

Coil Combination Method for Multiple-Echo Sequences and PSF Mapping

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INTRODUCTION: Phased array coils are increasingly used in MRI for improving the signal-to-noise ratio (SNR) or accelerating MRI acquisitions. Most image reconstruction approaches require a separate step to combine the data from the individual channels into a single composite image. Sum-of-squares technique is widely used, but it is unsuitable when the phase information needs to be preserved. Optimal combination approaches like phase alignment [3] or SENSE [4] have been proposed, which require additional calibration data. Adaptive reconstruction by Walsh et al.[1] offers several advantages over both sum-of-squares and calibration data based methods, but is computation intensive and prone to errors for strongly T_2^* -weighted data due to the requirement of spatial smoothness of image phases. In this work a new method for coil combination is proposed, which is particularly suited for multi-echo, multi-reference or spectroscopic acquisitions, which intrinsically contain information on the temporal phase evolution. The performance of the method is demonstrated on the PSF mapping [4] application, widely used for distortion correction in EPI and BOLD fMRI in particular.

METHODS: For an N -coil receiver array, image phase of coil i , measured with a gradient echo sequence can be written as $\varphi_i = \phi_0 + \phi_1 + \theta_i$, where ϕ_0 is defined by the B0 inhomogeneity, ϕ_1 is the transmit field phase and θ_i is the phase component of the individual receive coil sensitivities, which need to be defined correctly for each channel to avoid signal loss during data combination. The transmit field phase is typically spatially smooth presenting no problem for signal combination and thus can be neglected. The B0 induced phase component is dependent on the echo time and can be written as $\phi_0(TE) = \gamma \Delta B \cdot TE$. For multi-echo sequences ΔB can be defined from the measured data and receiver coil phase can be estimated as $\varphi_i(TE=0)$.

Reconstructed PSF mapping data are three dimensional for every measured slice, containing readout dimension, EPI phase encoding dimension and PSF encoding dimension [4]. If a Fourier transform is applied to these data along the EPI phase encoding direction, centered on the ideal PSF peak position for every PSF encoding step, the resulting data are equivalent to a spectroscopic acquisition without phase encoding [5]. Based on this spectroscopic information phase image at $TE=0$ can be calculated by a linear fitting, thus, receiver coil phase θ_i can be estimated for each pixel and coil based on the transformed PSF data. Thereafter, data from individual coils are divided by the resulting phase correction maps and can be added to generate a composite complex-valued data set.

The proposed coil combination approach was tested on in vivo PSF data acquired on a Siemens 7T scanner (Siemens Healthcare, Erlangen, Germany) equipped with an 8-channel head coil array (Rapid Biomedical, Würzburg, Germany). Imaging parameters were FOV = 212 mm, TE = 27 ms and $106 \times 80 \times 53$ matrix (partial Fourier acquisition and PSF field-of-view reduction factor of 2). PSF reconstruction was performed using (i) adaptive combination as in [1], (ii) direct complex addition and (iii) the proposed method.

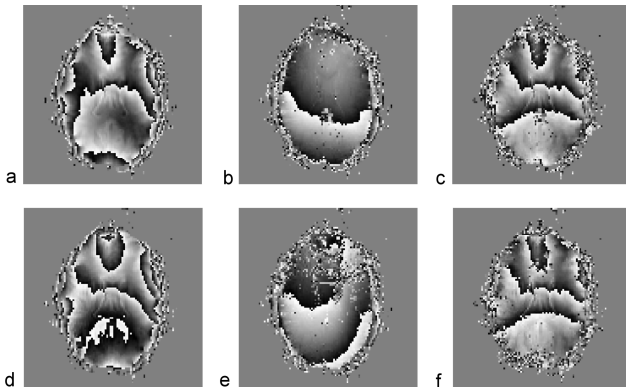


Fig. 1. (a) Original phase image for coil 1. (b) Calculated receiver coil phase for coil 1. (c) Object-induced phase estimated for coil 1. (d) Original phase image for coil 5. (e) Calculated receiver coil phase for coil 5. (f) Object-induced phase estimated for coil 5.

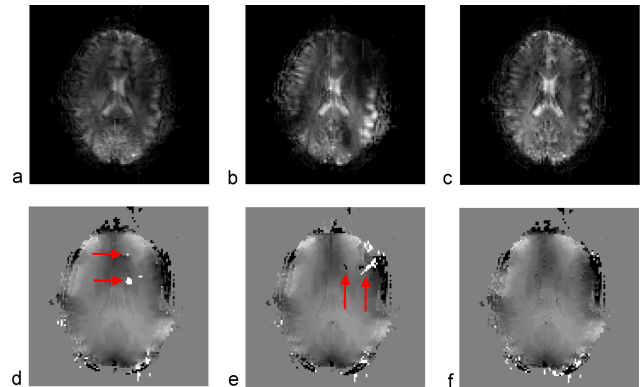


Fig. 2. Gradient echo images (a-c) and pixel shift maps (d-e) resulting from different PSF data reconstructions: (a, d) adaptive combination, (b, e) direct addition and (c, f) proposed combination approach. Artifacts in pixel shift reconstruction are marked with red arrows.

RESULTS: Fig. 1 displays the measured phase (a, d), calculated receiver coil phase (b, e) and the image phase without receiver coil phase (c, f) for coils 1 and 5, respectively. As can be visually appreciated from figures 1c and 1f, after subtracting receiver coil phase from the original image phase, the phase differences between different coils tend to disappear. Thus, these images may be added in complex domain without signal loss while preserving phase information. Fig. 2 shows gradient echo images (the first row) and pixel shift maps (the second row) resulting from different PSF reconstructions based on the same raw data. From the visual comparison of the gradient echo images it becomes apparent, that the presented combination method provides the best image quality. This finding is supported by the artifact-free pixel shift map reconstruction resulting from the proposed data combination, whilst both direct addition and adaptive combination suffer from minor artifacts (marked with arrows).

DISCUSSION AND CONCLUSIONS: The presented method is capable of separating the off-resonance induced phase component from the RF-induced phase contributions. For T_2^* -weighted imaging, as e.g. required for BOLD or SWI the B0-induced phase may become very significant and spatially inhomogeneous, presenting considerable complications for adaptive combination methods. It is to be noted, that a certain degree of SNR loss in phase images and pixel shift maps can be observed when using the proposed data combination. This is due to the spike noise, which can be seen in the calculated receiver coil phase (Fig. 1b and Fig. 1e), resulting from the low SNR of the data causing the linear fitting to failure. Since the RF-induced phase is spatially smooth, median filtering or other noise suppressing approaches may further improve performance of the algorithm.

Presented here is a computationally inexpensive phase preserving coil combination method for multiple gradient echo sequences. The method allows estimating phase component of the receiver coil sensitivity in coil arrays without a body coil reference by separating the B0-induced phase variation. Although the method has been tested using PSF mapping data, it can be extended to other multi-echo MRI sequences and spectroscopic applications.

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