A Generic Referenceless Phase Combination (GRPC) Method: Application at High and Ultra-High Fields

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Target audience: Scientists working with multiple receiver coils.

Purpose. Phase imaging is especially important at high to ultra high field strengths, both to map local field inhomogeneities and to highlight important anatomical structures (e.g. with Susceptibility Weighted Imaging, SWI). Although nowadays multiple coils are commonly used for MR image acquisition, accurate phase combination methods are lacking. The most widely used algorithm ("adaptive combine"[1]) is equivalent to the weighted complex sum of the single coil images for phase reconstruction. This approach may lead to destructive coil interferences showing up as phase singularities that cannot be unwrapped since an absolute phase reference is missing. Solutions to this problem either try to estimate individual coil-phase offsets from overlapping coil sensitivities[2], use additional scans as a reference[3,4], or high-pass filter the coil data[5]. These solutions, however, require tailored protocols, specific coil geometries or are only suitable in combination with a specific application, such as SWI, but not B_0 mapping. In this work, we present a generic referenceless phase combination (GRPC) method for accurate phase combination of images from arbitrary protocol and coil configurations that can be used in combination with any application ranging from B_0 mapping to SWI. GRPC was tested in the brain for 24 and 31 coil arrays at 3T and 9.4T.

Methods. In order to avoid artifacts in phase combination images, it is crucial to avoid that the signal from the different coils sum up to zero at any point of the combined images. To this end, we propose to maximize the generic expression

$$z = \max_{\phi_c} \sum_{x,y} \left\| \sum_c I_c(x,y) e^{i\phi_c(x,y)} \right\| \qquad [1]$$

where I_c is the complex signal intensity of the c-th coil element ($c = 1,\ldots,n$) with unknown spatial phase variation ϕ_c. Without loss of generality, the global phase of Eq. [1], arg(z), can be chosen to be zero, yielding a simplified and linearized version of Eq. [1],

$$z \overset{!}{=} \mathrm{Re}[z] = \max_{\phi_c} \sum_{x,y} \sum_c \mathrm{Re}\left[I_c(x,y) e^{i\phi_c(x,y)} \right] \qquad [2]$$

For spatially invariant coil phases, $\phi_c(x,y) = \phi_{c,0}$, i.e., zeroth-order phase approximation, Eq [2] becomes

$$\phi_{c,0} = -\sum_{x,y} \arg\left(I_c(x,y) \right) \qquad [3]$$

i.e., the conjugate phase of the complex signal average of each coil. For spatially variable coil phases, such as linear phase variations ($\phi_c(x,y) = \phi_{c,0} + x\phi_{c,x} + y\phi_{c,y}$, "first order correction"), Eq. [2] can be solved numerically. Imaging was performed with a 24-channel head coil at 3T, using a spoiled gradient echo sequence (TR/TE of 10/2.7 ms, matrix size $256 \times 256 \times 1$) and with a SWI protocol (TR/TE of 30/20 ms), and a 31-channel head coil at 9.4T with a SWI protocol (TR/TE of 40/16 ms, matrix size $512 \times 512 \times 1$). Phase images were reconstructed with *complex sum*, with a constant phase correction calculated from the phase difference between every coil and one reference coil ("*referenced correction*"), and with the proposed *GRPC* method to zeroth and first order.

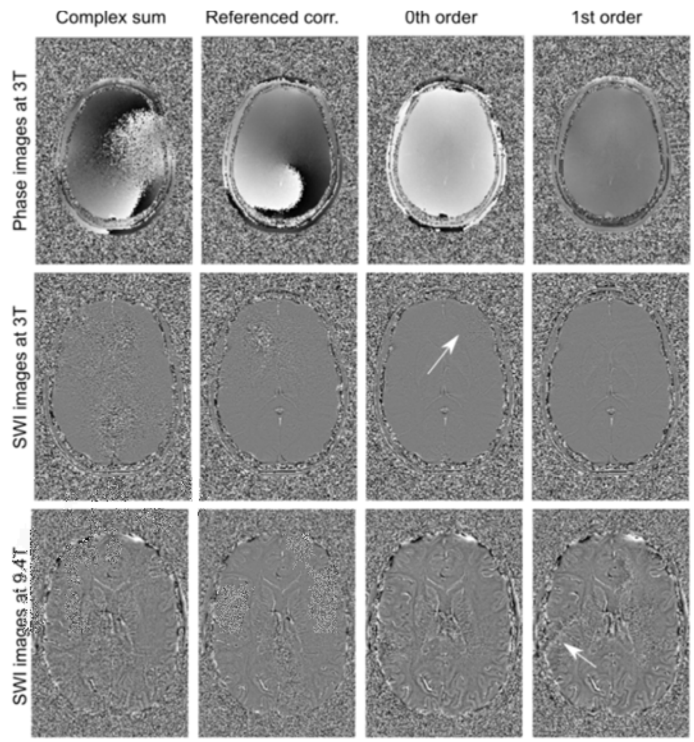

Fig. 1: Different phase reconstructions with different combination methods. The arrows show the most important differences between the 0th and the 1st order corrections.

Results. Illustrative phase images from the short-TE protocol are presented in the first row of figure 1. The *referenced correction* method typically still shows phase singularities, which can be removed with both, 0^{th} and 1^{st} order, GRPC correction. SWI phase images are shown after high-pass filtering for phase unwrapping: At 3T, a small artifact is present for the 0^{th} order GRPC correction, which is removed at 1^{st} order. At 9.4T, some artifacts are still present with both proposed GRCP corrections, but with a higher stability of the 0^{th} order method.

Discussion. The proposed GRPC method does not require any assumption in the scanning protocol or coil geometry (e.g. overlapping areas), therefore allowing widespread application. For large coil arrays, i.e., a very high number of coil elements, not all phase artifacts could be removed, but still the proposed method exhibits a better performance than existing contemporary phase combination techniques. Generally, zeroth order GRPC is faster and possibly more stable, especially in more complex coil sensitivity scenarios, like at ultra-high fields. Since the phase after GRPC is correct modulo a global phase offset, it can readily be used for all phase subtraction methods like B_0 mapping or phase contrast imaging.

Conclusion. A generic referenceless phase combination method was introduced for proper phase reconstruction of multichannel coils, exhibiting good performance even at ultra-high field with a high number of coils, that can be easily implemented for every sequence and scanning requirements.

References. [1]Walsh DO et al. 2000; MRM 43:682; [2]Hammond KE et al. 2008; Neuroimage 39(4):1682; [3]Robinson S et al.; 2011 65(6):1638; [4]Jellus and Kannengiesser, ISMRM 2014; [5]Koopmans et al.; 2008, MAGMA 21:149.