Dual-Polarity GRAPPA for the Robust Reconstruction of Multi-Channel EPI Data

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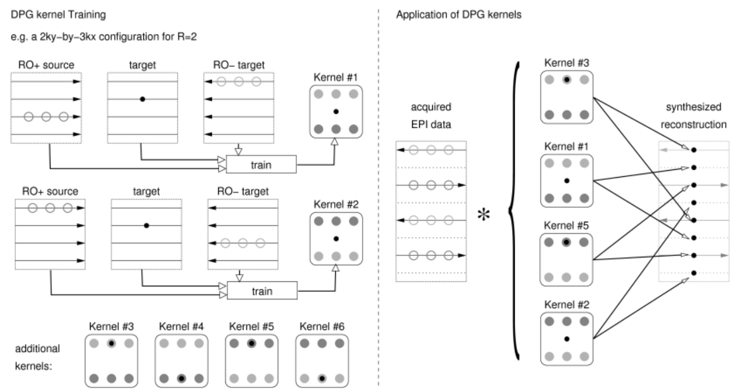
Target Audience: Physicists/Engineers interested in improved image quality of EPI-BOLD fMRI data, particularly at ultra-high field.

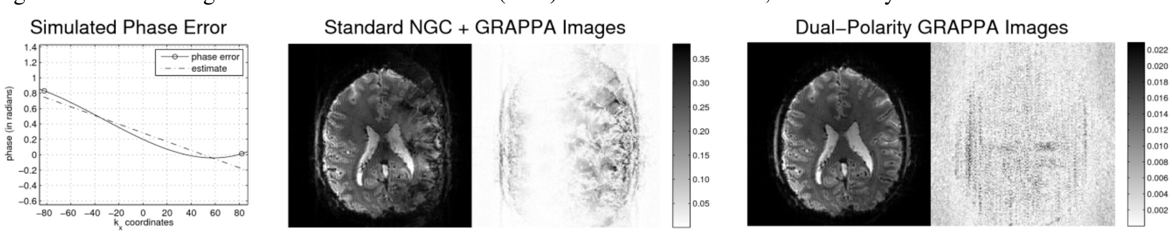
Purpose: Echo-planar imaging (EPI) is the sequence of choice for a variety of neuroimaging applications. Multiple artifacts are often present in EPI images, however, including Nyquist ghosts which occur when there is a mismatch between data sampled on positive readout gradients (RO+) vs. negative readout gradients (RO−) in the EPI echo train. Conventional methods model this sampling mismatch as a linear and constant phase error between the RO+ and RO− data, as measured in hybrid x-k_y space. In ultra-high field EPI experiments using surface-coil receive arrays, we have found this model to be insufficient, as previously reported[1]. To address this issue, we present the *Dual-Polarity GRAPPA* (DPG) method and demonstrate its ability to correctly estimate non-linear EPI phase errors. This method embeds the ghost correction parameters within a GRAPPA-like kernel to provide a high-order Nyquist ghost correction (NGC) parameterization. In addition, NGC consistency between the calibration and acquired accelerated data is maintained, which can also improve image quality[2].



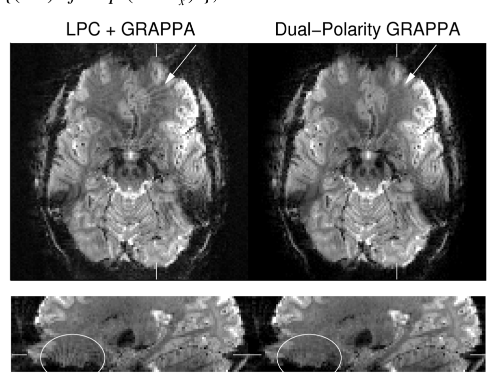
Methods: With DPG, we seek to directly reconstruct raw EPI data. Current methods to reconstruct accelerated EPI data involve two distinct steps: ghost correction of the accelerated data, followed by the application of a pMRI method such as GRAPPA. If the NGC in the first step is inaccurate—due to non-linear phase errors, for example—image quality will suffer. To enable proper correction of non-linear phase errors, we employ multiple GRAPPA-like kernels. As shown in the figure at right, each DPG kernel synthesizes k-space data from RO+ and RO− data in equal parts, without prior ghost correction.

