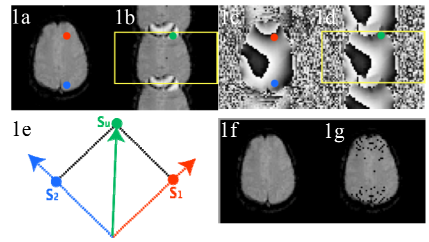
Phase-sensitive Reconstruction based on the Orthogonality (PRO) of under-sampled MRI

N-K. Chen[1]

[1]Brain Imaging and Analysis Center, Duke University, Durham, NC, United States

1. Introduction: To improve the scan efficiency of dynamic MRI, the k-space data may be under-sampled during acquisition and the un-acquired k-space data can be recovered in post-processing using one or more of the following strategies: 1) parallel imaging (Sodickson: MRM 38, 591, 1997; Pruessmann: MRM 42, 952, 1999), 2) partial Fourier method, and 3) UNFOLD technique (Madore: MRM 42, 813, 1999) among others. Here we report a new algorithm to reconstruct under-sampled dynamic MRI, based on the signal orthogonality from voxels separated by half of the FOV. Our data show that the new technique, termed *Phase-sensitive Reconstruction based on the Orthogonality (PRO)*, performs well for data acquired with both single-channel and multi-channel coils, and is complementary to existing fast MRI techniques (e.g., parallel imaging), enabling further reduction of aliasing artifacts in under-sampled MRI data.

2. Theory: Figures 1a and b compare the magnitude images reconstructed from full and under-sampled data (i.e., with even-ky lines zero-filled). As shown, voxels separated by half of the FOV (e.g., the red and blue voxels) may overlap in the under-sampled data (e.g., the green voxel). Using parallel imaging approaches, the two overlapping signals may be decomposed. However, when only one RF coil is used, the parallel imaging is not applicable.

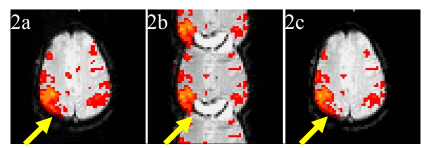


Assuming that the image-domain phase values in dynamic imaging are either time-independent or predictable, it is actually possible to decompose the overlapping signals shown in Fig 1b, even for data obtained from single-channel coil. For example, the phase values of the originally separated red and blue voxels, measured from full k-space data, are 44 and 137 degrees respectively (Fig 1c). If the phase values are stationary, the dynamic amplitudes of the two overlapping signals can be calculated by projecting the dynamically acquired under-sampled signals (e.g., the green vector shown in Fig 1e) into the vector space basis defined from the known phase angles. Basically, the vector amplitudes of two overlapping voxels (S1 and S2) can be solved from Equation 1, where θ1 and θ2 represent the original phase values of two voxels (known from other approaches); and S_U and θ_U are the amplitude and phase values of the under-sampled data where signals from two regions overlap.

$$\begin{cases} S_1 \times cos(\theta_1) + S_2 \times cos(\theta_2) = S_U \times cos(\theta_U) \\ S_1 \times sin(\theta_1) + S_2 \times sin(\theta_2) = S_U \times sin(\theta_U) \end{cases} \quad [1]$$

As shown in Fig 1f, the image reconstructed from the single-channel under-sampled data with Equation 1 is free from the aliasing artifact. In Section 3, a reconstruction scheme is further developed so that the PRO algorithm is applicable even when the phase values change during dynamic scans (e.g., due to Bo drifting in fMRI). It should be noted that, if the vectors from the originally separated two voxels are near parallel or anti-parallel, then the decomposition of two overlapping signals is unstable. Those voxels may be identified (based on the condition number) and excluded from the reconstruction. For example, the voxels with the condition number greater than 100 (or the angles between two vectors in the vector-space basis are smaller than 6-degree) are purposely nulled in Fig 1g. In Section 4, we will address this issue by integrating PRO with SENSE-parallel imaging method (Pruessmann 1999).

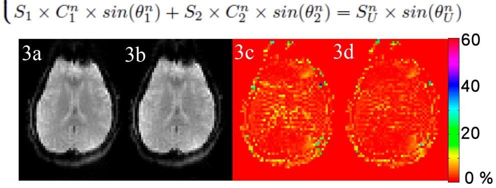
3. Application of PRO method to functional MRI: In fMRI scans, the image-domain phase values may change slowly over time, due to Bo drifting. Therefore, we have designed an acquisition and reconstruction scheme to enable PRO based reconstruction of under-sampled fMRI data (using either single-channel or multi-channel coils), even when the phase values change during fMRI scans.



