Phase optimized sensitivity estimation method for SENSE

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Introduction: MR phase images can provide additional structural information beyond magnitude images [1,2]. Because of potential usefulness of MR signal phase, the reconstruction of high quality phase images is important. SENSE [3,4] has proven its accuracy and efficiency to reconstruct magnitude images in many applications. For phase sensitive applications, it is noted that SENSE does not reconstruct an accurate phase image for each echo although it can preserve the dynamic phase changes among echoes [5,6,7]. This may hinder the application of SENSE in structural phase imaging. To obtain the optimal phase image reconstruction using SENSE, one needs the true coil sensitivity profile including both coil reception strength (magnitude) and the corresponding coil reception angle field relative to the object (phase). The conventional square-root-sum-of-squares (may be replaced with other norms) coil sensitivity estimation methods [3,4,8] may provide optimal magnitude reconstruction but it cannot reconstruct optimal phase images. The use of complex body coil image in estimating coil sensitivities may alleviate the issue [9] but it likely introduces the phase difference between body coil and surface coils, and moreover complex body coil images are not available in many applications. This work aims to improve the reconstruction quality for MR phase images using a phase optimized sensitivity estimation method for self-calibrated SENSE. The new sensitivity estimation method can lead to improved phase contrast images.

Methods: The parallel MR image reconstruction using SENSE [3] is given by:

$$\mathbf{p} = (\mathbf{C}^H\mathbf{C})^{-1}\mathbf{C}^H\mathbf{s} \qquad (1)$$

where $\mathbf{p}$ is the object in vector form, $\mathbf{C}$ is the unfolding matrix consisting coil sensitivity profiles, and $\mathbf{s}$ is the measured signal. The SENSE methods rely on the accuracy of the estimated coil sensitivity profiles. In the conventional sensitivity estimation procedure, the sensitivity of each coil is obtained by dividing the corresponding coil image with the square-root-sum-of-squares of the magnitude images in all the coils. The coil sensitivity estimated using this approach is optimized for magnitude image reconstruction, and we denote the resultant sensitivity as C_{mag}:

$$C_{mag} \coloneqq \frac{|s_l|\exp\{j\phi_{s,l}\}}{\sqrt{\sum_l |s_l|^2}} \approx |C_l|\exp\{j(\phi_{c,l}+\phi_p)\} \qquad (2)$$

where $|s_l|$ is the magnitude signal of the $l-\text{th}$ coil and $\phi_{s,l}$ is the corresponding phase, $|C_l|$ is the magnitude sensitivity of the $l-\text{th}$ coil and $\phi_{c,l}$ is the corresponding phase angle, and ϕ_p is the phase of the object. Note that C_{mag} contains not only the phase of the receive coil but also the phase of the object. If we substitute C_{mag} into (1) for SENSE reconstruction, we will obtain a magnitude reconstruction that is optimal w.r.t. the sum of squares of the cost function. However, ϕ_p cannot be optimally solved because it has been embedded in the sensitivity profiles and will be cancelled out with $\phi_{s,l}$ during reconstruction. To overcome this problem, we introduce a new sensitivity profile C_{pha} for improved phase reconstruction performance:

$$C_{pha} \coloneqq \frac{|s_l|\exp\{j\phi_{s,l}\}}{\angle\sum_l |s_l|\exp\{j\phi_{s,l}\}} = \frac{|s_l|\exp\{j\phi_{s,l}\}}{\angle\sum_l |C_l||p|\exp\{j(\phi_{c,l}+\phi_p)\}} = \frac{|s_l|\exp\{j\phi_{s,l}\}}{\exp\{j(\phi_p+\Delta\phi)\}} = |C_l||p|\exp\{j(\phi_{c,l}-\Delta\phi)\} \qquad (3)$$

where $|p|$ is the magnitude of object, and $\Delta\phi$ is the summed phase of all coils and is constant map for all coils. Unlike C_{mag} that contains the phase information of the object, C_{pha} includes the magnitude information of the object. Substituting C_{pha} into (1) can produce an optimal phase reconstruction and the magnitude is cancelled out with $|s_l|$. By the combination of (2) and (3), we can obtain the sensitivity that optimized for both magnitude and phase images:

$$C_{com} \coloneqq |C_{mag}|\angle C_{pha} \approx |C_l|\exp\{j(\phi_{c,l}-\Delta\phi)\} \qquad (4)$$

High spatial resolution MR datasets using Gradient Echo for T2* imaging were acquired in a 12 channel 3T Siemens system and in an 8 channel 7T Siemens system. The in-plane resolution for the 3T data was 0.5 mm^2 and for 7T was 0.25 mm^2. Both C_{mag} and C_{pha} were used to reconstruct complex images. For all the raw sensitivity profiles, we applied a 2D median filter with the size 20 by 20 on magnitude images and a Gaussian filter with std. 6 on phase images. The phase unwrapping was performed using the filtering technique suggested in [2]. The same filter size was applied in all phase images.

Results and discussion: As can be observed in both 3T (panel A in Fig 1) and 7T (panel B), C_{mag} reconstructs greater contrasts in magnitude images (a,e) while C_{pha} reconstructs greater phase contrasts (d,h). The decreased performance of C_{mag} in phase images is due to the phase cancellation during the reconstruction using Eq. (1). Images reconstructed using (4) are omitted here, and the results are similar to (a,e) in magnitude reconstruction and (d,h) in phase reconstruction.

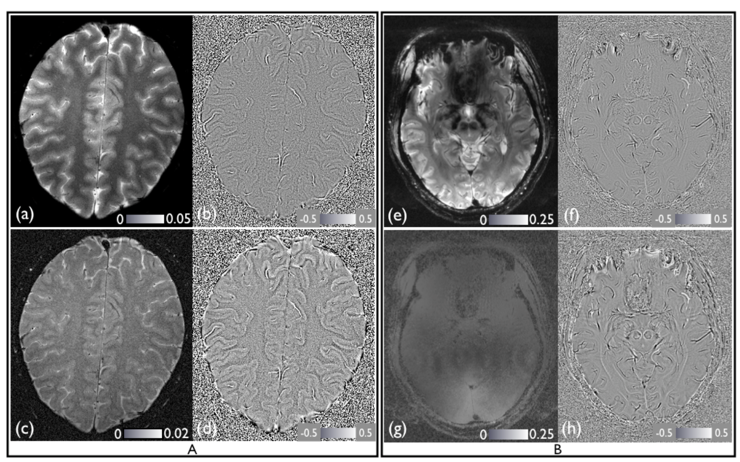

Figure 1: comparison of reconstructed images of 3T in panel A and 7T in panel B. (a,e) magnitude images reconstructed using C_{mag} and (b,f) corresponding phase images. (c,g) magnitude images using C_{pha} and (d,h) corresponding phase images. Phase images are displayed using radians.

Conclusion: In this work, we have provided an improved sensitivity estimation method for MR phase image reconstruction. Demonstrated in both 3T and 7T high resolution MR data, the new method provides improved phase contrast images. The phase optimized sensitivity estimation method is expected to be useful in both structural phase imaging and dynamic phase sensitive imaging applications.

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