Correction of EPI Nyquist Ghosts via GESTE with Spatial Calibration

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Introduction: Nyquist ghosting is a common artifact in EPI imaging. Recently, Hoge, et. al., proposed the Ghost Elimination via Spatial and Temporal Encoding (GESTE) method [1], which has demonstrated improved ghost correction performance relative to previous methods. One drawback of GESTE, however, is that two temporally encoded images are required to calibrate the parallel imaging reconstruction parameters required for image formation. This currently limits the method to applications where a temporal series of EPI images is acquired. In this work, we demonstrate that useful calibration data can be constructed by employing the necessary encoding along the slice dimension instead. This enables the method to be used in applications were only a single volume of data is acquired, such as Diffusion Tensor Imaging and T1 mapping with EPI.

Methods: In most EPI applications where a volume of data is acquired, at low resolution there is often considerable similarity between neighboring slices. This often carries over to the parallel imaging reconstruction parameters that are derived from the low resolution data. Our approach here is to leverage this spatial domain similarity to generate GRAPPA parameters of sufficient accuracy to employ in GESTE ghost correction. To calibrate GESTE using Spatial Calibration (GESTE-SC), we modulate the polarity of the 2D EPI readout gradients according to slice number. For the first line of k-space, odd slices are acquired using a positive readout gradient and even slices are acquired using a negative readout gradient. Data from neighboring slices can then be interleaved and filtered to form calibration data acquired on each readout polarity.

To form the calibration data, data from slice *n* is split into two sets: one for each readout polarity (positive and negative), each with an effective sub-sampling of 2x. To temporarily estimate the missing lines in each set, k-space data from the two neighboring slices, (*n-1*) and (*n+1*) are separated by readout polarity and averaged. This synthetic slice data is then merged with slice *n* to form two images---one with even lines from *n* and odd lines averaged from (*n-1*) and (*n+1*), and a second with odd lines from *n* and evens lines averaged from (*n-1*) and (*n+1*)---each with data at the full Nyquist rate and the same polarity. Because this calibration data is formed from three slices, Nyquist ghosts are likely. However, as with temporal encoding, Nyquist ghosts that are present in each positive or negative readout image will cancel when the images are coherently combined as in PLACE [2].

To estimate the GRAPPA reconstruction parameters for each slice, we employ a conjugate-gradient solver. With the assumption that variation in the GRAPPA parameters between slices should be small, we initialize the solver using coefficients from a neighboring slice. Reconstruction of the full volume starts from a set of three slices in the center that show the most commonality. Further, we limit the number if CG iterations to be 1/4 the full dimension of the system matrix. These constraints limit the variability in the GRAPPA parameters along the slice dimension, giving better stability in the estimation. Once GRAPPA parameters have been calculated, image reconstruction proceeds as in GESTE [2]. The original k-space data for each slice is separated by readout polarity, each effectively accelerated at 2x. GRAPPA is employed to estimate missing data in each set, and then the two sets are coherently combined to form the final image.

Results: GESTE-SC was tested on in-vivo EPI data of the human brain acquired using a standard 8-channel head coil on a 1.5T GE Signa (EPIC 14) MR scanner (GE Healthcare Systems, Milwaukee, WI, USA). Imaging parameters were: TR/TE= 2500 msec / 40 msec; slice thickness= 5 mm; FOV= 24 x 18 cm; image size= 64 x 48; 26 axial slices. We acquired two image volumes, each with alternating polarity readouts along the slice dimension, and with readouts in the second volume of opposite polarity from the first volume (temporally encoded). This enabled the images to be constructed both by GESTE and the method proposed here. We employed a 2x5 kernel for GRAPPA, yielding 80 ($2\ k_y \cdot 5\ k_x \cdot 8$ coils) reconstruction parameters.

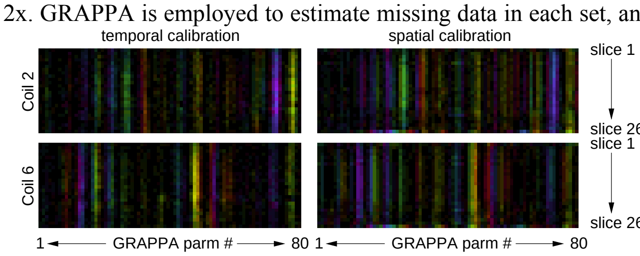

Fig 1: Comparison of (left) GRAPPA coefficient variability along the slice dimension for GESTE for two coils, and (right) the corresponding GRAPPA parameters estimated by GESTE-SC.

The left column of Fig 1 shows the GRAPPA parameters across all slices for two coils, as estimated from two volumes by GESTE. Pixel brightness/color corresponds to parameter magnitude/phase. The most notable feature is the low variability—particularly in the phase–of the GRAPPA coefficients across all slices in the volume. The right column of Fig 1 shows the corresponding GRAPPA parameters as estimated from a single volume via GESTE-SC. These parameters closely mimic the GESTE versions, suggesting the reconstructions should be quite similar.

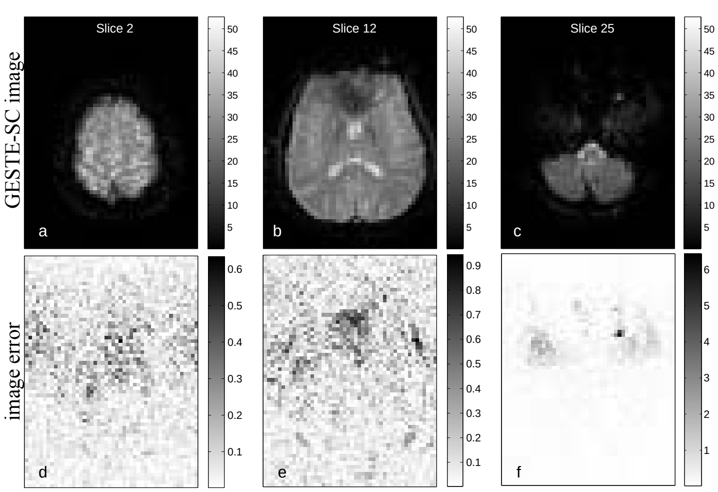

Fig 2: (top) 3 axial images reconstructed using GESTE-SC, (bottom) images of the difference between GESTE-SC and GESTE images to illustrate GESTE-SC errors.

The top row of Fig 2 shows three slices from the image volume reconstructed using GESTE-SC estimated GRAPPA parameters. These slices correspond to an upper/middle/lower slice in the volume, and represent the min/average/max reconstruction error per slice compared to the GESTE calibrated images. We note that for the majority of slices, the maximum difference in pixel value between the GESTE and GESTE-SC images are on the order of (0.9/50=) 1.8%. In the slice with the largest difference, the error is concentrated in a region of high spatial contrast.

Discussion: GESTE is an effective approach to reconstruct ghost free images from EPI data. We have shown here that the encoding necessary to calibrate GRAPPA for use in GESTE can be effectively performed in a single volume, by alternating the readout polarity of alternate slices. We anticipate that the ability to calibrate GESTE using spatial calibration will extend its usefulness in applications that do not rely on a temporal series of EPI data, such as DTI and T1 mapping.

References: [1] Hoge, Tan, Kraft. MRM 2010 (early view); [2] Xiang, Ye. MRM 2007;57:731–741.

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