Phase-preserving multi-coil combination with improved intensity modulation

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In an NMR phased array [1] each coil image will contain a different phase offset, due to the coil's geometry, wiring, receiver delays, and electrical properties under varied loads [2]. Due to the prevalence of flexible coil arrays, and as coil loading even in fixed coil setups varies per subject, coil phase offsets cannot be pre-calculated and stored for reconstruction. Coil images are usually combined using the magnitude sum-of-squares (SoS) operation, $S=\sqrt{(\sum S_i^2)}$. The SoS remains popular due to its ease of implementation and no requirements for a priori coil calibrations or measurements. However, aside from discarding phase information, the SoS exacerbates image intensity variation from the coil sensitivities. The intensity modulation grows as the size of individual coil elements get smaller, such as arrays with large numbers of coils.

The phase in each voxel in each coil image consists of phase accrual from field inhomogeneities, gradient and sequence encoding, and the coil receiver phase offset. By relating the phase in each voxel to an arbitrarily designated reference coil, the net phase difference $\theta_{net,i}$ for each of the *n-1* other coils depends only coil phase differences. In the absence of noise and other imperfections, the coil images may be combined by simply calculating the phase difference from one voxel in each coil, subtracting that phase, and summing the images. In practice, the limited spatial sensitivity of coils and inherent noise in the voxels precludes the use of this method. The absence of common coil signal, as well as noise sensitivity, can be handled by modeling the net coil phase offsets between every pair of coils. That is, the phase offset between any two coils can be found by traversing the other coils.

Materials and Methods: The coil-phase compensating reconstruction begins with complex, multi-coil images. An overdetermined linear system **y=Ax** is set up as such: The **x** vector contains the unknown net phase differences between the starting coil and all others, where $\theta(i,j)$ is the phase offset between coils *i* and *j*. The system model **A** maps to the data vector **y** as in Fig 1. For *n* coils, *n(n+1)/2 - 1* comparisons are modeled in **A**. The vector **y** contains the vectorized voxel-by-voxel phase differences for each comparison. Only voxels with sufficient signal in both coil images are used, and the phase difference is found by multiplying with the complex conjugate of the other voxel. Each row representing the comparison in **A** is replicated in **A** for each voxel in ***y*** that makes that comparison. This highly overdetermined system may be inverted and solved in a least-squares sense, giving the coil offsets in **x**. Once the differential coil offsets of the individual coils are determined, the offset is removed by multiplying each image with the corresponding complex conjugate of the phase offset, and the data may be combined into a single complex image.

$$\begin{bmatrix} vec(C_1C_2^*) \\ vec(C_1C_3^*) \\ vec(C_1C_4^*) \\ vec(C_2C_3^*) \\ vec(C_2C_4^*) \\ vec(C_3C_4^*) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ & \vdots & \\ 0 & 1 & 0 \\ & \vdots & \\ 0 & 0 & 1 \\ & \vdots & \\ -1 & 1 & 0 \\ & \vdots & \\ -1 & 0 & 1 \\ & \vdots & \\ 0 & -1 & 1 \\ & \vdots & \end{bmatrix} \cdot \begin{bmatrix} \theta(1,2) \\ \theta(1,3) \\ \theta(1,4) \end{bmatrix}$$

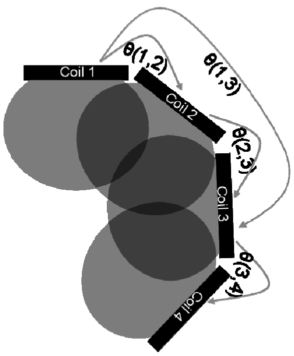

Figure 2. Coil phase estimation for a 4-coil setup. Ellipses in the **A** *matrix indicate replication of the line above.*