The calibration of DPG is similar to GRAPPA, except three fully-sampled data sets are required: ghost-free target, RO+, and RO−. These data are acquired via segmented EPI using temporal encoding. Ghost-free target image data is then constructed using GESTE for multi-shot EPI[3]. Fully sampled RO+ and RO− data is formed through appropriate sorting of all EPI segments. Once in place, weights are trained for multiple DPG kernels. To reconstruct an image, these kernels are convolved with the raw EPI data, using an appropriate kernel for each line of k-space. Due to the Nyquist ghost correction character of the DPG kernel, each line in the output image contains synthesized k-space. This is in contrast to traditional GRAPPA, where only missing k-space lines are synthesized.

EPI data was acquired on a 7T Siemens Trio MR scanner, using a 32-receive-channel head coil. The EPI sequence employed a custom FLEET-GESTE[4] pre-scan for temporal encoding of the ACS calibration data. Accelerated single-shot gradient-echo EPI data were then acquired with 1.5×1.5 mm^2 in-plane resolution, TE:25 ms; TR:2000 ms; BW:1776 Hz/pix; flip angle:75°, 128×128 matrix size, no partial-Fourier, nominal echo-spacing:0.67 ms, R=3 acceleration, 126 reference lines, 37 interleaved slices, with axial slice thickness 1.5-mm (no gap). Conventional images were formed by first ghost-correcting the EPI data using the Local Phase Correction (LPC) method of Feiweier[1], followed by GRAPPA. Both DPG and GRAPPA employed a $2k_y$-by-$5k_x$ kernel size.



To demonstrate the correction of high-order phase errors, an accelerated acquisition was simulated by R=4 sub-sampling of ghost-free target data. Phase errors were then introduced in hybrid, $\{x,k_y\}$, space according to the function $\tilde{k}(x,k_y,c) = k(x,k_y,c)\sum_{i=0}^{3}\exp\{(-1)^l\ j2\pi\ p_i(x/N_x)^i\}$, with $\{p_0,p_1p_2p_3\}=\{0.2, -1.25, -1.0, 1.2\}$, and l to shift lines either left or right.



Results: The simulation results, above, show that even in the presence of exaggerated high-order phase errors, the standard NGC approach performs well only in the linear region. In the paraboloic phase error region, the conventional approach breaks down and high artifact levels are present. In contrast, DPG produces a predominantly artifact free image. In-vivo images comparing the DPG method to a conventional approach are shown at right. In the upper right of the axial slice shown, significant phase interference artifacts are present in the LPC+GRAPPA method. These artifacts affect a number of slices above the paranasal sinuses, marked by the circle in the lower image. Our novel DPG method effectively mitigates most of these artifacts by providing improved ghost correction, resulting in significantly better image quality.

Discussion: Our results demonstrate that DPG is capable of automatically correcting higher-order EPI phase errors, without requiring an explicitly defined high-order phase error model a-priori. Furthermore, tSNR[5] measurements (not shown) in multiple subjects suggest that DPG will perform as well or better than traditional GRAPPA in fMRI studies.

References: [1] Feiweier T., 2013. US Patent 8,497,681. [2] Polimeni, Setsompop, Hoge. *Proc. ISMRM* 2014; 4397. [3] Hoge, Tan, Kraft, Polimeni. *Proc ISMRM* 2014; 1638. [4] Polimeni JR, et. al. *Proc ISMRM* 2013; 2646. [5] Triantafyllou, Polimeni, Wald. *Neuroimage* 2011;55(2):597–606. **Support:** NIH NIBIB K01-EB011498.