The Impact of Parallel Imaging Reconstruction on Image Phase: Implications for Phase-sensitive Imaging

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Introduction: Phase-sensitive MR applications such as multi-point chemical-shift or temperature imaging rely on accurate phase data to measure the phenomenon of interest. In previous studies applying SENSE [1] to phase-sensitive methods [2-4], it was noted that SENSE altered the phase of the combined-coil image, restricting the choice of calibration strategy. Recent work has demonstrated the application of autocalibrated data-driven parallel imaging methods to phase-sensitive imaging [5,6] with no apparent impact on image phase. This work examines the effect of parallel imaging reconstruction on image phase to identify sources of phase perturbation. These findings have important implications for the design of calibration strategies for phase-sensitive imaging.

Theory: In parallel imaging, the reconstructed image is modulated by the ratio of absolute coil sensitivities to calculated coil sensitivities [1]. The calculated coil sensitivity C_n' for coil n can thus be expressed as: $C_n' = C_n / C_{rec}$, where C_n is absolute coil sensitivity and C_{rec} is the modulation function on the reconstructed image. In self-calibrated SENSE [7,8], the calculated coil sensitivity C_n' can be found by dividing calibration data from coil n by the root sum-of-squares of calibration data from all coils, as follows:

$$C_n' = \frac{\sigma e^{i\phi} C_n}{\sqrt{\sum_l \left|\sigma e^{i\phi} C_l\right|^2}} = \frac{\sigma e^{i\phi} C_n}{\left|\sigma e^{i\phi}\right| \sqrt{\sum_l \left|C_l\right|^2}} = \frac{C_n}{e^{-i\phi} \sqrt{\sum_l \left|C_l\right|^2}}$$

where σ is the magnitude and ϕ the phase of the underlying calibration signal. Thus the modulation function in the denominator includes a phase term $e^{-i\phi}$ that depends on the phase of the calibration data. This modulation function imposes a $-\phi$ phase shift on any combined-coil image reconstructed with these coil profiles; thus, the same coil profiles (and hence the same calibration data) must be used for all points in multi-point phase-sensitive imaging in order to preserve the relative phase between points.

Suppose we separate the unaliasing and coil-combination steps and perform coil-by-coil SENSE to create complex images for each coil. The calculated sensitivity profiles now vary as a function of the coil to be reconstructed. The calculated coil sensitivity of coil n when reconstructing target coil m can be calculated:

$$C_n' = \frac{\sigma e^{i\phi} C_n}{\sigma e^{i\phi} C_m} = \frac{C_n}{C_m}$$

. The phase of the calibration data cancels out, so the modulation function in the denominator is equal to the absolute sensitivity of target coil m and is independent of the phase of the calibration data. Any single-coil image reconstructed with these coil profiles will be unaffected by calibration data phase; thus unique calibration data can be used for each point in a phase-sensitive scan and original phase will be preserved.

In any case where the modulation function is equal to the absolute sensitivity of a single coil (i.e. in coil-by-coil reconstructions), the modulation function will be independent of the phase of the calibration data. Because autocalibrated data-driven parallel imaging methods such as GRAPPA [9] or ARC [10] are coil-by-coil methods, they will likewise preserve the original phase of any single-coil reconstructed image. After parallel imaging reconstruction, phase-sensitive processing can be performed on complex individual-coil or combined-coil images [11].

