Full and hybrid 2-dimensional navigator echo correction: new techniques to suppress respiratory-induced physiological noise in echo-planar functional MRI

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Introduction

The spatio-temporal variation of magnetic field inhomogeneities in the brain due to normal subject respiration is a troublesome problem in fMRI, and particularly so at higher fields where sources of physiological noise can nullify potential gains that one may expect from increases in signal-to-noise ratio and blood oxygenation level-dependent (BOLD) contrast-to-noise ratio (CNR) [1]. An assumption held since 1994 is that field inhomogeneities induced by respiration are approximately uniform in an axial slice, and thus a global measurement and correction would be appropriate [2]. However, recent magnetic field measurements using RASTAMAP [3] show clear spatial variations in the field inhomogeneities between full inhalation and exhalation, suggesting that current correction strategies may not be adequate. Global and 1-dimensional (1D) navigator echo corrections applied to simulated fMRI data acquired using a 2-shot echo-planar imaging (EPI) sequence under the influence of the measured respiratory-induced frequency offset map (FOM) demonstrated both reductions and amplifications of this noise throughout an axial image [4]. Therefore, our goal was to develop a new 2-dimensional (2D) navigator echo correction technique to improve the suppression of respiratory-induced physiological noise in fMRI.

Methods

Experiments were performed on a Varian *Unity* INOVA whole-body 4 Tesla MRI scanner (Palo Alto, CA) with a Siemens Sonata gradient coil (Erlangen, Germany), and simulations were implemented using custom software written in MATLAB 7.0 (MathWorks, Natick, MA). Global and 1D navigator echo corrections are implemented as previously described [2,4]. A 2-shot 64 x 64 EPI sequence is simulated (TE = 22 ms, TR = 525 ms) to investigate the peak-to-peak respiratory-induced intensity fluctuation within an axial slice of a typical whole-brain fMRI experiment. In these experiments, the less-preferred gradient orientation is chosen (read in left-right direction and phase encode in anterior-posterior direction) [4] to investigate the performance of 2D navigator echo correction over either global or 1D correction using this gradient configuration.

<u>Full 2D Correction</u>

Step 1: By monitoring the phase of the center of k-space, select a complex reference image I_{ref} with minimal phase offsets from functional images collected at the beginning of each functional run.

Step 2a: As the FOM is modulated by the respiration cycle, separate estimates of ΔB must be made for k-space data acquired after each radiofrequency (RF) pulse. Estimate $\Delta B_{top} = \{\phi(I_{cur}) - \phi(I_{ref})\} / TE$ for each image, where I_{cur} and I_{ref} are formed using the inverse Fourier transform of only the top halves of k-space.

Step 2b: Repeat Step 2a to estimate ΔB_{bot} using only the bottom halves of k-space.

Step 3: Construct two complex N^2 x N^2 matrices G and D. G is the ideal encoding matrix where each row contains only the phase map in image space due to the gradients, and D is the distorted encoding matrix where each row contains the phase map due to both the gradients and the field inhomogeneities ΔB.

Step 4: If k_{acq} is the acquired k-space data (an N^2 x 1 vector), then $k_{acq} = Dm$, where m is the desired image. The corrected image is then $k_{2Dcor} = Gm = (GD^{-1})k_{acq}$ where D^{-1} is calculated by direct matrix inversion.

<u>Hybrid 2D Correction</u> (Steps 1, 2a, and 2b are the same as above.)

Step 3: Define a δ x δ square region in the center of k-space ($1 \leq \delta \leq N$). Construct G and D as above, but they now have dimensions of δ^2 x N^2. D^{-1} is now the N^2 x δ^2 pseudo-inverse of D.

Step 4: k_{center} is a δ^2 x 1 vector consisting of the data acquired in the center of k-space. The 2D corrections are applied to these data and $k_{center,2Dcor} = (GD^{-1})k_{center}$.