In our method, a ky under-sampling scheme, similar to that used by UNFOLD and T-SENSE (Kellman: MRM 45, 846, 2001), is chosen. Basically, odd-ky lines are acquired in fMRI time point number 1, 3 5 ... etc; and even-ky lines are acquired in time point number 2, 4, 6... etc. In order to characterize the slowly varying phase terms, the k-space data from two consecutive scans are combined to form alias-free images, from which phase values at every voxels can be measured (at a reduced temporal resolution). After performing the time-domain interpolation of voxel-wise phase values, the phase terms can be estimated for every dynamic scan time point. Afterward, the vector space basis (e.g., as schematically illustrated in Fig 1e) can be defined for every voxels at every dynamic time points, and thus the under-sampled dynamic data can be projected into the vector space basis to reveal the dynamic amplitudes of two overlapping signals (using Equation 1). For example, Fig 2a shows the functional activation map calculated from fully-sampled single-channel data with finger-tapping motor task. Significant activities in sensori-motor area are observed (as indicated by arrows). When the k-space data are under-sampled using the described paradigm, the Fourier transformed images have aliasing artifact and the functional activity in overlapping area cannot be detected due to destructive interference of overlapping signals (Fig 2b). Using the PRO method, alias-free data can be generated and the functional activity can be reliably detected (Fig 2c).

4. Integration of PRO and SENSE-parallel imaging (PRO-SENSE): It is well known that the aliasing artifact in under-sampled data can be reduced using parallel imaging methods (e.g., SENSE), when multiple RF coils with different sensitivity profiles are available. A general limitation in parallel imaging methods is that, when the sensitivity factors from overlapping signals are similar for all coils, then the decomposition of overlapping signals becomes unstable. On the other hand, the PRO algorithm is based on a different mathematical property, with its condition number determined by the angle between overlapping vectors. We found that, by integrating the SENSE-parallel imaging and PRO methods into a unified mathematical framework (termed PRO-SENSE), the condition number can be further reduced. Basically, those overlapping voxels with a large PRO-condition number can be solved with SENSE, and the overlapping voxels with a large SENSE-condition number can be solved with PRO. For parallel imaging with an acceleration factor of 2 based on n-channel RF coils, the signal amplitudes of two overlapping voxels (S1 and S2) can be solved by Equation 2, where θ^k_1 and θ^k_2 represent the original phase values of two voxels for coil number k (known from other approaches: see Section 3); S^k_U and θ^k_U are the amplitude and phase values of the under-sampled data for coil number k (where signals from two areas overlap); and C^k_1 and C^k_2 are the coil sensitivity factors in voxels 1 and 2 for coil number k.

$$\begin{cases} S_1 \times C_1^1 \times cos(\theta_1^1) + S_2 \times C_2^1 \times cos(\theta_2^1) = S_U^1 \times cos(\theta_U^1) \\ S_1 \times C_1^1 \times sin(\theta_1^1) + S_2 \times C_2^1 \times sin(\theta_2^1) = S_U^1 \times sin(\theta_U^1) \\ S_1 \times C_1^2 \times cos(\theta_1^2) + S_2 \times C_2^2 \times cos(\theta_2^2) = S_U^2 \times cos(\theta_U^2) \\ S_1 \times C_1^2 \times sin(\theta_1^2) + S_2 \times C_2^{21} \times sin(\theta_2^2) = S_U^2 \times sin(\theta_U^2) \\ \cdots\cdots\cdots \\ \cdots\cdots\cdots \\ S_1 \times C_1^n \times cos(\theta_1^n) + S_2 \times C_2^n \times cos(\theta_2^n) = S_U^n \times cos(\theta_U^n) \\ S_1 \times C_1^n \times sin(\theta_1^n) + S_2 \times C_2^n \times sin(\theta_2^n) = S_U^n \times sin(\theta_U^n) \end{cases} [2]$$



Figures 3a and b compare the fully-sampled EPI image and PRO-SENSE reconstructed under-sampled data, demonstrating the successful removal of aliasing-artifact in under-sampled data using PRO-SENSE. We have also compared the residual artifacts in SENSE reconstructed image (Fig 3c) and PRO-SENSE reconstructed image (Fig 3d). Our data show that, using the PRO-SENSE method, the residual error is further reduced by 15% as compared with the conventional SENSE-only reconstruction.

5. Conclusions: Using the novel PRO and PRO-SENSE algorithms, alias-free images can be reconstructed based on the orthogonality properties of under-sampled dynamic MRI data. The new technique is applicable to data obtained with both single-channel and multi-channel coils, and can be integrated with existing fast MRI methods (e.g., SENSE and UNFOLD) to further reduce aliasing artifacts.