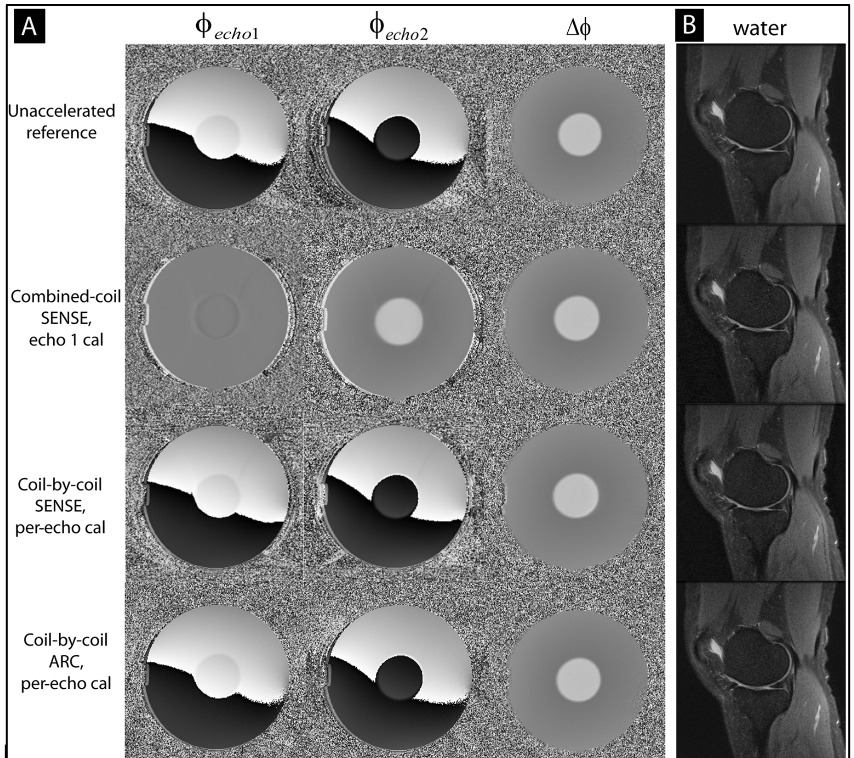

Figure 1. A: Phase images of water-fat phantom (inner cylinder = fat). Only 2 out of 3 echoes are shown, along with their phase difference. Combined-coil SENSE perturbed the phase of both echoes compared to the reference but preserved relative phase. Coil-by-coil SENSE and ARC had no impact on image phase. All images are from coil 1, except combined-coil SENSE. **B: In vivo water images decomposed by IDEAL reconstruction.**

Methods: Phantom and volunteer knee imaging were performed at 1.5T (Signa HDx, GE Healthcare) using an 8-channel coil. Fully sampled data were collected with a 2D fast spin echo sequence modified to acquire 3 echoes with varying water-fat phase shifts. First, unaccelerated images were reconstructed as a reference case. Data were then down-sampled by a factor of 2, with each echo including a central calibration region spanning 24 lines. Accelerated images of each echo were reconstructed using: 1) combined-coil SENSE with calibration data from echo 1 only; 2) coil-by-coil SENSE with calibration on a per-echo basis; and 3) coil-by-coil ARC with calibration on a per-echo basis. Finally, multi-coil IDEAL water-fat separation [12] was performed on all sets of images.

Results: Figure 1A shows phase images for echo 1 (ϕ_{echo1}), echo 2 (ϕ_{echo2}), and their phase difference ($\Delta\phi$) reconstructed using each method. In combined-coil SENSE with echo 1 calibration (row 2), the phase of both echoes is altered from the reference case. Note that the phase of echo 1 is very close to zero; since echo 1 acts as its own calibration data, its phase is subtracted from the final reconstructed image. The phase of echo 1 is similarly subtracted from echo 2, so their relative phase is preserved. If echo 1 and echo 2 had used per-echo calibration, their relative phase would *not* be preserved. For both coil-by-coil SENSE (row 3) and ARC (row 4), the original phases and phase differences are preserved despite their use of per-echo calibration, as predicted by theory. Successful in vivo IDEAL water-fat separation (Fig. 1B) confirms that all methods are compatible with a phase-sensitive reconstruction.

Discussion: This work demonstrates that the impact of parallel imaging reconstruction on image phase depends on the method used. In conventional SENSE, the merged unaliasing and coil-combination steps dictate that only one set of calibration data can be used in a multi-point phase-sensitive scan. When these steps are separated in a coil-by-coil SENSE or ARC approach, original image phase is preserved by parallel imaging reconstruction no matter what calibration data is used. This finding enables the use of flexible self-calibration strategies; for example, calibrating on each point separately may offer improved reconstruction quality when motion or other instability causes coil sensitivity to vary between points. Since phase-sensitive scans usually acquire the same lines for each point to maintain SNR, point spread function, and pulse sequence consistency across points, a per-point calibration scheme could offer better use of available calibration data.

References: [1] Pruessmann et al. 1999; MRM 46:638-51. [2] McKenzie et al. ISMRM 2004, 917. [3] Ma et al. 2005; MRI 23:977-82. [4] Bankson et al. 2005; MRM 53:658-65. [5] Lew et al. ISMRM 2007, 254. [6] Yu et al. ISMRM 2007, 3358. [7] McKenzie et al. 2002; MRM 47:529-38. [8] Wang et al. 2001; 1st Workshop on Parallel Imaging, 92. [9] Griswold et al. 2004; MRM 52;1118-26. [10] Beatty et al. ISMRM 2007, 1749. [11] Roemer et al. 1990; MRM 16:192-225. [12] Reeder et al. 2004; MRM 51:35-45.