Nonlinear Magnitude-Constrained Estimation of Image Phase for Accelerated Flow Imaging

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Introduction: Partial Fourier imaging with asymmetrical *k*-space sampling is a popular method to reduce MR scan times. Zero-filling the partial *k*-space data degrades image resolution compared to full *k*-space sampling and may introduce truncation artifacts. Partial Fourier (PF) algorithms such as homodyne [1] and POCS [2] are designed to synthesize the unsampled high spatial frequency content of image magnitude. However, standard PF methods are not capable of full resolution image phase recovery [3]. This limits the potential of partial *k*-space sampling for high resolution phase contrast (PC) imaging.

In this work, we describe a new partial *k*-space technique capable of full resolution image phase restoration. In standard PF algorithms, a low resolution image phase is used for image magnitude reconstruction. In our approach, the full resolution image phase is estimated using an image magnitude from a separate scan as a constraining function. If image magnitudes are consistent among multiple acquisitions, for example PC flow encoding, then efficient data reduction approaches may be designed using the method described next.

Theory: Estimation of a complex image from a vector of *k*-space values **s** is equivalent to the minimization of a residual norm $\left\|\mathbf{s}-\mathbf{EM}\exp\left(i\boldsymbol{\varphi}\right)\right\|_2$, where **E** is the matrix of Fourier coefficients, **M** is a diagonal matrix with image magnitude values on the main diagonal, and $\boldsymbol{\varphi}$ is a vector of image phase values. A nonlinear magnitude-constrained phase estimation algorithm, as illustrated in Fig. 1, was derived minimizing the residual with respect to $\boldsymbol{\varphi}$ and treating **M** as a known function.

Methods: We validated the new technique in numerical simulations on a Shepp-Logan phantom (SLP). The image phase was arbitrarily varied for small structures representing vessels in the range [-π,π]. The image phase was estimated from slightly more than half (52%) *k*-space data using image magnitude as a constraining function.

The technique was also validated in in-vivo measurements of flow in the carotid and vertebral arteries. Two series of axial 2D cine images were acquired using a standard interleaved phase contrast sequence (TE/TR=3.6/8.2 ms, no view sharing. VENC=150 cm/s, fractional echo 0.75) on a 3T system (GE Healthcare, EXCITE TwinSpeed) with flow encoding in the S/I and I/S directions. The data reduction scheme used in the study is shown in Fig. 2. The first flow encoded dataset was used in full, and only 52% of phase encoded lines of the other dataset were utilized for phase estimation (total 76% data). Five iterations were applied resulting in a total of 6 s reconstruction time per image (MATLAB implementation).

Results: After 15 iterations of the proposed technique with the Shepp-Logan phantom, the RMS error for image phase was reduced from 68% (zero-filled reconstruction) to 0.0004% (not shown here). In the in-vivo simulation, we found that there is a strong correlation between the magnitudes of individual flow encodes. The zero filled reconstruction showed substantial phase errors (Fig. 3), and led to significant underestimation of flow in both carotid and vertebral arteries (up to 35% flow underestimation for both arteries). The new method provided accurate flow quantification with RMS error ~1% (Fig. 4).

Discussion: Both traditional PF methods and the proposed method exploit partial *k*-space sampling for data reduction. However, unlike standard PF, the new technique targets image phase restoration. The proposed data reduction scheme is feasible, if the image magnitude correlates in the repeated acquisitions. Essentially, the new method provides means to share image magnitude information between individual scans while limiting data collection only to the level necessary for image phase estimation. The new method highlights a new perspective to MRI data acquisition/reconstruction.

We demonstrated applicability of the method for 1D PC flow quantification with total data reduction to 76%. As the number of datasets increases (3-directional PC flow measurements), the cost for obtaining the constraint may be further amortized to improve acquisition speed. (62.5%) The method may be particular useful for high resolution PC angiography, when phase information is required for depiction of small vessels [4]. The applicability of the technique to other PC methods such as temperature mapping and echo-planar spectroscopic imaging (EPSI) is under investigation. Another interesting research topic would be to modify the method for parallel MRI data reconstruction. Image magnitude constraints may have regularizing effect similar to that of the phase constraints [5].

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References: [1] Noll D, et al. IEEE TMI 1991, 10(2):194. [2] Haacke EM, et al. JMR 1991, 92:126. [3] Foo TKF, ISMRM 2000, 1718. [4] Gu T, et al. AJNR 26:743. [5] Samsonov AA, et al. MRM 2004, 52:1397.

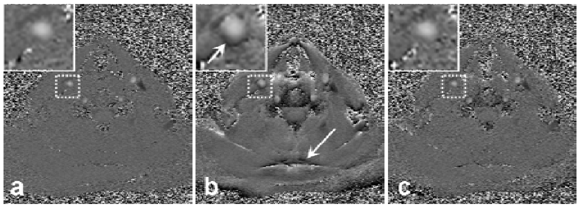

Figure 3. Image phases obtained from reference data (a), with zero-filled reconstruction (b), and the new method (c). Magnified ROI is in upper left corner. Phase errors present in zero-filled reconstruction (white arrows) are not seen with the new method.

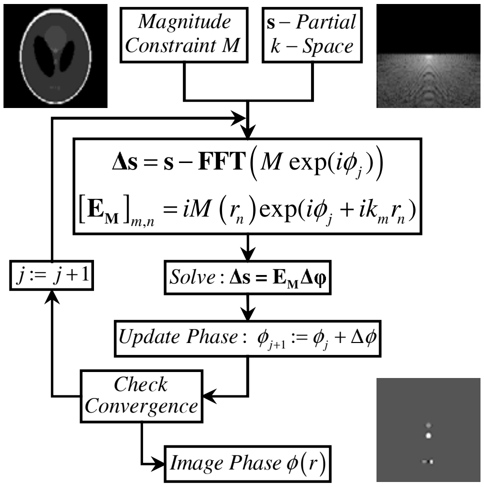

Figure 1. Flowchart of the proposed partial Fourier method for full resolution image phase estimation.

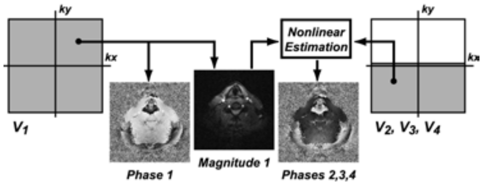

Figure 2. Accelerated PC flow velocity mapping (3D case, *V1-V4* are individual flow encoded datasets).

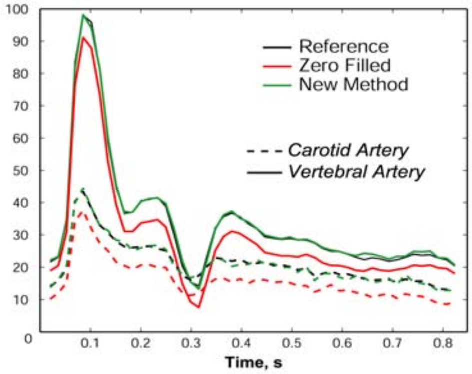

Figure 4. Arterial flow (one cardiac cycle) estimated from PF data with different methods. Zero-filled reconstruction underestimated flow up to 35%.