The coil phase offset estimation for a 4-coil system is illustrated in Fig 1. Using coil 1 as the starting coil, 3 phase offsets must be estimated. All coil 1 voxels that share enough sensitivity and signal with coil 2 are multiplied by the complex conjugate of the corresponding coil 2 voxel and placed in the **y** vector. This process is repeated for coils 3 and 4. Direct determination of $\theta(1,4)$ is difficult due to lack of sensitivity overlap between coils 1 and 4. By noting that $\theta(2,3) = \theta(1,3) - \theta(1,2)$, three more coil comparisons, $\theta(2,3)$, $\theta(2,4)$, and $\theta(3,4)$, may be modeled in **A** using terms in **x**. This greatly aids the $\theta(1,4)$ determination, as comparisons of coils 2 and 4 and coils 3 and 4 are incorporated.

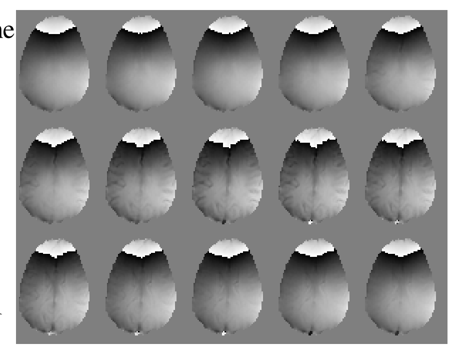

Figure 1. Raw phase maps before unwrapping from an 8-channel array in a DSC experiment. Phase maps through time show the bolus passage, which changes the resonant frequency, accruing phase.

Results Phase preservation is demonstrated in Fig 2. Maps from a bolus tracking experiment that uses 8 channel phased arrays for parallel imaging are shown. Complex coil images can use voxel phase to quantify contrast agent concentration. Even when complex information is not required, the coil-phase compensated combination is useful when many smaller coils are employed, such as in the 16-element 7T head array in Fig 3. The small coils have limited spatial sensitivity, which has two effects. First, direct comparison of voxel phase offsets between two spatially separated coils is not possible, due to few common voxels. Second, the steep sensitivity profiles create large image intensity variations after the SoS combination. This is notable in the posterior of the head in Fig 3, where the head was close to several coils. The coil-phase combination does contain coil sensitivity profiles, though they are less steep, due to the lack of squaring.

Conclusion A simple method to combine multiple receiver channel data, while preserving the complex phase information was presented. This method requires no prior information or calibration of the coils, and is robust against noise and can determine phase offsets between physically separated channels.

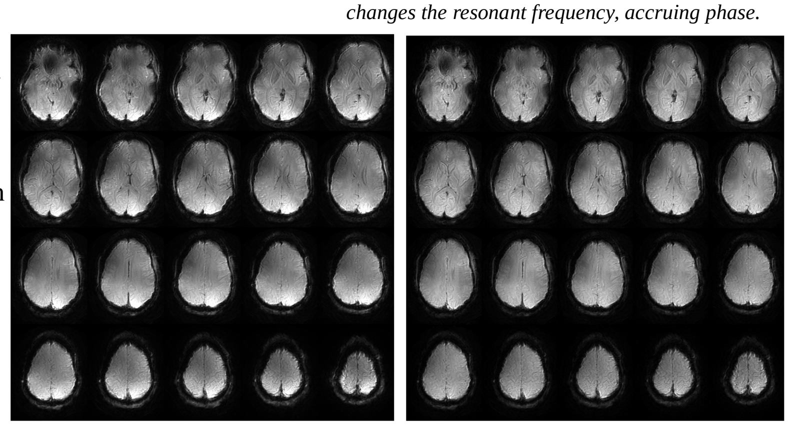

Figure 3. Combined coil images from a 16 Channel array at 7T, without off-resonance or intensity corrections. The sum-of-squares images (left) have a great intensity variation due to the squaring of the very local coil sensitivities. The coil-phase compensated combination (right) has a much flatter intensity profile.

References: [1] Roemer, MRM 16:192-225, 1990. [2] Walsh, MRM 42:682-690, 2000.

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