Step 5: Apply a global navigator echo correction to the remaining ($N^2 - \delta^2$) periphery points of k-space.

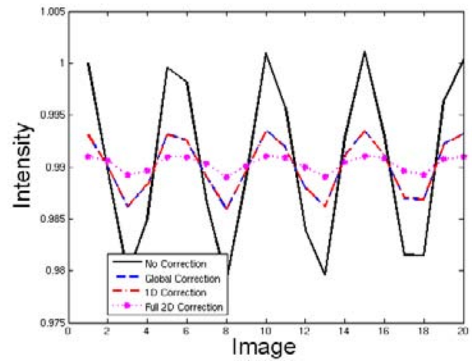

Figure 1: Normalized peak-to-peak pixel intensity fluctuation for an ROI with no navigator echo correction (2.22%), global correction (0.759%), 1D correction (0.752%), and full 2D correction (0.199%). Full 2D correction reduced this noise by an additional 0.55% beyond global or 1D correction.

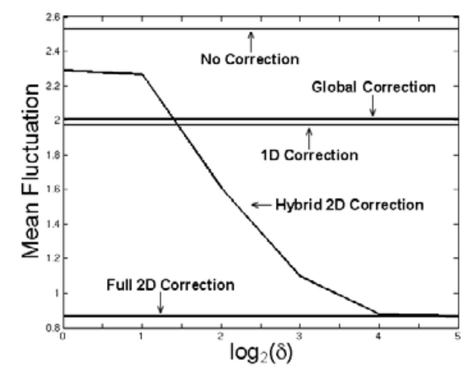

Figure 2: Mean percentage noise fluctuation within the gray matter ROI (acquired using a 2-shot EPI sequence) with hybrid 2D navigator echo correction for δ = 1, 2, 4, 8, 16, and 32. The mean noise fluctuation with no correction, global correction, 1D correction, and full 2D correction are shown for comparison. When δ = 16, the performance of hybrid 2D correction is virtually identical to full 2D correction.

Results

Figure 1 displays the evolution of the intensity for a representative single pixel region of interest (ROI) in gray matter. Intensity changes are due solely to the presence of the respiratory-induced FOM model [4]. The peak-to-peak signal intensity fluctuation is 2.22% with no phase correction, and decreases to almost identical values of 0.759% and 0.752%, respectively, for global and 1D corrections. This fluctuation is further decreased to 0.199% with full 2D correction, clearly demonstrating the usefulness of a robust 2D navigator echo correction technique in reducing this source of physiological noise by a full order of magnitude.

Discussion

Full 2D navigator echo correction may be considered the "gold standard" in suppressing respiratory-induced physiological noise in multi-shot EPI; however, it comes at a significant cost of both memory and computation time. *A priori* knowledge that these induced magnetic field inhomogeneities vary slowly in space [4] suggests that phase distortions will manifest themselves primarily in the low-frequency region of k-space. Rigorous 2D phase corrections should therefore be most beneficial when applied to the central δ x δ square region of k-space. Thus, the proposed partial 2D / global (i.e., hybrid) correction technique is a compromise between correction accuracy and execution time. Figure 2 shows the *expected value* of peak-to-peak noise fluctuations for δ = 1, 2, 4, 16, and 32 in a large ROI consisting of several hundred gray matter pixels. When $\delta > 4$, this noise level is decreased beyond the levels achieved using global and 1D corrections. Furthermore, when $\delta \geq 16$, the noise fluctuations are reduced to a level comparable to what is achievable using full 2D correction. Whereas full 2D correction may require several minutes to process each 64 x 64 image, hybrid 2D correction with δ = 16 requires only a few seconds per image, making it feasible to apply this technique to typical fMRI data sets that consist of thousands of individual 2D images. Future work will investigate extensions of this hybrid 2D navigator echo correction technique so that it may be used in the retrospective suppression of physiological noise in high-resolution fMRI studies utilizing 4 or 8-shot EPI sequences.

References

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