48 voxels per volunteer shown in the bottom panels of Figure 2; the phase plots generated from the ROI-averaged signals from each volunteer shown in the bottom panels of Figure 3.

These qualitative and quantitative comparisons suggest that ESPIRIT is consistently the best at preserving phase for both voxel-wise and ROI-averaged signals, as seen by how those signals form an ellipse in the complex plane and have visually similar phase profiles to the single coil data (Figures 2 and 3). ESPIRiT also has the lowest mean RMSE (0.25 and 0.02 rad) and standard deviation (0.17 and 0.01 rad) across all four healthy volunteers for both voxel-wise and ROI-averaged signals respectively (Figure 4), indicating it is the most consistent at preserving phase. IMPA and Adaptive Combine perform reasonably well, but they seem inconsistent in preserving phase over the 4 volunteers as seen by their larger standard deviations. While Simple RCC preserves phase for voxel-wise signals, it does not for ROI-averaged signals. Full phase RCC does not preserve phase well in either case.

Conclusion

This comparative study has shown that ESPIRiT consistently preserves phase for both voxel-wise and ROI-averaged phase-cycled bSSFP signals. Hence, for studies that require phase preservation (example: SWI and phase contrast imaging), ESPIRiT appears to be a good choice as it not only preserves phase well but also is independent of the pulse sequence used for image acquisition. This would ensure the validity of any assumptions made by these studies on the phase being preserved post-combination and their results.

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References

1. Wymer D., Patel K., et al. (2020). Phase-Contrast MRI: Physics, Techniques, and Clinical Applications. RadioGraphics.

2. Halefoglu, A.M., Yousem DM (2018). Susceptibility weighted imaging: Clinical applications and future directions. World journal of radiology, 30-45.

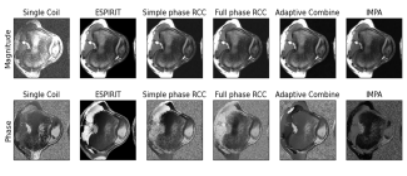
3. Xiang Q-S, Hoff M (2014). Banding artifact removal for bSSFP imaging with an elliptical signal model. Magnetic Resonance in Medicine.

4. Uecker M, Lai, P., Murphy, M.J. et al. (2013). ESPIRiT—an eigenvalue approach to autocalibrating parallel MRI: Where SENSE meets GRAPPA. Magnetic Resonance in Medicine., 71: 990-100

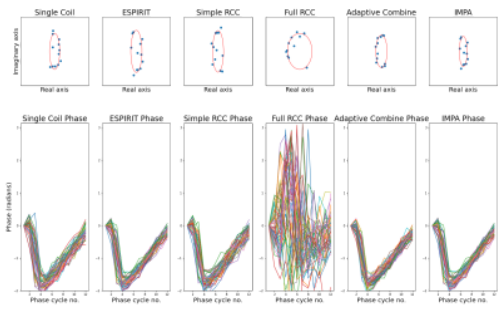
5. McKibben N, Tarbox G. DiBella E. (2020). Robust Coil Combination for bSSFP Elliptical Signal Model. ISMRM.

6. Xiang Q-S, Hoff M (2019). Intrinsic Multichannel Phase Alignment (IMPA) for bSSFP Imaging. ISMRM, (pp. 1-2).

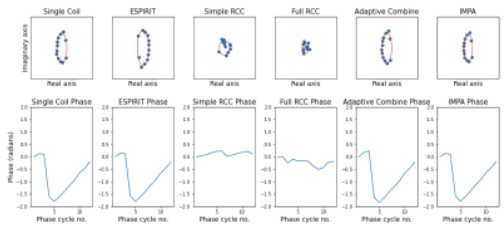
Figures



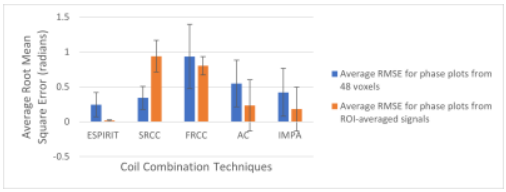
The cartilage-based magnitude and DC-offset-removed phase images acquired from the single-coil and multi-coil reconstructed images. The magnitude and phase plots have been windowed from 0 to 0.25 and -pi to pi rads, respectively. ESPIRiT[4], Simple Phase Robust Coil Combination, Full Phase RCC[5], Siemens Adaptive Combine, and Intrinsic Multichannel Phase Alignment (IMPA)[6] were compared. The magnitude images look similar. The phase images differ depending on the coil combination technique.



Top row: the scaled phase-cycled bSSFP signals acquired from 1 cartilage location across the multiple acquisitions are plotted on the complex plane for each method and single coil data. It is assumed that single coil data would have its phase uncorrupted except for noise and a DC offset. An ellipse was also fitted (red) to visually check phase preservation using the elliptical signal model. Bottom row: the characteristic phase plots for 48 cartilage voxels. Qualitatively, it is seen that phase is preserved for voxelwise signals when using ESPIRiT, Simple RCC, Adaptive Combine and IMPA.



Similar plots as Figure 2, except the signals used here were averaged within a Region of Interest (ROI) in patellar cartilage containing 24 voxels. From qualitatively comparing both the elliptical fits and the phase plots with the corresponding single coil data, it is seen that ESPIRiT, Adaptive Combine and IMPA are the best at preserving phase while Simple and Full Phase RCC do not form ellipses and also do not form the expected variation in phase over the various phase cycles.



The mean RMSE and standard deviation across 4 healthy volunteers is shown for: individual phase plots acquired over 48 voxels per volunteer and; phase plots acquired from ROI-averaged signals. The RMSE was found with respect to the signal coil data. ESPIRiT has the lowest mean RMSE for both voxel-wise and ROI-averaged signals (0.25 and 0.02 rad respectively) and also has a low standard deviation for both cases (0.17 and 0.01 rad respectively). It is the most consistent at preserving phase. Note: SRCC is Simple Phase RCC, FRCC is Full Phase RCC and AC is Adaptive Combine.

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